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FINAL REPORT

IMPROVED ROOF STABILIZATION TECHNOLOGIES

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TABLE OF CONTENTS

LIST OF FIGURES	ii
LIST OF TABLES	ii
1.0 INTRODUCTION	1
1.1 Background	1
1.2 Problem Statement	1
1.3 Research Objectives	1
2.0 ROOFING MANAGEMENT	2
2.1 Introduction	2
2.2 Key Elements of Roof Management	2
2.3 Roof Systems Information	3
3.0 MODEL DEVELOPMENT	5
3.1 Introduction	5
3.2 Traditional Roof Performance Prediction Modeling	5
3.3 Artificial Neural Networks (ANNs)	6
3.4 Classification of ANNs	6
3.5 Data Generation	8
3.5.1 Data Preparation	9
3.6 Training	10
3.7 Result	15
3.8 Evolutionary Computation	15
3.8.1 General	15
3.8.2 Application	15
3.8.3 Operators	16
3.9 Development of EA Model	16
3.9.1 Data Generation	16
3.9.2 Training	16
3.9.3 Results	16
4.0 ROOF INSPECTION PROCEDURES	21
5.0 MAINTENANCE AND REHABILITATION STRATEGIES	23
6.0 ECONOMIC ANALYSIS OF ROOFING PROJECT	25
6.1 Mathematical Formulation of Life-Cycle Cost Algorithm	26
6.2 Definition of Maintenance Strategies	28
7.0 Roof Product Information System	29
8.0 SUMMARY	39
9.0 REFERENCES	40
APPENDIX. Annotated Bibliography	

LIST OF FIGURES

Figure 1. Roof management process.....	3
Figure 2. Roof systems information.....	4
Figure 3. Scatter plot of Flashing Condition Index versus Roof Condition Index.....	10
Figure 4. Scatter plot of Membrane Condition Index versus Roof Condition Index.....	11
Figure 5. Scatter plot of AGE of roofing system versus Roof Condition Index.....	12
Figure 6. Predicted and Target values using the ANN.....	13
Figure 7. Scatter plot of Truthful and Predicted Values of RCI (Roof Condition Index).....	18
Figure 8. Evolutionary Algorithm.....	19
Figure 9. Hierarchical Migration.....	19
Figure 10. Sexual Crossover.....	20
Figure 11. Asexual Crossover.....	20
Figure 12. Maintenance and rehabilitation strategies at specific sites.....	23
Figure 13. Economic analysis of replacement costs.....	26
Figure 14. Main Switchboard.....	30
Figure 15. View/Add Company Data.....	31
Figure 16. Roofing Company Information.....	32
Figure 17. Roofing Products.....	34
Figure 18. View/Add Product.....	35
Figure 19. Roofing Company Summary Information.....	36
Figure 20. Roofing Products Summary.....	37
Figure 21. Company Product Details.....	38

LIST OF TABLES

Table 1. Sample of data from Micro ROOFER program.....	9
Table 2. Maintenance strategies in life-cycle cost algorithm.....	28

1.0 INTRODUCTION

1.1 BACKGROUND

Many U.S. Department of Energy (DOE) remediation sites have performed roof repair and roof replacement to stabilize facilities prior to performing deactivation and decommissioning (D&D) activities. This project will review the decision criteria used by these DOE sites, along with the type of repair system used for each different roof type.

Based on this information, along with that compiled from roofing experts, a decision-making tool will be generated to aid in selecting the proper roof repair systems. Where appropriate, innovative technologies will be reviewed and applied to the decision-making tool to determine their applicability. Based on the results, applied research and development will be conducted to develop a method to repair these existing roofing systems, while providing protection for the D&D worker in a cost-efficient manner.

1.2 PROBLEM STATEMENT

Deactivation and decommissioning (D&D) activities require that personnel have access to areas of structures (for example, a roofing system), some of which are more than 40 years old. In many cases, these structures have remained in a bad condition for many years. Very little preventive maintenance has been performed on them due to lack of funding or a defined plan of action. This situation has led to rapid deterioration of the existing roofing system, sometimes worsening already unsafe working conditions. In addition, deterioration models are not available for roofing systems to assist maintenance engineers and upper management in making consistent and cost-effective decisions related to the maintenance and rehabilitation of roofs.

1.3 RESEARCH OBJECTIVES

The objectives set out in the project are as follows :

1. Visit relevant sites and perform roof distress survey.
2. Perform condition assessment of roofing materials at related sites.
3. Compile a bibliography of existing roof maintenance and rehabilitation literature.
4. Redevelop a roofing deterioration model using evolutionary algorithm modeling from roof data obtained from USACERL (United States Army Corps of Engineers Construction Engineering Research Laboratories).
5. Develop a roof information system.

2.0 ROOFING MANAGEMENT

2.1 INTRODUCTION

Roof maintenance and rehabilitation decision-making is based on current (measured) and future predicted roof conditions. Therefore, accurate predictions of future roof conditions are essential for the effective maintenance, rehabilitation, and reroof decision-making. Unfortunately, roof condition data are very limited, and it is difficult to obtain consistent times series data of various stages of roof distress. Furthermore, accurate monitoring of roof conditions is an essential part of implementing an effective maintenance and rehabilitation policy.

Roof condition monitoring is quite complex and very non-standardized. This project develops a roof management system (RMS) and a comprehensive deterioration prediction model using Artificial Neural Network (ANN) and Evolutionary Algorithm (EA).

2.2 KEY ELEMENTS OF ROOF MANAGEMENT

Roof management decisions need to be made on the basis of predicted or deterioration models that are usually developed from roof condition data collected. The five components of the process are

- Data Collection and Monitoring
- Impact Modeling and Application of Impact Models
- Strategy Selection
- Strategy Implementation
- Objective Specification and Reevaluation.

Figure 1 shows the faculty management process that will be applied.

Figure 1. Roof management process.

2.3 ROOF SYSTEMS INFORMATION

Databases are logically the first building block of a roof management system. The database supports the information needs as well as the prediction module and feedback process. Using the information in the database, useful reports can be generated, such as

- Deficiency reports, which identify roof segments with a given type of distress exceeding a specified threshold level
- Performance histories, which display the variation of a given type distress as a function of age and for a specific roof type
- Maintenance, rehabilitation, and reconstruction actions.

Figure 2 shows a generic diagram of roof information systems.

Figure 2. Roof systems information.

3.0 MODEL DEVELOPMENT

3.1 INTRODUCTION

The roof management process is dependent on an extensive database, including an inventory of roof condition data, corrective maintenance and preventive maintenance activities, and cost data. The following methods will be used to develop models.

Roof deterioration models can be used to estimate the life-cycle impacts of investment in DOD facilities in terms of costs and benefits. Roof performance can be defined as the ability of the roof to provide service, including reliability, comfort, condition, and safety.

The management of roof by the government agencies responsible for roof planning, design, construction, and maintenance requires the ongoing allocation of substantial manpower and capital resources. This process is almost always carried out and managed by competent technical staffs who are ultimately responsible to executive and legislative branches. These branches demand the efficient and effective use of all resources under their jurisdiction, usually requiring justification and proof. Along with technical engineering improvement needs, this has encouraged the development of Roof Management Systems (RMSs). A RMS provides decision-makers with optimum strategies derived through clearly established rational procedures; it evaluates alternative strategies over an analysis period on the basis of predicted values of roof performance, and it involves an integrated, coordinated treatment of all areas of roof management. This shift toward using RMSs by agencies responsible for roof necessitates more reliable roof performance and prediction models. Most agencies use roof condition index (RCI) as primary indicator of roof's distress state and performance level.

Using data from the Corps of Engineers RMS, two artificial neural network (ANN) models will be developed to predict a roof condition index using its distress characteristics. Most modeling of this type done during the last 15 years uses multiple regression analysis. However, within the last decade, new modeling tools such as the Markov probability decision process and ANNs have been applied to various problems in infrastructure with promising results. Almost all the research was performed using the most common type of ANN called the Dot Product ANN, generally described as a feed forward, fully connected, back propagation network having a linear activation function and using supervised learning.

3.2 TRADITIONAL ROOF PERFORMANCE PREDICTION MODELING

The cost of gathering roof condition characteristics is a large part of the cost of a RMS. Being able to predict roof performance and/or key roof characteristics, e.g., condition index from the smallest set of actual measured characteristics, can yield large savings to the agencies responsible for the roofs.

Most researchers agree that no single prediction model applies to all roofs. This is due to the high variability in the number and type of roof characteristics measured by each agency for its roof as well as the summary roof performance indicator used. The diverse geographical regions in which the roofing systems are exposed is also a contributing factor.

3.3 ARTIFICIAL NEURAL NETWORKS (ANNS)

Among the useful features of ANN described by Hewitson and Crane (1994), several are favorable for roof prediction modeling. The first feature is its ability to represent any arbitrary non-linear function. Whereas in regression analysis linear relationships are needed, or at best pre-specified non-linearity, the neural net finds its own function without the constraint of linearity. The other useful features are its abilities to generalize a relationship from only a small subset of data, to remain relatively robust in the presence of noisy (i.e., containing random error) inputs or missing input parameters, and to adapt and continue to learn in the face of changing environments. ANNs have utility in a wide range of applications in transportation engineering and come in many different forms and structures. Whereas a very limited subset of the ANNs are used in this research, they are drawn from a rich group of potentially useful forms that hold great promise for further infrastructure (roof) modeling research.

3.4 CLASSIFICATION OF ANNS

The terminology used to classify and describe ANNs has generally universal definitions but as yet lacks the specificity needed to accurately describe a model. A simple scheme to classify ANNs is that organized by Faghri and Hua (1992) with modifications drawn from Hewitson and Crane (1994). This scheme addresses two basic issues:

- a) How are the processing units (or nodes) and their connections configured? (This is called the net's architecture.)
- b) How will weight values be assigned to the connections?. (This is called the net's learning rules.)

These authors divide the types of ANN architecture into four categories:

1. *Mapping ANNs*: Computes the sum of all the products of corresponding inputs and weights (called the activation function). Then the transfer function operates on it to produce the unit's outputs, that is,

$$Y = g[f(X, W)] \quad (1)$$

where: Y = outputs,

X = inputs,

W = weights,

f = activation function, and

g = transfer function.

2. *Recurrent ANNs*: Some (or all) the outputs are connected to the inputs. Thus, the activation function is a function of the inputs, the weights, and some (or all) outputs, that is,

$$Y = g[f(Y, X, W)], \text{ or} \quad (2)$$

$$y(t + 1) = g\{f[Y(t), X(t), W(t)] \quad (3)$$

where t denotes the time.

3. *Temporal ANNs*: Compute the rates of the changes of their outputs as a function of the outputs, the input and the weights, that is,

$$dY/dt = f(Y, X, W) \quad (4)$$

4. *Hybrid ANNs*: Combine supervised and unsupervised learning into one network.

The learning is classified into three categories:

1. *Supervised learning*: The ANN is trained on a set of input-output pairs. The weights are adjusted to minimize error of the outputs. Another set of input-output pairs, called testing data, is provided to test the effects of training.
2. *Self-organizing learning*: The network is trained on a set of inputs. No guidance is presented to the network about what it is supposed to learn. The ANN adjusts its weights to meet its own built-in criterion.
3. *Reinforcement learning*: The network is trained on a set of inputs. The target outputs are not provided for learning; instead, error signals of the output are given to the ANN. This process is analogous to reward or punishment.

Each of these simple categories of architecture and learning can be subdivided further into more specialized types, but this is only done, as described later, for the two ANNs studied. One aim in the design of this study was to make its methods and results as accessible as possible to the people within an agency who are charged with the day-to-day operation of their agency's RMS. Toward that end, each of the two ANN models studied was developed using commercially available microcomputer software that lends itself easily to experimentation by agencies.

The Dot Product ANN Model has a mapping ANN architecture and uses supervised learning. The learning method used was back-propagation. This type of model is one of the best known ANNs of any type. The activation function is commonly called the dot, or inner, product function. The transfer function selected was the sigmoid function.

$$f(X, W) = y = \sum_{i=1}^n W_i x_i + W_0 \text{ (dot product activation function)} \quad (5)$$

$$g(y) = \frac{1}{1 + e^{-y}} \text{ (sigmoid transfer function)} \quad (6)$$

The neural network studied will be developed and is described throughout this paper using "Propagator: Neural Network Development Software" and its user's manual developed in 1993.

The neural network model will be developed based on the following equation,

$$RCI = f(\text{Flashing Distresses, Membrane Distresses, Age})$$

The different distress type under Flashing and Membrane was weighted based on severity, quality, and density or deduct value. The Age is based on the inspection age. (Methodology about the weighting procedure is being analyzed.)

3.5 DATA GENERATION

Roof performance and roof condition data were obtained from the U.S. Corps of Engineers Roof database, and Micro ROOFER was used to analyze Flashing condition index (FCI), membrane condition index (MCI), and roof condition index (RCI). The Micro ROOFER was developed by the U.S. Army Construction Engineering Research Laboratories (USACERL). It is an engineering management system designed to provide managerial facilities for the management of a single-ply and built-up roofing system. It provides roof data and procedures for practical decision-making to identify cost-effective maintenance and repair needs for building roofs. Micro ROOFER software provided the user with the following capabilities:

- Data storage and retrieval
- Database administration
- Windows ease of use and functionality
- Determination of membrane, flashing, insulation, and overall roof condition rating
- Determination of optimal maintenance, repair, and replacement strategies
- Report generation for network and project level management.

Table 1 shows a sample of the data generated by the Micro ROOFER program.

Table 1.
Sample of data from Micro ROOFER program

FCI	MCI	AGE	RCI
63	95	8	73
54	100	8	68
57	98	8	64
77	100	9	67
39	88	19	11
45	94	19	61
61	94	8	72
73	94	8	80
75	82	7	75
66	94	8	75
26	96	8	75
50	97	8	76
58	82	8	77

FCI- Flashing Condition Index
MCI- Membrane Condition Index
RCI- Roof Condition Index
AGE- Age of Roofing System

3.5.1 Data Preparation

The following roof deterioration indices were chosen from the ROOFER Software: Roof Condition Index (RCI), Flashing Condition Index (FCI), Membrane Condition Index (MCI), and the age of the roofing system. The age of the roofing system was found by observing the difference between the last construction year and the last inspection year. The neuro software program was used in the modeling process. The input values were FCI, MCI, AGE, while the output value was RCI.

Scatter plots of Flashing Condition Index (FCI) and AGE of the roofing system each versus Roofing Condition Index (RCI) were determined. This is shown in Figures 3, 4, and 5. Figure 3 shows a scatter plot of FCI versus RCI. A good scatter plot is obtained. A good correlation of $r^2 = 0.8342$ was obtained for the analysis. The high value of the FCI is reflected in the corresponding high value of RCI. Figure 4 shows a scatter plot of MCI versus RCI, a correlation, r^2 of 0.2833 was obtained. The line of best fit shows the older the roof system, the smaller the value of the Roof Condition Index. Figure 5 shows a scatter plot of Age versus RCI. A correlation of $r^2 = 0.4048$ was obtained.

3.6 TRAINING

The proposed scheme for Roof Condition Index (RCI) involves the development of an ANN (Artificial Neural Network) that could be trained to predict the Roof Condition Index of the roofing system given the Flashing Index, Age, and Membrane Condition Index. Only network architecture was examined. The architecture consists of three input nodes (FCI, MCI, AGE), six hidden nodes, and one output node (RCI). One hundred training inputs were used, 35 inputs for validation, and about 55 inputs for testing. Figure 6 shows a scatter plot of the Target (Predicted) versus the Output values of the RCI (Roof Condition Index) using Artificial Neural Network.

Figure 3. Scatter plot of Flashing Condition Index versus Roof Condition Index.

Figure 4. Scatter plot of Membrane Condition Index versus Roof Condition Index.

Figure 6. Predicted and Target values using the ANN.

Adding many hidden layers gets the network to learn with fewer training cycles, and the mean square error becomes a little smaller but reduces the generalized ability of the network (Sorsa 1993).

The back-propagation learning algorithm, also known as the generalized delta rule, was used in the learning process. In back-propagation, each presentation of the data set and the input value (Flashing Condition Index, Age, and Membrane Condition Index) of the ANNs are compared with the output values and adaptive weights within the network and incrementally adjusted to minimize the output error. The linear transfer function was used on all the layers. The linear transfer function produces a linearly modulated output from the input. The back-propagation algorithm has demonstrated several advantages in addition to having the potential for determining networks with arbitrary mapping methods (2). A learning rate of 0.3 and a momentum term of 0.5 were used as the initial values for the selection of the architecture.

The error function is expressed as

$$E = \frac{1}{2} \sum_c \sum_j \left[y_i(c) - d_j(c) \right]^2 \quad (7)$$

where

$c = \text{input sample case}$

$j = \text{output sample case}$

$y = \text{actual output and}$

$d = \text{desired output}$

The overall objective is to minimize the error function by adjusting the interconnection weights. The training algorithm using back-propagation is well presented elsewhere. The initial weights and biases are as follows (Attoh-Okine 1994):

$$\theta_{ij}^{new} = \theta_{ij}^{current} - \eta \frac{\delta^t E_t}{\delta \theta_{ij}} + \alpha \left(\theta_{ij}^{current} - \theta_{ij}^{previous} \right) \quad (8)$$

$$w_{ij}^{new} = w_{ij}^{current} - \eta \frac{\delta^t E_t}{\delta w_{ij}} + \alpha \left(w_{ij}^{current} - w_{ij}^{previous} \right) \quad (9)$$

where α and η are learning rates. Back-propagation is accomplished in four steps:

Step 1: Normalized condition data generated by using simulation are presented to the input layer.

Step 2: One pair of corresponding inputs (FCI, MCI, AGE data) and the output (RCI) are presented.

Step3: Using actual RCI (output), the error with respect to desired RCI is determined.

Step 4: Error is used to adjust the connecting weight.

Step 5: Using the next data pair, the process is repeated until "correct" roughness is obtained for all inputs used for training.

3.7 RESULT

During training the network result is compared with the correct result, and the mean-square error (MSE) is computed as follows:

$$MSE = \frac{\sum (O - t)^2}{\text{No. of Patterns}} \quad (10)$$

where O = Output vector

t = target vector

MSE = 41.52

MAE = 4.8943

MAE is the Mean Absolute Error.

3.8 EVOLUTIONARY COMPUTATION

3.8.1 General

The three main concepts of current evolutionary computation research are genetic algorithms, evolution strategies, and evolutionary programming. All these computation techniques initialize the population of individuals and evolve them toward better and optimum requirements of the search space by means of stochastic process of selection, mutation, and recombination, if appropriate. These techniques differ in the specific representation, mutation operators, and selection procedures. In genetic algorithms, emphasis is on chromosomal operators based on an observed genetic mechanism (for example, crossover and bit mutation). Evolution strategies and evolutionary programming emphasize the behavioral link between parents and offspring rather than the genetic link (Saravanan and Fogel 1995).

3.8.2 Application

The evolution algorithm used here combines genetic algorithm with techniques from genetic programming, hill-climbing, heuristic search for the coefficients, and machine learning. Figure 8 shows the EA algorithms. The EA algorithm supports multiple ecosystems with multiple integration and intermarriage strategies. The ecosystem topologies include queue, circular queue, and hierarchy. Hierarchical migration and intermarriage were used for the analysis (Figure 9). Intermarriage is achieved by allowing mating between partners from different ecosystems. Ecosystems are an independent closed environment of individuals where the population live and produce. Multiple ecosystems may be created by allowing populations with a different configuration setup to evolve independently and concurrently. A number of selection strategies are available for the choice of migrants and foreign marriage partners.

3.8.3 Operators

Crossover operators - There are two types of crossover operators: sexual and asexual crossover. The sexual crossover takes as input two randomly chosen individuals (parents) and combines them to generate two children. Figure 10 shows the sexual crossover. Asexual crossover operation exchanges part of the same individual (Cuppini 1994). Figure 11 shows asexual crossover. The following types of asexual activities are implemented: inversion and mutation.

Members of the next generation are selected from previous generations with a probability associated with their fitness. Fitter strings (expressions) receive more copies in the next generation because of the higher probability of selection-survival of the fittest.

In the algorithm used, when the genetic algorithm discovers a new best expression, the EA uses hill-climbing to improve the expression. Newly discovered best expressions are then subjected to a heuristic search for optimization. All these stochastic events are linked to user configurable probabilities.

3.9 DEVELOPMENT OF EA MODEL

3.9.1 Data Generation

Roof data generated from the Micro ROOFER program shown in Table 1 in the earlier section was also used for the Evolutionary Algorithm analysis.

3.9.2 Training

Three ecosystems were selected, and the size of each ecology is 20. The subset of operators applied to this problem are addition, subtraction, multiplication, and division. Hill-climbing was introduced after 1000 reproductions.

Reproduction parameters were as follows. Sexual reproduction was done 90% of the time, and mutation was done only 30% of the time. During sexual reproduction, instructions were mated 80% of the time; only coefficients (local constants) were mated 10% of the time. The migration probability was 10%, and the intermarriage probability was also 10%. About 400 inputs were used for the analysis.

3.9.3 Results

The two equations shown below are the “best” equations produced by the EA algorithm.

$$RCI = K_1(MCI) + K_2(FCI) + K_3 AGE + K_4 \quad (11)$$

$$K_1 = 0.29, K_2 = 1.419, K_3 = 0.287, K_4 = -0.575 \quad r^2 = 0.9266$$

$$RCI = K_1(MCI) + K_2(FCI) \quad (12)$$
$$K_1 = 0.308 \quad K_2 = 0.692 \quad r^2 = 0.9396$$

Figure 7 shows a scatter plot of the truthful and predicted values of the Roof Condition Index using the above equations. The best fit curve is equation 11 with $r^2 = 0.9266$, followed by equation 12 with $r^2 = 0.9396$. It is clear that the algorithm is reliable in terms of r^2 .

Figure 7. Scatter plot of Truthful and Predicted Values of RCI (Roof Condition Index).

Figure 8. Evolutionary Algorithm.

Figure 9. Hierarchical Migration.

Figure 10. Sexual Crossover.

Figure 11. Asexual Crossover.

4.0 ROOF INSPECTION PROCEDURES

Generally, roof inspection should be performed by a team of at least two people, an inspector and a recorder. The inspector surveys the roof, identifying distresses and appropriate severity levels, defects, and quantities. The recorder enters the data on a roof inspection worksheet and assists in measuring distress quantities. The three areas normally inspected are interior areas, roof surface, and perimeter and overhang areas.

Interior Areas

- The most common sign of roof leakage is water stains on the ceiling or the walls.
- The location of the stains should be properly noted on the field notes.
- Critical areas of inspection include air conditioning ducts, plumbing and ventilation ducts, drain lines, and anchorage supports.
- Ceiling stains from roof leakage could have round, elliptical, or long narrow shapes.
- Careful inspection near the supports of roof decks (rafters or trusses) should be done. These areas serve as anchorage of roof panels (plywood, metallic, gypsum, etc).
- Changes in pitch or direction of slope of roofing system should be inspected.
- The presence of fungi growth on wooden panels is a clear indication of significant leakage. Dry and brittle fungus may indicate old leakage.

Roof Surface

- Walk the roof surface carefully since the roof decking could be very loose.
- Make a sketch of the existing roof.
- The sketch must note the following
 - * Areas of previous repair
 - * Areas that hold water
 - * Sections of deteriorated materials (i.e, rigid and brittle surfaces).
- Look for signs of ponding condition on the roof when it rains. This is usually indicated by a darkened area on the roof.
- Holding of water (ponding condition) on the roof system is caused by clogged drains or scuppers and should be noted during the inspection.
- Roof surfaces are prone to nails or staples coming up through the roofing membrane. They become points of weakness on the roofing system.
- Check the vertical seams on the parapet walls and the top of the wall for openings, cracks, or slippage. The seal at the top of the wall is often cracked or pulled away, and the nail heads may work out, leaving holes in the material.

- Pipe protrusions, skylights and chimney flashing, roof drains and roof top equipment should be checked.
- Plumbing stacks are sealed with PVC. The PVC normally deteriorates with time and should be carefully inspected. Plumbing leads are weather- or water-resistant and should be examined for mechanical injury.
- Rooftop equipment will often have "pitchpans" around the base that should be examined for damage, rusting-out of the metal, missing or shrinking tar sealant, and improper installation. An exposed metal flange on the roof means that the pitchpan is not properly sealed to the roof.
- Exhaust fans and vents have galvanized "roof jacks" of various designs, and these should also be checked for rust, damage, and proper installation.
- Vertical wall surfaces must be checked for cracks that allow water into the building through the roof flashings.
- Wall flashings are subject to cracks and diagonal ripples in the flashing material. These cracks should be checked.
- Look out for blisters that are the result of water being trapped between or beneath the plies. The moisture turns to vapor when heated by the sun and expands to cause the "blisters."

Perimeter and Overhang Areas

- Evidence of roof leakage may show up as stains on the exterior wall.
- Look for open joints or improper joints at the edge metal. Damaged or rusted-out eave metal may also be found.
- When inspecting the overhang, always look at the back of the fascia board as well as the front.

5.0 MAINTENANCE AND REHABILITATION STRATEGIES

AT SPECIFIC SITES – PRELIMINARY

Figure 12 shows the selection of maintenance and rehabilitation strategies at specific site levels. Models will be developed to select the optional maintenance and rehabilitation strategies.

Figure 12. Maintenance and rehabilitation strategies at specific sites.

Prioritization and Optimization of the Roofing System network preservation strategies are the central task of a Roof Management System.

Planning of Practical Standardized Roof Management should consider

- a) The effect on improvement of the existing roofing surface quality in terms of generalized Roof Condition Index, Roof Serviceability Index.
- b) The influence or impact on the existing roofing deterioration rate after applying any one of the standardized preservation actions.

When a roofing system reaches the minimum acceptable service level specified, a deficiency is created. In identifying deficient roofing systems and estimating sections in the network with future needs, both the existing roofing performance and treatment effect or influence on the future deterioration of the roof are considered using a prediction model. The prediction model used for this analysis was the Evolutionary Algorithm model and the Artificial Neural Network.

Integrating roofing deterioration with maintenance and rehabilitation treatment actions applied in each year within the programming period is recommended. If a roof performance analysis period goes beyond the initial service life of the alternative being considered, then the performance prediction should include separate deterioration models to consider the effects of the selected maintenance treatment(s) within the program period.

In other words, an integrated performance prediction model with regular treatments should be developed to predict the roof system over the analysis period.

In the flowchart shown in Figure 12, five alternative roof treatment strategies for performing Roof Network Preservation are defined. Each of the five treatment strategies, including routine and major maintenance, is shown. The effect on recoverability or improvement of the existing roof serviceability by applying each treatment is also shown in Figure 12. In other words, after implementation of a preservation action, the roofing system quality in terms of RCI (Roof Condition Index) will rise to a higher level, depending on which treatment strategy is selected. For instance, if Preservation Alternative Strategy 2 (i.e, routine maintenance) is selected for year t , then a rise in RCI can be obtained in that year.

Alternatively, if a minor rehabilitation treatment (that is, strategy 4) is selected in a particular year t , then RCI of the pavement will be upgraded that year. Following the jump in RCI after a treatment action is applied, a new deterioration model that reflects the improved roofing system by the treatment should be established to predict the pavement deterioration in the next year.

The procedure is repeated in each consecutive year until the entire analysis is completed for the integrated Roofing System performance prediction. It should be noted that the Roofing System deterioration rate during the time period when RCI is higher (newly constructed roof) is quite different from that when RCI is lower (aged roof).

6.0 ECONOMIC ANALYSIS OF ROOFING PROJECT

When a roof condition deteriorates below a prescribed minimum level, rehabilitation by means of reroofing must be performed. Basic routine maintenance such as maintenance of the roof drainage facilities, and the sealing of cracks that occur in membranes and flashings tend to slow down the roof deterioration process; thus, reconstruction or performing major rehabilitation can be deferred.

As the roof surface condition gets old, it is prone to rapid deterioration. User costs as well as basic routine maintenance costs also increase. If at a given time a decision is made to replace all the roof surfacing or flashing, a certain amount of capital is then invested. Sealing cracks and replacement of flashing can reduce the basic routine maintenance requirements. Because of the resulting improvement in roofing condition (Roof Condition Index), user costs are expected to decline. In addition, the service life of the roofing system is extended. The issue here is whether the benefits accrued in terms of reduced basic routine maintenance costs, reduced user costs, and opportunity costs gained because of the deferment of repair or rehabilitation equate or exceed the cost of the investment in crack sealing or flashing replacement.

If savings from the sealing are greater than the investment, the next issues are when is the most economic time to perform seal coating (with asphalt roofs) and how many seal coating activities should be performed during the roof life-cycle before the gain in repair becomes less than the cost. Figure 13 illustrates this concept.

If the seal coating or flashing replacement is delayed for a period of time, say from $t(s1)$ to $t(s2)$, the roof condition is expected to be worse at $t(s2)$ than $t(s1)$. Therefore, the seal coating or flashing replacement at a later date would be higher. The benefits from membrane sealing acquired from reductions in basic routine maintenance and user costs could be less than those from membrane sealing at the previous time, but there are gains in the added service life.

Figure 13. Economic analysis of replacement costs.

6.1 MATHEMATICAL FORMULATION OF LIFE-CYCLE COST ALGORITHM

The total life-cycle costs, as used in the present study, consist of reroofing, replacement or reconstruction costs, basic insulation and flashing routine maintenance costs, seal coating costs, and user costs. The replacement costs were considered to be a single payment made at a future year depending on the given standard for terminal condition. The basic insulation, flashing, or membrane routine maintenance costs were considered to be annual single payments at the end of

each year. Seal coating costs were treated as single payments made in the years in which sealing was carried out. User costs were accounted as annual single payments at the end of each year on the basis of the roof condition index (RCI) in that year.

Because future decisions on the timing of a particular type of maintenance activity are uncertain, it is common in a life-cycle costs analysis to assume certain sequences and types of maintenance work. This corresponds to the well-known repeatability assumption in financial analysis. After the first roof's life-cycle, the same work sequence and type are assumed to be repeated in perpetuity. Having established the basic assumptions of the proposed life-cycle costing approach, the present worth of reroofing costs is determined by applying the following formula:

$$PWV1 = RS (SPPWF, i, n) \quad (13)$$

where

PWV1 = present worth of rehabilitation (\$/ m²)

RS = reroofing cost

SPPWF = single payment present worth factor

i = discount rate

n = roof life-cycle (service life)

Similarly, the present worth of the periodic maintenance cost (sealing cracks, membrane and flashing replacement)

$$PWV2 = SC (SPPWF, i, t) \quad (14)$$

where

PWV2 = present worth of sealing, membrane replacement costs (\$/ m²)

SC = sealing, membrane replacement costs (\$/m²)

t = year at which sealing, membrane replacement is performed

The present worth of annual basic routine maintenance is calculated by using Equation 13.

$$PWV3 = \sum_{j=1}^n AMC_j (SPPWF, i, j) \quad (15)$$

where PWV3 is the present worth value of all annual basic routine maintenance costs during the roof service life (\$/m²). AMC_j is the annual basic routine maintenance cost at the jth year (\$/ m²).

Similarly, the present worth of user costs is determined by applying Equation 16.

$$PWV4 = \sum_{j=1}^n UC_j (SPPWF, i, j) \quad (16)$$

where PWV4 is the present worth of all annual user costs (\$/m²) and UC_j is the annual user cost at the jth year (\$/ m²).

The total present worth value of all life-cycle cost components under a maintenance strategy is calculated by using the following summation:

$$TPWV = PWV1 + PWV2 + PWV3 + PWV4 \quad (17)$$

This amount can then be viewed as an outlay to be made in perpetuity every n years. Then, the total present worth value in perpetuity can be expressed as

$$TPWV_p = TPWV \{ (1+i)^n / [(1+i)^n - 1] \} \quad (18)$$

Finally, the equivalent uniform annual cost in perpetuity for a maintenance strategy over the roof service life is determined by applying Equation 19.

$$EUAC_p(\text{in perpetuity}) = TPWV_p \cdot i \quad (19)$$

6.2 DEFINITION OF MAINTENANCE STRATEGIES

The analysis in the present roof study focused on basic routine maintenance and preventive periodic activities. Basic routine maintenance included maintenance of membrane flashing, drains, deck structure, and sealing of cracks in asphalt roofs. Roof drains are a critical component of a safe and functioning roof. The drains must be able to effectively facilitate the egress of water while remaining watertight at all connections. Water must be able to be removed as quickly and as efficiently as possible. If this is not done, two modes of failure can happen. The first mode of failure causes the roof membrane and substrate (insulation, deck) to get wet and begin deterioration. The second failure mode can cause the interior of the building and its content to sustain significant water damage.

Periodic maintenance activities are those used as preventive measures to repair minor damage and to hold the roof condition until higher-order treatments, such as reroofing, become necessary. Several maintenance strategies were included in the life-cycle cost analyses. Each strategy consisted of one or more maintenance activities. Table 2 lists the various maintenance strategies considered in the life-cycle cost analysis.

Table 2.
Maintenance strategies in life-cycle cost algorithm

Maintenance Strategies	Activities Performed
Do Nothing	None
Basic Routine Maintenance	Crack sealing in asphalt roofs, drainage repair, membrane and flashing repair, insulation replacement, adhesive and sealant repair

7.0 ROOF PRODUCT INFORMATION SYSTEM

Overview

There are numerous roof product vendors scattered all over the United States, each of them offering several varied products for roof construction, maintenance, and rehabilitation. Selecting the most appropriate and cost-effective roofing product for this purpose is not an easy task in an environment where there is no information database from which to select.

The development of the Roof Product Information System (RPIS) is an attempt to gather valuable information about roofing products available on the market and about the firms or vendors who carry these products. Contact information about each vendor and a summary of the product they carry together with technical details about each product can be stored and retrieved as and when needed.

RPIS is a form-driven database management system, developed in Microsoft Access 2.0. These forms enable the user to enter detailed information about the firms and vendors that sell roofing products. When the data is established, then the various roofing materials products associated with each firm can be entered. The system also allows the user to make various queries from the database. For example, a query can be made to filter out all vendors in Florida who carry a particular product.

Getting Started

Before you can run the RPIS application, you need to have the Microsoft Access database management system development application, which is part of Microsoft Office when properly installed on your computer.

To start the RPIS application

- 1) Copy the database file (Roofdba.db1) from the diskette provided to a desired directory location.
- 2) Create a shortcut onto your desktop using the techniques for creating shortcuts outlined in your Microsoft Windows manual. A shortcut will provide you a quick way to start **RPIS** without having to go to its permanent location in your file manager. If you have problems with creating a shortcut, go to the Microsoft Windows help menu for information.
- 3) After creating the shortcut, double-click on it to launch the **RPIS** application. The main switchboard shown in Figure 14 will be displayed on your screen. This is the main form you will use to access the various forms in the **RPIS** application.

Main Switchboard

From the main switchboard, you can either access or enter detailed information about the vendors or directly access or add information about the product each vendor carries.

Figure 14. Main Switchboard.

- 4) Click on the Company General Data button to add or view general information on each roofing company in the database.
- 5) Click on the Company Products button to add or view general information on the products each roofing company carries.
- 6) Click on the Modify Main Menu button to add, delete, or change the items on the main menu.

Note: This, however, must be used only for those who have good knowledge of the use of Microsoft Access.

- 7) To exit the **RPIS** application, click on the Exit button.

Company Information

RPIS allows you to enter general information about companies that carry roofing products. You can search for particular information by simply right-clicking in any of the attribute fields to display a dialog form where you can specify your search criteria. You may also set filter for any attribute that you want to deal with.

To view or add information for a company:

- 1) Click on the Company General Information button on the form shown in Figure 14 to display the form below. Then click on the View/Add Company Data to access the Roofing Company Information form displayed in Figure 16.

Figure 15. View/Add Company Data.

- 2) In the Roofing Company Information form, information about each company for which you have previously entered data is displayed one at a time as you scroll through the list using the navigation display buttons at the bottom of the form.
- 3) Click on the Company General Information button on the form in Figure 14 to display the form below, then click on the View/Add Company to access the Roofing Company Information form. For a particular company, you can view the roofing products it carries by pressing the View Company Product form to display the Roofing Products form shown in Figure 17.

Roof Company Information	
Company ID	1
Company Name	Duracool
Company Address	310 Cumorah Trail
Company City	Alpharetta
Company State	GA
Company Zip Code	30004
Telephone #	800-232-9606
Fax #	
Contact Person	Georgia Colman
Phone Called	☒
Catalog Received	☒
Notes	This company seems to be the best among the lot. Perhaps we may need to ask for a quotation from them for supply
<input type="button" value="View Company Product"/> <input type="button" value="Close"/>	

Figure 16. Roof Company Information.

Attribute Fields

<i>Company ID</i>	This field displays a unique identification number for the company. These numbers are automatically generated for you as you add new companies.
<i>Company Name</i>	This field displays the name of the company
<i>Company Address</i>	This displays the address of the company.
<i>Company City</i>	This displays the city in which the company is located.
<i>Company State</i>	This field displays the state in which the company is located.
<i>Company Zip Code</i>	This displays the zip code of the address of the company.
<i>Telephone #</i>	This displays the telephone number of the company.
<i>Fax #</i>	This displays the fax number of the company.

<i>Contact Person</i>	This field displays the telephone number of the person contacted for information about the company.
<i>Phone Called</i>	A check in this check box indicates that the company has been contacted by phone.
<i>Catalog Received</i>	A check in this check box indicates that the company has been contacted by phone and an information catalog has been received from the company.
<i>Notes</i>	This field displays any notes that you have previously entered about the company. This is intended give you brief information about the company.

Function Buttons

View Company Product	Click this button to access the roofing product form shown in Figure 17.
Close	Click to close this form and return to the previous menu.

*Note: To locate a particular attribute (Company ID, Company Name, etc.) right-click in the field to display the Microsoft Access Filter form shown on the right and enter the particular attribute you want to search for in the **Filter for** field.*

You may also sort a particular attribute in Ascending or Descending order by clicking on the particular field and then clicking on the Sort Ascending or Descending option on the Filter form.

Filter Form

Product Name	Product Description	Recommended Uses
Rust Treatment	Zinc-rich primer	rust inhibitor and prime
Asbestos Primer	Seal pores of asbestos prior to coating with Duracool Bit-Coat	primer sealer of asbest
Roof Wash	Concentrated detergent surfactant for cleaning all types of roof surfaces	roof cleaning and pre-t
Agri-Coat	White elastomeric acrylic coating	Any surface requiring p
Gator-fil	Acrylic cementitious aggregate filler for alligator cracks	Repair to asphaltic suri (mud-cracking)
Hypa-Coat	elastomeric acrylic coating	Rejuvenative coating pre-existing Hypalon ar

Record: 14 of 9

Specify a company and then scroll through the products they carry

Figure 17. Roofing Products.

Attribute Fields

- Company ID** This field displays a unique identification number for the company. The numbers are automatically generated for you as you add new companies.
- Company Name** This field displays the name of the company.
- Product Name** This column displays the names of the products the current company carries.
- Product Description** This column displays the descriptions of each product the current company carries.
- Recommended Uses** This column displays the various usage areas recommended for each product.

Note: There are other fields not displayed in this form but that can be viewed by using the horizontal scroll bar located at the bottom of the form to scroll through product attributes.

Function Button

- Close Form** Click to close this form and return to the previous menu.

Product Information

RPIS allows you to enter detailed information about each product carried by the companies you want to add to your database. You can store any information you have available about each product. Detailed technical information can also be added to facilitate better decision-making for the choice of appropriate product for your roof maintenance or rehabilitation project.

To Add/ View a product carried by a particular company:

- 1) Click on the Company Products button on the form in Figure 14 to display the form below.
- 2) Click on the View/Add Product to access the Roofing Company Summary Information form shown in Figure 19.

The screenshot shows a window titled "Product Switchboard". Inside, there is a sub-window titled "Roof Product Information System" with a "Main Menu" section. The menu contains two options: "View/Add Product" and "Return to Main Menu", each preceded by a small square icon. To the left of the menu is a graphic of a house with a roof being worked on. At the bottom of the window, a text prompt reads: "Click on a button above to select the appropriate option".

Figure 18. View/Add Product

- 3) In the Roofing Company Summary Information form, summarized information about each company for which you have previously entered data is displayed one at a time as you scroll through the list using the navigation buttons displayed at the bottom of the form.

Note: Alternatively, you may right-click in any field to display the Microsoft Access Filter form where you can specify a filter for a particular attribute.

- 4) Click on the View/Add Product button to view or add products for the selected company as shown in the Roofing Products Summary displayed in Figure 20.

Roofing Company Summary Information	
Company Name	Duracool
Company ID	1
Address	310 Cumorah Trail
Phone	800-232-9606
<div>View/Add Products</div> <div>Close</div>	

Figure 19. Roofing Company Summary Information.

Attribute Fields

Company ID	This field displays a unique identification number for the company. The numbers are automatically generated for you as you add new companies.
Company Name	This field displays the name of the company.
Product Name	This column displays the names of the products the current company carries.
Product Description	This column displays the descriptions of each product the current company carries.
Recommended Uses	This column displays the various usage areas recommended for each product.

Note: There are other fields not displayed in this form but can be viewed by using the horizontal scroll bar located at the bottom of the form to scroll through product attributes.

Function Button

Close Form	Click to close this form and return to the previous menu.
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- 5) In the Roofing Product Summary form, you may set a filter for a particular company or product and then click on the View Product Details button to display detailed technical information about the currently selected product as shown in Figure 21.

Roofing Products Summary

Company ID	1
Product Name	Hypa-Coat
Product Description	elastomeric acrylic coating
Unit Price	\$ 25
Dimension	
Recommended Uses	Rejuvenative coating system for application over pre-existing Hypalon and other single-ply roofing
Life Expectancy	12-15 Years

View/Add Product Details Close

Record: 1 of 9 (Filtered)

Figure 20. Roofing Products Summary.

Attribute Fields

<i>Company ID</i>	This field displays a unique identification number for the company. The numbers are automatically generated for you as you add new companies.
<i>Company Name</i>	This field displays the name of the company.
<i>Product Name</i>	This column displays the names of the products the current company carries.
<i>Product Description</i>	This column displays the descriptions of each product the current company carries.
<i>Recommended Uses</i>	This column displays the various usage areas recommended for each product.

Note: There are other fields not displayed in this form but can be viewed by using the horizontal scroll bar located at the bottom of the form to scroll through product attributes.

Function Button

<i>Close Form</i>	Click to close this form and return to the previous menu.
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Company Product Details	
Company ID	1
Product Name	Duracool
Dimension	
Percent Solids by Weight	67 ± 2 %
Flash Point	none F
Hardness, Shore A	55-65 ASTM D-412
Minimum Application Temperature	45 °F F
Packaging	5 gal, 55 gal/drum
Permeability	5 per ng/Pa/s/m ²
Flammability	equal F
Coverage	1 gal per 11 sq.ft. per gal
Viscosity	95-105 KU, 77° K
Specific Gravity	1.44
pH	8.6 ±
Color	White and other C
Tensile Strength at break	250 psi a
Tensile Elongation at break	550% at 7 psi
Service Temperature	30 °F
Drying Time	3 Hours at 100°F
Recommended Coverage	20 M ² (100 sq.ft.) / gal
Close	

Figure 21. Company Product Details.

Attribute Fields

- Company ID** This field displays a unique identification number for the company. The numbers are automatically generated for you as you add new companies.
- Company Name** This field displays the name of the company.
- Product Name** This column displays the names of the products the current company carries.
- Product Description** This column displays the descriptions of each product the current company carries.
- Recommended Uses** This column displays the various usage areas recommended for each product.

Note: There are other fields not displayed in this form but that can be viewed by using the horizontal scroll bar located at the bottom of the form to scroll through product attributes.

Function Button

- Close Form** Click this button to close this form and return to the previous menu.

8.0 SUMMARY

- Data collection practices in roof condition assessment is very lacking. Generally, in infrastructure management systems, large amounts of data are needed for deterioration prediction. Unfortunately, in roof systems, it is difficult to collect large amounts of data.
- Age, FCI (Flashing Condition Index), and MCI (Membrane Condition Index) can be used to predict Roof Condition Index (RCI). A new model based on evolutionary programming and neural network is described. It is governed by roof condition index, age, membrane condition, flashing condition, a set of designed standard treatment alternatives, and budget limitations for network preservation. Each standardized roof system treatment alternative, including minor and major maintenance rehabilitation, is defined by its level of improvement in the existing roofing surface. The system has incorporated roofing serviceability improvements obtained from maintenance or rehabilitation treatments applied within the program.
- The ANNs in roof deterioration modeling are feasible when a large database of roof condition data is available.
- The ANNs could form the basis for developing a generic intelligent roof deterioration process.
- In place of regression analysis, EA (Evolutionary Algorithm) techniques can provide the "best" deterioration models for roof condition.
- The EA can be used as a sensitivity analysis tool to determine which types of variables are needed for roof condition deterioration models.

9.0 REFERENCES

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- United States Army Construction Engineering Laboratories (USACERL) Technical Report "Roof Maintenance Management System."
- User's Manual e Evolutionary Algorithm Program for Windows 95.

APPENDIX

ANNOTATED BIBLIOGRAPHY

Title: Survey of Passive Leak Detection Technologies for Membrane Roofing

Author: Bailey, D., Ditman, J., Dupuis, R., Buckner, A.

Source: U.S. Army Corps of Engineers, Construction Engineering Research Laboratories

Date: 1994

ABSTRACT

The U.S. Army has a large inventory of buildings with low-slope membrane roofs. Eventually, most of these roofs will experience flaws that allow water intrusion. The cost resulting from water damage to the roofing system, structure, and building contents that can occur between the time a leak begins and is located and repaired can be very high. A passive roof leak detection system (PRLDS) could help Army managers by providing early leak detection and could potentially reduce the Army's roofing maintenance budget.

This study determined that a PRLDS contains four components: sensors, signal, transmission medium, and signal processing unit. The sensors can be resistive, capacitive, circuit bridging, or fiber optics.

Sensor placement and spacing on a roof determine the system's "resolution" and should be based on the system cost and the interior use of the structure. A discussion of the reliability, compatibility, durability, and maintainability of components is included.

This study also determined that several moisture-sensing technologies are feasible, including a water-activated battery/transmitter, a variety of probes, moisture detection tape, and coated wires. Because little documented experience with these new technologies exists, it is recommended that field investigations be conducted and design specifications be developed.

Title: Three-Year Field Test Summary for Experimental Modified Bitumen Roofing at Fort Polk, La

Author: Bailey, D., Rossiter, W., Seiler, J.

Source: U.S. Army Corps of Engineers, Construction Engineering Research Laboratories

Date: 1992

ABSTRACT

This report presents results of the first three years of a 10-year field evaluation on three modified bitumen roofing systems at Fort Polk, LA. This work is part of a research effort being conducted by the U.S. Army Construction Engineering Research Laboratories (USACERL) to identify alternative, easy-to-install roofing systems that can improve the performance of Army roofing reducing life-cycle costs.

Three different modified bitumen-roofing systems were installed on building 920 of Fort Polk. At the time of installation, researchers tested the roof membrane materials for initial properties to provide a basis for comparison with later samples. Test samples for each roofing system were removed annually for three years, and the sample section was patched. Properties of the membrane materials evaluated are those considered essential to good roofing performance. For most properties, American Society of Testing Materials (ASTM) standard test methods are used. In addition, the roofs are inspected visually once each year. Preliminary findings indicate that the test roofs are performing excellently.

Title: Predictive Service Life Tests for Roofing Membranes: Phase 1

Author: Cash, C., Bailey, D.

Source: U.S. Army Corps of Engineers, Construction Engineering Research Laboratories

Date: 1993

ABSTRACT

The Army and roofing industry have extensive field experience with roofing membranes. Roofing manufacturers, however, have been changing the composition of the membranes and introducing new materials at an increasing pace. Despite the initial satisfactory rating of some of the new products, their long-term durability is unknown. Army roofing managers need reliable tests to predict the durability of roofing membranes.

The objective of this study was to characterize roofing membrane material based on in-service performance requirements and criteria and to identify degradation factors and mechanisms that can be used to propose accelerated aging tests for service life prediction of roofing membranes.

This study determined that existing criteria and measurements for performance testing are inadequate. Predictive service life tests should be developed based on physical and chemical degradation measured after accelerated aging tests in a variety of climates. Degradation modeling and standard test methods should be incorporated into the test process.

Title: Long-Term Field Test Results for Polyvinyl Chloride (PVC) Roofing

Author: Rossiter, W., Lechner, J., Bailey, D., Foltz, S.

Source: U.S. Army Corps of Engineers, Construction Engineering Research Laboratories

Date: 1995

ABSTRACT

The U.S. Army Construction Engineering Research Laboratories (USACERL) recently completed a 10-year field exposure study of the performance of polyvinyl chloride (PVC) roofing membrane materials. Membranes from three manufacturers were installed at Chanute Air Force Base, IL, Dugway Proving Ground, UT, and Fort Polk, LA. A major difference in the roof constructions was that, at Chanute, the membranes were ballasted whereas, at Dugway, and Fort Polk, they were mechanically attached except for one case that was fully adhered. The intent of the USACERL study was to compare the results of laboratory tests of membrane properties with field performance. Periodically, over the 10 years, USACERL visually inspected the roofs to evaluate their performance and removed samples for laboratory characterization of selected mechanical and physical properties. The performance was generally satisfactory, whereas problems related to membrane shattering and splitting occurred at Chanute. Statistical analysis of the 10-year data set was conducted. Because of the less-than-satisfactory performance at Chanute, the data analysis was focused on determining whether changes in any of the measured properties were consistently different for samples from Chanute than samples from Dugway and Fort Polk. The results did not discriminate between the performance of the PVC membranes at Chanute and those at Dugway or Fort Polk. For example, it was observed that all samples at the three sites were lost during the exposure period. Two of the three membrane samples from Chanute did not lose significantly more plasticizer than those from Dugway or Fort Polk.

Title: Roofer: Membrane and Flashing Condition Indexes for Single-Ply Membrane Roof Inspection and Distress Manual Roofing

Author: Bailey, D., Brotherson, D., Tobiasson, W., Foltz, S., Knehans, A.

Source: U.S. Army Corps of Engineers, Construction Engineering Research Laboratories

Date: 1993

ABSTRACT

Because no procedures exist to inspect and evaluate the conditions of single-ply membrane roofing systems within the ROOFER program, the U.S. Army Construction Engineering Research Laboratories (USACERL) developed this inspection and distress manual for these roofing systems. Included is the standardized information needed to conduct the visual inspection survey, including names, descriptions, severity levels, measurement criteria, causes, and photographs of membrane and flashing distresses. Procedures for distress density calculations are also provided. Roof inspectors can use this information to objectively determine the indexes that reflect the 1) ability of the membrane and flashing to perform their functions, 2) needed level of maintenance, and 3) waterproof integrity.

Title: Roofer: An Engineered Management System (Ems) for Bituminous Built-Up Roofs

Author: Bailey, D., Brotherson, D., Tobiasson, W., Knehans, A.

Source: U.S. Army Corps of Engineers, Construction Engineering Research Laboratories

Date: 1989

ABSTRACT

This report gives instructions for using ROOFER, an engineered management system for bituminous built-up roofs that is designed to help military installations make the best use of roof maintenance and repair (M&R) funds.

This system includes procedures for dividing roofs into manageable sections; collecting and maintaining inventory information, surveying, rating, and evaluating roof condition; and determining general M&R needs and priorities.

The overall roof condition rating procedure is based on the Roof Condition Index, which is composed of separate condition indexes for the membrane, flashing, and insulation.

Title: Membrane and Flashing Condition Indexes for Built-Up Roofs
Volume II: Inspection and Distress Manual

Author: Shahin, M., Bailey, D., Brotherson, D.

Source: U.S. Army Corps of Engineers, Construction Engineering Research Laboratories

Date: 1987

ABSTRACT

Because no systematic procedures exist to determine priorities and select repair strategies for low-slope roofs, the U.S. Army Construction Engineering Research Laboratories (USACERL) is developing a roof maintenance management system that will provide a practical decision-making procedure to identify cost-effective repairs.

As part of the system for built-up roofs, this volume presents the standardized information needed to conduct the visual inspection survey, including names, descriptions, severity levels, measurement criteria, causes, and photographs of membrane and flashing distresses. Procedures for distress density calculations are also provided. Roof inspectors can use this information to objectively determine the indexes that reflect the 1) ability of the membrane and flashing to perform their functions, 2) needed level of maintenance, and 3) waterproof integrity.

Volume I describes the development and verification of the indexes.

Title: Reroof or Repair? Choose Carefully

Author: Monterose, Peter J.

Source: Construction Specifier v 39 n 11 Nov 1986. p 80-84, 86-88, 90-93

Date: 1986

ABSTRACT

This publication gives guidance of the methodology to follow in order to assess the condition of a roof system. From the methods described, a final conclusion can be made about the complete replacement or repair of a roof system. The steps for the assessment of a roof system are explained in detail from the recollection of data (i.e., original drawings and specification reviews, visual inspections, samples and testing).

A base criterion of what kind of roofing problems could be repaired and what conditions could indicate the need of reroof is provided. Some considerations for reroof design are included (i.e., structural capacity, chemical exhausted on roof, rooftop traffic, roof slopes and ponding, accessibility, building codes and standards, cost analysis).

Title: Performance Study of Single-Ply Roof Membranes in the Northeast United States

Author: Peterson, Richard H.

Source: Roofing Research and Standards Development: 2nd Volume. ASTM Special Technical Publication No 1088. USA. p 82-96

Date: 1990

ABSTRACT

Single-ply roof membranes have been in extensive use in the northeast region of the United States for a period of over 12 years. Although numerous systems and application procedures have been employed, there has been limited publication of field performance data on in-situ systems. This study involves the review of both EPDM roof membranes and PVC roof membrane systems that were placed in service between 1977 and 1984. The roof systems included in the study are all reroofing systems of known construction, contractors, material manufacturers, and design. The performance study included a review of the documented history of each roof from design through construction and post-construction. Warranty claims, if applicable, were reviewed as well as other available recorded data.

Building occupants/owners were interviewed to provide additional undocumented data. All roof systems in the study were inspected to establish existing conditions and to evaluate the level of deterioration of the various roof system components.

Accumulated data from documented history, interviews, and field observations are analyzed and defects are summarized. Causation of defects and deterioration were also considered and classified into one or more of the categories of design deficiency, material performance, improper workmanship, and/or lack of appropriate and regular maintenance.

Conclusions relative to the performance of the systems studied will be presented and considerations given to the effect on performance by known system changes.

Title: Specifying Membrane Roofing. A Systematic Approach

Author: Henshell, Justin

Source: Construction Specifier v 40 n 11 Nov 1987. p 102-108

Date: 1987

ABSTRACT

Thirty-five years ago, writing specifications for roofing was fast and simple. The specifier only had to decide whether to call for a smooth or aggregate surfaced built-up roof and whether a 15-year, instead of a 20-year, bond would suffice. If ambivalent about the bitumen type, the

specifier offered the bidder the option of using either coal tar pitch or asphalt. From there, it was a simple matter to select the appropriate specification numbers from the catalog of the relatively few manufacturers of roofing materials. The insulation thickness was usually selected for its ability to span the flutes in the metal deck.

Today, writing roofing specifications is much more complex. First, there are bewildering numbers of membranes and insulation. The latest NRCA Roofing Materials Guide lists over 475 roofing systems and 200 insulations currently marketed in the United States. The specifier must decide how to install the system--by hot hopping, self-adhering, adhering with cold adhesive, torching, mechanically fastening, welding with solvents, welding with heat, or by loose laying and ballasting. He must contend with compatibility of materials, complicated flashing systems, and shorter-term guarantees, as well as Underwriters' Laboratories' and Factory Mutual's requirements for fire and wind uplift. Some help is available from organizations such as the American Institute of Architects Professional Systems Division, Single-Ply Roofing Institute, National Roofing Contractors Association, Asphalt Roofing Manufacturers Association, and Rubber Manufacturers Association.

There are, of course, manufacturers' specifications in various formats, but they only provide a point of departure. Every project has special conditions impossible to cover in a standard specification. Since the specifier can seldom, if ever, adapt unedited standard specifications (or manufacturers' specifications) to a project, this article outlines a systematic approach to the adaptation process and discusses some considerations for using and editing these specifications.

This article is arranged in accordance with the CSI Standard three-part Section Format. Broad-scope type specifications are favored for all projects because there is less chance of a conflict than when using several narrow-scope sections. Moreover, the majority of projects rarely have more than two types of membranes or roofing systems. It is, in fact, desirable to limit the types of membranes on a single project to simplify future maintenance.

Title: Roof Failures and How to Avoid Them

Author: Adler, David L.

Source: Construction Specifier v 42 n 1 Jan 1989 p 72-80

Date: 1989

ABSTRACT

Roof failures have many different definitions. A roof's basic function is to protect the building interior against weather. Other requirements may include fire and wind resistance, serviceability to routine roof traffic, use as a service platform or recreational area, and pleasing appearance. Failure in any of these functions can result in a roof failure, by definition. Failure can also be defined by the amount of risk. The hazard of exposure of a warehouse full of tires versus an art gallery containing priceless items, or a hospital operating room, is obvious. In the latter case,

even a small leak can be disastrous, while in other situations, water intrusion may be only an annoyance or an inconvenience.

Failure by degree is another measure. Specifiers are often asked to evaluate a roofing system's ability to be reliably repaired. This judgment must also include economics of the repair program.

A difficult problem to deal with is when "failure" is obvious from appearance (e.g., a severely blistered built-up roof), but general leakage does not occur. A similar situation occurs when moisture is trapped in the system or attachment of the system is inadequate, but leakage or wind damage occurs infrequently or not at all. Roofing failures of this type are seldom separately identified by owners or occupants but are usually discovered during roof condition surveys. However, they are roof failures and generally fit into the following discussion as if they had resulted in a leakage. Unfortunately for the construction industry, the experience is that legal redress is difficult to obtain until a cause-effect relationship is established by occurrence of leakage (damage). For the purpose of this article, a roof failure occurs when the roofing system leaks prematurely, and the leakage is either uncontrollable by routine maintenance or cannot be corrected by simple repairs.

Title: Causes of Premature Roof Failure in New Construction

Author: Martin, Robert

Source: Construction Specifier v 43 n 11 Nov 1990 p 110-114

Date: 1990

ABSTRACT

Roof failures are rarely instantaneous. They seldomly produce immediate, disastrous results – in terms of leakage and interrupted operations. Most roof failures can be avoided or their effects at least minimized. Unfortunately, whether old or new, roof systems tend to be taken for granted. Like any other pieces of operating equipment, all roof systems need attention to wear, abuse, and neglect. Yearly detection of real and potential problems can eliminate the cause of a roof failure and the subsequent expense of reroofing.

Title: Evaluating Roof Conditions: A Key to Enhanced Roof Service

Author: Dworkin, Joseph F.

Source: Construction Specifier v 41 n 11 Nov 1988 p 90-93, 95

Date: 1988

ABSTRACT

Over the past 10 years, progress has been made toward educating design professionals in specifying roofing systems for new projects. In the forefront of an industry-wide effort at upgrading the designer's knowledge and understanding of roofing technology are the National Roofing Contractors Association (NRCA), Roofing Industry Educational Institute (RIEI), and the Asphalt Roofing Manufacturers Association (ARMA).

Manufacturers of roofing materials have also been providing users and specifiers information on new roof systems. The Single-Ply Roofing Institute (SPRI) and the Society of the Plastics Industry, Inc., among others, have been publishing regular updates to keep designers abreast of developments within the industry.

In marked contrast, reroofing and roof maintenance information available to consumers such as professional and commercial property managers and individual building owners is scarce.

Direct marketing companies specializing in the sales and distribution of their own brand of "black-line" roof maintenance products provide the bulk of such information. The history of some roofing companies can be traced to the mid-'50s and '60s when postwar economies and building booms put tremendous pressures on construction resources and services. These firms were built on the efforts of field sales people, some of whom may have been short on roof experience but long on enthusiasm. Armed with rudimentary technical literature and backed by sympathetic managers, these early sales people made the most of a generation of preservation-conscious property owners. They talked repairs, coating, and maintenance to the tune of tens of million of dollars in annual sales. Yet, until the late '70s, this segment of roofing was almost unknown.

It took the 1974 oil embargo and the steep rise in crude asphalt prices to focus attention on the value of maintaining existing roofs. The use of asphalt and coal tar-based mastics, emulsions, and resaturants soared. Maintenance became the backbone for many established contractors as new construction work dipped. Since the early 1980s, the curve has flattened with the advent of single-ply elastomeric roofs and modified bitumen systems.

Today, bituminous roofs make up the majority of roof construction worldwide. But more attention has been paid to their design than to maintenance or repair. Solutions to bituminous roof problems are, however, being addressed; the growing number of roofing alternatives has fostered an entire industry of roof inspection and evaluation. A competent roofing consultant can often save clients time and money by assessing roof conditions and providing solutions to a usually perplexing set of problems.

Title: 'DAMM' Method

Author: Magowan, James E.

Source: Construction Specifier v 41 n 11 Nov 1988 p 84-88

Date: 1988

ABSTRACT

What is the DAMM* Method? DAMM stands for the four basic areas of concern in the roofing process: **D**esign, **A**pplication, **M**aterial, and **M**aintenance of the roof system. There is no secret to the method, really.

It is quite simple. It involves the combination of practices and techniques developed and used over the years. With the exception of some Acts of God, all roof successes and failures can be traced back to the use or non-use of the "DAMM" method. The process starts with the design, followed by the development of specifications, selection of materials, and includes the ensuing process of construction and follow-up. It applies to all systems regardless of type: built-up, single-ply, metal, asphalt shingle, or wood. It correlates with all the new technological developments in roofing including the thermal insulation and complete new membrane and fluid systems now introduced into the North American market.

Let's look at the various stages of the roofing process and the problems facing design professionals and owners alike. These problems are at the root of non-adherence to the "DAMM" method. Probably the three most important constraints a design professional must wrestle with in all phases of the process are knowledge, time, and budget. These are the culprits that tend to lead them astray. Designers need to be constantly aware of constraints and the ways in which they can circumvent the obstacles they present.

Title: When is it Safe to Re-Cover an Existing Roof?

Author: Warseck, Karen

Source: National Engineer v 92 n 3 Mar 1988. p 8-9

Date: 1988

ABSTRACT

Most roofing systems manufacturers state in their sales literature that their products can be used, in some cases, to re-cover an existing roof. At first glance, the advantages appear overwhelming. The owner saves the cost of tear-off. The noise, dirt, and inconvenience of tear-off are eliminated. The building remains somewhat watertight during the installation of the new roof.

Normal operations are less disturbed by the roofing work. All these are very compelling arguments.

However, the realities of the situation require careful consideration. First of all, the reason roof replacement is under consideration is because the existing system leaks. A roof is rarely assessed for major work simply because it has exceeded its projected life span. Most likely, it has leaked and been patched on many occasions over a long period of time. This means that water has entered the existing system and is probably being retained in the insulation.

Thus, in a typical reroofing situation, there are various degrees of wet insulation under a membrane of dubious integrity. Logically, this is not the best substrate to which to attach a new and expensive roof. Furthermore, manufacturers will not warranty an installation over a wet or faulty substrate. Unfortunately, "faulty" is usually not defined until warranty repairs are required.

Title: Comparing Roofing Options

Author: Holzhauer, Ron

Source: Plant Engineering (Barrington, Illinois) v 48 n 5 Apr 1994. p 62-68

Date: 1994

ABSTRACT

The roofing membrane is the first line of protection against the elements. In fact, the membrane is the only waterproof component in the system and must protect the less weather-resistant items, such as insulation and decking. There are five types of roofing system membranes applied to industrial plants: built-up, modified bitumen, single-ply, metal, and foam. (A combination of built-up and modified bitumen is also gaining popularity.) The five basic versions offer different physical characteristics for dealing with the local environmental conditions and have varying costs, installation procedures, and maintenance requirements.

There is no single roofing system that universally outperforms all others, but one or two are probably the best choices for specific situations. Regardless of the type, however, installation is the critical factor in attaining a successful job. The best materials eventually fail and usually quickly, if not applied properly. Poor or impractical design is the other major contributor to roof failure. Because of the complexities associated with blame assessment for failure, roof warranties should be examined very carefully to see who covers what very early in the game.

The section "Common Roof Problems" itemizes some of the factors that attack roofs and how to solve or prevent them. The section "Roof Inspection Program" details the steps necessary to establish a comprehensive maintenance program for maximizing roof life.

Title: Recovering Damaged Roofs

Author: Nadal, Michael A.

Source: Plant Engineering (Barrington, Illinois) v 49 n 2 Feb 6 1995. p 47-48

Date: 1995

ABSTRACT

Worn-out or damaged roofs are a common plant problem. Many of these roofs are far past the point where maintenance or patch replacement can save the surface. At this point, only two viable options exist: tear the roof off and start over or recover it.

Tear-off becomes less desirable as every passing year raises tipping costs and adds new environmental regulations for disposal of the old materials. Recovering involves important concerns about re-entrained moisture, deck integrity, and geometry of existing flashing, evaluating all the economic, environmental, and technology issues involved in a tear-off versus recover reroofing situation can be difficult.