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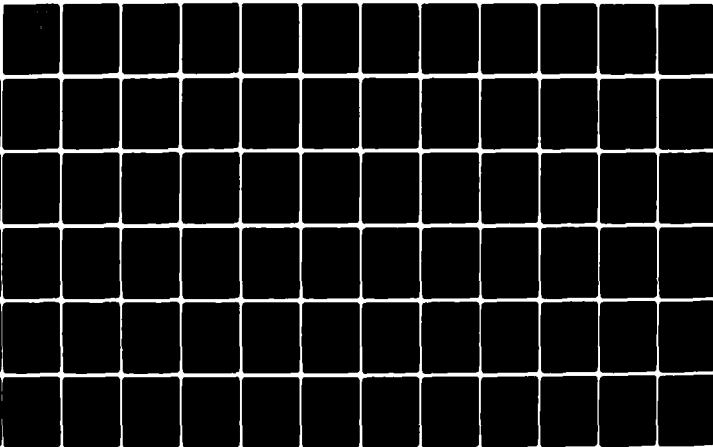
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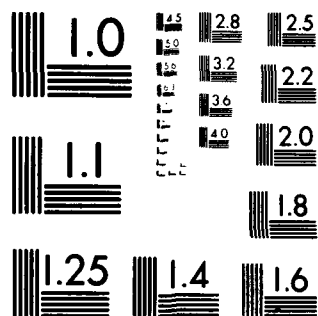
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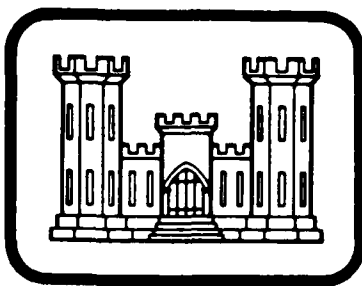


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REPORT FESA-TS-2080, TASK ORDER 10

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PERFORMANCE EVALUATION OF VINYL REPLACEMENT WINDOWS

P. B. SHEPHERD
JOHNS-MANVILLE SALES CORPORATION
RESEARCH & DEVELOPMENT CENTER
KEN-CARYL RANCH
DENVER, COLORADO 80217

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✓ maintenance. It was surprising to find that a window's thermal transmittance coefficient, U value, had only a small impact on the economic evaluation.

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SUMMARY

Old windows, leaky windows, single pane windows, and poorly installed windows may contribute to a large amount of energy use in heated buildings. The purpose of this study was to obtain and evaluate information and data on the durability, performance, and economy of vinyl replacement windows.

Vinyl windows are defined as windows whose frame and sash lineal components have been extruded from polyvinyl chloride compounds. A colored weathering surfacing of a second compound, such as acrylic, may be fixed to the exterior of the polyvinyl chloride lineals. A replacement window is generally considered to be a window of "prime" quality but with attached or separate flanges and/or fitting pieces to permit insertion of the window into a variety of openings left by the removal of the original window. A prime window is one constructed for installation in new construction but which may also be used in retrofit and renovation circumstances.

Vinyl windows can be fabricated with a low coefficient of heat transmission, U value, and low air infiltration. The same is true of wood windows. Thermally efficient metal windows are also available, but their U values may not be so low as is achieved with vinyl and wood. The energy conserving potential of various windows may be compared using conventional equations involving U value, air infiltration and degree days. This is explained in Appendix A. Life cycle costing is also explained in Appendix A. Another approach to window thermal analysis may be taken through mathematical modelling. An example of this is given in Appendix B.

It is not possible to make a general statement on which type of window may be the best choice. The most energy efficient window may not always be the most economical choice. Installed price, air infiltration, degree days and required maintenance may vary considerably among windows and geographic locations.

Therefore, each circumstance should be carefully analyzed using the methods provided in this report.

Replacement of existing windows should be considered only when repairs, caulking, weatherstripping and a storm window will not correct a badly damaged or worn out unit. When replacement becomes necessary, the new window should be a prime window of improved thermal design. This report provides methods for comparing the thermal performance of candidate windows. It is, perhaps, unfortunate that there is no public specification to guide the purchaser in selecting vinyl replacement windows. A suggested specification has been incorporated in this report and may be used as one tool in selecting among vinyl windows.

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PREFACE

Dr. P. L. Earle, Consultant, provided initial information for the market survey. His valuable experience in curtain wall design and component selection was most helpful.

Mr. F.A. Gill, Senior Research Chemist, was a major contributor in the area of vinyl weathering and longevity based upon his long association with vinyl siding compounding, testing and manufacture.

Mr. R. H. Neisel, Research Associate, provided inputs relating to building codes.

Mr. M. Albers, Research Physicist, was a valuable resource in the areas of mathematical modeling and heat transfer.

Mr. K. Olsen, Senior Financial Analyst, prepared the financial analysis segments of Life Cycle Costing.

Mrs. Rosie Waterbury, Secretary, proved to be of special value to this study. She was in the process of remodeling her house just as this Task Order commenced. Her experiences with manufacturers' representatives and window installers gave us valuable, first-hand exposure to real-world installed prices of several types of replacement windows.

The following persons contributed valuable ideas and information through personal interviews:

Mr. Dale E. Stroud, Product Manager, B.F. Goodrich Chemical Division.

Dr. James W. Summers, R&D Group Leader, B.F. Goodrich Chemical Division.

Mr. Richard J. Kruszynski, Sales Product Engineer, B.F. Goodrich Chemical Division.

Mr. W. Todd, Majestic Building Products, Denver, Colorado.

Mr. R. Durham, Consultant, Durham International.

Mr. C. A. Carstensen of Perma-lite provided information on foreign-made windows.

INTRODUCTION

Windows and their role in residential energy use and conservation may be viewed by some as a topic addressed by contradiction and confusion. There are sources which advise one to minimize the glazing area in homes.¹ There are sources which advise one to maximize the glazing area on south facing walls.² There are sources which suggest optimizing glazing area on east and west walls.³ People are confronted repeatedly by advertisements displaying the relative thermal conductivities of window construction materials. The disparity of these numbers is misleading when it comes to the selection of windows having different frame materials of construction. Single, double, and triple glazing are the subject of other articles.^{4,5}

The purpose of this report is to survey only one facet of windows -- vinyl replacement windows. The general subject of windows in an energy conservation plan has been reported by others.⁶ The scope and requirements of this assignment were to, "...conduct a literature and market survey to determine the availability and capability of vinyl replacement windows to save energy and the potential cost effectiveness of these windows for retrofit and renovation in existing buildings. An evaluation of information will be made concerning energy savings, cost effectiveness, installation, operation, maintenance, safety, code compliance, product longevity, and product warranty limitations."

"Vinyl replacement windows" is an expression which must be defined at the outset. "Vinyl" in this context means that the basic window frame and glass support members are comprised of extruded shapes of polyvinyl

chloride compound. This thermoplastic compound may be identical or very similar to that used for a number of years in the exterior building product, vinyl siding. The compound consists of a number of ingredients which may include:

- polyvinyl chloride resin
- titanium dioxide pigment
- optional colorants
- ultraviolet absorbing agent
- lubricant
- stabilizer

"Replacement" seems to be not a rigid term of definition. It appears that a "replacement window" may be a prime window unit supplied with integral or accessory flanges, etc., to facilitate installation in a number of different circumstances. In this sense, a prime, wood window in the hands of a reasonably experienced carpenter might also be considered a "replacement window." Any so-called replacement window may also be fit into new construction as a prime window. A survey made by the author at Fort Rucker, Alabama, on November 1, 1979, revealed that all windows requiring replacement are replaced with new, prime, double-hung, wood windows. It was determined that windows at this facility are of standard, so-called "stock," sizes and may be obtained from local lumber sources. Neither special carpentry skills nor unusual fitting techniques are required. Whenever a prime window needs to be replaced because of rot, damage, or other conditions not correctable with caulking, weatherstripping and possibly installation of a storm window, it should be replaced with a new prime unit of thermally improved design and fabrication.^{7,8} Identification of suitable thermal design and fabrication, especially in vinyl replacement windows, is one subject addressed by this report.

The history of windows whose frames are profile shapes extruded from polyvinyl chloride compound is not clear. One source attributed the beginnings of this product to Germany.⁹ One of the present American window brands, "Trocal," had its start in Germany and the German company, Dynamit Nobel, is reported to supply the "Trocal" window extrusions. It has been reported that

vinyl windows have a 39 percent share of market in Germany. This large market share was believed attributable in part to the fact that wooden windows produced in Germany following World War II were of very poor quality. German vinyl windows appear to be of very rugged construction with metal reinforcing inserts in the vinyl extrusions. The extrusions themselves were reported to have wall thicknesses of 0.115 to 0.170 inches. American vinyl window extrusions, on the other hand, were reported to have wall thicknesses in the range of 0.065 to 0.070 inches.

Vinyl has also been used in at least one Canadian window, Weatherseal, for about twenty years. The principle uses of vinyl in Canadian windows is as a cladding for wood and aluminum and as accessory parts not exposed directly to the weather. The extent of the availability of "all-vinyl" windows in Canada was not determined.

Vinyl windows were first sold in America during the early 1960's. This window was called Koroseal, and it was assembled from extrusions supplied by the B. F. Goodrich Company.

Very few of the firms who market vinyl windows may be classified as integrated manufacturers. Only the following named firms were reported to extrude vinyl window frame profiles, assemble, and market the completed window.

Fiberlux Corporation
Poly-Tex Corporation
Thermall Industries
Vinyl Building Products
Certain-teed Products Corporation

It appears that other sources of completed window units are assemblers of window components. The frame extrusions are produced by a small number (probably six) of companies who sell long lengths of window frame profiles, called lineals, to local converters. These converters cut the lineals, insert glazing, and complete the window fabrication. The local converter may also sell and install the completed windows. He may also

sell completed units to home improvement contractors. It was not clear whether the converter or the home improvement contractor solicits builder sales. The manufacture and distribution of vinyl windows seems to hold many parallels with the aluminum storm window business. The existence of a large number of regional and local converters has made it extremely difficult to obtain authenticated, technical and performance data on many specific window brands.

This report consists of the Market Survey, Literature Survey, Specifications for Windows, Performance Considerations, and Criteria for Window Selection. The Appendices contain a means to calculate life-cycle costing and a mathematical model of a window's thermal performance.

MARKET SURVEY

Method

The following actions were taken to secure a broad base of information relative to the manufacture, use, performance, and cost of vinyl replacement windows:

- .letter to manufacturers,
- .interviews with various sources associated with window industry and replacement window use,
- .consultant's attendance at trade shows in Germany and in Chicago.

Letter to Manufacturers

The letter sent to manufacturers is reproduced on the following page. The source of manufacturers solicited was the Thomas Register¹⁰ and all firms listed under the following categories were solicited:

- .vinyl windows
- .replacement windows
- .plastic windows
- .storm windows



**Johns-Manville
Sales Corporation**

Research & Development Center

Ken-Caryl Ranch
Denver, Colorado 80217
(303) 979-1000

October 23, 1979

Dear Sir:

The Johns-Manville R&D Center has been contacted to provide a study on the advantages and use of plastic replacement windows. We would like to receive from you advertising and technical literature, selling prices and installation costs for your window units. We are especially interested in independent testing results of compliance of your various plastic window units to the performance and physical standards of the following public specifications:

Air infiltration by ASTM E283
ANSI/NWMA I.S. 2-73
ANSI/AAMA 302.9, 1977
ANSI A 134.1
AAMA Standards of Thermal Performance

We are also interested in mathematical models and life cycle costing examples of plastic windows in both new and retrofit circumstances.

Yours truly,

P. B. Shepherd

Approximately 300 inquiries were mailed and the pertinent response was very poor. The names of respondents are listed below:

State Metal Awning Inc.
131 Shonnard Street
Syracuse, New York 13209

Trocal Window Systems
Dynamit Nobel of America, Inc.
105 Stonehurst Court
Northvale, New Jersey 07647

Evans Products Co., Inc./Remington Aluminum
100 Andrews Road
Hicksville, New York 11801
(Vinylview Windows)

Vinylume Products, Inc.
134 E. Woodland Ave.
Youngstown, Ohio 44502
(Vinylume Windows)

A great many replies were received from manufacturers of specialty plastic windows which had no application to the exterior walls of buildings. Additional manufacturers' literature was obtained through the good offices of consultants, from home improvement contractors, and at trade shows. These manufacturers were:

Poly Company of America, Inc.
Highway 5
East Langdon, South Dakota 58249

Rusco Industries Inc.
RD#2, Box 124
Cochran, Pennsylvania 16314

Vinyl Bash, Inc.
3707 W. 73rd Ave.
Westminster, Colorado 80030

ThermoFrame by
the Mintz Company
(no address on literature)

Certain-Teed Products Corp.
Valley Forge, Pennsylvania

Dura/Frame Windows
Durham Manufacturing, Inc.
6950 N. W. 12th Ave.
Ft. Lauderdale, Florida 33309
(These windows are no longer available.)

The information obtained from manufacturers' literature is used throughout this report. This information was of limited help in addressing the goals and objectives of the assignment, because of inconsistencies in the nature of technical data supplied by the window companies.

A number of window manufacturers who do not produce polyvinyl chloride replacement windows volunteered literature on their products. These windows fell into a category which might be described as either hybrid or composite. For example, these windows included aluminum or vinyl cladding on wood, and frames structurally composed of two materials such as vinyl and aluminum. These windows may present promising alternatives where thermal efficiency, low maintenance and long-proved structural components are desired attributes. The respondents in this category are listed below.

ROLScreen Company
Pella, Iowa 50219
(Aluminum clad wood)

Winterseal of Flint, Incorporated
209 Elm Street
Holly, Michigan 48442
(Aluminum outside, vinyl inside)

Alcoa Building Products Incorporated
2 Allegheny Center
Pittsburgh, Pennsylvania 15212
(Aluminum and vinyl, weatherside varies)

Weather Shield Manufacturing Incorporated
PO Box 309
Medford, Wisconsin 54451
(Aluminum clad wood, vinyl clad wood)

Anderson Corporation
Bayport, Minnesota 55003
(Vinyl clad wood)

This cross section of window constructions provided a good representation for the various types in the market place. A complete list of the different window construction materials appears below:

Wood
PVC clad wood
Aluminum clad wood
Aluminum
Aluminum with thermal break
PVC-clad aluminum
Extruded PVC
Metal reinforced PVC
Steel
Foamed polystyrene
PVC clad CPVC
PVC and aluminum

Physical and performance properties claimed by those manufacturers who responded are tabulated in Tables 1 and 2 on the following pages. Each reported value is footnoted to indicate the source of the test method used. Occasional failure to disclose the test methods made it difficult to compare the various window units. Another potential area of confusion lies in comparison of "U" values. ASTM C-236 is the only accepted, public test method for this attribute. Some laboratories can test windows with a single dimension up to five feet. Many others are limited to smaller sizes. Window "U" values should be reported for the actual size tested. Thermal performance of other size windows may

not be precisely extrapolated from area or perimeter comparisons. The "U" values of other window sizes may be estimated using the mathematical model in Appendix B. Such a procedure for estimating window thermal performance is, at best, useful for approximate comparisons. Small differences in "U" values between different windows should not be viewed as significant.

The Architectural Aluminum Manufacturers Association has a test method for "Condensation Resistance Factor" which has been claimed to be of value in comparing one facet of apparent thermal performance among windows. This method has not been adopted by ASTM or ANSI.

TABLE 1
REPORTED PROPERTIES OF VINYL WINDOWS

<u>Manufacturer</u>	<u>Trocal</u>	<u>Polyco</u>	<u>Vinyl- lume 500</u>	<u>Evans Vinylview</u>	<u>State Metal Awning "Finesse"</u>	<u>Certain- Teed</u>
Style	Casement	Various	Dbl Hung		Dbl Hung	?
Air Infiltration, cfm/ft	0.01 ^a	d	0.29 ^a	0.59btu/ in ^c	---	---
Water Penetration, no leak at psf						
Cyclic	15 ^a	d	2.86 ^a	---	---	---
Static	15 ^a	d	4.00 ^a	---	---	---
Uniform Load Deflection, in.	0.038 ^a	d	0.198 ^a	---	---	---
Uniform Load Structural						
Exterior, psf	40 ^a	d	40 ^a	---	---	---
Interior, psf	20 ^a	d	20 ^a	---	---	---
Permanent Deformation, in.	0.024 ^a	d	---	---	---	---
Horizontal Deflection, in.	0.020 ^a	d	0.200 ^a	---	---	---
Wind Load						
Exterior, psf	91 ^a	d	---	---	---	---
Interior, psf	52 ^a	d	---	---	---	---
Permanent Deformation, in.	0.035 ^a	d	---	---	---	---
U Value	---	0.37 ^c	---	0.61 ^c	0.52 ^c	0.65 ^c
Condensation Resistance Factor	74	---	---	50 ^c	58 ^c	55 ^c

^a ANSI A134.1-1972

^c Method not reported

^b Calculated, not tested

^d Claim to exceed NWMA requirements

TABLE 2
REPORTED PROPERTIES OF COMPOSITE WINDOWS

<u>Manufacturer</u>	<u>Weather Shield</u>	<u>Alcoa</u>	<u>Season All</u>	<u>Andersen</u>
Style	All	Various	---	"Typical"
Air Infiltration, cfm/ft	0.09-0.17 ^f	---	---	0.25 ^b
Water Penetration, no leak at psf				
Cyclic	e	---	---	
Static	e	---	---	
Uniform Load Structural				
Exterior, psf	e	30-55 ^g	---	
Interior, psf	e	30-55 ^g	---	
Permanent Deformation, in.	e	---	---	
Horizontal Deflection, in.		---	---	
Wind Load				
Exterior, psf	e	---	---	
Interior, psf	e	---	---	
Permanent Deformation, in.	e	---	---	
U Value	---	0.60-0.68 ^g	---	0.52 ^b
Condensation Resistance Factor	---	51-55 ^g	---	

^a ANSI A134.1-1972

^e Claim to comply with ANSI 134.1 or 134.2

^b Calculated, not tested

^f AAMA I.S. 2-(yr)

^c Method not reported

^g AAMA 1502.6

^d Claim to exceed AAMA requirements

Interviews

Personal interviews were held with a number of persons in an effort to describe the composition and market channels of the vinyl replacement window business. Information was also sought concerning performance experience, life expectancy, test data of other than manufacturers' claims, and cost effectiveness. Persons who graciously agreed to supply information were:

Mr. Robert Durham, Consultant and President of
Durham International
Fort Lauderdale, Florida

B.F. Goodrich Chemical Company
Cleveland and Avon Lake, Ohio

Mr. Dale E. Stroud, Product Manager
Mr. Richard J. Krusznski, Sales Product
Engineer
Dr. James W. Summers, R&D Group Leader

Dr. P. L. Earle, Consultant
Denver, Colorado

Mr. F. Gill, Senior Research Chemist
Johns-Manville Research & Development Center
Denver, Colorado

Mrs. Rosie Waterbury
Johns-Manville,
Denver, Colorado

Mrs. Waterbury was considering replacing the windows in her home just as this study commenced. Her brother had purchased an installation of replacement vinyl windows several months prior. Their practical and real-life interface with the process of choosing and purchasing replacement windows added a valuable dimension to this study.

Mr. Durham was a pioneer in the extrusion of profiles for the frames of vinyl windows. He was identified early-on as an outstanding, world-wide

consultant in this field. His willingness to cooperate in this study was outstanding and the quality of information provided was excellent.

The B. F. Goodrich Company is a major manufacturer of polyvinyl chloride resin and extrusion compound used in vinyl building products such as windows and siding.

Dr. P. L. Earle is an energy consultant who has assisted Johns-Manville in several studies relating to energy conservation products and methods.

Mr. F. Gill was the principle technical professional assigned to Johns-Manville's vinyl siding business several years ago. His experience with vinyl building products, data on the weatherability of vinyl compounds, and industry contacts were of great help.

Interviews with window manufacturers were considered as a response to the letter survey and are not separately cataloged here. All of the information obtained through interviews was cataloged according to the subjects referenced in the index. This information was then integrated into the overall presentation. It is not within the scope of this report to separately summarize each interview.

LITERATURE SURVEY

The literature survey was conducted by Ms. Suzanne D. A. Graham who is on the Corporate Information Center staff at the Johns-Manville Research & Development Center. Computer sources were used extensively. The primary and most productive sources for reference materials were:

NTIS-National Technical Information Service
U. S. Department of Commerce
Springfield, Virginia

Compendex Engineering Index Inc.
New York, New York

Energyline Environment Information Center, Inc.
New York, New York

Ismec Data Courier, Inc.
Louisville, Kentucky

One hundred forty-seven citations were disclosed in the search. Nearly two dozen of these were selected based on the brief synopsis supplied for each citation and these were obtained from appropriate sources. Very little was disclosed relating specifically to vinyl replacement windows. Much valuable information was obtained relating to the quality, performance, design and selection of windows in general. That information pertinent to the objectives of this study has been incorporated in this report, footnoted, and listed in the Reference Section. All literature citations which were found as relating to windows have been incorporated in the Bibliography.

SPECIFICATIONS

There are a number of public specifications and standards relating to windows. These were generally written by industry associations and are intended to be applied to a specific type of window, i.e., wood, steel or aluminum. The technical and market surveys disclosed no industry standards or public specifications written for vinyl (replacement) windows in the United States. Canadian CSA Standard A274 references vinyl windows. However, the document appears to be more applicable to vinyl clad windows having wood or metal structural cores.

Following is a list of specifications, standards and codes applicable to windows. Each is discussed in detail and, finally, physical and performance guidelines are recommended for use in selecting vinyl windows or in comparing them to alternative choices.

ASTM E283 Standard Test Method for Rate of Air Leakage Through Windows, Curtain Walls and Doors.

ASTM E330 Standard Test Method for Structural Performance of Exterior Windows, Curtain Walls and Doors Under the Influence of Wind Loads.

ASTM E547 Standard Test Method for Water Penetration of Exterior Windows, Curtain Walls and Doors by Cyclic Static Air Pressure Differential.

ASTM E331 Standard Test Method for Water Penetration of Exterior Windows, Curtain Walls and Doors by Uniform Static Air Pressure Difference.

ASTM E405 Standard Methods of Wear Testing Rotary Operators for Windows.

ASTM E163 Standard Methods of Fire Tests of Window Assemblies.

ANSI/NWMA I.S. 2-73 Wood Windows

ANSI/AAMA 302.9 Specifications for Aluminum Windows

ANSI A134.1 Specifications for Aluminum Windows

AAMA 1502.6 Voluntary Standards and Tests of Thermal Performance of Residential Insulating Windows and Sliding Glass Doors.

Code for Energy Conservation in New Building Construction, December 1977 jointly prepared by BOCA, ICBO, NCSBCS, and SBCCI.

BOCA Basic Building Code, 1979.

Uniform Building Code, 1979 Edition.

Standard Building Code, 1979 Edition.

One and Two Family Dwelling Code, 1975, jointly prepared by BOCA, ICBO, NCSBCS and SBCCI.

ASTM E-283 is a frequently referenced method for testing the air leakage of windows. The test method does not specify the pressure drop to apply across the

window. A pressure of 1.567 foot pounds per square foot is referenced in the Energy Conservation Code and a maximum air leakage of 0.5 cfm per foot of operable sash crack is specified. The pressure of 1.567 foot pounds per square foot is considered to approximate the effect of a 25 mph wind. The equipment used to perform the E-283 test may also be used in E-330, E-331 and E-547 which are described in the following paragraphs. The equipment used in these tests is basically a wall section containing an apperture to receive a test window. The wall section is affixed to an air chamber which contains calibrated water sprays. The chamber is provided with means for controlled pressurization and evacuation. Suitable pressure and volume measuring devices are specified.

ASTM E-330 is a test for the structural performance of windows under wind loads. There are two different procedures contained in this method. Procedure A describes a regimen of preselected loading and deflection measurement. Procedure B requires loading the window to failure as well as recording deflection measurements.

ASTM E-547 and ASTM E-331 are tests for measuring the resistance of a window to penetration by rain under prescribed conditions of pressure and water flow. E-547 is a cyclic test designed to create a sort of pumping action whereas E-331 uses static pressure.

ASTM E-405 is a test designed to evaluate the durability of rotating hardware used on casement type windows.

ASTM E-163 is a rather severe fire test incorporating a resistance to a hose stream. It appears to be a very severe test for residential windows.

There are no public standards for vinyl windows in America and, therefore, no guidelines for judging a window's acceptability based on its performance in the various tests. There are voluntary standards for wood windows, ANSI/NWMA 2-73, and for aluminum windows,

ANSI/AAMA 302.9 and ANSI 134.1. Some manufacturers of vinyl windows have referenced these standards in their literature.

For example:

Trocal has offered test data showing the performance of their window against ANSI A134.1; yet the unit tested was smaller than specified in the standard.

Fiberlux claimed in 1977 compliance with ANSI 302.9, yet the unit tested failed in uniform load deflection and both horizontal and vertical load, unglazed.

Rusco has claimed A134.1 compliance yet cautions, "don't support unit by corner".

Building codes have had no requirements pertinent to residential replacement and prime windows until the four major code groups published jointly, the Code for Energy Conservation in New Building Construction. This code does specify an air leakage limit, 0.5 cfm per foot of sash crack at 1.567 pounds per square foot. It also references the use of window "U" value but does not specify a maximum limit for "U" value.

The absence of voluntary standards and public specifications for vinyl windows makes it difficult to offer definitive guidelines for the selection and purchase of such units. The following specification is offered as a suggestion based upon accepted values for other building materials and windows. It is hoped that the window industry and ANSI may soon publish a specification for consumer guidance.

Suggested Specifications for Vinyl Replacement Windows

1. Frame and lineals construction material.

The compounds from which the window parts are extruded shall meet the following requirements.

- 1.1. All polyvinyl chloride components used to fabricate --- windows have been extruded from polyvinyl chloride compounds expressly formulated for exterior exposure and use. The outdoor color stability and impact strength retention of this compound has been tested for at least two years by --- at ---.
- 1.2. All polyvinyl chloride components used to fabricate --- windows shall comply with NBS Voluntary Product Standard PS 55-72, paragraph 3.10.
- 1.3. All polyvinyl chloride components used to fabricate --- windows shall comply with ASTM D-1784 Class ----- - The compound is to be designated by a series of five numbers and a letter suffix chosen as follows.

(First Number)	1
(Second Number)	2, 3, 4, 5 or 6
(Third Number)	3, 4, 5, or 6
(Fourth Number)	4, 5, or 6
(Fifth Number)	4, 5, or 6
(Suffix)	C

Note: Typical compound classes are:

12454 - C
13454 - C
13447 - C

- 1.4. All chlorinated polyvinyl chloride components

used to fabricate --- windows shall comply with ASTM D-1784 - Class -----.

(First Number)	2
(Second Number)	2, 3, 4, 5, or 6
(Third Number)	3, 4, 5, or 6
(Fourth Number)	4, 5, or 6
(Fifth Number)	5, 6, 7, or 8

1.5. Components of white and pastel colored windows shall be composed of polyvinyl chloride.

1.6. Components of dark colored windows shall be composed of chlorinated polyvinyl chloride co-extruded with a cap stock of weatherable polyvinyl chloride.

2. Glazing.

Glazing panels shall be composed of glass of a type and thickness agreed upon between purchaser and seller. The glazing panels must comply with local building codes whenever applicable. A minimum of two parallel glazing panels (dual glazing) shall be provided.

3. Hardware.

All hardware supplied as a part of the window shall comply with the appropriate "hardware" section of ANSI Specification A134.1.

4. Physical and Performance Properties.

4.1. Air Infiltration.

Air infiltration for all types and sizes of windows shall be 0.5 cfm per foot of operable sash crack, maximum. Testing shall be in accordance with ASTM E283 with a pressure of 1.567 foot pounds per square foot.

4.2. Thermal Conductance.

The coefficient of heat transmission, U value, of all windows having a nominal size of 15 square feet or larger shall not exceed 0.60 BTU/sq ft/°F/hr. Windows of smaller size shall not exceed 0.50 BTU/sq ft/°F/hr. Testing shall be in accordance with ASTM C-236 at a mean temperature of 70°F.

4.3. Other properties.

Additional physical and performance properties of vinyl windows shall be in accordance with ANSI Specification 134.1 for each of the following types.

DH-B1-HP	Double hung (also single hung)
C-B1-HP	Casement
P-B1-HP	Projected
A-B1-HP	Awning
HS-B1-HP	Horizontal sliding
J-B1-HP	Jalousie
VS-B1-HP	Vertical sliding

CONSIDERATIONS APPLICABLE TO REPLACEMENT WINDOW SELECTION

A great deal has been written about energy criteria applicable to the size, location and installation of prime windows. This was briefly discussed in the Introduction. Most of these considerations do not apply to the selection of replacement windows. Other considerations such as window management with drapes and shades are also not within the scope of this Task Order. There remain, however, a large number of factors to be considered when making a decision whether or not to

replace a window and in deciding among the various alternatives of window types and sources. The factors to be considered which are discussed as topics within this section include:

Should a Window Be Replaced?

Selection Factors For Vinyl Replacement Windows -

- energy conservation
- cost effectiveness
- installation
- operation
- maintenance
- safety
- building codes
- product life (durability)
- product warranty
- rain penetration

Should a Window Be Replaced?

It has been previously mentioned that a window should be replaced only when conditions such as rot, damage or structural movement are not correctable with caulking, weatherstripping, or, possibly, storm windows.¹¹ When replacement becomes necessary, only prime windows of thermally improved design and construction should be used.¹² Any experienced carpenter or Facilities Chief of Buildings may determine, by inspection, if a window should be replaced.

Selection of Vinyl Replacement Windows.

The following sub topics represent the factors to be considered when selecting a new window unit to replace one which is not repairable. The discussion is aimed at vinyl windows, but the considerations may be applied to many other types of windows. Specific selection criteria derived from the following factors are presented in the next section of this report.

Energy Conservation

Two measurable qualities of a window relate

directly to its role in energy conservation. The first quality is "U" value, which is a measure of the window's thermal conductance. The lower the "U" value of the total window, the better will be the thermal performance of the window. The second measurable quality is air infiltration. The lower the value, the better will be the thermal performance of the window. It is important to note that the benefit of a good, thermally efficient window can be negated by poor or improper installation.

Advertisements for vinyl windows sometimes stress the relative "U" values of the frame materials thus making vinyl windows seem to appear far superior to metal frame windows. This sort of presentation tends to be misleading when related to total window thermal performance. The frame material may represent only a small portion of the total window area and this frame material is significant only to conductive heat losses.^{13,14} This relative insignificance of frame material was borne out by detailed laboratory testing which showed that heat flow associated with leakage was much larger than that due to thermal conduction in many of the walls tested.¹⁵ Another source confirmed that conduction through wood window frames is negligible compared to the glass area but that for metal frame windows, the conductance per square inch of frame is about equal to that per square inch of double glazing.¹⁶ Since the area of framing is so small, relative to the area of the glass, the framing material may have little impact on the total thermal performance of the window.

Air infiltration is an important characteristic. Most modern windows from major manufacturers are tested for compliance with public standards for air infiltration. As was pointed out in the Sabine study,¹⁷ air leakage can be a much more significant factor than conduction in the overall thermal performance of a window. It is perhaps unfortunate that leakage tests are made at standard room temperature conditions. The relative coefficients of thermal expansion for vinyl and metal suggest that windows made from these frame materials may leak air to a somewhat greater extent at lower temperatures than would be suggested by laboratory test results obtained at room

temperature. The following list of expansion coefficients illustrates a comparison of three frame materials.

Wood	25×10^{-7}	in/in/°F
Aluminum	130×10^{-7}	in/in/°F
PVC	300×10^{-7}	in/in/°F

Consider as an example, a three foot lineal made from each of the above materials. The window is made and installed at 70°F. When the temperature drops to 0°F the length of the three foot piece for each of the frame materials will be:

Wood	35.994 inch
Aluminum	35.967 inch
PVC	35.924 inch

This suggests that crack widths contributing to air infiltration test results at room temperature may widen by up to the following amounts at 0°F.

Wood	0.006 inch
Aluminum	0.033 inch
PVC	0.076 inch.

Air infiltration testing of windows at low temperatures might be a worthwhile subject for laboratory studies. It seems that there is not a major difference between the materials. However, low temperature air infiltration testing using ASTM E-253 is suggested because a window is a three dimensional system whose shrinkage performance may not be accurately represented by simple, linear models.

Window selection for thermal performance should be heavily influenced by available air infiltration test results. Air infiltration and thermal conductance have been included in the procedures for selecting among window alternatives.

It is critical to note that poor or improper installation may negate the anticipated benefits of a thermally efficient replacement window. One field study disclosed that the majority of leakage occurred around

the window frame, between the frame and the wall, and that proper caulking reduced the measured leakage by 60 percent.¹⁸

An important factor relative to window thermal performance is glazing. Double glazing is regarded as essential and triple glazing can be of value in very cold climates. The analytical methods of selection provided in this report will aid in selecting the proper glazing, provided the manufacturer will disclose measured "U" values for each of the window units being considered. Note that we have concerned ourselves only with heating circumstances. This is because the National Bureau of Standards has reported that improving window thermal performance by adding storm windows was of value only during the heating season.¹⁹

Window size has not been considered in this study. The need for replacement presents an opportunity to consider installing larger windows on south walls in heating climates and smaller windows on north walls. However, the impact of window size on building energy use is not within the scope of this study on vinyl replacement windows. It is, however, pointed out for future consideration that changing window sizes according to exposure direction may have a sizeable impact on energy conservation.

Cost Effectiveness

The following factors should be considered when calculating cost effectiveness of windows and comparing life-cycle costs of windows.

Energy efficiency or BTU per year heat loss attributable to the window.

Required maintenance such as painting, glazing, replacement of balance, lock and other hardware.

Initial installed cost.

Life expectancy to required replacement.

The expected life of a window may be a critical

2

factor in calculating cost effectiveness. A difference of ten years in assumed life may have a major impact on cost comparisons; yet, little has been published about the life expectancy of the American residential window.

Let us assume that a window will be replaced only when it has been judged to be non-repairable; for example, the sash has warped out of the frame. There are certainly wood windows which have lasted over 100 years. Yet vinyl windows have been used in America for less than 20 years. It would be unfair to make a life-cycle cost comparison using 100 years for wood and only 20 years for vinyl windows. Department of Energy methods of life-cycle costing as explained in the Federal Register resolve this apparent dilemma because they call for a "study period" of 20 years.²⁰ Where life cycle costing has been mandated, a window life of 20 years is recommended for all windows. Even 20 year extrapolation of investment, energy cost escalation, and carpenter wage rates is viewed as an uncertainty and, perhaps, useful only for comparative purposes.

Installation

There is really only one factor to consider in the installation of replacement prime windows - cost. Considerations of window removal, framing preparation, insertion, fitting and final trim will all be reflected in the installation cost. When window replacement is to be done by outside contractors, it is only necessary to obtain competitive bids on the various window units being considered. When windows are to be replaced using in-house carpenters, there are usually two possibilities.

1. Use any type of window meeting the selection criteria when the window to be replaced is of a contemporary stock size.
2. Use a so-called replacement window when the window to be replaced is not of a contemporary stock size. The accessory fins and expanders of replacement windows should make framing changes unnecessary.

It is interesting to note that ASTM Committee E06 approved late in 1979 installation practices under the Standard entitled, "Proposed Standard Practice for the Installation of Storm Windows, Replacement Windows, Multi-Glazing, Storm Doors and Replacement Doors". Society adoption of the Standard is anticipated during 1980.

Operation

The operation of windows is influenced by window design, hardware, fabrication, and proper installation. ANSI Specification A134.1 calls out an operating force for windows. This may be a useful guideline. Experience and first-hand inspection may provide equally useful guidelines.

Maintenance

Vinyl windows are claimed by many to require no maintenance. This is, of course, not true as any window may require replacement of broken glazing, adjustment or replacement of hardware, and cleaning. Since these may apply equally to all windows, they are ignored when comparing the one maintenance requirement which differs among windows - painting and puttying. The anticipated painting frequency for the various types of windows within the 20 year life-cycle analysis period is shown below for various window frame materials.

Wood -	6 years outside 7 years inside
Vinyl Clad Wood	
White and pastel -	None outside 7 years inside
Dark colors -	Unknown
Aluminum clad wood factory painted -	10 years outside 7 years inside
Aluminum	
Mill finish -	None
Anodized -	None
Factory Painted -	10 years
Solid Vinyl -	None

CPVC with vinyl
capstock, dark color -

Unknown

It must be understood that these are estimates offered for use in comparative analysis. It was not within the scope of this study to fine-tune repainting estimates according to climate, exposure and paint quality differences.

Safety

There are no safety requirements relating to residential prime windows in the major building codes. The principle practical consideration relates to emergency egress and ease of breakage for fire fighting. Vinyl prime/replacement windows may be considered the equal of all other windows in these regards. The significant safety variable in window construction is the glazing material and all windows found in this study were made with conventional, breakable glass. Sash and muntin construction in some windows may enhance the ease of emergency exit. This was not considered to be a significant factor.

Code Compliance

The major building codes have no requirements which would relate to window replacement. Local code variations and local code authorities may differ. Therefore, it should be determined from the local building inspector if a building permit is required for window replacement. For example, Chapter 54 of the Uniform Building Code might be interpreted as applying to residential replacement windows. In such cases, windows subject to human impact must meet UBC Standard 54-2.

The Code of Energy Conservation in New Building Construction jointly prepared by BOCA, ICBO, NCSBCS and SBCCI was not considered to be applicable to renovation and replacement. Some individual building inspectors might choose to act otherwise. In such cases, the rather common standard for air infiltration (maximum 0.5 cfm per foot of crack) would be applied.

FHA has minimum property standards relating to windows and ASHRAE 90-75 specifies window performance for energy efficient buildings. Both of these documents apply to new construction.

Product Longevity

The longevity or durability of vinyl windows is a difficult area for purchasers to investigate and evaluate. The exterior durability performance of vinyl siding in America suggests that it is possible to produce light colored vinyl compounds of acceptable durability for use in window frame construction. However, the word "vinyl" does not insure, nor even imply, acceptable durability.

There are no public standards relating to the exterior durability of polyvinyl chloride compounds or extruded shapes. The purchaser must, therefore, rely on the integrity of window suppliers. About the only insurance of acceptable weathering quality available to the purchaser might be to insist on written assurance in the form of a statement such as the following,

"All polyvinyl chloride components used to fabricate --- windows have been extruded from polyvinyl chloride compound expressly formulated for exterior exposure and use. The outdoor color stability and impact strength retention of this compound has been tested for at least two years by --- at ---."

Such a statement is, of course, not applicable to windows which are produced with a weatherable cap stock. Trocal windows are made from PVC but have an acrylic cap stock exposed to the weather on all colors except white. The durability of this cap stock is unknown. "Acrylics" are regarded by many as having superior durability to "vinyls". However, one should not make purchasing decisions based on the reputation of generic plastic names. There can be both poor and good weathering acrylics just as there are different vinyls designed for interior use and for exterior use. A second family of cap stock surfaced vinyl windows is being introduced. These are darker colors, usually in the brown-red

family. Such darker colors attain a higher surface temperature when exposed to the sun. The frames underlying these cap stock colors should not be produced from PVC compounds because of the risk of exceeding the heat distortion temperature of the lineals when the dark color is exposed to the sun. Chlorinated polyvinyl chloride (CPVC) is the compound recommended by B.F. Goodrich to be used as the structural base under dark cap stocks. CPVC has a higher heat distortion temperature than PVC.

ASTM D-1784 is a specification which may be applied to vinyl window frames. While it does not relate to outdoor durability, the strength and chemical resistance requirements may be pertinent to product longevity. Page 29 in this report contains the details on how to call out the proper classes in ASTM D-1784 for vinyl window lineals.

National Bureau of Standards Voluntary Product Standard PS55-72 for Rigid Vinyl Siding contains references to weatherability which may be applied to vinyl window extrusions. Paragraph 3.10 contains the criteria and paragraph 4.10 the test methods.

Another good test for longevity is field experience. Vinyl windows have been used in America for less than 20 years. It is suggested that the suppliers of candidate windows be asked to show and demonstrate their window units which have been in service at least five years.

Product Warranty Limitations

Very few window manufacturers referred to any warranties or guarantees. A summary of replies appears below:

Anderson Vinyl Clad Wood	No warranty reference
Weather Shield Vinyl or Aluminum Clad Wood	No warranty reference
Alcoa Vinyl and Aluminum Structure	No warranty reference

Polyco Vinyl	Frame and sash guaranteed 20 years. No reference to terms of guarantee.
Evans Vinyl	No warranty reference.
Vinylume Vinyl	Five year warranty, says no visual obstruction on interior surfaces of insulating glass. Life of window guarantee against material and workmanship defects. Does not cover glass or screens. Charge for on-site service calls, otherwise remove window, and ship back to factory.
Trocal Vinyl with Exterior Acrylic Cladding	No warranty reference.
State Metal Awning "Finesse"	20 year warranty of freedom from inherent defects. Lists specific examples. Contains disclaimer of "fitness for use".
Mintz Company, Thermo Frame	No warranty reference.
Certain-Teed	"Satisfaction guaranteed", is only reference.

Historic Preservation

Repairs to or replacement of windows in buildings on Army Facilities may require attention to preservation of the historic qualities of the facade and architecture. This factor may add to the cost of replacement windows and may also negate the use of vinyl windows for replacement purposes.

Acoustic Properties

Windows with low air infiltration ratings and tight fitting installation flanges may have beneficial acoustic as well as thermal properties. This could be advantageous in high outside noise areas such as in cities or near aircraft facilities. Nothing has been published on the "as-installed" acoustic qualities of the various replacement window candidates. Research and testing in this area may be desirable.

CRITERIA FOR SELECTION OF VINYL REPLACEMENT WINDOWS

The need for a replacement window should be established before proceeding to the various steps involved in choosing a specific window. Remember that a replacement window is needed only when the existing window cannot be repaired and upgraded with caulking, weatherstripping and a storm window. When it has been determined that a replacement window is required, the following steps will insure selection of an acceptable quality window of suitable cost effectiveness.

1. Obtain competitive bids from at least two sources after first inspecting each candidate window for workmanship and operation.
2. Obtain written certification that each window will comply with the suggested specifications on pages 36 through 43. Request a copy of the pertinent testing report.
3. Calculate the life-cycle cost for each alternative following the procedures detailed in Appendix A. Note that a supplementary analysis tool is contained in Appendix B. This procedure entails the application of a mathematical model to the thermal performance of a window.
4. Compare the results of Item three to the examples in Appendix A. This may show that it would be desirable to obtain additional quotations on thermally improved design aluminum, wood and hybrid windows.
5. Obtain and retain copies of warrantys and guarantees offered by each window manufacturer.
6. A separate energy conservation analysis for each window may be made using the data calculated within Appendix A.

The final selection of a replacement window will most likely be dictated by the life-cycle cost comparison. This comparison includes energy costs over the 20 year study period. The most economical window

alternative might be rejected in cases where the supplier is unable to supply compliance certification and authenticated testing data to permit comparisons with competing windows.

CONCLUSIONS

Vinyl replacement windows offer the potential of reducing heat loss when they are used in both renovation and retrofit circumstances.

The dollar savings achieved through energy conservation may make window replacement an attractive action to consider.

Selection of the type of window (vinyl, metal, wood) will be strongly influenced by the installed cost, and secondly, by the measured air infiltration performance of each window.

RECOMMENDATIONS

Analyze the energy savings and life-cycle costs using the methods in Appendix A to determine the measurable benefits of window replacement and to select the most beneficial type of window.

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APPENDIX A

LIFE CYCLE COSTING OF WINDOWS

Basis: Forced replacement, select among window types.

Elements of Cost/Saving: initial total installed cost; annual net energy consumption for heating; periodic maintenance.

The elements of cost and expense in comparing window types are as follows:

- removal of existing window
- cost of replacement window
- labor to install replacement window
- maintenance of replacement window if required
- annual energy loss attributable to window
- life of replacement window

Annual Net Energy Consumption

Since we are concerned with comparing one window to a second or third, we are concerned principally with "U" value and air infiltration. Obtain these values from the window manufacturer based upon tests on the actual style and size of window being considered. If the manufacturer is unable to provide data, the following table may be used only for the purpose of making life cycle cost comparisons. These data must not be used to represent quality or performance of specific types of windows.

"U" Value of Residential Windows¹
Single and Double Hung, Casement and Slider

<u>Frame Material</u>	<u>Single Pane</u>	<u>Double Pane</u>
Vinyl	0.75	0.45
Wood	0.80	0.50
Thermal Break Aluminum	1.00	0.55
Aluminum	1.10	0.70

The above data may be used for comparison purposes of windows up to 3 feet to 5 feet with approximately 80 percent glass areas.

Also, use the manufacturers' data on air infiltration. Multiply the figure by the appropriate perimeter and time interval to obtain cubic feet per hour. If no data are available, calculate air infiltration as follows:

- for windows with no factory installed weatherstripping:

$$V = 240 \times L \times W$$

- for windows with factory installed weatherstripping on all mating edges:

$$V = 36 \times L \times W$$

where:

V = air infiltration, cubic feet per hour

L = length of window, feet

W = width of window, feet

¹ASHRAE Handbook, 1977 Fundamentals; Chapter 22.
Various manufacturers' literature.

Calculate the annual heat loss for each window being considered using the following formula:

$$H = 24D (AU + 0.018V)$$

H = annual heat loss attributable to window, BTU

D = heating degree days for location being studied. Obtain from weather bureau, airport, or ASHRAE Handbook, 1976 Systems.

A = area of window, square feet

U = thermal conductance of window
BTU/sq ft/°F/hr

V = air infiltration of window, cubic feet per hour

The annual heating cost incurred by each window for one year may now be calculated as follows:

$$E = \frac{H}{r} \times C$$

where:

E = annual heating cost, dollars

H = annual heat loss for each window from previous section

C = cost of fuel used in building, dollars per BTU

r = efficiency of heating system in building expressed as a decimal (70% = 0.70)

The cost of fuel expressed in dollars per BTU may be calculated from conventional billing units as follows:

Electric - divide dollars per kwh by 3413

Natural Gas - divide dollars per CCF by 100,000

divide dollars per therm by 100,000

No. 2 Oil - divide dollars per gallon by 140,000

If the efficiency of the heating unit is not known, the following may be used for this comparative calculation.

Electric - 1.00

Natural Gas - 0.70

No. 2 Oil - 0.60

Periodic Maintenance

Periodic maintenance for the various types of windows has been assumed to consist only of painting. Painting frequency or schedule will vary according to building location, compass exposure, shading and paint quality. Use an annual painting frequency based on experience in your area if this is known. If this is not known, use the following data for the comparative calculations. Note that a study period of only 20 years is used based upon the suggestions contained in DoE life-cycle costing guidelines¹.

¹Federal Register, Part IV Department of Energy;
April 30, 1979.

<u>Type of Window</u>	<u>Paint Once Each</u>
Vinyl (incl. vinyl clad wood)	0 years
Mill finish aluminum	0 years
Anodized aluminum	0 years
Painted Aluminum	10 years
Wood	6 years outside, 7 years inside

The cost to paint a window may be determined from area experience, estimates obtained from painters, or from construction estimating guides¹.

The life of a window should be taken as 20 years for analysis purposes according to DoE guidelines.²

¹Moselle, Gary ed; National Construction Estimates; Craftsman Book Company

²Federal Register; Part IV Department of Energy; April 30, 1979

Example of Life Cycle Costing

Compare three different double hung replacement windows.

1. Vinyl replacement window, double pane, factory weatherstripped.
2. Vinyl clad wood, double pane, factory weatherstripped
3. Unfinished wood, single pane, no factory weatherstripping.

Cost of Removal

The cost of removal usually applicable to all three alternatives is estimated to be \$30.00.¹

Cost of Replacement Window

Use for this example an original rough opening of 3 feet, 2 inches by 5 feet, 8 inches.

- Vinyl Replacement =	\$332.25	material
	29.50	labor
	<u>\$361.75</u>	
 - Clad wood =	 \$173.50	 material
	29.50	labor
	10.50	paint one side
	<u>\$213.60</u>	
 - Unfinished Wood =	 \$ 60.70	 material
	29.50	labor
	21.20	paint two sides
	<u>\$111.40</u>	

¹Building Construction Cost Data (1977)

Annual Maintenance

- Vinyl replacement - none
- Clad wood - paint inside of window in 7th and 14th year
- Unfinished wood - paint outside in 6th, 12th, and 18th year; paint inside in 7th and 14th year.

Painting cost is \$10.60 per side in 1979.

Annual Energy Loss and Cost

Obtain U and V values from page 53.

-Vinyl U = 0.45

$$V = 36 \times 5 \times 3 = 540$$

- Clad wood U = 0.50

$$V = 36 \times 5 \times 3 = 540$$

- Unfinished wood U = 0.80

$$V = 240 \times 5 \times 3 = 3600$$

Calculate heat loss using equation on page 54.
Assume the location is Fort Carson, Colorado. Use 6423 degree days for Colorado Springs.

- Vinyl

$$\begin{aligned} H &= 24 \times 6423 (15 \times 0.45 + 0.018 \times 540) \\ &= 2,538,883 \text{ BTU per year} \end{aligned}$$

- Clad wood

$$\begin{aligned} H &= 24 \times 6423 (15 \times 0.50 + 0.018 \times 540) \\ &= 2,654,497 \text{ BTU per year} \end{aligned}$$

- Unfinished, single pane wood, no weatherstripping

$$H = 24 \times 5423 (15 \times 0.80 + 0.018 \times 3600)$$

$$= 11,838,873 \text{ BTU per year}$$

Now, using the equation on page 54, calculate the annual energy cost attributable to each window assuming a gas furnace of 70 percent efficiency and a natural gas cost of \$3.67 per 1,000,000 BTU.¹

$$\text{- Vinyl} \quad E = \frac{2,538,883 \times \$3.67}{0.70 \times 1,000,000} = \$13.281/\text{year}$$

$$\text{- Clad Wood} \quad E = \frac{2,654,497 \times \$3.67}{0.70 \times 1,000,000} = \$13.921/\text{year}$$

$$\text{- Unfinished wood} \quad E = \frac{11,838,873 \times \$3.67}{0.70 \times 1,000,000} = \$62.071/\text{year}$$

It is important to note that these annual energy cost estimates are useful only for comparative analysis. These costs do not represent actual heating costs attributable to a window because a number of factors such as wall orientation and interior shades will significantly influence the energy performance of a window.

¹Federal Register, June 1979

Summary of Input

	<u>Vinyl Double Glass Weatherstrip</u>	<u>Vinyl Clad Wood Double Glass Weatherstrip</u>	<u>Wood Single Glass No Weatherstrip</u>
Purchase cost plus removal and installation	\$391.75	\$243.80	\$141.40
Annual Energy Cost	\$ 13.28	\$ 13.92	\$ 62.07
Painting cost \$10.60 per side in years	None	7,14	6,7,12,14,18

Life Cycle Cost Analysis

	<u>Vinyl</u>	<u>Vinyl Clad Wood</u>	<u>Wood</u>
A. Purchase Cost + all labor	\$391.75	\$243.80	\$141.40
B. Annual Energy Cost	13.28	13.92	62.07
C. Multiply by Present Worth Factor for 20 Years, 10 percent	8.966	3.966	8.966
D. Life Cycle Energy Cost (B x C)	119.07	124.81	556.52
E. Painting Cost X Appropriate Present Worth Factor (Yr)	None	(7)10.60 x 0.513 (14)10.60 x 0.263	(6)10.60 x 0.565 (7)10.60 x 0.513 (12)10.60 x 0.319 (14)10.60 x 0.263 (18)10.60 x 0.180
F. Life Cycle Painting Cost	None	8.22	19.50
G. Total Life Cycle Cost (A + D + F)	\$510.82	\$376.82	\$717.42

The vinyl clad wood window of improved thermal design was the clear choice in this example. The reader is cautioned not to generalize based upon this one example. Each circumstance should be calculated using actual costs for the products and services in effect.

Basis: Renovation. An existing old wood window with single pane glass and no factory weatherstripping may be replaced with an energy efficient window. Data from the previous example may be used to illustrate this case. The annual energy cost and maintenance may be used for the single pane wood window in good condition. Removal and replacement costs for this window are now ignored since this window represents an existing window.

Life cycle cost analysis proceeds as follows:

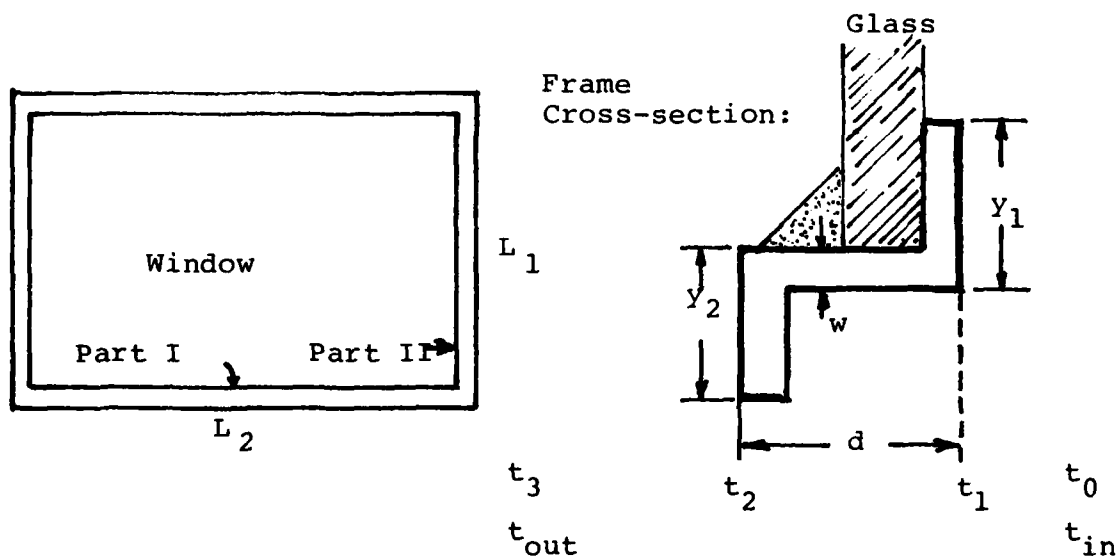
	Vinyl	Vinyl Clad Wood
A. Purchase Cost + all labor	\$391.75	\$243.80
B. Reduced Annual Energy Cost Versus Wood	(48.79)	(48.15)
C. Multiply by Present Worth Factor for 20 years, 10 Percent	8.966	8.966
D. Life Cycle Energy Savings	(437.45)	(431.71)
E. Reduced Life Cycle Painting Cost Versus Wood	(19.50)	(11.28)
F. Total Life Cycle Cost (Savings) (A + D + E)	(65.20)	(199.19)

Both the vinyl and vinyl clad wood windows offer a net savings over 20 years. An alternative not investigated was storm windows over the existing window. This example may be worth calculating whenever a retrofit circumstance is being considered.

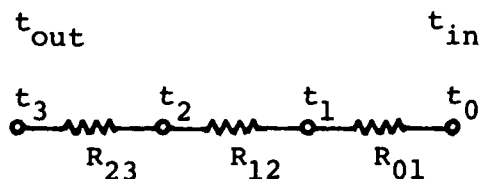
APPENDIX B MATHEMATICAL MODEL FOR HEAT LOSS THROUGH WINDOW FRAMES

To approximate the heat loss through a window frame, several dimensions of the frame must be known along with the conductivity of the frame material. Next, the temperatures of the frame surface must be determined inside and out. These temperatures will depend on the air temperature inside and outside, and the frame dimensions and conductivity.

An average window and frame:



Making a resistance analog of the frame cross section:



The heat flow through each of these resistances must be equal.

$$q_{01} = q_{12} = q_{23}$$

$$q = CA\Delta T = \frac{A}{R} \Delta T = KA \frac{\Delta T}{\Delta X}$$

So,

$$\frac{A_{01}}{R_{01}} (t_0 - t_1) = \frac{A_{12}}{R_{12}} (t_1 - t_2); \text{ let } \frac{A_{01}}{R_{01}} = Z_{01}, \text{ etc.}$$

Then,

$$t_1 = \frac{t_0 \frac{Z_{01}}{Z_{12}} + t_2}{\frac{Z_{01}}{Z_{12}} + 1} \quad \text{and} \quad t_2 = \frac{t_3 \frac{Z_{23}}{Z_{12}} + t_1}{\frac{Z_{23}}{Z_{12}} + 1}$$

now, the free convection coefficients (h) must be calculated.

$$h = \frac{N_{NU} k_{air}}{l}; \text{ where } l \text{ is the characteristic vertical length,}$$

$$N_{NU} = C (N_{GR} N_{PR})^m = C (N_{RA})^m$$

where,

laminar flow: $C = 0.59, m = \frac{1}{4}$ for $10^4 < N_{RA} < 10^9$

turbulent flow: $C = 0.129, m = 1/3$ for $10^9 < N_{RA} < 10^{12}$

Calculate the Rayleigh numbers (N_{RA}) for an example window frame to determine laminar or turbulent flow.

Example:

Assume $T_{out} = 30^\circ\text{F}$, $T_{in} = 70^\circ\text{F}$, and $T_{frame} \approx 50^\circ\text{F}$

Then,

	<u>Inside</u>	<u>Outside</u>
T_m Mean Temperature	60°F	40°F
ρ Average Density	0.07633 pcf	0.07938
C_p Specific Heat	0.2404 Btu/lb°F	0.2404
k Air Conductivity	0.01466 BTU/hr·ft·°F	0.01416
μ Dynamic Viscosity	0.04339 lb/ft·hr	0.04208

Also,

L_c = crack length; perimeter length of frame = $2 (l_1 + l_2)$

l = characteristic vertical length

g = gravitational acceleration = 4.173×10^8 ft/hr²

β = coefficient of expansion $\approx (T \text{ absolute})^{-1}$ of air at ∞ .

$$t = |t_{\text{surface}} - t_{\text{air}}|$$

Now,

$$N_{RA} = N_{GR} N_{PR} = \frac{l^3 \rho^2 g \beta \Delta t}{\mu^2} \frac{\mu C_p}{k} = \frac{\rho^2 g \beta C_p}{\mu k} (l^3 \Delta t)$$

Let,

$$y_1 = y_2 = 0.083 \text{ ft (1 inch)}$$

$$l_1 = 4 \text{ ft} \quad L_c = 18 \text{ ft}$$

$$l_2 = 5 \text{ ft}$$

$$d = 0.125 \text{ ft (1.5 inch)}$$

$$w = 0.0104 \text{ ft (1/8 inch)}$$

Outside:

Part I.

$$N_{RA} = \frac{(0.07938)^2 (4.173 \times 10^8) (460 + 30)^{-1} (0.2404)}{(0.04208) (0.01416)} \{l^3 \Delta t\}$$

$$= 2.165 \times 10^6 \{(4)^3 (20)\} = 2.77 \times 10^9$$

This is turbulent flow.

Part II

$$N_{RA} = 2.165 \times 10^6 \sqrt[7]{(.083)^3 20} = 2.476 \times 10^4, \text{ laminar flow}$$

Inside:

Part I

$$N_{RA} = \frac{(.07633)^2 (4.173 \times 10^8) (460 + 70)^{-1} (.2404)}{(.04339) (.01466)} \sqrt[7]{1^3 \Delta t}$$

$$= 1.734 \times 10^6 \sqrt[7]{(4)^3 20} = 2.219 \times 10^9, \text{ turbulent flow}$$

Part II

$$N_{RA} = 1.734 \times 10^6 \sqrt[7]{(.083)^3 20} = 1.983 \times 10^4, \text{ laminar flow}$$

Now, calculate the free convection coefficients,

$$h = \frac{K_{air}}{l} N_{NU} = \frac{K_{air}}{l} C (N_{RA})^m$$

Laminar:

inside,

$$h = \frac{K_{air}}{l} (.59) N_{RA}^{1/4} = K_{air} (.59) (1.734 \times 10^6)^{1/4} l^{-1} (1^3 \Delta t)^{1/4}$$

$$= (.01466) (.59) (1.734 \times 10^6)^{1/4} \left(\frac{\Delta t}{1}\right)^{1/4} = .314 \left(\frac{\Delta t}{1}\right)^{1/4}$$

outside,

$$h = (.01416) (.59) (2.165 \times 10^6)^{1/4} \left(\frac{\Delta t}{1}\right)^{1/4} = .320 \left(\frac{\Delta t}{1}\right)^{1/4}$$

Turbulent:

inside,

$$h = \frac{K_{air}}{l} (.129) N_{RA}^{1/3} = (.01466) (.129) (1.734 \times 10^6)^{1/3}$$

$$\left(\frac{\Delta t}{1}\right)^{1/3} = .227 \left(\frac{\Delta t}{1}\right)^{1/3}$$

outside,

$$h = (.01416) (.129) (2.165 \times 10^6)^{1/3} \left(\frac{\Delta t}{1}\right)^{1/3} = .236 \left(\frac{\Delta t}{1}\right)^{1/3}$$

Therefore a good approximation to h for all calculations is,

$$\text{laminar} - \quad h \approx .32 \left(\frac{\Delta t}{1}\right)^{1/4}$$

$$\text{turbulent} - \quad h \approx .23 \left(\frac{\Delta t}{1}\right)^{1/3}$$

now, use these to calculate the required terms. Considering each of the four frame members.

$$Z_{01} = \{A_{01}\} \quad h_{01} = 2\{y_1 l_1\} (.23) \left(\frac{t_0 - t_1}{1_1}\right)^{1/3} + 2\{y_1 l_2\} (.32) \left(\frac{t_0 - t_1}{y_1}\right)^{1/4}$$

$$Z_{12} = \frac{w L_c k_{\text{frame}}}{d} ; \quad w = \text{total width of all horizontal members.}$$

$$Z_{23} = \{A_{23}\} \quad h_{23} = 2\{y_2 l_1\} (.23) \left(\frac{t_2 - t_3}{1_1}\right)^{1/3} + 2\{y_2 l_2\} (.32) \left(\frac{t_2 - t_3}{y_2}\right)^{1/4}$$

Since the convection terms depend on temperature, t_1 and t_2 must be solved for by an iterative method. First calculate t_1 , then use this to find t_2 , and use this new t_2 to find t_1 , etc. This process should continue until t_1 and t_2 no longer change significantly.

AREAS:

$$A_{01} = y_1 L_c$$

$$A_{12} = w L_c$$

$$A_{23} = y_2 L_c$$

Thermal Conductivities -

Aluminum ≈ 95 Btu/hr. ft. $^{\circ}$ F

Steel ≈ 30 Btu/hr. ft. $^{\circ}$ F

Vinyl ≈ 0.12 Btu/hr. ft. $^{\circ}$ F

Wood ≈ 0.075 Btu/hr. ft. $^{\circ}$ F

Air ≈ 0.015 Btu/hr. ft. $^{\circ}$ F

Let t_3 or t_{out} equal the average temperature during the heating season and n be the number of days in the heating season.

Then

$$q \text{ lost/year} = 24 n K_{\text{frame}} \frac{A}{d} \Delta T ; \text{ where } \Delta T = t_1 - t_2$$

$$\frac{z_{01}}{z_{12}} = \frac{2y_1 d}{w K_{\text{frame}}} \left[.23 \left[\frac{t_0 - t_1}{l_1} \right]^{1/3} + .32 \left[\frac{t_0 - t_1}{y_1} \right]^{1/4} \right]$$

$$\frac{z_{23}}{z_{12}} = \frac{2y_2 d}{K_{\text{frame}}} \left[.23 \left[\frac{t_0 - t_1}{l_1} \right]^{1/3} + .32 \left[\frac{t_2 - t_3}{y_2} \right]^{1/4} \right]$$

Using the previous example values,

1) Aluminum frame

$$\frac{z_{01}}{z_{12}} = 0.0210 \left[0.63 (t_0 - t_1)^{1/3} + 1.863 (t_0 - t_1)^{1/4} \right]$$

$$\frac{z_{23}}{z_{12}} = 0.0210 \left[0.63 (t_2 - t_3)^{1/3} + 1.863 (t_2 - t_3)^{1/4} \right]$$

The constants are the same in this case because,

$$y_1 = y_2$$

After iteration on the temperatures:

t_3	t_2	t_1	t_o
30°F	48.90°F	51.11°F	70°F

Then, assuming there are 200 days in the heating season with the average outside temperature = 30°F .

$$q \text{ lost/year} = 24(200)(95) \frac{0.0104 (18)}{0.125} (51.11 - 48.90) = 1.508 \times 10^6 \frac{\text{BTU}}{\text{year}}$$

2) Steel frame (assuming same frame dimensions, etc.)

$$\frac{z_{01}}{z_{12}} = 0.06651 \left[0.63 (t_o - t_1)^{1/3} + 1.863 (t_o - t_1)^{1/4} \right]$$

$$\frac{z_{23}}{z_{12}} = 0.06651 \left[0.63 (t_2 - t_3)^{1/3} + 1.863 (t_2 - t_3)^{1/4} \right]$$

After iteration:

t_3	t_2	t_1	t_o
30°F	46.96°F	53.05°F	70°F

Then,

$$q \text{ lost/year} = 7188 (30) (53.05 - 46.96) = 1.313 \times 10^6 \frac{\text{BTU}}{\text{year}}$$

3) Vinyl frame (again, same dimensions, etc.)

$$\frac{z_{01}}{z_{12}} = 16.63 \left[0.63 (t_o - t_1)^{1/3} + 1.863 (t_o - t_1)^{1/4} \right]$$

$$\frac{z_{23}}{z_{12}} = 16.63 \left[0.63 (t_2 - t_3)^{1/3} + 1.863 (t_2 - t_3)^{1/4} \right]$$

After iteration:

t_3	t_2	t_1	t_o
30°F	30.94°F	69.06°F	70°F

Then;

$$q \text{ lost/year} = 7188(0.12)(69.06-30.94) = 3.289 \times 10^4 \frac{\text{BTU}}{\text{year}}$$

Of course, if each window dimension was different, most of the calculation would have to be repeated. However, for this example, the dimensions were assumed the same.

Radiation

Worst possible case: aluminum frame with high emittance (0.8) and a black background (1.0) outside.

$$q \text{ lost/year} = \frac{24n y_2 L_c \sigma \{(t_3+460)^4 - (t_2+460)^4\}}{\frac{1}{\epsilon_{\text{background}}} + \frac{1}{\epsilon_{\text{frame}}} - 1}$$

$$\approx \frac{24(200)(0.0104)(18)(1.7143 \times 10^{-9}) \{(51.11+460)^4 - (48.9+460)^4\}}{\frac{1}{1.0} + \frac{1}{0.8} - 1}$$

$$\approx 1.45 \times 10^3 \frac{\text{BTU}}{\text{year}} \quad \text{This is 0.1 percent of the heat lost by conduction and convection.}$$

Radiation in the other cases would be even less and can therefore be neglected.

To determine the time to recover an investment in vinyl windows:

$$\text{Number of years to recoup investment} = n = \frac{\log\left\{\frac{P(a-1)}{s} + a\right\}}{\log a}$$

$$\text{where } a = \frac{(1+f)}{(1+i)}$$

and,

S = Operating cost savings in first year

C = Cost of heating per therm (10^5 BTU)

f = Annual percentage rate of fuel price increase

i = percentage interest rate on alternative investment

P = added cost of windows

$$S = \{q \text{ lost/year}^{(\text{old windows})} - q \text{ lost/year}^{(\text{vinyl windows})}\} \frac{C}{10^5}$$

Suppose:

$$C \approx \$0.40, f \approx 15\%, i \approx 13\%, P \approx \$332$$

Then,

$$a = 1.14, S = 4 \times 10^{-6} \Delta q$$

- 1) Replace aluminum windows with vinyl windows:

$$S = 4 \times 10^{-6} (1.508 \times 10^6 - 3.298 \times 10^4) = 5.90$$

$$n = \frac{\log \left\{ \frac{332(1.14 - 1)}{5.90} + 1.14 \right\}}{\log(1.14)} \approx 16.8 \text{ years}$$

- 2) Replace steel windows with vinyl windows

$$S = 4 \times 10^{-6} (1.313 \times 10^6 - 3.298 \times 10^4) = 5.12$$

$$n = \frac{\log \left\{ \frac{332(1.14 - 1)}{5.12} + 1.14 \right\}}{\log(1.14)} \approx 17.7 \text{ years}$$

These estimates do not include effects of air infiltration or wind. If there would be a significant number of windy days then the payback period would be shorter.

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Alexandria, VA 22333

Commander, DARCOM
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Air Force Weapons Lab/AFWL/DE
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Research Division
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Strategic Air Command
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Offutt AFB, NE 68112

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NCOIC
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ATTN: SP6 Cathers
PO Box 300
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NCOIC
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APO New York 09081

HQ, USA Health Services Cmd
Bldg 2792
ATTN: HSLO-F
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HQDA
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WASH DC 20314

Mr. David White
Defense Audit Service
888 North Sepulveda Blvd.
Suite 610
El Segundo, CA 90245

NAVFAC
ATTN: John Zekan
Code 0833
Hoffman Building
200 Stovall Street
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Facilities Engineering Command
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Naval Base, Building 77
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