ORNL/TM-11291

OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

MARTIN MARIETTA ENERGY SYSTEMS LIBRARIES

3 4456 0348609 2

Chlorofluorocarbon (CFC) Technologies Review of Foamed-Board Insulation for Buildings

D. L. McElroy
M. P. Scofield

OAK RIDGE NATIONAL LABORATORY
CENTRAL RESEARCH LIBRARY
CIRCULATION SECTION
4500N ROOM 175
LIBRARY LOAN COPY
DO NOT TRANSFER TO ANOTHER PERSON
If you wish someone else to see this report, send in name with report and the library will arrange a loan.

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors [illegible] cal Information, P.O. Box 62, Oak Ridge [illegible] 576-8401, FTS 626-[illegible]

Available to the public from the National [illegible] Department of Commerce, 5285 Port Royal Rd. [illegible]
NTIS price codes—[illegible]

This report was [illegible]
the United States [illegible]
agency thereof [illegible]
implied, or assumes [illegible]
pleteness, or usefulness [illegible]
closed, or represents [illegible]
Reference herein [illegible]
trade name, trademark [illegible]
tute or imply its [illegible]
Government [illegible]
expressed herein do not necessarily [illegible] States
Government or any agency thereof.

ORNL/TM-11291

Metals and Ceramics Division

CHLOROFLUOROCARBON (CFC) TECHNOLOGIES REVIEW OF FOAMED-BOARD INSULATION FOR BUILDINGS

D. L. McElroy
M. P. Scofield

Date Published - March 1990

Prepared for
DOE Office of Buildings and Community Systems
EC 01 01 00 0

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

MARTIN MARIETTA ENERGY SYSTEMS LIBRARIES

3 4456 0348609 2

CONTENTS

LIST OF TABLES

CHLOROFLUOROCARBON (CFC) TECHNOLOGIES REVIEW OF FOAMED-BOARD INSULATION FOR BUILDINGS*

D. L. McElroy and M. P. Scofield†

ABSTRACT

This report reviews the use of foamed-board building insulation and alternative technologies to reduce the use of chlorofluorocarbons (CFCs). CFCs harm the environment by depleting the ozone layer in the stratosphere. Thermal insulations are reviewed to introduce current rigid-foam insulation technology, and alternatives to meet the Montreal Protocol requirements are presented. Analyses of the energy-use impact from alternatives for building envelopes are described. The primary purpose of this report is to provide comments in a matrix table about foam insulations (e.g., rigid polyurethane foam, rigid extruded polystyrene foam, and alternatives) and about primary concerns (e.g., applications, availability, development risks, environmental health and safety, and energy and economic impacts). An appropriate federal role would be to support development and execution of a broad-based research program in cooperation with industry to prove the applicability of new insulation products. The estimated cost to complete an existing research menu of 29 projects in 5 years is $16 million.

---

1. THERMAL INSULATION TECHNOLOGY

1.1 INTRODUCTION

Insulation material alternatives to chlorofluorocarbons (CFCs) are needed because CFCs are damaging the ozone layer in the stratosphere. Any depletion of the ozone is critical since it controls the radiative balance in the atmosphere; this has caused worldwide concern because of the adverse environmental impacts resulting from destruction of this protective stratum in the upper atmosphere. The primary purpose of this review is to provide comments in a matrix table of concerns for materials considered as alternatives to CFCs for use in foamed-board insulations in

*Research sponsored by the Office of Buildings and Community Systems, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

†U.S. Department of Energy.

buildings. Section 1 reviews thermal insulation technology, Sect. 2 describes CFC alternatives, and Sect. 3 presents an impact analyses. The matrix table is discussed in Sect. 4. A review of DOE-sponsored research is given in Sect. 5, and conclusions are discussed in Sect. 6.

A successful thermal insulation technology includes three interrelated activities: (1) production, (2) application, and (3) properties. Federally sponsored efforts have emphasized determination of properties (characterization) and analysis of applications.[1] Clearly, these latter two activities are impacted by the insulation that is produced by industry; but until now, the as-received product has been the starting point for property and applications research. With energy regulation, the foam-aging phenomena, and the advent of the Montreal Protocol[2] and 40 CFR Pt. 82 (refs. 3 and 4), alternate product suggestions are emerging from the applications and properties studies.

1.2 APPLICATIONS

Commercially available thermal insulations are widely applied in building envelopes and building equipment to conserve energy. Table 1.1 lists typical applications.[5]

Table 1.1. Typical applications for thermal insulations

Building envelopes	Building equipment	Other
Residential		
Floors	Refrigerator/freezers	Refrigerated transport
Walls	Freezers	Portable coolers
Attics	Refrigerators	District heating and cooling systems
Foundations	Beverage vending machines	
	Water heaters	
Commercial		
Walls		
Roofs		
Foundations		

Source: S. K. Fischer and F. A. Creswick, *Energy-Use Impact of Chlorofluorocarbon Alternatives*, ORNL/CON-273, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1989.

1.3 PROPERTIES

One purpose of a thermal insulation is to conserve energy by reducing heat flow from its intended area of use. The material often enhances other desirable features including personal comfort, noise reduction, high strength-to-weight ratio, and mechanical rigidity. Within a thermal insulation, heat flows from high temperatures to low temperatures by conduction, convection, and radiation. The thermal resistance value (R-value) of an insulation depends on the ability of the material and structure to control each mode of heat transfer. A high R-value corresponds to high resistance to heat flow. The R-value of a homogeneous material is defined as:

$$\text{R-value} = \frac{\text{thickness}}{\text{thermal conductivity}} \quad . \tag{1}$$

The thermal conductivity (K) is a material property of the particular insulation. The R-value for an insulation system is raised by increasing the thickness of the insulating system; or for a particular system thickness, the designer can choose a material with a lower thermal conductivity.

Thermal insulations are low-mass (low-density) solids used in various forms including batts, boards, loose fills, spray applied, and foamed in place. These low-mass-type insulations have densities (ρ) generally in the range 0.6 to 3 lb/ft^3 or 1 to 5% of the ρ of water.* Table 1.2 shows the variety of solid materials used as low-mass-type insulations, and Table 1.3 shows the nominal R-value per inch of insulation at 75°F.

The thermal conductivity of an insulation normally increases when temperature rises and is dependent on the density of the particular insulation product. Various product types span a density range, but a particular product can be produced to have a specific density in this range. The thermal conductivity increases when temperature rises because the thermal conductivity of gas within the insulation increases when temperature rises and heat transfer by radiation increases when temperature rises. The thermal conductivity-density dependence is the sum of heat transfer terms and normally has a minimum at low density. Some products, such as low-density fiberglass batts, are designed for the portion of the thermal conductivity-density relationship where thermal conductivity decreases when density increases. Other products can be designed for use where thermal conductivity increases when density increases.

---

*Although the policy of the Oak Ridge National Laboratory is to report work in SI units, customary units are used in this report. The insulation industry in the United States at present operates entirely with customary units. The use of the SI units would limit the usefulness of this report for the primary readership. The SI equivalents of units used in this report are listed in Appendix A.

Table 1.2. Solids used in mass-type insulations

Nonplastics	Plastics
Fiberglass	Polyurethane
Rock wool	Polyisocyanurate
Cellulose	Expanded polystyrene
Perlite	Extruded polystyrene
Vermiculite	Phenolics
Fiberboard	
Cellular glass	
Insulating concrete	
Gypsum	
Plywood	
Foil-faced laminated board	
Insulating brick	

The materials with low R-values (R/in. < 5) have structures that are open to air. The materials with high R-values (R/in. ≥ 5) have a rigid, closed-cell structure that contains a low-thermal-conductivity gas such as a CFC. In both cases, the total heat transfer can be approximated as the sum of the individual heat transfer mechanisms. For a low-ρ fiberglass batt, 0.6 lb/ft^3 (ref. 6),

$$K(75°F) = A + B \times \rho + C/\rho \quad , \tag{2}$$

where A, B, and C are constants;

$$K(total) = K(\text{conduction by air}) + K(\text{conduction by fibers}) + K(\text{radiation})$$

$$0.32 = (0.18 + 0.003 + 0.14)\ Btu \cdot in./h \cdot ft^2 \cdot °F$$

$$100\% = 56\% + 1\% + 43\% \quad .$$

For a 2-lb/ft^3 polyurethane foam[7]:

$$K(total) = K(\text{conduction by gas}) + K(\text{conduction by struts and cell walls}) + K(\text{radiation}) \tag{3}$$

$$0.121 = (0.061 + 0.02 + 0.04)\ Btu \cdot in./h \cdot ft^2 \cdot °F$$

$$100\% = 50\% + 16\% + 34\% \quad .$$

Table 1.3. Nominal thermal resistance per unit thickness value for some typical insulations, R-value per inch at 75°F

Material	Density (lb/ft³)	R-value per inch (h·ft²·°F/Btu)	Source[a]
	Nonplastics		
1. Air, conduction only	0.08	5.5	1
2. Air, with radiation, ΔT = 50°F		<1	2
3. Loose fills			3
Fiberglass	0.6	2.2	
Rock wool	2	3.0	
Cellulose	3.0	3.5	
Perlite/vermiculite	2–11	3.7–2.5	4
4. Fiberglass batt	0.6	3.2	3
5. Fiberboard		2.8	5
6. Cellular glass		2.6	5
7. Gypsum	44	0.8	6
8. Plywood	30	1.3	7
	Plastics		
9. Rigid polyurethane foam	2	7.2	8–10
10. Rigid extruded polystyrene		5.0	8–10
11. Expanded polystyrene	1.0	3.9	8–10
	1.5	4.2	
12. Phenolics	2–3	8.3	8–10

[a]This table is repeated in Appendix B with a listing of sources.

Equations (2) and (3) provide a means to predict the K-value and R/inch value for a new product.

The rigid, closed-cell plastic foam insulations have the highest R-value per unit thickness of all commercially available thermal insulations. This characteristic is mainly due to the low thermal conductivity of the gas contained in the closed cells. Table 1.4 shows the gas K for CFC-11, CFC-12, and air at 75°F. Appendix B provides a description of the nomenclature for CFCs.

Table 1.4. Gas thermal conductivity at 75°F[a]

Gas	K, (Btu·in.)/(h·ft²·°F)	W/m·K
Air	0.180	0.026
CFC-11	0.057	0.00824
CFC-12	0.067	0.00962

[a]Gas K-values in the literature may show as much as ±10% range in value at a given temperature.

1.4 FOAM AGING

Prior to the Montreal Protocol[2] agreements to phase out the use of CFCs, two factors influenced foam insulation technology and applications: foam aging and energy regulations. Foam aging occurs because the thin-plastic cell walls, nominally less than 1 μm thick, are permeable to gas diffusion. The composition of the gas in the cell changes with time after manufacture as air diffuses into the cell and CFC diffuses out of the cell. The gas composition controls the gas thermal conductivity, so the K of foam increases with time after manufacture. Aging decreases the R-value per unit thickness and hence the thermal efficiency of the foam.

Table 1.5 provides diffusion coefficient values for several important gases.[8,9] The effective diffusion coefficient for gases through foam walls increases with temperature.

Table 1.5. Relative and effective diffusion coefficients for gases at 75°F through polyurethane

Gas	Coefficient: Relative	Coefficient: Effective ($cm^2/s \times 10^8$)
Carbon dioxide (CO_2)	200	202
Oxygen (O_2)	50	46.8
Nitrogen (N_2)	10	7.6
Chlorofluorocarbon-11 (CFC-11)	0.2	0.2–0.6

Plastic foam producers follow American Society for Testing Materials (ASTM) standards to age board products and measure the resulting aged-product K-value. The results are not without controversy, because many contend that field exposures promote larger decreases in R-value than do controlled laboratory tests. The National Roofing Contractors Association[10] (NRCA) has adopted a conditioning procedure (180 d ± 5, 73.4°F ± 3.6, 50% relative humidity ± 5%) prior to standard ASTM testing (C 177, C 236, and C 518 if comparable to the absolute values of C 177) to provide accurate and consistent information. NRCA and the Midwest Roofing Contractors Association[10] (MRCA) recommend that designers, users, and other affected parties use an R-value of 5.6/in. as a reasonable guide when calculating thermal resistance of polyisocyanurate and polyurethane insulation boards over their normal life in a roofing system. ASTM C 1013-85 (ref. 11) specifies this conditioning procedure because of the lack of validation data for an accelerated conditioning technique of a 90-d exposure in a 140°F oven. ASTM C 1013-85 (ref. 11) specifies these three test methods for thermal resistance determination at 75°F with a 40°F minimum temperature gradient on test sample(s) at the full insulation board thickness. In case of dispute, test method C 177 is the reference method.

Board is produced with membrane facers that may be either permeable (such as conventional organic/inorganic facers) or relatively impermeable (such as an aluminum foil) to lengthen the gas diffusion path. For a 1-in.-thick, 4-ft-wide, 8-ft-long board faced with an impermeable foil, the distance to the board center is increased from 0.5 to 24 in. Because the gas diffusion rate is proportional to the square of distance, theoretically the rate of change of gas composition at the board center should be decreased by a factor of 2304 $(24/0.5)^2$. In practice, the effectiveness of impermeable facers is often less than predicted, because of pinholes in the facer, poor adherence of the facer to the foam, or fractured cells within the foam under the facer, which reduces the distance for diffusion.

For example, Jim Walters Research Corporation[12] reports R/inch values for design R-values for 6-month performance of 5.6 for permeable facer boards and 7.2 for impermeable facer board. The latter value is based on tests for boards aged at 75°F as follows:

15 months	R/in.:7.2
68 months	R/in.:7.04
11 years	R/in.:6.91

Many factors affect R/inch values including foam facer, foam density, cell size, cell wall thickness, polymer composition, manufacturing process, foam/facer interfacer, and exposure environment. There is no such thing as one polyurethane (polystyrene, polyisocyanurate, or phenolic); they are chemical families with millions of relatives. All tend to show R-value loss with time after manufacture, and this phenomenon appears to be a linear function of log time. This relation allows laboratory aging rates to be predicted and 5-year predictions from data collected 100 to 180 d after manufacture. Field performance rarely equals laboratory values for R/inch.

Models that predict the gas composition of the closed cells as a function of exposure have been developed. These models provide a theoretical basis for predicting aged R-value.[8,9] Laboratory testing of thin sections of foams as a function of time may provide results to validate models that predict R-values for boards as a function of exposure.

1.5 ENERGY PERFORMANCE STANDARDS

A second factor that affected foam insulation technology prior to the Montreal Protocol was the pending energy performance standards for appliances, including residential refrigerator/freezers (R/F). These standards affect building equipment applications, but any resulting insulation improvements can change insulations for buildings. In 1987, a typical 16 to 18 ft^3 R/F with automatic defrost and a top-mounted freezer used about 1100 kWh/year (ref. 13). California regulations require that a similar unit sold in California after January 1, 1987, use only 978 kWh/year, and by 1992 use only 677 kWh/year (ref. 14). Pending federal regulations would require that similar units produced after January 1, 1990, consume only 950 kWh/year (ref. 15). These regulations prompted appliance manufacturers to study improved insulations as a means to achieve energy reductions. At least one R/F manufacturer obtained patents on powder-filled evacuated panels with an R-value per inch of over 20. Current foamed-in-place R/F insulations have an R-value of about 8/in., and a shift to 20/in. could save as much as 550 kWh/year per R/F unit.[16]

Although the initial application for such panels is in R/Fs, numerous other insulation applications currently met by foam insulations could benefit from such panels if they proved to be economically feasible and were commercially available. In addition, these energy regulations prompted studies on ways to improve existing foam insulations.[8] These studies included (1) decreasing the cell size to the 0.1- to 0.2-mm-diam range to increase the cell strut density and decrease the radiative heat transport and (2) increasing the amount of solid in the cell walls and decreasing the amount in the cell struts to increase the wall resistance to gas diffusion.

2. CHLOROFLUOROCARBON TECHNOLOGY REVIEW AND FOAM INSULATION ALTERNATIVES

2.1 REVIEW

This section provides a background to the summary notes in the matrix table (see Table 4.1) on alternatives to CFCs for insulations.

The U.S. Environmental Protection Agency (EPA) Regulatory Impact Analysis (RIA) (refs. 4 and 17) treats seven specific use areas for CFCs:

1. commercial and residential refrigeration and air conditioning,
2. mobile air conditioning,
3. production of plastic foam and foam insulation products,
4. sterilization of medical equipment and instruments,
5. solvent cleaning of metal and electronic parts,
6. aerosol propellants and other miscellaneous uses, and
7. fire extinguishing.

Area 3 (production of plastic foam and foam insulation products) is divided into four subareas:

3.1 molded flexible polyurethane foam,
3.2 slabstock flexible polyurethane foam,
3.3 rigid polyurethane foam, and
3.4 rigid extruded polystyrene foam.

This report focuses on areas 3.3 and 3.4, which are insulations, and provides limited comments on flexible stock, which is not used as insulation.

Starting July 1, 1989, the Montreal Protocol will freeze CFC production at 1986 levels for the Group I controlled substances shown in Table 2.1.

The Montreal Protocol requirements include production decreases for these and other chemicals (Group II: Halon 1211, Halon 1301, and Halon 2402), trade restrictions, record-keeping requirements, and periodic assessments to determine whether changes in the control provisions are

Table 2.1. Group I controlled substances

Group I chemicals	Ozone depletion potential[a]	Relative greenhouse warming potential[b]
CFC-11 ($CFCl_3$)	1.0	0.4
CFC-12 (CF_2Cl_2)	1.0	1.0
CFC-113 ($C_2F_3Cl_3$)	0.8	0.3–0.8
CFC-114 ($C_2F_4Cl_2$)	1.0	0.5–1.5
CFC-115 (C_2F_5Cl)	0.6	1–3

[a]Relative to CFC-11, which is assigned the value of 1.00.

[b]Relative to CFC-12, which is assigned the value of 1.00.

warranted. EPA estimates that 5 to 7 years of research and development will be needed to produce safer chemicals for new products.[17]

2.2 FOAM INSULATIONS

Chemicals with low ozone-depletion potential being developed as CFC substitutes are shown in Table 2.2.

In addition, industry is testing blends of Group I chemicals with other chemicals as a means to reduce CFC usage, but with loss of thermal efficiency of insulations. The other chemicals are often called fast diffusers and leave the product quickly. One goal of the industry search is to obtain a "near drop-in" chemical that requires a small change in the production process and meets the Montreal Protocol requirements. The other chemicals include H_2O - CO_2, butanes and pentanes, methyl chloride, and ethyl chloride.

EPA notes that the production of plastic foam and foam insulation products accounts for 28% of the ozone-depleting potential of CFCs. The CFC usage for four major foam types are given in Table 2.3. These foams are described below in terms of uses, current alternatives, and future alternatives.

2.2.1 Molded Flexible Polyurethane Foam

Used for automobile seat/back cushions and other products, the foam types range from very soft, low-density foams to hard, dense foams. CFC-11 is used to make the former in a closed mold process. The CFC-11 helps reduce the foam density, but all of this gas is released to the atmosphere at the factory. If CFC-11 is not used, the foam will have a higher density. High-resilience foam can be produced with water-blown formulations. Substitutes for CFC-11 include HCFC-123 and HCFC-141b.

Table 2.2. Foam insulation alternatives to chlorofluorocarbons

Chemical	Potential use	Ozone depletion potential[a]	Greenhouse warming potential[b]
HCFC-22	Alone and in blends, for food packaging, fast food freezing, leak testing of fire extinguishers, and possibly refrigeration	0.05	0.07
HCFC-123	Undergoing toxicity testing for possible use in foam manufacturing, chillers, and solvent cleaning	≤0.03	0.01
HFC-134a	Undergoing toxicity testing for possible future use in refrigeration, chillers, and mobile air conditioners; and foam manufacturing	0.0	<0.01
HCFC-141b	Undergoing toxicity testing for possible use in certain foam, refrigeration, and aerosol applications	≤0.1	0.05
HCFC-142b	For possible use in certain foam, refrigeration, and air conditioning applications	0.06	<0.2

[a]Relative to CFC-11, which is assigned a value of 1.00.

[b]Relative to CFC-12, which is assigned a value of 1.00.

Molded flexible polyurethane foams are not used as thermal insulations, so no adverse energy impact exists for this product type.

2.2.2 Slabstock Flexible Polyurethane Foams

Used as furniture cushions, carpet underlay, and bedding, the softer foams are produced with CFC-11. The foam is produced on moving belts and subsequently cut to shape. Product substitutes and process changes are being considered as alternatives to CFC slabstock. Built-up cushions are more expensive and less durable than those made from flexible slabstock. Process changes include recovery of CFC-11, other blowing agents such as methylene chloride, and soft polyol foams. Both HCFC-141b and HCFC-123 are potential blowing agents. Because slabstock is not used as a thermal insulation, no adverse energy impact is associated with this product.

Table 2.3. Chlorofluorocarbon use and foam produced

	Current usage (metric tons of gas)		Foam tonnage (metric tons)
	CFC-11	CFC-12	
Molded flexible polyurethane foam (CFC-11)	3,300		
Slabstock flexible polyurethane foam (CFC-11)	11,500		440,000
Rigid polyurethane foam (CFC-11 and CFC-12)	40,000	6,700	300,000
Rigid extruded polystyrene foam (CFC-12)	9,200		
Boardstock (1.1×10^9 board ft)			87,000
Foam sheet (packaging material)			208,200

2.2.3 Rigid Polyurethane Foams

These foams are produced by CFC-11 or CFC-12 volatization in liquid plastics to yield a rigid, closed-cell structure containing the blowing agent. These products are used as insulating materials in building and industrial applications as rigid bunstock or laminated boardstock, poured-in-place foams, or spray-applied foams. The applications include various types of insulation for low-sloped roofs, building sheathing, building foundations, walls, refrigerators, freezers, storage tanks, and door cavities. This classification includes polyisocyanurates.

After manufacture, the gas composition in the cells of rigid polyurethane foams changes because of inward diffusion of nitrogen (N_2) and oxygen (O_2) and outward diffusion of CFC. The latter process is very slow and may require decades for completion. Currently available alternatives with lower R/inch capacity include expanded polystyrene bead board, extruded polystyrene boardstock, fiberglass, and fiberboard. These alternatives would require thicker sections to achieve the same insulating capacity, and this requirement could become an economic issue. No other materials exist with the equivalent insulating capacity for the poured or sprayed applications. Future alternatives include HCFC-123 and HCFC-141b as substitute blowing agents.

2.2.4 Rigid Extruded Polystyrene

This foam is produced by high-pressure extrusion of molten polystyrene containing CFC-12 to yield foam boardstock or foam sheet. The foam boardstock is used for many insulating applications, and the foam sheet is used for disposable packaging. The alternatives for foam sheet include other disposables (paper, plastics, metal foils, and their laminates) and HCFC-22, which has Food and Drug Administration (FDA) approval for food packaging. HCFC-22 has an ozone-depletion potential of 0.07 compared with 1.0 for CFC-12. The food service and packaging industry has a program that the food industry has adopted, which includes use of HCFC-22.

Despite the change to the use of HCFC-22, an environmental group, Citizen's Clearinghouse for Hazardous Waste,[18] maintains that no amount of CFCs is acceptable and wants industry to use recycled paper. The foam packaging industry is seeking a substitute such as HFC-134a with zero ozone-depleting potential. This alternative would require toxicity testing and FDA approval.

Numerous product substitutes with lower insulating capacities are currently available for rigid extruded polystyrene boardstock. These products include fiberglass board, expanded polystyrene, cellular glass, and insulating concrete; but they require greater thicknesses and may not be equally useful as foundation insulations.

Dow Chemical USA, a major producer of rigid extruded polystyrene boardstock, announced that this year (1989) a substitution would be made at all of their domestic and international plants.[19] While this may include the use of HCFC-22, it is noteworthy that the lead time for a production process change such as this can require at least 1 year to be certain of the choice and, additionally, up to 1.5 years to acquire needed regulatory approvals for the product. Anouncements by Dow Chemical, summer 1989, confirmed their use of HCFC-142b. Availability of a new rigid extruded polystyrene boardstock this year is evidence of industry commitment to meet and exceed the Montreal Protocol requirements by a process change. This new product may provide a target for other foam manufacturers and an alternative to the rigid polyurethane foam boardstock industry. Future alternatives could include HFC-134a (zero ozone-depletion potential).

Rigid (closed-cell) phenolic foam thermal insulations are produced with the use of CFC-11 or CFC-113. Approximately 1500 metric tons of CFC gases were required. Because this usage represents only 3% of the CFC gases used for insulations, a discussion of phenolics is excluded from this section.

A large number of alternative gases are being considered as blowing agents for the rigid foam. It is important to compare the thermal resistance of insulations at the same mean temperature such as 75°F, or at a mean temperature that is representative of the particular end-use application. Table 2.4 compares fresh (unaged) foam R/inch values calculated from gas K-values. A constant term, 0.073 Btu·in./h·ft²·°F, is assumed to represent radiation and solid conduction for a 2-lb/ft³ rigid polyurethane foam as suggested by Eq. (2), Glicksman,[7] and Lund, Richard, and Shankland.[20] Table 2.4 contains R/inch values for some aged products. These R-values are, however, largely unknown for the new foams because the diffusion rates of the alternate gases are different for the different foams and need to be determined.[21]

Table 2.4. Thermal conductivity at 75°F for various gases and projected fresh foam K and R/inch values[a]

Gas	Gas K	Fresh foam		Aged foam
	(Btu·in./h·ft²·°F)	K (Btu·in./h·ft²·°F)	R/in. (h·ft²·°F/Btu)	R/in. (h·ft²·°F/Btu)
Air	0.18	0.253	3.95	3.9
CO_2	0.107	0.180	5.56	3.9
CFC-11 ($CFCl_3$)	0.057	0.130	7.69	6.2
CFC-12 (CF_2Cl_2)	0.067	0.140	7.14	5.0
HCFC-22 (CHF_2Cl)	0.073	0.146	6.85	~4
HCFC-123 (C_2HF_3Cl)	0.072	0.145	6.90	
HCFC-124 (C_2HF_4Cl)	0.075	0.148	6.76	
HFC-134a ($C_2H_2F_4$)	0.094	0.167	5.99	
HCFC-141b ($C_2H_3FCl_2$)	0.070	0.143	6.99	
HCFC-142b ($C_2H_3F_2Cl$)	0.077	0.150	6.67	
Air/CFC-11 (50/50)	0.118	0.191	5.24	
CO_2/CFC-11 (33/66)	0.073	0.146	6.85	
CO_2/CFC-11 (50/50)	0.082	0.155	6.45	
Butane (C_4H_{10})	0.100	0.173	5.78	
Pentane (C_5H_{12})	0.089	0.162	6.17	

[a]Projected fresh foam values are with gases contained in the closed cell: K(foam) = K(gas) + 0.073 Btu·in./h·ft²·°F.

3. ENERGY IMPACT ANALYSIS

3.1 INTRODUCTION

The report entitled *Energy-Use Impact of Chlorofluorocarbon Alternates* by S. K. Fischer and F. A. Creswick[5] provides a valuable assessment of national energy impacts for building equipment, building envelopes, and transportation. Fischer and Creswick note: "There is a strong likelihood that national energy use will increase through the use of environmentally acceptable alternative chemicals and technologies."

3.2 METHODOLOGY

Their methodology for establishing the energy impacts included establishing a *base case* national annual energy use for Group I CFCs, followed by comparison with energy use for the four alternate strategies listed below:

1. The *preferred response* that uses foam insulations with HCFCs to replace Group I CFCs. This strategy assumes "near drop-in" substitute chemicals that are used even though these are not yet commercially available. The product properties are typically within 10% of those obtained by Group I CFCs.

2. A *fallback position* that replaces currently used CFC-blown foam insulations with the most energy efficient available non-CFC insulation.

3. A *worst-case scenario* that replaces all CFC-blown foam insulation without regard to energy efficiency.

4. An *advanced technology* that develops highly efficient insulation and refrigeration systems.

Fischer and Creswick note: "If the 'near drop-in' compounds can be developed as substitutes for Group I CFCs, there will not be a significant increase in national energy use. But if this is not possible there will be an increase of about one quad [1 quad = 1 Btu × 10^{15}] per year. . . .The major energy impacts will occur in those applications that rely almost exclusively on CFC-blown foam insulation."

The Fischer/Creswick energy impacts for building envelopes are summarized in Table 3.1. The table and their summary comments follow.

Table 3.1. National energy impacts of alternative building envelope technologies (quad/year)

Application	Preferred response	Fallback position	Worst-case scenario	Advanced technology solution
Residential walls	0.01	0.02	0.05	-0.04
Residential Foundations	0.00	0.17	0.32	*a*
Commercial walls	0.02	0.04	0.08	-0.08
Commercial roofs	0.03	0.11	0.20	*a*
Subtotal	0.06	0.34	0.65	-0.12

[a]Advanced technologies are not evaluated for these applications.

Source: S. K. Fischer and F. A. Creswick, *Energy-Use Impact of Chlorofluorocarbon Alternates*, ORNL/CON-273, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1989.

3.3 RESULTS AND CONCLUSIONS[5]

"There are also fairly large impacts for buildings applications in which foam boards or sprayed urethane are used alone rather than in conjunction with fiberglass batts, as is the case with foundation insulation and the roofs and walls of some commercial buildings. Those applications in which foams are used in addition to fiberglass batts, such as in residential walls, have a low impact. Additionally, the 0.06, 0.34, and 0.65 quad/year for the preferred, fallback, and worst-case scenarios for building thermal envelopes are based on current levels of usage in building construction. However, residential and commercial construction trends are towards using higher proportions of CFC-blown foams, and these lost opportunities for energy conservation are in addition to the impacts identified here."

"A vigorous R&D program can alleviate most, if not all, of the adverse energy impacts that could occur as a result of not using CFC-11 and CFC-12 in the applications studied. The successful development of (and industry acceptance of) vacuum-insulated panels for appliance applications and some building applications can lead to significant energy savings, particularly for household refrigerators, freezers, and water heaters. To improve efficiencies of mechanical refrigeration systems, researchers at ORNL are developing an R&D plan to assess these opportunities."

3.4 ENERGY IMPACTS

3.4.1 Walls

Chapter 11, Residential Insulation, of the Fischer/Creswick report[5] provides an analysis for walls for single-family and multifamily residences that replaces equal thicknesses of alternate materials for currently used CFC-blown-foam sheathing. An analysis by Petersen and Fanney[22] showed that substituting greater thicknesses of a less effective insulation for the CFC-blown foam *is justified* on life cycle costs, depending on the type of windows used. The equal thickness analysis is a conservative assumption (i.e., the actual energy impacts will be lower than estimated).

The base case is new construction of opaque walls that uses 14% rigid extruded polystyrene (CFC-12), 11% rigid polyurethane (CFC-11), and 75% fiberboard or plywood (i.e., the substitution is for 25% of the nationwide wall area). The alternatives considered are given in Table 3.2.

Table 3.2. Energy impact analysis for walls

Strategy	Energy penalty (quad/year) wall fraction		
	25%[a]	50%[b] industry	100%[c]
1. Preferred response	0.01	0.02	0.04
Polystyrene with HFC-134a for polystyrene with CFC-12 (R:4.59 for R:5.0)			
Polyisocyanurate/polyurethane (PIR/PUR) with HCFC141b for PIR/PUR with CFC-12 (R:6.86 for R:7.2)			
2. Fallback position	0.02	0.04	0.08
Expanded polystyrene for both (R:4.17)			
3. Worst-case scenario	0.05	0.10	0.20
Fiberboard for both (R:2.64)			
4. Advanced technology	-0.04	-0.08	-0.16
Panels for both (R-10)			

[a]For 25% of opaque walls.

[b]Industry recommendation for 50% of opaque walls (Appendix D).

[c]For 100% of opaque walls.

The energy penalties for walls is relatively small because only 25% of currently built walls use foam sheathing. A fourfold increase in energy penalty would result if 100% of exterior walls were being sheathed with CFC foam. Another reason for the relatively small energy penalty is that the foam sheathing for walls is an add-on to a cavity that contains R-13 fiberglass. The U.S. Department of Energy (DOE) *Insulation Fact Sheet*[23] recommended R-value for new construction is an

R-19 wall. Industry representatives provided evidence that at least 50% of exterior walls are sheathed with CFC foams (see Appendix D). Among the cases considered by Fischer and Creswick,[5] this recommended level is met by only one inch of rigid polyurethane (CFC-11 or HCFC-141b) sheathing. Construction using 2 × 6 in. studs on 24-in. centers with 0.5-in. gypsum wallboard and 0.5-in. backerboard siding achieves R-19 walls without using CFC foam sheathing. This construction method results in no energy penalty but involves a cost for expanding the wall thickness to accommodate more insulation. Petersen and Fanney[22] noted that this construction method is not a cost-effective means of reducing usage of CFC-blown insulation.

3.4.2 Foundations

Chapter 12, Foundation Insulation, of the Fischer and Creswick report[5] provides three estimates of energy penalties for CFC foam alternatives for foundation insulation (Table 3.3). All of these penalties arise from potential unavailability of economical extruded polystyrene (EXPS).

These four scenarios are based on potential foundation insulation energy savings contained in *Impact of CFC Restrictions on U.S. Building Foundation Thermal Performance*,[24] by J. E. Christian. Both studies[5,24] use the same potential energy savings numbers. The number of housing units affected differs. Fischer and Creswick[5] assume an entire building stock turnover; Christian's projection is based on an estimate of new construction starts from 1990 until 2010 and assumes 30% retrofit of existing stock during that time. The second major difference is an estimate of the worst-case scenario. Christian estimates a total energy impact of 0.83 quad/year. This estimate is based on (1) the assumption that an economic environmentally acceptable EXPS would not be available between 1990 and 2010; (2) the new energy standards for foundations recommended in 1988 and 1989 would not be implemented and, as a result, the same high fraction of uninsulated new foundations built today would remain unchanged in the future; and (3) expanded polystyrene (EPS) and fiberglass drainage insulation board would continue the current EXPS market share but would not enlarge the overall foundation insulation market.

The scenario by Christian is based on the hypothesis that an inside basement with insulation is unacceptable. Fischer and Creswick[5] assumed that 85% of new construction would be insulated on the inside with fiberglass foundation walls, because current interior insulation is more common. Moisture damage and footer freezing are more likely when insulation is placed on the inside of the foundation wall. Homeowner surveys of those who added interior foundation insulation have reported occasional mildew or odor problems, believed to be due to moisture seepage into the basement insulation cavity.

For the first time, the CABO *Model Energy Code, 1989 Edition* (MEC),[25] has a complete set of foundation insulation requirements consistent with the payback of the recommendations for above grade envelope components.

Table 3.3. Energy impact analysis for foundations

Strategy	Energy penalty (quad/year)	
	Fischer and Creswick	Foundations remain uninsulated
1. Preferred response Assumes substitute cost-effective blowing agent is quickly found for CFC-12 currently used in extruded polystyrene	0	
2. Fallback position Commercially available insulation alternatives used to satisfy all basement and crawl space insulation requirements. Only energy impact is slabs assumed to go uninsulated	0.17	
3. Worst-case scenario Fischer and Creswick assume 15% of basements and crawl spaces would have used extruded polystyrene but, because of restrictions, will go uninsulated, which leads to 0.15 quad energy savings lost, added to the assumption that no slabs are insulated 0.17 quad.	0.32[a]	0.831[b]

[a]Based on 15% of all basements and crawl spaces uninsulated.

[b]Based on 15% of currently insulated foundations fraction going uninsulated and 100% of the current fraction of uninsulated foundations which would have been insulated if *Model Energy Code, 1989 Edition*, and ASHRAE 90.2P were implemented.

Local code bodies are now debating whether to implement this new version of the MEC. Second, ASHRAE 90.2P (ref. 26), the residential energy standard, which is in public review, also contains a complete set of foundation insulation recommendations. The perception that EXPS may not be available in the future and that moisture damage risk is greater with interior foundation insulation places at risk the broad acceptance of systematic foundation insulation levels. Some may argue that until environmentally acceptable EXPS or a suitable replacement is available, foundation insulation code upgrades should be placed on hold.

Fischer and Creswick[5] assumed that 15% of the basement and crawl-space walls would be uninsulated to obtain the energy loss impact for the worst case. If, instead, they had assumed that in the future the same fraction of basements and crawl spaces currently being built uninsulated (the "additional" building stock referred to in Tables D1–D3 of Fischer and Creswick's report) continue being built uninsulated (the 1989 MEC and ASHRAE 90.3P are not implemented) because of the CFC adverse impacts and uncertainty about the long-term performance of other commercially available insulations for below grade applications, then the loss of energy savings would increase to 0.83 quad for the worst case.

3.4.3 Commercial Construction

Chapter 13, "Commercial Construction," of the Fischer and Creswick report[5] provides an analysis for five building walls for commercial construction (Table 3.4). Because Petersen and Fanney[22] concluded that an adverse energy impact would likely occur for foam-core panels and concrete-masonry walls with interior insulation, only these were analyzed by Fischer and Creswick. The percentage of walls used was 20 or 40% in the various strategies.

Table 3.4. Energy impact analysis for commercial walls

Strategy	Energy penalty (quad/year)	
	Fischer and Creswick	100% of walls
1. Preferred response (20% of walls) Rigid polyurethane (HCHC-141b for CFC-11) (R-6.86 for R-7.2)	0.01	0.05
2. Fallback position (20% of walls) Expanded polystyrene (R-4) for both foams	0.05[a]	0.25
3. Worst-case scenario (40% of walls) Decrease R-values by 8%	0.11	0.28
4. Advanced technology option (40% of walls) Increase R-values by 4.5%	-0.08	-0.20

[a]Industry would increase this penalty to 0.07 quad.

Fischer and Creswick emphasize that only coarse estimates are given and presume that a refined analysis would decrease the energy penalty. Assuming 100% of commercial walls would increase the values. The very high cost of interior floor space is an important economic consideration.

Industry representatives (see Appendix D) expressed concern about the basis for the percentage of wall fractions and whether the fallback position of EPS foam panels is realistic. This usage would increase the energy penalty from 0.05 to over 0.07 quad/year. Industry representatives suggested that a more detailed analysis be done.

3.4.4 Low-Sloped Roofs

Chapter 14, "Low-Sloped Roofs," of the Fischer and Creswick report[5] provides an analysis (see Table 3.5) that assumes 65% of commercial roofs use CFC foams and that all are built up with two 1-in. layers of insulation with an average R-value of 6.38/in.

An advanced technology was not considered. The 1983 Chang and Busching energy savings analysis[27] was used to estimate energy penalties

Table 3.5. Energy impact analysis for low-sloped roofs

Strategy	Energy penalty (quad/year)	
	65% of roofs	100% of roofs
1. Preferred response	0.03	0.05
Foam with HCFC-141b (Same thickness as CFC-blown foam)		
2. Fallback position	0.11	0.17
Expanded polystyrene or fiberglass (Variable thickness: two-thirds equal thickness, one-third equal R-value)		
3. Worst-case scenario	0.20	0.31
Expanded polystyrene or fiberglass (Same thickness as CFC-blown foams)		

for a roof stock of 33 × 10^9 ft^2. The 65% CFC-blown foam market penetration is a 1988 estimate. The second column assumes a 100% changeover for each strategy.

3.4.5 Alternate Analyses

Fischer and Creswick[5] state that their preferred response (the lowest energy penalty) involves assuming the commercial availability of drop-in compounds. If these compounds are not developed successfully, national energy use will increase 1 quad/year (building envelopes, 0.34 quad/year). More detailed analyses are needed, and if the assumptions are changed then the resulting energy impact will change.

Energy analyses are complex, and oversimplification can bias the results. The worst-case scenario for building equipment (1.52 quad/year) and building envelopes (0.65 quad/year) imply a significant energy penalty (2.17 quad/year; in dollar terms, at $3.3 billion/quad, a total of $7.16 billion/year using $18/barrel oil).

Representatives of the CFC industry have expressed concerns about the Fischer and Creswick energy penalty analyses. Industry concerns are cited above and summarized in Appendix D. Industry representatives have suggested that more detailed analyses would be useful and raised the question of whether retrofit applications have been included in the existing analyses.

EPA[17] provides 1985 production data for rigid extruded polystyrene foam board feet and rigid polyurethane foam tonnage (see Table 3.6). These data can be used to calculate equivalent board feet of insulating boards.

If all board production was 1 in. thick and was used in stand-alone applications, then the energy saved in a single year by use of insulation

Table 3.6. Calculated board feet

	Metric tons	Board feet	Assumed property	
			lb/ft^3	R/in.
Rigid polystyrene	87,000	1.15 × 10^9		5
Rigid polyurethane	300,000	3.97 × 10^9	2.0	7.2
Fiberboard				3.0

containing CFCs relative to fiberboard can be calculated as a function of the annual temperature difference (see Table 3.7):

$$q(\text{annual}) = \frac{\Delta T}{R}\ (8760\ \text{h/year})\ (\text{board-ft production})\ ,$$

Table 3.7. Boardstock: ΔT energy impact analysis

1-in.-thick material	Annual heat flow (10^{13} Btu for assumed ΔT)				
	10°F	20°F	30°F	40°F	50°F
Rigid polystyrene 1.15×10^9 board ft	2.01	4.03	6.05	8.06	10.08
Rigid polyurethane 3.97×10^9 board ft	4.83	9.67	14.50	19.33	24.17
Fiberboard					
1.15×10^9 board ft	3.36	6.72	10.08	13.44	16.80
3.97×10^9 board ft	11.6	23.2	34.8	46.37	57.96
Energy reduction ΔQ					
Rigid polystyrene	1.36	2.69	4.03	5.38	6.72
Rigid polyurethane	6.77	13.53	20.30	27.04	33.79
Total in quad/year	0.081	0.162	0.243	0.32	0.40
Total × 1.26	0.10	0.20	0.30	0.40	0.50

This calculation yields energy impacts for one year only that are, as expected, below those of the Fischer and Creswick[5] worst-case analysis for buildings (0.65 quad/year) but near the fallback-position analysis (0.34 quad/year). Obviously, the energy impacts increase with annual temperature difference, which is the basic reason that the building equipment energy impacts exceed those of the building envelope (an annual ΔT of 10°F corresponds to 3650 degree-days, which is near the Oak Ridge environment, whereas a ΔT of 40°F roughly corresponds to the operating condition of a refrigerator). The energy impact values would increase four times if the comparison were made with 0.5-in.-thick board stock. The energy impacts would decrease significantly if the applications were not stand-alone boards but were used in series with other insulation. Industry representatives suggested that these values be increased by 26% to account for the growth in board production since 1985.

The foregoing energy impact analyses for building envelopes are compared in Table 3.8. The energy impact ranges from -0.28 to 1.52 quad/year depending on the particular strategy one assumes to represent the future. The fallback positions and the boardstock ΔT (40) value yields an average energy impact of about 0.4 quad/year. If this value persisted until the year 2000, then the 10-year energy penalty would be about 4 quads. If the current $18/barrel prices for Texas Intermediate Crude Oil rises linearly to $40/barrel (7%/year), then a total 10-year energy impact would cost about $22 billion for building envelopes.

Table 3.8. Comparison of building envelope energy impact analysis (quad/year)

Application	Preferred response	Fallback position	Worst-case scenario	Advanced technology solution
A. Fischer/Creswick				
Residential walls	0.01	0.02	0.05	-0.04
Residential foundations	0.00	0.17	0.32	*a*
Commercial walls	0.02	0.04	0.08	-0.08
Commercial roofs	0.03	0.11	0.20	*a*
Subtotal	0.06	0.34	0.65	-0.12
B. This text values				
Residential walls (50%)	0.02	0.04	0.10	-0.08
Residential foundations	0	0.17	0.83	
Commercial walls (100%)	0.05	0.25	0.28	-0.20
Commercial roofs (100%)	0.05	0.17	0.31	
Subtotal	0.12	0.63	1.52	-0.28
C. This text, boardstock ΔT analysis				
	10°F	30°F	50°F	
Text	0.08	0.24	0.40	
Text × 1.26	0.10	0.30	0.50	

[a]Not analyzed.

4. MATRIX TABLE

4.1 INTRODUCTION

The primary purpose of this report is to provide comments in the attached matrix table (Table 4.1) on concerns about materials considered as alternatives to CFCs for foamed-board insulations for buildings. The specific comments in the matrix table are discussed under the subdivisions used by EPA. For buildings, two product types are primary headings:

Topic 1. Rigid polyurethane foam, and

Topic 2. Rigid extruded polystyrene foam.

Both primary product types contain subheadings for alternative blowing agents that are being studied as substitutes for Group I chemicals. Topic 3, alternative materials, includes three vacuum concepts and lists currently available substitute materials.

The horizontal subheadings provide abbreviated responses to six topics, with the first horizontal row describing currently available rigid foams.

1. Applications: Cites proven end-uses for existing products. These end-uses are targets for new products, but each product application must be proven by testing.

2. Availability: Cites current chemical availability for production quantities and cites projected timing for gas-producing plants.

3. Development risks: Cites risk to product change in terms of missing gas-reduction targets.

4. Environmental health and safety: Cites gas properties, ozone-depletion potential (ODP), greenhouse warming potential (GWP), toxicity, and flammability.

5. Energy impact: Compares estimated R-value of new product to that of existing product(s) as a ratio; text estimates energy impact.

6. Economic impact: Compares price of gas in new product to existing gas price.

7. Comment: Cites primary current issues.

It is important to comment that the entire thermal insulation industry is competing for the end-use applications. The foam-board industry has captured major fractions of building applications in the past 10 years by displacing previously used insulations such as fiberglass. For example, in roofing, foam usage ranged from 45 to 75% of all insulation used in 1987; and available surveys show that residential wall foam in sheathing use represented at least 25 to 30% of the market in 1985 and over 40% in 1987. For sheathing, the 1986 survey showed that 14% was polystyrene, 23% polyurethane, and 75% fiberboard or plywood. Thus, individual product restrictions or advances can result in significant competitive changes in end-use decisions.

The matrix table (Table 4.1) compares alternative blowing agents, including blends and extenders (CO_2) for replacements to CFC-11 and CFC-12 blown products. The CFC-11 and CFC-12 gases are uniquely suitable to produce rigid polyurethane and rigid extruded polystyrene foams. Foam-production criteria include modest costs, appropriate volatility (normal boiling point between 32 and 122°F), nonreactivity (lack of chemical reactions with plastic foam), adequate solubility in prefoaming, effective heat of vaporization for foaming, low vapor thermal conductivity to be an insulant, low molecular weight to achieve volumetric efficiency, and nonflammablity and low toxicity for processing and application safety. CFC-11 and CFC-12 do not meet environmental requirements for low ODP or low GWP.

The alternative blowing agents are those that have passed initial feasibility studies using these replacement criteria and appear to be worthy of further study to quantify the limitations of each. Environmental health and safety factors are primary criteria: low ODP, low GWP, nonflammability, and low toxicity. All alternates show ODPs below 0.05 and GWP below 0.1.

4.2 CANDIDATE COMMENTS

1. HCFC-22 is a currently available major product with direct replacement potential for both CFC-11 and CFC-12. The low boiling point requires foaming process adaptations. High diffusion out of foam leads to rapid air replacement and less insulating efficiency (an aged product with R:4.2/in. is expected for a fresh foam with R:6.8/in.).

2. HCFC-142b is being manufactured in limited quantities, and additional production plants are expected in 1990–91. Properties are similar to those of CFC-11, except it is flammable; but it is nonflammable if blended with HCFC-22. A blended gas foam would lose HCFC-22 rapidly, which could change insulating and flammability properties. Rigid extruded polystyrene foam R-value is expected to be 4.7/in. or 5% below existing CFC-12 products (5/in.).

3. HCFC-124 is limited to laboratory quantities but has properties near those of CFC-12. Foam properties are unknown, but fresh foam R/inch of 6.7 is expected (a 7% insulation impact, initially).

4. HFC-134a is becoming commercially available, but its status is unknown until toxicity tests are complete. DuPont has announced that

Table 4.1. Matrix table of alternatives to chlorofluorocarbons for foamed-board insulations for buildings[a]

	Applications	Availability	Development risks	Environmental health and safety	Energy impacts	Economic impacts	Comments
1. RIGID POLYURETHANE FOAM (CFC-11 and CFC-12)	Low-slope roofs, sheathing, wall cavities, door cavities	Rigid boardstock poured in place or spray-applied foam tonnage: 300,000 mt; gas tonnage 47,000 mt	Industry survival requires change; CFC-11 and CFC-12 costs are escalating	CFC-11 ODP:1, GWP:0.4 CFC-12 ODP:1.0, GWP:1.0 Nonflammable Low toxicity	85% of worst-case scenario is 0.55 quad annually; aged base R:7.2/in.; fresh base R:8/in.	If industry dies, energy costs for 0.55 quad annually is $1.8 billion	(1) Industry needs lead time to make and prove new products work; (2) Products become noncompetitive
Alternative Blowing Agents							
1.1 HCFC-123		Gas availability is increasing for R&D tests but still limited	Modest to low risks depending on toxicity test results	ODP:<0.03, GWP:0.01 Nonflammable Toxicity tests in progress	Fresh R:7.2/in. or 10% less effective	1.5X to 2X CFC-11	Need toxicity test results and R&D on foams, particularly attack of plastics
1.2 HCFC-141b		Gas available for R&D testing	Modest, but flammability is a safety issue; could require explosion-proof equipment; toxicity data needed	ODP:<0.1, GWP:<0.05 Flammable range and toxicity unknown	Calculated fresh R:7/in. or 12% less effective; tests showed R:6.7/in.	1.5X to 2X CFC-11	Need toxicity test results and R&D on foams, particularly attack of plastics
1.3 HCFC-22 (blends with CFC-11)		Major existing product	Low	ODP:0.05, GWP:0.07 Nonflammable Proven low toxicity	Expect R:6.7/in. fresh or 16% less effective	1.2X to 2X CFC-12	Low boiling point, rapid diffuser out of foam
1.4 CFC-11/CO_2		CO_2 is widely available	Low	See CFC-11 above	Fresh R:6.85/in. for 1/3 CO_2, 16% less effective	Extender may reduce gas cost investment in foam	Industry is pursuing this topic

Table 4.1. (continued)

	Applications	Availability	Development risks	Environmental health and safety	Energy impacts	Economic impacts	Comments
2. RIGID EXTRUDED POLYSTYRENE FOAM (CFC-12)	Low-slope roofs, sheathing walls, foundations, roads	Boardstock, 1.1 x 10^{9} board feet; foam tonnage: 87,000 mt; CFC-12: 9,200 mt	Industry must change to survive; product changes announced in mid-1989; CFC-12 gas costs are escalating	ODP:0.1, GWP:1.0 Nonflammable Low toxicity	15% of worst-case scenario is 0.1 quad annually; base R:5/in.; fresh 7.2/in.	Cost for 0.1 quad is $0.3 billion annually	Imminent product change expected; will compete with rigid polyurethane products
Alternative Blowing Agents							
2.1 HCFC-22		Currently a major product	Low risks, but less insulating capacity is a deterrent	ODP:0.05, GWP:0.07 Nonflammable Proven low toxicity	Fresh R:4.2/in. is expected or 40% less effective	1.2-2X CFC-12	Low boiling point; rapid diffuser out of foam
2.2 HCFC-142b		Limited quantities until 1990/91 plants on-line	Modest risks due to flammability requiring process changes; blends with HCFC-22 are nonflammable	ODP:0.05, GWP:<0.2 Flammable Low toxicity	Expect fresh R/in. 4.75; 35% less effective	2X-4X CFC-12	Flammability must be addressed; could be feasible candidate
2.3 HCFC-124		Limited to laboratory quantities; no commercial plants announced	Attractive properties but lacks availability	ODP:<0.05, GWP:<0.1 Nonflammable Low toxicity, but testing needed	Expect R:6.7/in. fresh, aging unknown; fresh is 7% less effective	Unknown	Need R&D on properties that may prompt production; low diffusivity
2.4 HFC-134a		DuPont: 450-mt plant in 1990; others to have plants in 1992-93	Best ODP demands study; modest risks	ODP:0.0, GWP:<0.01 Nonflammable Toxicity tests are in progress; test results in 1992	Expect R:6/in. fresh, or 16% less effective	3X to 5X CFC-12	Toxicity must be resolved; low diffusivity is expected
2.5 Butane and pentane as blends		Very available	Gases used to produce first foams; processing requires safety measures	Flammable	Fresh R/in. 5.7 to 6.2, or 17% less effective	Very inexpensive	Poor choice; products not likely to meet requirements

Table 4.1. (continued)

	Applications	Availability	Development risks	Environmental health and safety	Energy impacts	Economic impacts	Comments
3. ALTERNATIVE MATERIALS	Low-sloped roofs, sheathing walls, foundations						
3.1 Advanced Materials Powder-filled evacuated panels Silica-aerogel insulations Compact vacuum insulations		Very limited; for demonstration tests	Moderately high for all; appliances are first logical application	None known	-0.12 quad/year R:20/in. or better than R:7.2/in. rigid foams; R:15 for 0.1 in.	$0.3 billion savings/year	Problems to be solved: reliability, aging, lifetime, automated production, cost reduction
3.2 Currently Available Substitute Materials Fiberglass board Perlite board Expanded polystyrene Fiberboard Cellular glass Insulating concrete Gypsum Plywood Foil-faced laminated board Insulating brick		Widely available	None	None	Poorer insulations than rigid foams; same R-value; requires thicker sections	Costs less than rigid foams	This group represents the worst-case scenario; energy impact 0.5 to 1.5 quads/year.

[a] CO_2 = carbon dioxide; GWP = greenhouse warming potential; ODP = ozone-depletion potential; R&D = research and development.

a one-million-pound production plant for HFC-134a will be completed in 1990 (ref. 28). HCF-134a gas conducts 40% better than CFC-12, which projects a fresh foam with 16% less effectiveness.

5. Various blends and extenders are being studied to replace some of the CFC-12 in use, including CFC-12 with HCFC-22, with butane, pentane, or HCFC-142b. Generally, prices are higher and foams have poorer mechanical strength and less insulating capacity.

6. HCFC-123 is a strong candidate to replace CFC-11 if current testing shows low toxicity. HCFC-123 gas is a 25% better conductor of heat than CFC-11, which leads to a fresh-foam energy penalty of 6.9/8 or 14%. Molecular weight is greater than that of CFC-11, which calls for 11% more HCFC-123 gas for foaming (tests used 25% more). R&D tests show that HCFC-123 attacks structural plastics used in refrigerator/freezers (ABS and HIPS). Aging for 300 d is similar to aging of CFC-11. An HCFC-123 foam increased by 0.04 K-units, which corresponds to an aged R/inch of 5.5 (ref. 18).

7. HCFC-141b is a candidate alternative to CFC-11 but has a vapor flammable range in air between 6.4 and 15 vol % and unknown toxicity. HCFC-141b gas conducts 22% better than CFC-11, which leads to a fresh-foam energy penalty of 7/8 or 12%. The low molecular weight of HCFC-141b implies 31% greater expansion capacity than that of HCFC-123 and 15% greater than that of CFC-11. Thus, blends of HCFC-141b and HCFC-123 could match the expansion capacity of CFC-11. HCFC-141b, like HCFC-123, attacks polymers. Early foam-aging tests show that HCFC-141b reaches an R/inch of 5.3 in 300 d (ref. 18).

8. CFC-11/CO_2 mixtures as blowing agents can reduce CFC-11 gas usage and still produce a foam product. This mixture yields a less effective foam product, depending on the CO_2 concentration, because the K of CO_2 (0.107) is 87% more than the K of CFC-11 (0.057).

   Calculated R-values for fresh foams are: 100% CO_2 R:5.6/in., 50% CO_2 R:6.4/in., and 33% CO_2 R:6.8/in. If an ideal gas barrier could be created and only lateral diffusion of N_2 and O_2 were allowed, then, theoretically, such products would perform better than CFC-11 foams with no barriers.

4.3 ALTERNATIVE MATERIALS

The matrix table heading "3. Alternative Materials," includes two subheadings: "3.1 Advanced Materials," which use a vacuum to produce high thermal resistance systems; and "3.2 Currently Available Substitute Materials," which provide less thermal resistance than rigid-foam products. Some technical background is provided below, because since the former are a newer concept than that of rigid foams.

The advanced materials category includes two soft vacuum (1 to 70 mm Hg) concepts (powder-filled evacuated panels and silica aerogel insulations) and one hard-vacuum (10^{-7} mm Hg) concept (compact vacuum insulation). Vacuum insulation technology was discovered by Sir James Dewar in the eighteenth century. Current hard-vacuum cylindrical and spherical systems obtain R-values of over 100/in. to allow effective shipment and storage of cryogenic liquids such as liquid helium (4.2 K) and liquid nitrogen (77 K).

In the mid-1930s, Kistler[29] noted that high R-values/inch were obtained at modest vacuums for aerogels and small-diameter powders. In the mid-1950s, evacuated flat-metal panels were studied by the General Electric Company (GE), but the study was abandoned because of high costs and high heat leakages by the outer metal envelope.[30,31] In 1981, DOE funded a technical assessment on advanced insulations for appliances.[16] This assessment yielded three important observations: (1) an annual energy savings of about one quad [10^{18} joules (J), 0.947×10^{15} Btu] would result if an insulation with a K = 0.05 Btu·in./h·ft²·°F and R = 20/in. were used in appliances; (2) theoretical analyses of 12 candidates indicated that neither evacuated nor gas-filled insulation systems could meet the K-value target; and (3) materials property information was not available to verify these promising candidate systems. In addition, this report identified U.S. Patent 4,159,359 issued to L'Air Liquide, France,[32] which showed K-values below 0.035 Btu·in./h·ft²·°F for evacuated panels containing fumed silica particles when tested at low temperatures (-120°F).

DOE funded research at Oak Ridge National Laboratory (ORNL) to obtain property information on candidate systems that might obtain R = 20/in. A series of ORNL publications described tests on air-filled and evacuated powders.[33-37] These tests showed that high thermal resistance depends on decreasing gas-phase conduction and decreasing radiative transport in the system without significantly increasing the contribution due to solid-phase conduction. For example, particulate thermal insulations containing air at atmospheric pressure as the gas phase have the K of air as a limiting value unless the effective pore size can be reduced to less than the mean free path in the gas phase. Because the K for air at 75°F and one atmosphere pressure is 0.18 Btu·in./h·ft²·°F, practical R-values per inch are limited to 5.5. However, the K-values obtained for beds composed of small-diameter, pure-amorphous-fumed silica particles at 75°F and atmospheric pressure show a minimum K of 0.146 Btu·in./h·ft²·°F (R/in. of 6.8). Thus, when as-received powders from two companies (Cabot and DeGussa) are compacted, K is obtained in air at one atmosphere that is only 80% of the thermal conductivity of air. Thus, K is determined by an assembly of particles that changes two heat transfer components: reduced gas conduction by a mean-free-path effect and reduced radiative transport by increased density.

Recently, two U.S. patents[38,39] were issued to GE for panels evacuated to 1 mm of Hg containing a filler material of precipitated silica with or without fly ash that achieved high thermal resistance (R-20/in.) at room temperature. These systems achieve high thermal resistance by using small-diameter powders to produce void spaces with dimensions much smaller than the mean free path of the interstitial gas. This process reduces the contribution of gas conduction to the K-value of the system. The GE panel construction consists of a filler, an inner porous bag, and an outer barrier envelope. The gas permeability of the barrier is crucial to maintaining the system vacuum and R-value. The GE panels are hand produced to sizes up to 15 × 18 × 1 in.

During the early 1980s, some refrigerators produced in Japan included evacuated panels containing perlite and embedded in polyurethane foam as a thin-walled, high-resistance system. Production of such units was stopped because of the high costs of producing and installing the units.

ORNL reported R/inch values for evacuated panels from France, Japan, and the United States, both as-received and for times up to 78 months after manufacture, as follows:

Country	R/inch value (mo = month)	
France	15 mo:16.8	78 mo:9.6
Japan	1 mo:18	38 mo:9
United States	1 mo:19.3	34 mo:14.5

The powder-filled evacuated panels show R/inch values that approach 20/in., which degrade with time. Their one-atmosphere value is expected to be near 7/in., which is higher than aged rigid foams. Before this technology can be successfully applied to building equipment or building envelopes, the reliability issue must be resolved, the material cost reduced, and an automated production concept demonstrated. These are formidable barriers, but as Fischer and Creswick[5] note, this advanced technology option could provide energy savings of 0.8 quad/year. Current R&D is focused on demonstrating the effectiveness of panels.

ORNL has completed baseline tests on the ice-melting rate of three types of portable coolers, and industry is producing panels that will be foamed into the envelopes of a set of portable coolers. The results should be available in 1990. This cooperative effort was preceded by an assessment of this industry that identified an automated technique to produce the panels.

Current manual labor and material costs are about $2.50/board ft or about $0.13/board ft-R. A horizontal form, fill, and seal machine (as used in food packaging) might provide an automated process with a projected labor and materials cost of $0.85/board ft or $0.04/board ft-R. The costs of current rigid-foam insulations are below $0.03/board ft-R.

A major concern for evacuated panels in any application is the loss of vacuum due to even one pinhole-sized puncture. Research at the

Massachusetts Institute of Technology (MIT) is in progress on improving the effectiveness of rigid foams by including a number of small evacuated panels in boards. Such a composite might obtain an R-value of 10/in. and avoid the single-puncture problem.

This technology is not ready to allow industry to comply with the Montreal Protocol. However, the above demonstrations and those in progress by major appliance producers could yield substantial benefits.

4.3.1 Silica Aerogel Insulation

Quantum Optics (Thermolux) in California is in the process of commercializing a silica aerogel product that obtains an R of 20/in. at 0.1 atmosphere. The slab-like product is produced by making a gel from a silicon-containing chemical, alcohol, and water. The liquid in the gel is removed by a supercritical drying process to yield an open-pore, low-density structure. The slab is then vacuum packaged in a manner similar to that of evacuated panels in a barrier envelope.

Quantum Optics is fabricating 7 × 7 × 3/4 in. slabs for refrigerator performance testing by WCI Refrigeration Division (funded by EPA, Electric Power Research Institute (EPRI), Snohumish, Pacific Power and Light Company, and National Resources Defense Council).

Prototype (1989) and commercial (1990) plants are being planned to produce up to 100,000 ft^2 of evacuated aerogel per year.[40]

4.3.2 Compact Vacuum Insulation

Compact vacuum insulation (CVI), being developed at the Solar Energy Research Institute (SERI), is an extension of the laser sealed vacuum insulation window that SERI is developing.[41] CVI consists of a vacuum gap contained in a metallic enclosure, which is sealed by laser welding. A very low internal vacuum ($<10^{-6}$ mm Hg) is required for this concept, and additional internal layers and low emittance coatings may be needed. Resistance of 15/panel for panels approximately 0.1 to 0.25 in. thick have an estimated cost of $\$2/ft^2$.

In March 1989, the first test panel of CVI was successfully fabricated and tested at SERI. The insulation value for the 0.2-in.-thick panel measures R-5, which compares favorably with a typical value of R-7 for 1-in.-thick, CFC-blown, polyurethane foam insulation used in refrigerators. SERI researchers expect that further development of this novel vacuum insulation concept will result in a 0.1-in.-thick panel with an insulation value of R-15. In collaboration with the three major U.S. manufacturers, SERI will install the improved versions in four full-scale refrigerators over the next 12 months.

4.3.3 Current State of the Art

Advanced evacuated thermal insulation technology was recently reviewed by H. A. Fine with an emphasis on material costs and problem identification.[62] These thermal insulations have been shown to have the potential for significant energy conservation if employed in residential and commercial refrigerator/freezers. Many materials and systems have been proposed for incorporation into refrigerator/freezers to achieve this potential.

The state of the art for advanced evacuated insulations that might achieve resistivities of 20 was established by reviewing measurements available in the open literature on the dependence of the thermal performance of many materials on internal pressure. The materials cost for the powdered, fiber, foam, and multilayer materials were then found by contacting the manufacturers of the products. Possible candidates for inclusion into refrigerator/freezers are described and ranked on the bases of their thermal properties and materials costs.

Several filler materials were found that may be used to make super insulation panels with material costs of less than $1.00/board ft, if a plastic laminate is used for the container required to maintain the necessary vacuum levels. Materials in this category include: Beverly silica dust, open-cell polyurethane foam, fine perlite, 2.7-lb/ft^3 fiberglass, and 3.61-lb/ft^3 fiberglass with CFD Al, precipitated silica, and precipitated silica/fly ash mixtures. Materials costs approaching $3.00/board ft will result if metallic containment is required.

5. DOE-SPONSORED RESEARCH

The U.S. Department of Energy has sponsored research relevant to CFC technology through the Office of Buildings and Community Systems Division of Building Systems and Division of Building Equipment. Results from this research are the basis for much of the foregoing text, and a 1977–88 chronology of CFC-related activities is given in Appendix E of ref. 17. Table 5.1 summarizes the activities including building materials property tests, insulation for appliances, field testing for roof and foundation applications, energy impact analyses, cooperation with EPA, and two public/private workshops on alternative insulations containing CFC (June 9–10, 1988, and January 31, 1989). A clear conclusion is that the DOE-sponsored research has established a firm base in CFC technology, and this base is being used to initiate individual projects focused on CFC-related issues. A second clear conclusion, derived from the following material, is that DOE-sponsored research should be conducted in concert with industry.

The Joint Public/Private Workshop on Alternatives for Insulations Containing Chlorofluorocarbons was held June 9–10, 1988. This workshop was attended by 69 participants from industry, academia, and government agencies. The first CFC workshop is reported in ORNL/CON-269.[19] The attendees assigned priority rankings to 29 research projects of a CFC research menu and voted on who should be responsible for each of government, industry, or cooperative. Table 5.2 is a reproduction of the project ranking. ORNL staff estimate that a 5-year R&D program to conduct these projects would cost about $16 million.

Table 5.1. Chronology of U.S. Department of Energy activities relevant to chlorofluorocarbon research

Year	Activity
1977	Recommended standard reference materials
1981	Analyzed advanced insulation for appliances
1981–1986	Demonstrated R-20/in. insulations
1982–1983	Field tested EXPS below grade
1981–1989	Basic research on foam behavior
1985–1987	Field tested phenolic foam for roofs
1985	Developed foundation insulation levels for ASHRAE 90.2P
1986–1988	Produced *Building Foundation Design Handbook*
1987	Identified energy impact of CFC restrictions for foundations
1987	Identified energy impact of CFC restrictions for walls and roofs
1987	Assessed foam-in-place urethane foams
1987	Discussed industry/government CFC research needs
1988	Tested HCFC-22 blown extruded polystyrene
1988	Provided DOE preliminary project listing
1988	Held first joint public/private workshop research menu
1988	Coordinated DOE/EPA sponsorship of basic foam research
1988	Delivered SRM 1449 with R-7/in.
1988	Initiated cooperative project on R-20/in. panels in portable coolers
1989	Held second joint public/private workshop
1989	Participated in United Nations Environment Program Review of CFC insulation technology
1989	Initiated cooperative (industry/government/university) project on HCFC-123 and HCFC-141b foams for roofs

Table 5.2. Chlorofluorocarbon research project ranking[a]

Code	Research project title	Score	
		Tech.	Pub/Pri[b]
C.4.1	Public/private research menu	4.3	2.16
C.4.2	DOE/ORNL[c]/industry workshop	4.13	1.87
C.1.12	Database of physical properties	4.04	3.29
C.1.11	Protocol to predict thermal performance	3.8	1.96
C.1.4	Identify new blowing agents	3.7	3.51
C.1.6	Environmentally acceptable blowing agents	3.66	2.5
C.2.6	New facing materials	3.59	3.46
C.4.5	Energy impact for walls and roofs	3.53	1.72
C.3.1	CFC manufacturing recovery processes	3.51	3.51
C.1.2	Low K standard reference material	3.39	0.98
C.1.3	Database for alternate blowing agents	3.24	3.27
C.1.1	Accelerated foam aging for design R-values	3.23	2.41
C.2.2	Evacuated Panel "super insulation"	3.11	2.94
C.2.3	Components for super insulations	3.05	2.78
C.1.5	Field test project	3.02	1.98
C.2.1	Composites with high thermal resistance	3.02	2.91
C.4.4	Establish essential material properties	2.91	2.8
C.3.4	CFC destruction	2.84	2.25
C.1.8	Thermal resistance measurements	2.79	2.31
C.4.3	Critical assessment of product property tests	2.74	2.22
C.3.2	CFC incineration	2.71	2.43
C.3.6	CFC adsorbents	2.64	1.75
C.3.5	CFC recapture at R/F[d] retirement	2.55	2.5
C.1.10	Manufacture of environmentally acceptable foams	2.51	3.86
C.1.9	Thermal conductivity of expanded polymers	2.2	2.04
C.2.4	Non-CFC systems	2.18	2.57
C.2.5	Non-CFC foundation insulation	2.02	1.98
C.3.3	Recycling panels	1.82	2.39
C.1.7	Calculation methodology-flammability testing	1.145	1.98
	Average score	3.01	2.52

[a]These rankings were determined by workshop participants, as reported by J. E. Christian and D. L. McElroy, pp. 106–8 in *Results of Workshop to Develop Alternatives for Insulations Containing CFCs – Research Project Menu*, ORNL/CON-269, Oak Ridge National Laboratory, Oak Ridge, Tenn., December 1988.

[b]Technical merit: 0, low; 5, high. Public/private: 0, public; 5, private.

[c]DOE/ORNL = U.S. Department of Energy/Oak Ridge National Laboratory.

[d]R/F = refrigerator/freezer.

The top two projects were to (1) prepare the research menu (i.e., deliver a consensus plan for private industry and government) and (2) host semiannual government/industry workshops as a forum to exchange results and guide future research. Because of the latter, the second workshop was held at the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) meeting in Chicago on January 31, 1989. The second workshop examined a single cooperative industry/government project on the long-term performance of substitute insulations for roofing containing CFC 123 and CFC 141b.

The first meeting of the steering committee for this cooperative industry/government project occurred on April 18, 1989, and witnessed production of prototype foam boards. The project involves the Society of the Plastics Industry, the Polyisocyanurate Insulation Manufacturers of America, NRCA, DOE, EPA, MIT, and ORNL. The project, although restricted to roofing applications, involves production of boards with on-line production equipment, analysis of physical properties of the boards at several industrial laboratories, thermal aging studies at ORNL, and examination of installed systems for impacts on long-term performance. The objectives of the testing are to provide a comprehensive examination of the materials and systems properties of roof insulations produced with these replacement chemicals and to provide a protocol for testing of other alternate systems that will appear later. The project is estimated to cost about $400,000 and be completed in 1991.

A third workshop has not been planned, but an obvious missing link is a similar research project that focuses on R/F needs and the new foams. It may be that a technical committee on insulations for R/F that is currently being organized will address this issue.

The Third National Program Plan (1988) prepared by the Building Thermal Envelope Research Coordinating Council (BTECC) includes a chapter on building materials research needs prepared by the Building Thermal Envelope Materials Research Coordinating Committee (RCC) of BTECC. This chapter lists 81 projects, which recently were ranked by RCC. The top-ranking project was entitled, "Effect of Aging on the R-Value of Foamed Board Insulation Products." The project objective focuses on the fact that laboratory measurements over time do not simulate the effect of installed conditions in the long-term insulation properties of foamed-board insulation. This fact particularly applies to roofing applications where insulation is more exposed to the vagaries of the weather. Controlled measurement of changes in R-value after periods of outdoor exposure are needed to determine the true performance of insulation products. Establishment of a performance database is desired. This database would be useful to architects and building owners who lack information on the real thermal properties of foamed-board insulation for extended time periods. The results of this project would permit a more informative choice of insulation products. A six-speaker seminar was held on June 7, 1989, in Washington, D.C., to provide an overview of foam aging.

6. CONCLUSIONS

1. The CFC issue is enormous. Industry produces over 400,000 metric tons of rigid foam-board insulation annually and therein consumes over 60,000 metric tons of CFC-11 and CFC-12. This consumption is equivalent to 6 billion board ft of foam and represents the most effective thermal insulation that is commercially available. If environmentally acceptable alternative gases and foams are not available, the estimated energy impact for building applications alone is between 0.65 and 1.5 quad/year.

2. Industry is pursuing a variety of alternative blowing agents to CFC-11 and CFC-12 for producing rigid-foam-board insulations. Development risks to foam-insulation producers include the commercial availability of the alternative blowing agents and their subsequent acceptance by regulatory agencies. The new products will be less hazardous to the environment but more expensive and less effective thermal insulations (lower R/inch values).

3. A new rigid extruded polystyrene foam-board product was announced and became available for buildings application in mid-1989. The new product will reduce the CFC problem because the polystyrene industry provides about 20% of the total rigid-foam tonnage. However, a major problem persists for the rigid-polyurethane industry.

4. Use of the rigid-foam-industry products in buildings applications conserves energy, which benefits the nation. The federal government should support the development and execution of a broad-based research program in cooperation with industry. This program should include proving the applicability of new products and determination of new product properties. The estimated cost of completing an existing research menu of 29 projects in 5 years is $16 million.

5. The federal government should accelerate R&D efforts on advanced, high-risk materials technologies that could reduce CFC use and energy use in building equipment and building envelopes by as much as 0.8 quad/year.

7. REFERENCES

1. *Insulation Materials, Testing and Applications*, ASTM STP-1030, American Society for Testing and Materials, 1989.

2. *Protocol on Substances that Deplete the Ozone Layer*, "United Nations Environment Programme, Final Act," Montreal, September 1987.

3. "Protection of Stratospheric Ozone: Final Rule and Proposed Rule," 40 CFR Pt. 82, *Fed. Regist.*, Vol. 52, pp. 47486–523, Dec. 14, 1987.

4. "Protection of Stratospheric Ozone: Final Rule," 40 CFR Pt. 82, *Fed. Regist.*, Vol. 53, pp. 30566–602, Aug. 12, 1988.

5. S. K. Fischer and F. A. Creswick, *Energy-Use Impact of Chlorofluorocarbon Alternatives*, ORNL/CON-273, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1989.

6. R. P. Tye et al., *An Experimental Study of Thermal Resistance Values of Low-Density, Mineral-Fiber, Building Insulations Batts Commercially Available in 1977*, ORNL/TM-7266, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1980.

7. L. R. Glicksman, "Methods to Enhance the Insulating Values of Closed Cell Foam," to be published, ASHRAE IV, American Society of Heating, Refrigeration, and Air Conditioning Engineers, December 1989.

8. L. R. Glicksman and M. R. Torpey, *A Study of Radiative Heat Transfer Through Foam Insulation*, ORNL/Sub/86-09099/3, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1988.

9. A. G. Ostrogorsky, "Aging of Polyurethane Foams," Sc.D. thesis, Massachusetts Institute of Technology, Cambridge, 1983.

10. *The NRCA Technical Bulletin*, National Roofing Contractors Association, Rosemont, Ill. (Bulletin 10, July 1981; Bulletin 11, November 1981; and November 1987).

11. ASTM Standard C1013-85, "Standard Specification for Membrane-Faced Rigid Cellular Polyurethane Roof Insulation," March 1985, *1988 Annual Book of ASTM Standards*, American Society for Testing and Materials, 1988.

12. J. Hagan, Jim Walters Research Corporation, Building Thermal Envelope Materials Seminar, Washington, D.C., June 1989.

13. Press Release, Association of Home Appliance Manufacturers, Chicago, Ill., July 6, 1987.

14. *Appliance Efficiency Standards*, P400-00-029, California Energy Commission, Sacramento, Calif. (amended August 1985).

15. National Appliance Energy Conservation Act of 1987, Publ. L. 100-12, Stat. 83, March 17, 1987.

16. W. T. Lawrence and F. E. Ruccia, *Development of Advanced Insulation for Appliances, Task I Report*, ORNL/Sub/81-13800/1, Oak Ridge National Laboratory, Oak Ridge, Tenn., June 1981.

17. Environmental Protection Agency, *How Industry is Reducing Dependence on Ozone-Depleting Chemicals*, June 1988.

18. Betsy Kaufman, "How Much Can it Hold?," *Knoxville News-Sentinel*, April 24, 1989.

19. J. E. Christian and D. L. McElroy, *Results of Workshop to Develop Alternatives for Insulations Containing CFCs — Research Project Menu*, ORNL/CON-269, pp. 106–8, Oak Ridge National Laboratory, Oak Ridge, Tenn., December 1988.

20. E. A. E. Lund, R. G. Richard, and I. R. Shankland, "A Performance Evacuation of Environmentally Acceptable Blowing Agents," *SPI Polyurethane* 88, 290–96 (1988).

21. W. R. Strzepek, "Cellular Insulations," Chapter 3.4, *Handbook of Applied Thermal Design*, McGraw, 1988.

22. S. Petersen and H. Fanney, *Technical and Economic Analysis of CFC-Blown Insulations and Substitutes for Residential and Commercial Construction*, NBSIR 88-3829, U.S. Department of Commerce, National Bureau of Standards, July 1988.

23. *Insulation Fact Sheet*, DOE/CS-0180, U.S. Department of Energy, January 1988.

24. J. E. Christian, *Impact of CFC Restrictions on U.S. Building Foundation Thermal Performance*, ORNL/CON-245, Oak Ridge National Laboratory, Oak Ridge, Tenn., December 1987.

25. CABO, *Model Energy Code, 1989 Edition*.

26. ASHRAE 90.3P, "Residential Energy Standard," in review.

27. T.-C. Chang and H. W. Busching, *Energy Savings Potential of Roofing Research*, ORNL/Sub/82-22293/1, p. 28, Oak Ridge National Laboratory, Oak Ridge, Tenn., December 1983.

28. DuPont Company, *Corporate News*, announcement by Kathleen H. Forte, September 29, 1988 (one-million-pound plant for HFC-134a, 1990).

29. S. S. Kistler, Coherent Expanded Aerogels, *J. Phys. Chem.* 52(36), 1932.

30. H. M. Strong, F. P. Bundy, and H. P. Bovenkirk, "Flat Panel Vacuum Thermal Insulation," *J. Appl. Phys.* 31(1), 39–50 (1960).

31. H. M. Strong et al., "Thermal Insulating Panel and Method of Making Same," U.S. Patent 3,179,549, April 20, 1965, Assignee: General Electric Company.

32. P. Pellaux-Gervais and D. Goumy, "Insulating Material with Low Thermal Conductivity, Formed of a Compacted Granular Structure," U.S. Patent 4,159,359, June 26, 1979, Assignee: L'Air Liquide, Paris.

33. D. L. McElroy et al., *Development of Advanced Thermal Insulation for Appliances*, ORNL/CON-159, Oak Ridge National Laboratory, Oak Ridge, Tenn., June 1984.

34. D. W. Yarbrough et al., *Development of Advanced Thermal Insulation for Appliances*, ORNL/CON-199, Oak Ridge National Laboratory, Oak Ridge, Tenn., May 1986.

35. D. W. Yarbrough et al., *The Thermal Resistance of Perlite-Based Evacuated Insulation for Refrigerators*, ORNL/CON-215, Oak Ridge National Laboratory, Oak Ridge, Tenn., September 1986.

36. G. L. Copeland et al., "Insulations with Low Thermal Conductivity," 18th Thermal Conductivity Conference, Rapid City, S.D., Oct. 3-5, 1983.

37. D. W. Yarbrough, T. W. Tong, and D. L. McElroy, "Use of Fine Powders for High Thermal Resistance," *High Temp. Sci.* 19, 213-25 (1985).

38. Robert W. Barito and Kenneth L. Downs, "Precipitated Silica Insulator," U.S. Patent 4,636,415, Jan. 13, 1987, Assignee: General Electric Company, Louisville, Ky.

39. Robert W. Barito and Kenneth L. Downs, "Insulation Formed of Precipitated Silica and Fly Ash," U.S. Patent 4,681,788, July 21, 1988, Assignee: General Electric Company, Louisville, Ky.

40. Marlo R. Martin, "Silica Aerogel Insulation," presentation to Energy Conservation Program for Consumer Products, Washington, D.C., Jan. 12, 1989.

41. D. K. Benson and C. E. Tracy, "Laser Sealed Vacuum Insulation Window," U.S. Patent 4,683,154, July 28, 1987.

42. H. A. Fine, "Advanced Evacuated Thermal Insulations: State-of-the-Art," in press, *J. Therm. Insul.*

APPENDIX A

SI EQUIVALENTS OF CUSTOMARY UNITS

Appendix A

SI EQUIVALENTS OF CUSTOMARY UNITS

Property	Customary unit	SI equivalent
Dimension	in.	25.4 mm
Dimension	ft	0.3048 m
Density	lb/ft^3	16.02 kg/m^3
Mass	lb	453.6 g
Thermal conductivity	$Btu\cdot in./ft^2\cdot h\cdot °F$	0.144 $W/m\cdot K$
Thermal resistance	$ft^2\cdot h\cdot °F/Btu$	0.1762 $K\ m^2/W$
Temperature	°F	°C = (5/9)(°F - 32)
Distance	mile	1.6 km

APPENDIX B

CHLOROFLUOROCARBON NOMENCLATURE NOTES

Appendix B

CHLOROFLUOROCARBON NOMENCLATURE NOTES

The nomenclature used to describe chlorofluorocarbons (CFC) is dominated by abbreviations. The CFC prefix refers to fully halogenated chlorofluorocarbons. Halons are fluorocarbons that contain bromine atoms. CFC compounds with hydrogen in their molecular structure are referred to as HCFC compounds; those without chlorine in their molecular structure are referred to as FC. (Europeans often use HFA for HCFC, where HFA represents hydrofluoroalkanes.)

The suffix numbers are keyed to whether the CFCs are derivatives of methane (CH_4), two digits (e.g., "11" suffix of "CFC-11"), or ethane (C_2H_6), three digits (e.g., "113" suffix of "CFC-113"). H. Kruze and Heese showed the suffix code as follows:

For two-digit suffixes, the first digit is the number of hydrogen atoms +1, and the second digit is the number of fluorine atoms. For three-digit suffixes, the first digit is the number of carbon atoms -1, the second digit indicates the number of hydrogen atoms +1, and the third digit indicates the number of fluorine atoms. The suffix a or b (e.g., "b" suffix of "HCFC-141b") refers to the structure of the compound. Some replace CFC with R, but this can be confused with R-value (thermal resistance value) for insulations.

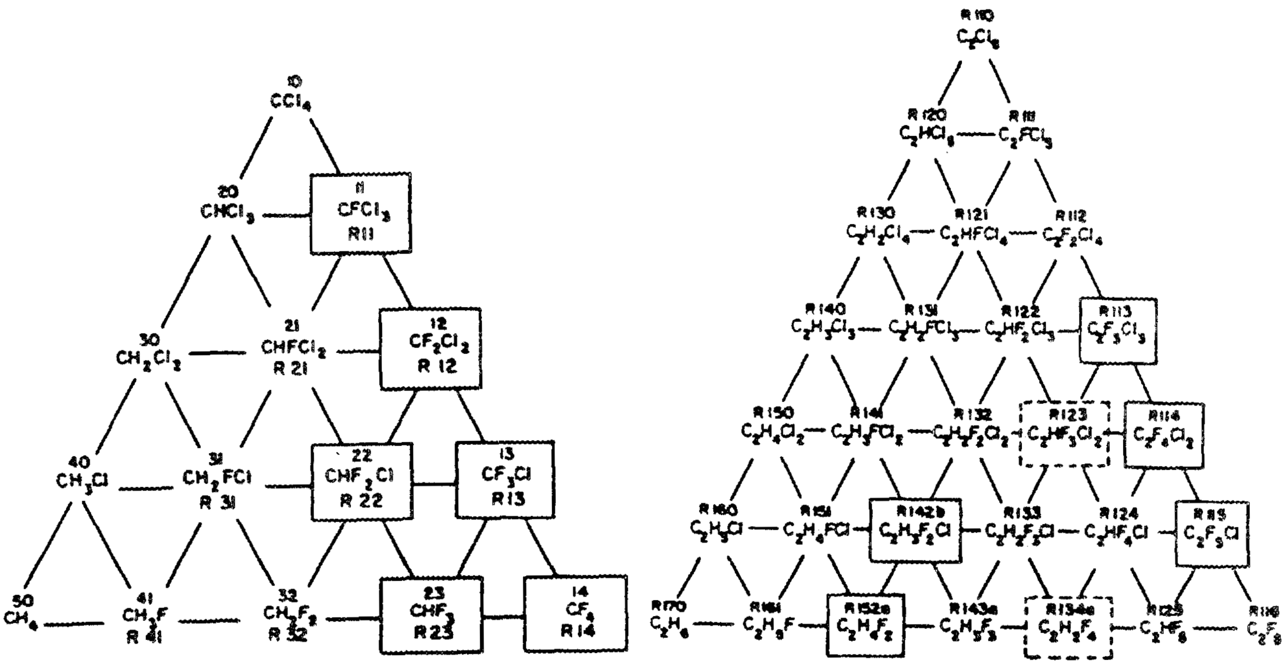

Fig. B.1. CFC derivatives of methane and ethane. *Source:* Reprinted with permission from H. Kruze and V. Heese, *Possible Substitutes for Fully Halogenated Chlorofluorocarbons Using Fluids Already Marketed*, Purdue University, West Lafayette, Ind., July 1988.

APPENDIX C

NOMINAL THERMAL RESISTANCE
OF TYPICAL INSULATION MATERIALS

Appendix C

Table C.1. Nominal thermal resistance per unit thickness value for some typical insulations, R-value per inch at 75°F[a]

	Material	Density (lb/ft^3)	R-value per inch ($h \cdot ft^2 \cdot °F/Btu$)	Source
		Nonplastics		
1.	Air, conduction only	0.08	5.5	1
2.	Air, with radiation, ΔT = 50°F		<1	2
3.	Loose-Fills			3
	Fiberglass	0.6	2.2	
	Rock wool	2	3.0	
	Cellulose	3.0	3.5	
	Perlite/vermiculite	2–11	3.7–2.5	4
4.	Fiberglass batt	0.6	3.2	3
5.	Fiberboard		2.8	5
6.	Cellular glass		2.6	5
7.	Gypsum	44	0.8	6
8.	Plywood	30	1.3	7
		Plastics		
9.	Rigid polyurethane foam	2	7.2	8–10
10.	Rigid extruded polystyrene		5.0	8–10
11.	Expanded polystyrene	1.0	3.9	8–10
		1.5	4.2	
12.	Phenolics	2–3	8.3	8–10

[a]Sources are listed on the following page.

Table C.1. Information Sources

1. R. W. Powell, C. Y. Ho, and P. E. Liley, *Thermal Conductivity of Selected Materials*, NSRDS-NBS-8, Nov. 25, 1966.

2. Calculated from ref. 1 and a radiation heat transport between two infinite surfaces with a total hemispherical emittance of 1 and spacing of 1 in. See H. A. Fine et al., *Analysis of Heat Transfer in Building Thermal Insulation*, ORNL/TM-7481, December 1980.

3. Insulation Fact Sheet, DOE/CS-0180, U.S. Department of Energy, January 1988.

4. *An Assessment of Thermal Insulation Materials*, BNL-50862, Brookhaven National Laboratory, Upton, N.Y., June 1978.

5. G. E. Courville and J. O. Kolb, *Economic Analyses of Insulation Materials Used in Low-Slope, Built-Up Roof Systems*, ORNL/TM-9004, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1984.

6. R. S. Graves, D. L. McElroy, D. W. Yarbrough, and H. A. Fine, *The Thermophysical Properties of Gypsum Boards Containing Wax*, proceedings of 21st International Thermal Conductivity Conference, in press.

7. A. TenWolde, J. D. McNatt, and L. Krahn, *Thermal Properties of Wood and Wood Panel Products for Use in Buildings*, ORNL/Sub/87-21697/1, Oak Ridge National Laboratory, Oak Ridge, Tenn., September 1988.

8. W. R. Strzepek, "Cellular Insulations," Chap. 3.4, *Handbook of Applied Thermal Design*, McGraw, 1988.

9. *ASHRAE Handbook of Fundamentals*, American Society of Heating Refrigeration, and Air-Conditioning Engineers, 1985.

10. SPI Polyurethane Division k Factor Task Force (16 members), *Rigid Polyurethane and Polyisocyanurate Foams: An Assessment of Their Insulating Properties*, pp. 323–37, Society of Plastics Industry, 1988.

APPENDIX D

SUMMARY OF MINUTES OF MEETING OF OAK RIDGE NATIONAL LABORATORY STAFF WITH INDUSTRY REPRESENTATIVES

MAY 11, 1989

May 22, 1989

Distribution

Summary of Meeting of ORNL Staff with Industry Representatives - May 11, 1989

J. E. Christian, G. E. Courville, and D. L. McElroy met with G. F. Bauman (Mobay), J. Hagan (Jim Walter Research Corp.), and R. Riley (BASF) to discuss the draft report, CFC Technologies Review - Foamed-Board Insulation for Buildings (Draft 1, May 5, 1989).

1. The report outline, summary, and conclusions were distributed and discussed.

   "All suggested that the conclusions be more quantitative, i.e. times, tonnage, R/D costs, quad/costs, accumulated loss, and incorporate how CFC impacts the DOE 'Bill of Rights' (5 criteria)."

2. Section D - Energy Impact, was reviewed in detail, starting with how the Fischer/Creswick report is summarized and then focusing use and comments on the results for Chapters 11, 12, 13, and 14.

2.1 Walls - Chapter 11. The draft report quotes the Fischer/Creswick analysis for 25% of the nationwide residential wall area and lists a four-fold increase, i.e. 100% of walls. Industry (Hagan) provided the LSI survey (August 1988) which shows that nearly 50% of walls are sheathed with polystyrene/polyurethane. Industry recommends doubling the Fischer/Creswick values. Industry noted that Petersen/Fanney misinterpreted the LSI survey (August 1986) in obtaining the 25% factor. Growth in wall fraction was noted:

   1985 (27%), 1986 (35%), 1987 (40%), 1988 (?45%), 1989 (?50%). Industry noted that Tables 11.1 and 11.2 contain errors and could be clearer.

2.2 Foundations - Chapter 12. J. E. Christian explained an analysis that increases the worst-case scenario from 0.32 quads to 0.8 quads. Industry supported this inclusion.

2.3 Commercial Construction - Chapter 13. The Fischer/Creswick analysis uses reduced wall area due to large window fractions in commercial construction. Industry would like to know the basis for the 50% and 30% fractions. The fallback position assumes that EPS can be in foam core panels, and industry doubts this assumption, and recommends increases in the fallback position energy impact from 0.05 to 0.07 quad. Industry believes a more detailed analysis of buildings could be done.

Distribution
Page 2
May 22, 1989

2.4 Low-Sloped Roofs – Chapter 14. G. E. Courville explained the Fischer/Creswick analysis and noted that the fallback position assumes increases in thickness to maintain a constant R-value as well as different thicknesses in northern and southern areas. Industry suggested that the next analysis could include local use conditions for foams in roofs, which would change the base case.

2.5 The energy impact analysis that uses board foot production was described. Industry suggested increasing the 1985 production by 25% to represent 1989 production and to include an R-4/in. case with the R-3/in. case.

3. Are there other specific concerns? Industry responded:

3.1 Major producers of potential alternate gases (HCFCs) are balking at committing money to construct HCFC plants. The foam industry survival rests on HCFC 141b and HCFC 123 being commercially available.

3.2 Regulations to tax gas users impacts foam production decisions.

3.3 Industry needs firm federal endorsement that alternate gases are acceptable alternatives and will not become controlled chemicals. New data on HCFC 141b gives a range of ODP values. A decision to ban all chlorine bearing gases could dramatically alter current efforts.

3.4 Industry suggested that the fallback position is the more probable future scenario.

3.5 Industry does not know what impresses policy makers: quads, money, or energy cost increases.

4.0 J. Hagan provided a note on May 16, 1989, indicating his belief that the existing energy impact analysis did not address retrofit applications. This is noted in Section E.

D. L. McElroy, Metals and Ceramics Division, Building 4508, MS-6092 (4-5976)

DLM:glc

<u>Distribution</u>:

G. F. Bauman	J. Hagan
J. E. Christian	R. Riley
G. E. Courville	M. P. Scofield

INTERNAL DISTRIBUTION

1-2. Central Research Library
3. Document Reference Section
4-6. Laboratory Records Department
7. Laboratory Records Department, RC
8. ORNL Patent Section
9-11. M&C Records Office
12. M. A. Brown
13-16. G. L. Burn
17. R. S. Carlsmith
18. K. W. Childs
19. J. E. Christian
20. G. E. Courville
21. P. S. Gillis
22. T. G. Kollie
23. M. A. Kuliasha
24-28. D. L. McElroy
29. D. E. Reichle
30-35. S. D. Samples
36. R. B. Shelton

EXTERNAL DISTRIBUTION

37. Robert L. Alumbaugh, Naval Civil Engineering Laboratory, Port Hueneme, CA 93043

38. James L. Andersen, Foam Enterprises, Inc., 13630 Watertower Circle, Minneapolis, MN 55441

39. Robert Anderson, 441 Intrepid Court, Boulder City, NV 89005

40. John Andrews, Custom Building Magazine, P.O. Box 998, Yarmough, ME 04096

41. Mildred Autrey, Oklahoma State University, Room 340 H.E., Cooperative Extension Service, Stillwater, OK 74078

42. Claes Bankvall, Swedish National Testing Institute, P.O. Box 857, S-501 15 BORAS Sweden

43. R. W. Barito, R. W. Barito and Associates, Inc., 9011 Cardiff Road, Louisville, KY 40242

44. H. Biejermann, 137 Louise Avenue, Ste. 8, 1050 Brussels, Belgium

45. Mark Bomberg, Institute for Research in Construction, Ottawa, Ontario K1A 0R6, Canada

46. J. J. Boulin, U.S. Department of Energy, CD-131, FORSTL, Washington, DC 20585

47. S. Bourdeau, Fishburn Building Sciences Group, Ltd. Steeles Avenue, Horby, Ontario LOP 1EO Canada

48. Maribeth Bradfield, NCMA, P.O. Box 781, Herndon, VA 22070

49. Stephen Braun, MIMA, 1420 King Street, Alexandria, VA 22314

50. B. Buchanan, Computer Science Department, University of Pittsburgh, Pittsburgh, PA 15260

51. Richard Coursey, JPS Elastometricx, 395 Pleasant Street, Northampton, MA 012061

52. Richard G. Crooks, Thermal Products International, 1020 William Pitt Way, Pittsburgh, PA 15238

53. Dave Crouse, Omega Point Labs, 6868 Alamo Downs Parkway, San Antonio, TX 78238

54. Ed Cusick, Rock Wool Manufacturing Company, Box 506, Leeds, AL 35094

55. J. J. Cuttica, Gas Research Institute, 8600 W. Bryn Mawr Avenue, Chicago, IL 60631

56. Clayton DeKorne, Journal of Light Construction, RR2, Box 146, Richmond, VT 05477

57. Andre Desjarlais, Holometrix, Inc., 99 Erie Street, Cambridge, MA 02139

58. A. H. Jenssen, Isolatak International, P.O. Box 478, Netcong, NJ 07857

59. Rene Dupuis, Solar Research Institute, P.O. Box 5576, Madison, WI 53705

60. Wayne P. Ellis, Standards Consultant, 754 Bob Bea Lane, Harlesville, PA 19438

61. Engineering and Housing Support Center, Attn: CEHSC-FB-S, Ft. Belvoir, VA 22060-5516

62. Floyd England, P. O. Box 4578, Waco, TX 76715

63. T. A. Farkas, NAHB, 15th and M Streets, NW, Washington, DC 20005

64. Mark Feirer, Fine Homebuilding, 63 South Main Street, Newton, CT 06470

65. R. P. Fesler, Freedenberg Spunweb Company, Durham, NC 27704

66. Mike Foisy, Innovative Energy, 3319 Fizgerald Road, Suite 10, Rancho Cordova, CA 95742

67. T. W. Freeman, Dow Chemical Company, 3825 Columbus Road, SE, Granville, OH 43023

68. Smith A. Funk, Roofing Products Division, Celotex Corporation, P.O. Box 31602, Tampa, FL 33631-3062

69. Phil Gibson, 102 S. Superior Street, Angula, IN 46703

70. Richard J. Gillenwater, Carlisle SynTec Sytstems, P.O. Box 7000, Carlisle, PA 17013

71. William P. Goss, Mechanical Engineering Department, University of Massachusetts, Amherst, MA 01003

72. Francis A. Govan, ZBA, Inc., 23 E. Seventh Street, Cincinnati, OH 45202

73. Joseph R. Hagan, Jim Walter Research Corporation, 10301 Ninth Street, North, St. Petersburg, FL 33716

74. D. B. Hales, Moisture Systems, Inc., 1233 W. Loop South, Houston, TX 77027

75. Jeff Harris, Northwest Power Planning Council, 851 SW Sixth Avenue, Suite 1100, Portland, OR 97208

76. Tom Harris, BASF Canada Inc., 345 Carlinguire Drive, Rexdale, Ontario, N9W 6N9 Canada

77. S. Raiz Hasan, ITW Buildex, 1249 W. Bryn Mawr, Itasca, IL 60143

78. Ron Haynes, SOUTHNAVFACENGCOM, 2155 Eagle Drive, Charleston, SC 29411

79. Bion D. Howard, NAHB National Research Center, 400 Prince George's Blvd., Upper Marlboro, MD 20772-8731

80. K. C. Howerton, Federal Trade Commission, S-4631, Sixth and Pennsylvania Avenue, NW, Washington, DC 20580

81. Brian L. Huson, Hull and Company, 5 Oak Street, Box 4250, Greenwich, CT 06830

82. Bowen Hyma, Energy Saver Imports, Inc., P.O. Box 347, Broomfield, CO 80238

83. John E. Jenssen, 4840 Gaywood Drive, Minnetonka, MN 55345

84. James M. Joyce, Huntsman Chemical Corporation, 5100 Banbridge Blvd., Chesapeake, VA 23320

85. P. Joyner, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303

86. Kenneth Labs, Progressive Architecture, P.O. Box 1361, Stamford, CT 06904

87. Faith H. Klareich, CSR, Incorporated, Suite 300, 4300 King Street, Alexandria, VA 22302

88. P. G. Klemens, Department of Physics, University of Connecticut, Storrs, CT 06269-3046

89. J. L. Lach, Manville Corporation, 1625 K Street, NW, Washington, DC 20006

90. Robert A. LaCosse, 207 Withorn Lane, Mt. Prospect, IL 60056

91. Gene Leger, Leger Designs, 256 Middle Branch Road, New Boston, NH 03070

92. Fran W. Lichtenberg, BPI - Polyurethane Division, 355 Lexington Avenue, New York, NY 10017

93. T. S. Lundy, Center for Manufacturing Research and Technology Utilization, P.O. Box 5077, Cookeville, TN 38505

94. James E. Magowan, Roof Industry Consultants, Inc., 7080 Donlon Way, Suite 104, Dublin, CA 94568

95. William F. Martin, Roof Design Works, Inc., 1111 Northshore Drive, Knoxville, TN 37919

96. Robert F. Martin, Roof Maintenance Systems, P.O. Box 67, Farmingdale, NJ 02727

97. Kenneth D. Mentzer, MIMA 1420 King Street, Alexandria, VA 22314

98. Merle McBride, OCF, 2790 Columbus Road, Route 16, Granville, OH 43023-1300

99. John McCorkle, 6720 S. Steels Street, Littleton, CO 80122

100. Hugh McDermott, RCG/Hagler, Bailly, Inc., 370 L'Enfant Promenade, SW, Washington, DC 20024-2518

101. Duvon McGuire, Regal Industries, Route 1, Box 46, Crothersville, IN 47229

102. R. Gerry Miller, Jim Walter Research Corporation, 60301 Ninth Street, North, St. Petersburg, FL 33716

103. Lamont Millspaugh, Reflectix, Inc., P.O. Box 108, Markleville, IN 46056

104. D. E. Morrison, Michigan State University, 201 Berkey Hall, E. Lansing, MI 48824-11111

105. Ned Nisson, Energy Design Associates, P.O. Box 1709, Ansonia Station, New York, NY 10023

106. Richard E. Norris, 1102 G. San Pablo Avenue, Albany, CA 94706

107. David G. Ober, Manville Sales Corporation, P.O. Box 5108, Denver, CO 80217

108. T. J. Ohlemiller, Center for Fire Research, National Bureau of Standards, Gaithersburg, MD 20899

109. Robert E. Oliver, U.S. Department of Energy, 100 Independence Avenue, SW, Washington, DC 20585

110. R. L. Perrine, Engineering and Applied Sciences, University of California, Los Angeles, CA 90024

111. Steve Petersen, National Institute of Standards and Technology, Bldg. 101, Gaithersburg, MD 20899

112. Robert W. Phillips, Jr., Roof Consultants Institute, 7424 Chapel Hill Road, Raleigh, NC 27607

113. D. C. Portfolio, Tremco, Inc., 10701 Shaker Blvd., Cleveland, OH 44104

114. Frank Powell, 11218 Cattail Lane, Jacksonville, FL 32223

115. Nancy S. Reece, Solar Energy Research Institute, 1617 Cole Blvd., Golden, CO 80401

116. Harold J. Roberts, Jr., 13524 Welch Road, Dallas, TX 7522-5291

117. David L. Roodvoets, Dow Chemical, P.O. Box 575, Granville, OH 43023

118. Walt Rossiter, National Institute of Standards and Technology, BR/B348, Gaithersburg, MD 20899

119. Mike Russo, RSI Magazine, 7500 Old Oak Boulevard, Cleveland, OH 44130

120. J. Patrick Rynd, V.C. Industries, 137 E. Avenue, Box 423, Tallmadge, OH 44275

121. William W. Seaton, ASHRAE, Inc., 1791 Tullie Avenue, Atlanta, GA 30329

122. Stephen Selkowitz, Lawrence Berkeley Laboratory, Windows and Daylighting Group, 90-3111, Berkeley, CA 94720

123. E. L. Schaffer, U.S. Forest Products Laboratory, 1 Gifford Pinchot Drive, Madison, WI 53705

124-133. M. P. Scofield, Department of Energy, CE-131, FORSTL, 1000 Independence Avenue, Washington, DC 20585

134. M. Sherman, Jim Walter Reserach Corporation, 10301 Ninth Street, North, St. Petersburg, GL 33716

135. Bob Shern, Owens-Corning Fiberglas, 1 Levis Square/Fiberglas Tower-23, Toledo, OH 43659

136. C. J. Shirtliffe, IRC/NRCC, Bldv. M-24, Ottawa, ON K1A0R6 Canada

137. Albert Seinner, Roofing Service Association, Inc., 1111 Northshore Drive, Knoxville, TN 37919

138. George H. Sievert, Society of the Plastics Industry, 1275 K Street, NW, Washington, DC 20005

139. David R. Smith, National Institute of Standards and Technology, Boulder, CO 80303-3328

140. G. A. Smith, Factory Mutual Research Group, P.O. Box 9102, Norwood, MA 02062

141. Tom Smith, MRCA, One O'Hare Centre, Bosemont, IL 60018

142. Russell K. Snyder, 6288 Montrose Road, Rockville, MD 20852

143. Raymond L. Sterling, Underground Space Center, University of Minnesota, 500 Pillsbury Drive, SE, Minneapolis, MN 55455

144. Eric Stern, BPCO, Inc., 0244 St. Patrick, LaSalle, Quebec, H8R-1R8, Canada

145. Edward R. Story, Insul-Tray, Inc., P.O. Box 3111, Redmond, WA 98073-3111

146. Phillip Stumpf, Major Industries, 49 Frederick Place, Morristown, NJ 07960

147. R. Sullivan, National Center for Appropriate Technology, Box 3838, Butte, MT 59702

148. Stephen S. Szoke, National Concrete Masonry Association, P.O. Box 781, Herndon, VA 22070

149. Daniel Tempas, P.O. Box 515, Granville, OH 43023

150. Shirley Tewes, Small Homes Council, 1E St. Mary's Road, Champaign, IL 61820

151. Timothy Tong, Department of Mechanical and Aerospace Engineering, Arizona State University, Tempe, AZ 85287

152. George Tsongas, Mechanical Engienering Department, Portland State University, Portland, OR 97207

153. Adrian Tuluca, Steven Winter Associates, Inc., 50 Washington Street, Norwalk, CT 06854

154. R. P. Tye, Holometrix Inc., 99 Erie Street, Cambridge, MA 02139

155. Carl R. Vander Linden, Vander Linden and Associates, 5 Brassie Way, Littleton, CO 80123

156. Martha G. VanGeem, Construction Technology Lab, Inc., 5420 Old Orchard Road, Skokie, IL 60077

157. Robert B. Walters, Manville Reserach and Development, P.O. Box 5108, Denver, CO 80217

158. Carl Wangman, PIMA, 104 Wilmot Road, Suite 201, Deerfield, IL 60015-5195

159. J. R. Warner, ACEC Research and Management Foundation, 1015 15th Street, NW, Washington, DC 20005

160. Barbara A. Wejtechko, VC Industries, 137 East Avenue, Box 423, Tallmadge, OH 44278

161. J. R. Wells, Owens-Corning Fiberglas, Bldg. 20-1, 2790 Columbus Road, Granville, OH 43023-1200

162. Bruce Wilcox, 454 Santa Clara, Oakland, CA 94610

163. M. Williams, Department of Economics, Northern Illinois University, DeKalb, IL 60115

164. Brian J. Witelan, Sapnatic, Inc., 100 Dan Road, Canton, MA 02021

165. William J. Woodring, GAF Building Materials Corporation, 1361 Alps Road, Wayne, NY 07470

166. D. C. Wysocki, Mobay Corporation, Mobay Road, Pittsburgh, PA 15205-9741

167. David W. Yarbrough, Tennessee Technological University, Box 5013, Cookeville, TN 48505

168. R. Zarr, National Institute of Standards and Technology, Building 226, Room B-320, Gathersburg, MD 20899

169. U.S. Department of Energy, Assistant Manager for Energy Research and Development, Oak Ridge Operations Office, P.O. Box 2001, Oak Ridge, TN 37831-8600

170-179. U.S. Department of Energy, Office of Scientific and Technical Information, Office of Information Services, P.O. Box 62, Oak Ridge, TN 37831

For distribution by microfiche as shown in DOE/OSTI-4500, Distribution Category UC-365 (Energy Conservation)