**METAL BUILDINGS STUDY:
PERFORMANCE OF MATERIALS AND FIELD VALIDATION**

FINAL REPORT

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ABSTRACT

A 5000 square-foot metal building located at Brookhaven National Laboratory has been monitored over a winter season. Energy flows through wall sections were monitored using portable calorimeters. Air infiltration was measured using perfluorocarbon tracers, and the associated heat losses were calculated. Slab losses were assessed through a comparison of measured temperature gradients with results obtained through the use of heat-flow meters. The effect of thermal bridges and compressed insulation in locations where support beams are joined to the exterior skin was found to increase heat losses significantly. A retrofit strategy including spray insulation of beams is projected to save 30% on heating energy.

1. INTRODUCTION

1.1 Significance of the Type of Building

During the past decade an increasing number of small and large businesses and community-oriented institutions chose metal buildings for their various commercial and institutional activities. The motives for this choice ranged from the low initial cost of metal buildings to the great flexibility in design, the fast assembly and the existence of an intricate dealer/contractor network.

In addition, the manufacturing capacity for metal buildings reached a versatility that enables a customer to select among a variety of designs. Components can be added to each other, and buildings can be "tailored" to best match the demands of the user. Within a short time, the pre-engineered and pre-fabricated components are transported to the construction site and assembled in an efficient, time-saving fashion.

Because of these advantages, construction of metal buildings outpaced general nonresidential construction since 1984. In 1985, over 300 million square feet of commercial buildings with a retail value of \$ 1.5 billion were sold and assembled. Only ten years earlier the sales volume hardly reached a third of this value. It is estimated that about 30% of the newly constructed buildings - approximately 100 million square feet - are warehouses of the type that will be the focus of this report.

As outlined in an earlier report [1] there is little ambiguity about the number of 300 million square feet of metal buildings constructed annually. Estimates about the average size of the warehouses, however, vary substantially. While some surveys indicate that construction activity is highest among buildings smaller than 10,000 square feet, others point to an increasing average building area and mention a more likely value of 10,000 to 20,000 square feet.

Lacking more specific data the assumption of an average warehouse floor area of 10,000 square feet might be flawed but is not unreasonable. Out of the estimated total of 3,500 million square feet of existing metal buildings, about 1,200 million square feet are warehouses. Assuming an average size of 10,000 square feet, then the number of warehouses currently in operation ranges from 100,000 to 150,000 units. Unfortunately, there is no estimate on the number of metal buildings in the other categories such as offices, churches, and agricultural buildings because figures on average building size cannot be verified and deterioration rates are not readily available.

1.2 Materials and Energy-Related Problems in Metal Warehouses

A particular feature of metal warehouses is their low first cost and their fast, simple and efficient assembly. Unfortunately, that very efficiency and speed gives rise to certain disadvantages in maintenance and comfort.

When metal buildings are put together in the field, the initial step in the sequence of construction is the building of a support structure. Vertical columns are connected to the slab and so-called horizontal wall girts and roof purlins are attached to these columns. The rigid skeleton formed in this way is now ready for insulation and wall panels. Usually, blankets of rolled-out fiber glass insulation are tied to the eave strut (highest horizontal beam) from where they hang loosely to the floor slab. At this point, the assembly crews bring the outer wall panels to the frame, press them toward the insulation and then fasten them permanently to the girts with metal screws. This process sandwiches and compresses the insulation between the beams and the outer wall.

It has long been suspected that the combined effect of compressed insulation and metal fasteners protruding through the insulation is responsible for large heat losses. The metal fasteners act as thermal bridges between the beams of the interior support structure and the outer walls. To make things worse, the beams and walls constitute extended surfaces not unlike fins in high performance heat exchangers. The thermal bridging of the beam-fastener conduit also produces dangerous cold spots where water vapor condenses. Hence, metal fasteners are prone to increased corrosion and degradation.

Infiltration is another area of concern in metal warehouses, and is a source of substantial energy waste. The insulation in many of these buildings is covered on the interior with vinyl sheets to protect the envelope against vapor and air intrusion. Often, the vinyl sheets are not taped together along their vertical seams but are only stapled together, and in some cases not even connected at all. Thus, innumerable convenient routes for convection currents are left open and air and humidity can pass freely to and through the insulation. In fact, infrared photographs clearly demonstrate the preferred heat flow paths along the seams of these vinyl sheets.

Finally, as with other slab-on-grade construction, metal warehouses of this type suffer from substantial heat losses through the slab and slab perimeter. Since foundation walls and slabs are most often insufficiently insulated or not insulated at all, the soil surrounding the slab, acting as a heat sink, extracts large quantities of energy. As a result, a high fraction of the total energy - up to one fifth, as will be shown - escapes through the slab and slab perimeter.

1.3 Previous Conservation Efforts of Industry

Manufacturers of metal buildings have long been aware of the energy problems associated with compressed insulation and thermal bridges. However, up to the present, the exact magnitude of energy conduction via thermal bridges was not known. The present study is the first experimental attempt to shed light on the complex heat transfers, including the fin effect of beams and compressed insulation.

Industry's efforts to eliminate heat transmission through the walls were started in the mid 70's. The most efficient approach, the so-called sandwich panels, consisted of a foam core sandwiched between an exterior and interior

metal skin. Depending on the thickness of this composite wall, resistance values as high as R-25 were achieved. With the decline in oil prices, the cost of the highly efficient panels became less attractive and, consequently, consumer demand for sandwich panels diminished sharply.

Several other energy-savings measures were introduced by industrial researchers. A notable example were special insulation blocks which had to be inserted between beams and roof panels. One company (Star Manufacturing Company) advocated high-thread fasteners which increased the space between outer walls and beams and hence decreased the undesired effect of compressed insulation.

Particular systems for installing blanket insulation were developed which virtually eliminated seams, wrinkles and sags of the traditional insulation and also increased insulation values. A comparison for various insulation methods of a major metal buildings manufacturer (Butler Manufacturing Company) is reproduced in Table 1. The last column indicates that the more sophisticated "Roll Runner Insulation System" can yield up to 10% higher R-values. Figure 1 depicts calculated and tested U-values for traditional and Roll Runner insulation as a function of insulation thickness.

1.4 History and Scope of Study

The origins of the current "Performance of Materials and Field Validation" program go back to efforts undertaken during another program at Brookhaven, the "Small Buildings Field Validation" program. Starting out to verify computer simulations of residential buildings with field data, the scope of the "Small Buildings" program soon evolved to include the thermal behavior of whole integrated buildings, elucidating the interaction between equipment, envelope and occupants.

Around 1983 a sub-program dealing with commercial buildings was established. Metal buildings were its first target because of the growing importance of this type of building and its relative homogenous industry-wide construction practice.

In 1984 a literature review was started which showed that little was known about the intricacies of heat losses in metal buildings. By that time, industrial researchers had begun to experimentally determine heat losses through whole wall sections, insulation programs were developed, and the sandwich panels had been on the market for several years. But the more subtle pathways, thermal bridges, and bypasses had not been evaluated and their magnitude could not be assessed with any confidence.

Also in 1984, several meetings of subcontractors, DOE and BNL managers, resulted in a preliminary program plan, which foresaw a computerized study of the national potential for energy savings as well as the monitoring of one or several metal buildings in the field. The plan was presented to the industry and enthusiastically approved.

In 1985 Brookhaven researchers worked on the selection criteria for the test building and generous manufacturers arranged several field trips to buildings

BUTLER ROOF U-VALUES							
PANEL TYPE (Purlins 5'-0" o.c.)	INSULATION THICKNESS* (Inches)	CALCULATED (Theoretical) U-VALUE		TESTED (ACTUAL) U-VALUE			
				Traditional MBMA Insulating Method		Roll Runner Insulating Method	
		Winter 45 Mean Temp.	Summer 75 Mean Temp.	Winter 45 Mean Temp.	Summer 75 Mean Temp.	Winter 45 Mean Temp.	Summer 75 Mean Temp.
Butlerb II On Zee-Type Purlin	1-1/2"	.16	.17	.20	.22	.16	.18
	2"	.12	.13	.19	.21	.16	.18
	3"	.08	.09	.14	.15	.13	.14
	4"	.06	.07	.12	.13	.11	.12
	6" (3" x 3")	.04	.05	.09	.10	.08	.09
	7" (3" x 4")	.04	.04	N/T	N/T	.08	.09
MR-24 On Uninsulated Zee-Type Purlin	1-1/2"	.16	.17	.17	.18	—	—
	2"	.12	.13	.14	.16	—	—
	3"	.08	.09	.11	.12	—	—
	4"	.06	.07	.09	.10	—	—
MR-24 On Insulated Zee-Type Purlin	1-1/2"	.16	.17	.15	.16	.12	.12
	2"	.12	.13	.12	.13	.11	.12
	3"	.08	.09	.09	.10	.08	.09
	4"	.06	.07	.08	.09	.07	.08
	6" (3" x 3")	.04	.05	N/T	N/T	.05	.06
MR-24 On Insulated Truss-Type Purlin	1-1/2"	.16	.17	.15	.15	.13	.13
	2"	.12	.13	.12	.13	.12	.12
	3"	.08	.09	.10	.11	.09	.10
	4"	.06	.07	.08	.09	.07	.08
	6" (3" x 3")	.04	.05	.07	.08	.06	.07
	7" (3" x 4")	.04	.04	N/T	N/T	.05	.06
F-103 Zee-Type Purlin	1"	.10	.10	—	.10	—	—
	2-1/2"	.04	.04	—	.05	—	—
CMR-24 On Zee-Type Purlin	3/4"	—	—	.10	.11	—	—
	1-3/4"	—	—	.05	.06	—	—
CMR-24 On Truss-Type Purlin	3/4"	—	—	.10	.11	—	—
	1-3/4"	—	—	.05	.06	—	—

Table 1: Calculated and Tested U-Values
for Roof Components

"U" VALUE

INSULATION THICKNESS

Guarded Hot Box test results using 0.6 lbs/cu ft density insulation with a 3 mil vinyl facing, at a mean temperature of 45°F. Tests conducted with standard roof panels on uninsulated Z-purlins unless otherwise noted. Thicknesses are nominal due to manufacturing variances.

Figure 1. Calculated and Tested U-Values versus Insulation Thickness

in various north eastern locations. In 1986 a nation-wide data base and a computer simulation of an "average building" were concluded. Finally, at the beginning of 1987 the current "Materials Properties and Field Validation" program was formally created and the monitoring of a metal building at Brookhaven Laboratory started in January, 1988.

2. EXPERIMENTAL SETUP

2.1 The Brookhaven Metal Building

2.1.1 General Description

The metal test building is situated at Brookhaven National Laboratory, Long Island, New York. At 41 degrees latitude and at an elevation close to sea level, the typical eastern Atlantic sea climate dominates the weather. Characteristically, the foggy skies, wetness and clouds of wintertime are extended rather late into spring. Summers and falls are hot and humid. The weather experienced in the middle of Long Island is somewhat cooler than that of nearby New York. The annual average degree-days reported by the laboratory amount to 3400 C-days (6200 F-days).

Figure 2 is a photograph of the Brookhaven Metal Building which was purchased from Pascoe Steel Corporation in 1980. The structure roughly 5000 square feet, prefabricated, ready-cut, with a rigid frame and metal panels was assembled on a concrete slab in late 1980 and has since served as a storage facility. It is representative of the thousands of inexpensive warehouses, offices and agricultural buildings that have sprung up recently in such vast numbers throughout the country.

The test building's two 120 feet east-west facades are each supported by seven interior vertical steel columns both on the north and south side. Attached to these columns are four horizontal girts, namely (Figure 3): the slab I-beam, the two center Z-shaped girts, and the eave strut. The two center girts separate the walls into three equal sections of 4.5 feet in height. The interior frame of the roof is composed of two center purlins and two closely spaced gable purlins, all extended along the 120 feet length of the roof.

One of the 40 feet-long side walls has a large, 12 x 14 feet sliding door. In addition to this large shipping door the building is equipped with three hinged personnel doors and five aluminum sash windows with cast acrylic panes. Adjustable 4 x 4 feet louvers are installed in the upper part of the east and west walls to enhance natural ventilation.

The envelope consists of 26 gauge steel panels, 3 feet wide, pre-cut to a length of 14 feet. Thus, the wall panels exactly match the 14 feet height of the vertical columns. Similarly, the roof panels with their pre-cut length of 20 feet can be readily installed on the roof frame. The ribs in the panels convey structural strength and the baked-on finish provides resistance against corrosion. Walls and roofs are insulated with three inches of fiber glass insulation. The vinyl facing material forms a "quasi" air and vapor barrier portraying all the defects described earlier.

2.1.2 Heating System

A tremendous benefit for the project was the fact that the test building was equipped with electrical heaters. Thus, energy consumption could be recorded

Figure 2. Photograph of the Brookhaven
Metal Building

Figure 3. The Interior Support Structure

directly and accurately without employing efficiency conversions. The six electrical heating units, rated at a performance of 15 kW each, were regulated by a simple thermostat. The electrical energy consumed was locally stored and integrated in low-profile recorders, from which the data were transmitted in 15-minute intervals via autodial modem to a main frame computer at Brookhaven's plant engineering. Here, the data were stored on a hard disk as hourly entries in daily files. Printouts were available on demand.

2.2 Data Acquisition System

2.2.1 General

Owing to special circumstances two data acquisition systems operated throughout the test period. The first system was received as a loan from the National Bureau of Standards (NBS) and it monitored the calorimeters (see section 2.3.1). The second system, owned by Brookhaven had been used previously to monitor the "Danish House" [2] and it recorded signals from the thermocouple and heat flux meter.

Due to time constraints, it was not possible to integrate the two systems and the data from each were stored separately in each of the two computers. After a week of data-gathering, the collected information was transmitted to an IBM-AT with the help of special software packages (Uniform and Crosstalk). Further processing and analysis was then accomplished with Lotus 1-2-3 on the IBM-AT.

2.2.2 The BNL Data Acquisition System

Figure 4 shows the various parts of the Brookhaven data system (BNL system). The Acurex data logger scanned the 18 thermocouple and 12 heat flux meter sensors in intervals of 15 seconds and displayed the data instantaneously on a Lear CRT terminal. The readings were averaged and stored over periods of an hour.

A data acquisition program residing in the 64 K memory a small Northstar Horizon computer captured the data from the datalogger and stored them on disk. After about a week, the disk was full and was replaced. The data acquisition program further prompted hourly printouts on the Teleprinter Model 43. An example of such a printout is presented in Figure 5, with an explanation of the channel numbers in Figure 5a. The printouts were useful in case of power surges which occasionally interrupted the data storage process.

2.2.3 The NBS Data Acquisition System

Figure 6 shows the main components of the NBS system. Two pulse initiating Wh-meters monitored the electrical energy consumption of two calorimeters. The Wh-meter counts signals were scanned every minute by a data logger, then displayed on the terminal, and hourly averages were stored on floppy disks in the Cromenco computer. In addition to the calorimeters the NBS system also incorporated four heat flux meters which had been assembled by NBS staff.

Figure 4. The Brookhaven Data Acquisition System

```

*** STATUS: Drive = 1 Days left on disk = 1
11:05:05 APR10, 1987
060 14.2911 DEGC 061 1.3201 DEGC 062 18.3542 DEGC 063 20.2911 DEGC 064 21.3847 DEGC
065 22.2853 DEGC 066 22.7853 DEGC 067 23.0194 DEGC 068 23.2911 DEGC 069 24.331 DEGC
070 24.2828 DEGC 071 24.2 DEGC 072 24.7036 DEGC 073 24.4 DEGC 074 31.2994 DEGC
075 19.2207 DEGC 076 8.1817 DEGC 077 4.0986 DEGC 078 1.30725 DEGC 079 1.6205 DEGC
080 0.000 DEGC 081 1.000 DEGC 082 0.000 DEGC 083 0.440 DEGC 084 9.1003 DEGC
085 7.5 DEGC 086 -0.0017 DEGC 087 -3.1486 DEGC 088 0.64245 DEGC 089 0.39362 DEGC

```

```

*** STATUS: Drive = 1 Days left on disk = 1
12:05:05 APR10, 1987
060 16.3192 DEGC 061 12.4255 DEGC 062 18.5361 DEGC 063 20.694 DEGC 064 21.7065 DEGC
065 22.3901 DEGC 066 23.2571 DEGC 067 21.0321 DEGC 068 20.3162 DEGC 069 20.4830 DEGC
070 22.0366 DEGC 071 29.8076 DEGC 072 24.0991 DEGC 073 30.9899 DEGC 074 40.1326 DEGC
075 29.714 DEGC 076 8.3818 DEGC 077 8.0995 DEGC 078 0.05911 DEGC 079 1.04663 DEGC
080 1.04739 DEGC 081 0.656 DEGC 082 0.942 DEGC 083 0.15767 DEGC 084 9.37526 DEGC
085 4.83734 DEGC 086 -0.25505 DEGC 087 -0.96842 DEGC 088 0.24072 DEGC 089 5.41801 DEGC

```

```

*** STATUS: Drive = 2 Days left on disk = 1
13:15:05 APR10, 1987
060 12.2246 DEGC 061 1.5803 DEGC 062 18.1127 DEGC 063 21.0587 DEGC 064 22.0803 DEGC
065 22.0902 DEGC 066 23.6664 DEGC 067 21.4537 DEGC 068 21.6026 DEGC 069 21.1244 DEGC
070 22.2517 DEGC 071 31.2650 DEGC 072 24.4178 DEGC 073 33.6477 DEGC 074 44.4463 DEGC
075 21.4860 DEGC 076 8.6444 DEGC 077 8.11263 DEGC 078 0.03635 DEGC 079 0.95236 DEGC
080 0.9448 DEGC 081 0.7702 DEGC 082 0.88770 DEGC 083 0.14119 DEGC 084 9.33464 DEGC
085 5.19434 DEGC 086 -10.8824 DEGC 087 -0.10365 DEGC 088 0.17763 DEGC 089 5.84940 DEGC

```

```

*** STATUS: Drive = 2 Days left on disk = 1
14:15:05 APR10, 1987
060 18.1652 DEGC 061 17.6314 DEGC 062 18.8805 DEGC 063 21.5681 DEGC 064 22.5664 DEGC
065 23.0754 DEGC 066 24.511 DEGC 067 21.9517 DEGC 068 22.8258 DEGC 069 22.1105 DEGC
070 23.3653 DEGC 071 31.8675 DEGC 072 29.3723 DEGC 073 32.5 DEGC 074 41.7787 DEGC
075 22.8538 DEGC 076 0.0019 DEGC 077 8.12148 DEGC 078 -0.15906 DEGC 079 0.57534 DEGC
080 0.54701 DEGC 081 0.47319 DEGC 082 0.06436 DEGC 083 -0.00000 DEGC 084 4.40151 DEGC
085 0.4554 DEGC 086 -9.05020 DEGC 087 -4.43500 DEGC 088 -0.17344 DEGC 089 0.05313 DEGC

```

Figure 5. Copy of Hourly Printout of BNL Data Acquisition System

CENTER OF BUILDING THERMOCOUPLES

- 60 Outdoors
- 61 Slab
- 62 1 inch above slab, center of building
- 63 5 ft "
- 64 10 ft "
- 65 15 ft "
- 66 20 ft "

NORTH WALL THERMOCOUPLES

- 67 Wall, north, immediately underneath vapor barrier, between vinyl sheet and insulation.
- 68 Wall, north, between insulation and actual wall panel.
- 69 Wall, north, at panel/girt connection
- 75 Wall, north, directly at panel

ROOF THERMOCOUPLES

- 70 Roof, north, immediately underneath vapor barrier, between vinyl sheet and insulation.
- 71 Roof, north, between insulation and actual wall panel.
- 72 Roof, north, at panel/girt connection

SOUTH WALL THERMOCOUPLES

- 73 Wall, south, between insulation and wall panel
- 74 Wall, south, direct at panel

GROUND THERMOCOUPLES

- 76 Ground, 1 ft
- 77 Ground, 2 ft

HEAT FLOW METERS ON NORTH WALL

- 78 Wall, north, center between beams
- 88 Wall, north, 2 inches over beam

HEAT FLOW METERS ON GIRTS

- 79 Girt, north, vertical section next to fastener
- 80 Girt, north, vertical section next to fastener
- 81 Girt, north, vertical section between fasteners
- 82 Girt, north, horizontal section

HEAT FLOW METER ON SOUTH WALL

- 86 Girt, south, vertical section between fasteners
- 87 Wall, south, center between beams

HEAT FLOW METERS ON SLAB

- 84 Slab, 6 inches from perimeter
- 85 Slab, center
- 89 Slab, 10 feet from perimeter

HEAT FLOW METERS IN CALORIMETER

- 83 in Wall calorimeter

Figure 5a: List of Channels in Figure 5

Figure 6. The NBS Data Acquisition System

2.2.4 Weather Data

The Brookhaven Weather Station, located about 2 miles south of the Metal building, collected hourly solar radiation data, the daily and monthly degree-days and relative humidities. Table 2 shows the monthly degree-days for the winter of 1987 at the Laboratory.

2.3 Sensors

2.3.1 Calorimeters

Inherently extremely simple devices, the NBS calorimeters nevertheless exemplify several basic tenets of heat transfer. In essence, a calorimeter is an ordinary box where one side has been left open. This side can be attached to one of the surfaces of the envelope, e.g. walls, roofs or windows. The box of the NBS calorimeter is made of plywood and measures 4 x 6.5 x 1 feet. Electrical wire heating elements are suspended close to the back wall of the calorimeter and thermopiles are embedded on the inside and outside of the box (Figure 6). Once the calorimeter is attached to a building surface, an airtight space is created between the envelope and the calorimeter walls. That space is maintained at a temperature equal to the temperature of the building's interior with the following control strategy.

Whenever the temperature in the calorimeter space sinks below the room temperature a controller relay is activated by the thermopile, electrical energy flows to the heating elements and is measured by the pulse initiating kWh meters. As soon as equilibrium between the temperature of the room and calorimeter is reached again, the thermopile opens the relay and electricity is shut off. The energy introduced into the calorimeter's space is equivalent to the heat loss through the building envelope, because the zero temperature differential to the room prevents heat flow in that direction. Consequently, heat can only escape through the building wall but not back into the building. This unidirectional heat flow divided by the area of the calorimeter area and by the time elapsed establishes the heat loss per unit time and unit area.

In the metal building, one of the two calorimeters was permanently placed over the horizontal girt on the north wall to record and quantify the heat losses through the girt, the metal fasteners and the compressed insulation (see Figure 7). The other calorimeter was placed between the beams and measured the heat loss of an ordinary wall section with insulation undisturbed and at nominal thickness.

As outlined in the general description the structural elements of the metal building's wall are the slab L-beam, two horizontal Z-shaped girts and a top eave strut. Figure 7 graphically depicts how the two Z-girts separate the walls into three sections of about 4.5 feet height. It was assumed that the lower section close to the slab would suffer higher heat losses due to its proximity to the ground. To prove this assumption, the wall calorimeter was placed in the lowest wall section during the first part of the monitoring period and then was moved to the middle section for the last two weeks. It

TOTAL HEATING DEGREE DAYS

<u>MONTH</u>	<u>1981</u>	<u>1982</u>	<u>1983</u>	<u>1984</u>	<u>1985</u>	<u>1986</u>	<u>1987</u>
Jan.	1409	1323	1024	1247	1258	1084	1108
Feb.	906	950	919	809	945	1031	1000
Mar.	897	902	743	983	760	808	780
Apr.	485	601	521	536	457	528	468
May	235	206	334	309	268	229	269
June	28	102	48	62	94	76	34
July	0	13	2	7	5	16	6
Aug.	10	26	14	3	14	44	43
Sept.	101	147	124	185	141	147	103
Oct.	483	410	385	301	374	395	495
Nov.	638	562	602	664	551	710	628
Dec.	994	799	1038	803	1074	918	
Annual	6186	6041	5754	5909	5941	5986	

TOTAL COOLING DEGREE DAYS

<u>MONTH</u>	<u>1981</u>	<u>1982</u>	<u>1983</u>	<u>1984</u>	<u>1985</u>	<u>1986</u>	<u>1987</u>
Jan.	0	0	0	0	0	0	0
Feb.	0	0	0	0	0	0	0
Mar.	0	0	0	0	0	0	0
Apr.	0	0	3	0	7	0	0
May	24	10	4	2	25	49	49
June	120	38	101	144	36	78	135
July	293	231	261	176	204	211	259
Aug.	187	126	217	213	147	134	133
Sept.	39	47	141	39	98	34	39
Oct.	0	8	19	4	4	17	0
Nov.	0	3	0	0	0	0	0
Dec.	0	0	0	0	0	0	
Annual	663	463	746	578	521	523	

Table 2: Monthly Degree-Days at
Brookhaven National Lab

Figure 7. Location of Heat Flux Meters

was hoped to obtain a quantitative estimate of the relative magnitudes of the heat losses occurring in the central and lower wall sections.

2.3.2 Heat Flow Meters

Figure 7 shows the location of the heat flow meters in the metal building and Table 3 lists them in numerical order.

Heat flux meters were attached to the north wall, the south wall, the floor slab and the girts. Calorimeter readings can be considered quite accurate because of their size and "smart" technique of data collection. In contrast, heat flow meter accuracy is severely impeded by heat flux distortions and varying contact resistances. Hence, heat flux sensors always must be calibrated against a suitable standard.

For our procedures this calibration was effected by installing some of the heat flux meters within the calorimeters. A comparison of the outputs of the calorimeter and heat flow meter enabled the evaluation of calibration constants, which then were input into the conversion mechanism of the Acurex datalogger. Toward the end of the monitoring period one of the two calorimeters was placed on the slab to calibrate the slab heat flow meters.

2.3.3 Thermocouples

Figure 8 depicts the location of the thermocouples; Table 4 lists these sensors.

Thermocouples 1 through 6 indicated any possible stratification in the center of the building. Thermocouples 7 through 13 provided information on the temperature profile through the north wall. Together with the calorimeter outputs these temperatures allowed calculations of heat flow rates per degree temperature difference between the indoors and outdoors. The reciprocal value of these rates, the R-values, then could be checked against the manufacturer's specifications.

The "calorimeter thermocouples" were installed within the calorimeter spaces to provide an additional check on the temperature equilibrium between calorimeter and building interior. Occasional adjustments were made to compensate for a slight drift in the instruments. Two thermocouples were inserted into the beam calorimeter (T20 and T21, Figure 8) to examine possible stratification induced by the Z-girt.

HEAT-FLOW METERS

HEAT FLOW METERS ON WALL

1	Wall, north, center between beams
2	Wall, north, 2 inches over beam

HEAT FLOW METERS ON GIRTS

3	Girt, north, horizontal section
4	Girt, north, vertical section next to fastener
5	Girt, north, vertical section next to fastener
6	Girt, north, vertical section between fasteners

HEAT FLOW METER ON SOUTH WALL

7	Wall, south, center between beams
8	Girt, south, vertical section between fasteners

HEAT FLOW METERS ON SLAB

9	Slab, 6 inches from perimeter
10	Slab, 10 feet from perimeter
11	Slab, center

HEAT FLOW METERS IN CALORIMETER

12	in Wall calorimeter
13	in Beam calorimeter

Table 3: List of the Positions of the Heat-Flow Meters

Figure 8. Location of Thermocouples

THERMOCOUPLES

THERMOCOUPLES IN BUILDING CENTER

- 0 Outdoors
- 1 Slab
- 2 1 inch above slab, center of building
- 3 5 ft "
- 4 10 ft "
- 5 15 ft "
- 6 20 ft "

WALL THERMOCOUPLES

- 7 Wall, north, on vapor barrier
- 8 Wall, north, immediately underneath vapor barrier, between vinyl sheet and insulation.
- 9 Wall, north, between insulation and actual wall panel.
- 10 Wall, north, directly at panel
- 11 Wall, north, at panel/girt connection (area of compressed insulation and metal fasteners).
- 12 Wall, north, on outside wall panel (at height of beam calorimeter)
- 13 Wall, north, on outside wall panel (at height of wall calorimeter)
- 14 Wall, south, between insulation and wall panel
- 15 Wall, south, direct at panel

ROOF THERMOCOUPLES

- 16 Roof, north, immediately underneath vapor barrier, between vinyl sheet and insulation.
- 17 Roof, north, between insulation and actual wall panel.
- 18 Roof, north, at panel/girt connection

CALORIMETER THERMOCOUPLES

- 19 Wall calorimeter
- 20 Beam calorimeter, upper half
- 21 Beam calorimeter, lower half
- 22 Beam calorimeter, on girt

GROUND THERMOCOUPLES

- 23 Ground, 1 ft
- 24 Ground, 2 ft

Table 4: List of Thermocouples

3. THEORETICAL CALCULATIONS

3.1 Heat Losses Using the TIMA Heat Transmission Coefficient

The ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.) Handbook of Fundamentals [3] cautions that in the case of metal-skinned structures the calculations are subject to special problems not covered by the Handbook. The ASHRAE Standard 90A-80 distinguishes between type A and B buildings, but the U-values are based on degree days and no mention is made of metal buildings. When accurate estimates are required, the recommendation always has been to test the proposed building section in a guarded hot box - a time-consuming and costly procedure.

TIMA, the Thermal Insulation Manufacturers Association, in 1977 completed an extensive series of large-scale calibrated hot-box tests using nine by fourteen foot building sections to match as nearly as possible the actual field construction. A empirical formula for estimating heat losses in metal buildings was derived. The equation takes into account purlin or girt spacing, number of fasteners, and the thickness of the glass fiber insulation. TIMA claims that the formula is accurate within 3%.

Before the TIMA formula became available, heat losses in metal buildings were estimated to be 10 to 15% greater than the calculated values [4]. The tests, however, showed that the error in calculated U value increased as the insulation thickness increased. While the error was between 10% and 15% for 1.5 inches of insulation thickness, it rose to about 40% for 4 inches of insulation.

The reason for the divergence is the fact that the heat losses through fasteners and the compressed insulation at purlins is essentially constant. Conversely, in areas where the insulation is not compressed—between the purlins—heat losses decrease with increasing thickness of insulation. Hence, the relatively high fasteners/purlin heat loss constitutes a higher percentage of the reduced heat loss at greater thickness of insulation.

Early in the test program, it became evident that purlin size and skin configuration had little effect on the thermal performance of glass fiber blanket insulation [4]. The same was not true of fastener population and purlin spacing. With this knowledge and the remaining data, the following correlation was developed:

$$U = 0.012 + [0.255/(0.31 R_{1,o} + t)] \cdot (1 - N/L) + (N/L)(1.98 + 0.065n) \quad (1)$$

where,

- U = U-value, Btu/h-F-ft²
- R_{1,o} = Sum of inside and outside air film R-values, h-F-ft²/Btu
- t = Insulation thickness, inches
- L = Length of building section perpendicular to purlins or girts, ft
- N = Number of purlins or girts encompassed by the dimension L
- n = Fastener population, number per ft.

For the Brookhaven metal building these values are:

$R_o = .17$ for winter design conditions with outside 15 mph wind
 $R_i = .61$ for heat flow upward
 $t = 3$ inches
 $L = 14$ ft
 $N = 3$
 $n = 1$ per foot.

With these values Equ. 1 yields:

$U = 0.1302 \text{ Btu/hr-ft}^2\text{-F}$
 $R = 7.68 \text{ h-ft}^2\text{-F/Btu.}$

Without the TIMA formula and using a conductivity for fiber glass of $k = .02 \text{ Btu/h-ft-F}$, the corresponding U- and R-values for 3 inches would have been $U = 0.08$ and $R = 12.5$, respectively. Thus, the TIMA R-value, $R = 7.68$ is about 40% less than the ASHRAE R-value ($R = 12.5$), highlighting the influence of fastener and girt thermal bridging. In the next chapter, these theoretical calculations will be compared to test findings in the BNL metal building. It will be shown that the predictions are excellent.

3.2 Infiltration Losses.

For infiltration:

$$Q = ACH \cdot V \cdot \rho \cdot c_p \cdot (T_i - T_o) \cdot t \quad (2)$$

where,

ACH = Air changes per hour
 V = Building volume, ft^3
 ρ = Density, lb/ft^3
 c_p = Specific heat of air, Btu/lb-F
 T_i = Indoor temperature
 T_o = Outdoor temperature
 t = Time.

With a building volume of $83,210 \text{ ft}^3$, the values of $\rho = 0.075$, and $c_p = 0.24$ and with the proper conversion factor of 3413 Btu/kWh , Equation 2 can be rewritten as:

$$Q = (10.63) \cdot (ACH) \cdot (F.\text{days}) \quad (2a)$$

where Q is expressed in kWh. Because air changes were determined in the field experiments with a tracer gas (Chapter 3) and degree-days were known from the BNL weather station, all the variables in Equation 2a are given. Since the total heat losses are also known by the kWh consumption of the electrical heaters, Equation 2a affords a simple and direct evaluation of that fraction of the energy balance which is due to infiltration.

3.3 Slab Losses

Slab losses can be approximated by the ASHRAE formula:

$$Q = F2 \cdot P \cdot (T_i - T_o) \cdot t \quad (3)$$

where,

F2 = Heat loss coefficient, Btu/h-F-ft of perimeter
P = Perimeter or exposed edge, ft
T_i = Indoor temperature
T_o = Outdoor temperature
t = Time.

The ASHRAE Handbook presents an F2-value for uninsulated metal stud walls of F2 = 1.2 Btu/h-F-ft. With the given perimeter of the BNL test building (320 ft) and the proper conversion factor (3413 Btu/kWh) Equation 3 becomes:

$$Q = (2.7) \cdot (F \cdot \text{days}) \quad (3a)$$

where Q is expressed in kWh. Equation 3a again enables a fast determination of the slab losses as percentage of the total energy losses during one month. As will be shown in Chapter 3, the ASHRAE formula slightly underpredicts the slab losses.

3.4 DOE-2 Model of an "Average" Metal Building

3.4.1 The DOE-2 Model

One of the foremost goals of the present study was to acquire information on the energy requirements of metal warehouses, on a nation-wide basis. The tool to gain these insights was the DOE-2 computer program, with input from an extensive survey. Because of the special problems associated with metal-skinned buildings, there were questions about the applicability of the general DOE-2 computer code to the metal warehouse building type. Hence, one of the priorities of the field testing was to verify the computer algorithm.

The version of DOE-2 used for the modeling was PC-DOE, an adaption for micro-computers of the original DOE-2.1B program. PC-DOE calculated the energy consumption of a building by simulating its hour-by-hour performance for each of the 8760 hours of the year. One-dimensional heat flows were assumed but the effect of thermal bridges and bypasses was not accounted for to reduce the complexity, running time and cost of the program. With these simplifications, certain inaccuracies were introduced which might be negligible for ordinary building types, but could be more consequential for metal-skinned buildings.

In general, DOE-2 models buildings in accordance to their shape, the thermal properties of the building materials, the size and position of the walls, floors, roofs, windows and doors. Other parameters entering the code are the transient effects of occupancy, lighting schedules, operation of equipment as well as temperature and humidity controls. DOE-2 is organized into several interactive sub-programs, namely LOADS, SYSTEM, PLANT, ECONOMICS and WEATHER.

The LOADS simulator is responsible for the various loads of the building such as transmission through walls, roofs, doors, windows and infiltration. The effects of thermal mass, the placement of insulation, building location and orientation, and certain architectural features also are considered. The SYSTEMS program simulates the performance of heating, ventilation and air conditioning. It modifies the output of the LOADS program to produce actual thermal loads for each zone based on its hourly variable internal temperature.

3.4.2 Description of the Prototypical Metal Building

The dimensions of the modeled building were close to but not identical with the monitored test building. The floor area of the simulated structure was 7500 square feet comprising a total volume of about 100,000 ft³. Roof and wall construction were similar to the test building; both were slab on grade construction. However, 24-gauge steel panel cladding was assumed rather than the 26 gauge panel of the test structure, and two instead of one overhead metal doors were incorporated into the model.

Infiltration rates were changed from 0.4 to 1.0 and 2.0 ACH and several insulation levels were considered (see next paragraph) to account for a wide range of real situations. Lighting was assumed to be suspended fluorescent luminaires with 1 watt/square foot of energy input, and occupancy was set at 15 people, Monday to Friday, doing medium intensity factory work. Room temperature in winter was held at 65 F with a 10 F setback from 4 pm to 8 am.

3.4.3 Weather and Insulation Data

Seven representative locations in the United States were chosen and the results were extrapolated to regional areas. These locations and regions were:

Location	Region
Boston	Northeast
Atlanta	Southeast
Fort Worth	Southeast
Chicago	Midwest
Denver	North Central
Portland	Northwest
Los Angeles	Pacific

The following insulation levels were considered:

Ceiling R-value	Wall R-value
0	0
10	6
19	10
22.5	25

For these insulation options three different infiltration rates were simulated, namely 0.4, 1.0 and 2.0 ACH. The computer matrix thus created described various scenarios which will be discussed in the next chapter.

4. EXPERIMENT RESULTS

4.1 Total Heat Losses and Overall U-Values

Data were gathered for the winter months of January through April of 1987. During January some start-up problems were encountered, but in February, March and April all components of the data acquisition systems functioned properly. The total heat losses were assumed to equal the heat input by the electrical heaters. Table 5 gives the total heat losses, degree-days and the normalized, overall heat loss coefficient.

U_o , the normalized heat loss per square foot of floor area and degree-day is a measure of the overall energy efficiency of a building. Comparable values of U_o for residential housing are 2 Btu/ft²-F-day in the case of superinsulated homes and 5 Btu/ft²-F-day for more general construction practices. The relative consistency of the metal building U_o values - about 12 Btu/ft²-F-day for all months - is a reassuring fact regarding the accuracy of the data acquisition procedure.

4.2 Infiltration

4.2.1 Description of BNL/AIMS

In March of 1987 two infiltration tests were undertaken using Brookhaven's Air Infiltration Measurement System (BNL/AIMS). The major advantage of BNL/AIMS is its simple and reusable field kit, whose two components both about the size of a cigarette, are shown in Figures 9 and 10. Perfluorocarbon tracer (PFT) sources (Figure 9) emit an inert gas which quickly spreads throughout a room and creates a rather uniform concentration. The presence of the tracer gas can then be detected by capillary adsorption tube sampler (CATS) as depicted in Figure 10. The CATS are analyzed in an electron capture gas chromatograph.

PFT sources and CATS tubes are deployed in "strategical" locations throughout a building so that an average concentration of tracer gas is maintained and detectable in the space. In essence, the theory of the method is based on the following assumptions:

- a) constant and known emission rate of the source
- b) negligible tracer concentration in the incoming air
- c) steady state, i. e. changes of the tracer concentration in the space are negligible,
- d) infiltration = exfiltration.

With these assumptions, the flow rates of the tracer into and out of the control volume are equal, namely:

$$\dot{V}_{in} = \dot{V}_{out}$$

(4)

WEATHER DATA AND KWH CONSUMPTION OF HEATERS

Month	Degree-days	Heat Loss		Overall Heat-Loss Coefficient, Uo Btu/ft ² -F-day
	F.days F-days	kWh	MBtu	
February	1000	17,455	59.556	12.4
March	780	12,824	43.755	11.7
April	468	8,485	28.952	12.9

Table 5. Degree-Days, Heat Losses and Normalized
Heat-Loss Coefficients

Figure 9. Perfluorocarbon Tracer Source

Figure 10. Capillary Adsorption Tube
Sampler

$$\text{or } \dot{S} = \dot{E} \cdot C \quad (5)$$

$$\text{and } \dot{E} = \dot{I} = \dot{S} / C \quad (6)$$

where

- $\dot{S}$ = Source or emission rate of tracer, nL/h
- $\dot{E}$ = Exfiltration rate, m³/h
- $\dot{I}$ = Infiltration rate, m³/h
- $\dot{C}$ = Average concentration of tracer in space, nL/m³.

Because the average concentration, C, is known through the CATS analysis and because the source rate, S, is predetermined in the laboratory, Equation 6 allows the calculation of I, the infiltration rate.

4.2.2 Infiltration Measurements and Losses

The first infiltration test in the metal building was started on March 3 and lasted for 10 days. Four PFT sources with the tracer PMCH (perfluoro-methylcyclohexane) and four CATS were deployed in the four corners of the building. In addition, one set of a source and sampler was positioned in the center, about 15 feet above ground, to include any possible influences of stratification.

During the 10-day test the average outdoor temperature was 35.9 F (2.17 C) and an average indoor temperature of 64.6 F (18.13 C) was maintained. The average wind speed of 4.65 miles/h (2.08 m/s) was below the ASHRAE design wind speed of 15 miles/h. During the second test from March 16th to 26th, very similar conditions prevailed.

The findings of both experiments are presented in Tables 6 and 7. The two overall air exchange rates (see line 2 in the Tables) came very close to each other with values of 0.489 and 0.487, respectively. An average ACH of 0.488 was assumed and the infiltration heat loss was calculated with Equation 2:

$$\begin{aligned} Q &= \text{ACH} \cdot V \cdot \rho \cdot c_p \cdot \Delta T \cdot t \\ &\quad [\text{m}^3 \cdot \text{kg}/\text{m}^3 \cdot \text{kJ}/\text{kg} \cdot \text{C} \cdot \text{C} \cdot \text{hr}/3600 \text{ kJ/kWh}] \\ &= 0.488 \cdot 2356 \cdot 1.204 \cdot 1.012 \cdot 16 \cdot 240/3600 = 1494 \text{ kWh.} \end{aligned}$$

With an incoming energy during the 10 day test period of 4518.9 kWh, infiltration losses of 1494 kWh amounted to about 33 % of the total. In April after two more weeks of testing the value was 32.7% of the total due to infiltration.

Interestingly, the more approximate but also faster way of Equ. 2a., namely:

$$Q = (10.63) \cdot (0.488) \cdot (F \cdot \text{days}) \quad (2a)$$

BNL-AIMS

05-31-1987

PROJECT W. LOSS
HOUSE METAL BLDGSTART 10 00 105-11-1987
STOP 10 00 105-21-1987FILE 1042A.
ANALYZED 05-24-1987

***** RATES *****

OVERALL INFILTRATION RATE = 1151.7 = 124.1 m³/h
OVERALL AIR EXCHANGE RATE = 0.489 = 0.058 1/h

Z O N E	ZONE LOCATION	SOURCE Q25C QTY (nL/m)	RATE QT (nL/h)	EXFILTRATION RATE (m ³ /h)	INFILTRATION	
					SD	ACH
1	1	25.5	3816	1151.7	124.1	0.489

***** ANALYSIS *****

Z O N E	VOL TYPE	SOURCE TYPE	AVG. TRACER CONC.	
			(pL/L) ± SD	
1	1	PMCH	5.05	0.20

CATS#	CONCENTRATION (pL/L)			
	PMCH	POCB	POCH	PMCP
1	5.145	0.000	0.005	0.011
1	4.717	0.000	0.002	0.008
1	5.141	0.000	0.007	0.008
1	5.226	0.000	0.006	0.014
1	5.074	0.000	0.009	0.008

C.F.	COEFFICIENTS FILE			
	POCB	PMCP	PMCH	POCH
0.90	0.90	0.97	0.82	

***** NOTES *****

The standard deviation in the source strength has been set at 10 %.
The standard deviation in the volume measurement has been set at 5 %.

Table 6: Results of First Tracer
Infiltration Test

BNL-HIMS

05-20-1987

PROJECT: W. LOSS
HOUSE: METAL BLUGSTART: 06:00 (03-16-1987)
STOP: 06:00 (03-20-1987)FILE: 1254A
ANALYZED: 05-11-1987

***** RATES *****

OVERALL INFILTRATION RATE = 1148.5 = 137.9 (m³/h)
OVERALL AIR EXCHANGE RATE = 0.487 = 0.063 (1/h)

Z	ZONE	SOURCE RATE	EXFILTRATION	INFILTRATION					
N	LOCATION	Q25C QTY	BT	RATE	SD	RATE	SD	ACH	SD
E		(mL/n)	(mL/h)	(m ³ /h)		(m ³ /h)		(/h)	
1		25.5	5	5816	1148.5	137.9	1148.5	137.9	0.487 0.063

***** ANALYSIS *****

Z	VOL	SOURCE	AUG. TRACER	
N	n ³	TYPE	CONC.	
E			(pL/L) ± SD	
1	2356	PMCH	5.06 ± 0.34	

CONCNS		CONCENTRATION (pL/L)			
		PMCH	PCCB	PMCH	PMCP
1	5268	4.558	0.000	0.076	0.026
1	6975	5.025	0.000	0.140	0.027
1	3133	5.387	0.000	0.125	0.023
1	5111	5.358	0.000	0.068	0.019
1	2013	4.991	0.000	0.003	0.000

C.F.:	PCCB	PMCP	PMCH	PCCH	COEFFICIENTS FILE
	0.93	0.93	0.97	0.86	31000386

***** NOTES *****

All gas volumes are reported at 25 C. and 1 atm.
 The standard deviation in the source strength has been set at 10 %.
 The standard deviation in the volume measurement has been set at 5 %.

Table 7: Results of Second Tracer
Infiltration Test

yielded comparable percentages. For instance, in February 1000 F-days were accumulated and 17,455 kWh were consumed, yielding a fraction of 29.7 % accountable to infiltration. For the other test months the following numbers were computed:

	F-days	Infiltration Equ. 2a. kWh	Total Heat Loss kWh	Infiltration %
February	1000	5187.4	17,455	29.7
March	780	4046.2	12,824	31.6
April	468	2427.7	8,485	28.6
Average				29.97

Using the simplified degree-day approach, a slightly lower average infiltration percentage of 30 % was found.

4.3 Slab Losses

4.3.1 Temperature Measurements

On March 4 and 7 slab temperatures were measured with a spot radiometer. While March 4 was relatively cool with an average temperature of 30 F outdoors, three days later the mercury had risen 20 F to an unseasonably high 50 F. During both days a very peculiar, uneven temperature line could be observed which is depicted in Figure 11.

In this Figure temperatures were plotted in one-foot intervals from the perimeter to the center. Around the perimeter up to about 2 feet inward, the slope of the temperature line - the gradient - was quite steep and average temperatures in this area were about 5 F lower than in the adjacent, more intermediate section. In that intermediate area, which was about 10 feet wide, temperatures were higher but the temperature gradient was significantly lower than in the perimeter. The central area, finally, featured even higher temperatures and a lower gradient.

4.3.2 Heat Flow Measurements

Based on Figure 11 three distinct heat flow regions were established, the center, intermediate and perimeter region with widths of 16, 10 and 2 feet, respectively. Those sections, their areas in square feet and the location of the three slab-heat flux meters is pictured in Figure 12. It was intuitively assumed that the center, "half center", and perimeter heat flow meter adequately represented the heat losses in their respective areas. Proof of this assumption would require the placement of heat-flow meters in short distances from the center to the edge over a sufficiently large area; such a proof is beyond the scope of this study but will be attempted during the second year of monitoring.

Figure 11. Slab Temperature Profiles

Figure 12. Slab Heat Flow Regions and Slab Heat Losses

Also plotted in Figure 12 are the averages of the readings from the various heat-flow sensors. The sensors were calibrated during a two-week period in April by placing a portable calorimeters next to the individual sensor. Not surprisingly, the two outputs deviated significantly from each other. Because the calorimeter data were consistently lower - by 30% - the heat flow meter readings had to be adjusted by a factor of 0.70. It is these adjusted values that appear in Figure 12.

Inspection of Figure 12 reveals that the perimeter losses of 14.69 W/m² are almost 6 times higher than the center losses of 2.62 W/m². Contrary to ASHRAE assumptions, however, the total losses in the center and intermediate area together were by no means negligible since their sum amounted to more than 43.4% of the edge losses. It came as no surprise, therefore, that the ASHRAE formula which focuses mainly on the perimeter losses under-predicted the measured heat losses by about 17 %.

The measured and calibrated sensor readings when averaged on a daily basis yielded a portion of 18.3 % accountable to slab losses. The corresponding monthly heat loss values as well as the results of the ASHRAE formula, Equation 3a., namely:

$$Q = (2.7) \cdot (F \cdot \text{days}) \quad (3a)$$

can be compared in the following Table.

	F-days	Total Out kWh	Slab Equation (3a) kWh	Losses 18.3% of Total kWh	Percent Difference
February	1000	17,455	2700	3194	- 18%
March	780	12,824	2106	2347	- 11%
April	468	8,485	1264	1552	- 23%

4.4 Wall and Roof Transmission Losses

4.4.1 R-Values

With the beam calorimeter straddling the girt and the wall calorimeter attached first to the lowest and then to the center wall section (see paragraph 2.3.1) heat fluxes and inside and outside temperature differences were recorded and converted to R-values. Table 8 lists heat-flow rates, temperature differences, U-values and R-values for the night hours of a two-week period at the end of March. The striking result of this Table is that the average wall R-value ($R = 11.04$, Table 8 in row: "average R-value lower wall") was 80% higher than the average beam R-value ($R = 6.13$). In other words, heat losses through the beams and compressed insulation exceeded by 80 % those occurring through ordinary wall sections. Also interesting was that the calculations of an overall R-value accounting for beam as well as wall losses yielded a value close to the TMA R-value of section 3.1. How this number was derived is described in the following paragraph.

Beam Flux Wm ²	Wall Flux W/m ²	Delta T C	Beam-Area R-value F-ft ² -h/Btu	Wall R-value F-ft ² -h/Btu	Pastener R-value F-ft ² -h/Btu H ₅	Girt R-value F-ft ² -h/Btu H ₆
16.92	9.68	19.02	6.12	10.81	3.75	4.58
12.63	7.23	14.24	6.29	11.00	3.89	4.86
7.46	3.93	9.11	6.00	11.55	3.58	4.49
11.27	6.39	13.21	6.22	10.97	3.86	4.81
12.17	6.58	13.34	5.85	10.80	3.59	4.57
10.46	5.95	12.39	5.91	10.57	3.35	4.27
11.22	6.49	12.69	6.15	10.64	3.78	4.76
11.45	6.78	13.62	6.76	11.40	1.43	1.84
8.67	4.70	9.11	5.97	11.02	1.75	2.19
7.76	4.07	9.29	6.04	11.65	3.93	4.87
Average R-Value Lower Wall			6.130325	11.04	3.29	4.12
6.752968	3.14	7.52	5.84	13.28	3.813	4.35
10.07070	5.16	10.68	6.09	11.88	3.996	4.62
10.59293	5.90	12.16	6.52	11.72	3.802	4.38
12.89077	6.69	14.70	6.65	12.80		
Average R-Value Center			6.28	12.29	3.87	4.45
(Beam R-Value) . (Area Portion)			4.1			
(Wall R-Value) . (Area Fraction)				3.89		
Average Overall Wall R-Value				8.02		

Table 8. R-Values for Beam and Wall Calorimeter

4.4.2 Proportional Allocation of R-Values to Wall Areas

The spatial, proportional allocation of the R-values to certain portions of the wall area was solved in the following way. Figure 13 shows the arrangement of the two calorimeters, the beam calorimeter and the wall calorimeter. Because there were two Z-girts, two beam calorimeters were necessary to adequately represent the heat loss of the beam area, but only one was available.

The beam calorimeter on the lower Z-girt in Figure 13 was the one actually installed on the girt. The upper calorimeter is a "hypothetical" calorimeter drawn onto the girt to graphically clarify the aerial distribution of the calorimeters. Inspection of Figure 13 suggests that the beam calorimeter R-values should be allocated to two thirds of the wall area: the remaining third was the region for which the wall calorimeter was responsible. The two-to-one ratio of beam to "in-between-beam" areas and the subsequent proportional attribution of heat losses to these areas was tried for several days in March. Excellent heat balance closures of less than 4 % were achieved.

Heat losses through the wall and roof could now be calculated for the entire test period. Those losses, together with the infiltration and slab losses, enabled the establishment of energy balances around the metal building for February, March and April. Astonishingly, the energy balance closure for the whole test period was as low as 2 %. A pie chart of the various heat losses is presented next.

Because of this favorable outcome, confidence was gained that the 2/3 to 1/3 appropriation of R-values matched quite closely the heat-flow patterns in the actual building. Consequently, these ratios were used to calculate an average R-value for the entire wall. Taking 2/3 of the beam R-value and 1/3 of the wall R-value and adding the two numbers yielded an overall R-value, $R_{\text{overall}} = 8.02$ (Table 8, bottom). It is noteworthy that R_{overall} is only 4 % higher than the TIMA R-value of $R = 7.7$ (see section 3.1).

4.5 Special Observations

4.5.1 Pie Chart of Heat Flow Pathways

Figure 14 is a pie chart of the various losses. The contribution of the beam area exceeds all other losses being almost 40% of the total. However, the concept of "beam area" includes areas of 21 inches width above and below the girt. The heat loss through the 3 inch girt itself is even higher, with approximate girt R-values of only 2/3 of the overall "beam area". The last column in Table 8 contains girt R-values measured with uncalibrated heat-flux meters. Therefore, the values are approximate and certain deviations have to be taken into account, which are discussed in the next section.

4.5.2 Thermal Bridges Through Fasteners and Girt

Figure 7 of section 2.3.2 showed the location of the heat-flow meters in the metal building. A total of four sensors were attached to the girt. More

Figure 13. Allocation of R-Values to Wall Area

PATHWAYS OF HEAT LOSS

BNL METAL BUILDING 1007E

Figure 14. Pathways of Heat Loss

the girt. More specifically, one sensor, H3, measured the horizontal heat loss of the Z-girt and H4, H5 and H6 recorded heat flows through the vertical part of the girt which directly faced the compressed insulation.

Table 8 on (page 37) presented values recorded by H5, the sensor closest to the fastener and H6, the sensor between fasteners. Although the heat-flow meters were not calibrated, the numbers nevertheless convey a certain sense for the order of magnitude of the thermal bridges through fasteners and girt. Generally, along the girt, R-values between R-4 and R-5 were observed. The fastener R-value was even lower with averages around R-3.5. These findings suggest that the girt heat losses proper were probably more than 50% higher than the average heat loss shown as "beam area" heat loss. In addition, the effect of thermal bridging through fasteners exceeded girt values by 15 to 20%.

The following statements can be made about the possible deviation of the readings of the heat-flow meters from reality. It was observed that the slab heat-flow meters overpredicted the energy flows by 30%, and that the heat flow meter placed on the north wall gave values 12 % higher than the calorimeter output. Depending on the surface and surface resistance values of this magnitude probably are representative of the range of deviations encountered with these devices. Hence, it is assumed that girt and fastener R-values are accurate within an error margin of 20%.

4.5.3 Heat Loss of Center Section versus Heat Loss of Lower Wall Section

As discussed, the wall calorimeter was removed from the lower wall section and placed in the central wall area between the girts for about two weeks. Table 8 (page 38) details the average R-values for both configurations. As expected, the wall R-value of $R = 12.29$ for the center area (see column "Wall R-value", row "Average R-Value Center") out-performed by about 11% the lower wall R-value of $R = 11.04$ (see Table 8, column "Wall R-value", row "Average R-Value Lower Wall"). Hence, the assumption was confirmed that the lower wall sections lost more heat, probably due to condensation humidity, holes formed by corrosion and the proximity to the ground.

4.5.4 Reduced Heat Loss Through South Wall Due to Solar Radiation

During periods of sunshine, high temperatures were measured inside the south wall (T15 in Figure 8) and negative, incoming heat fluxes (H7, Figure 7), occasionally larger than the positive outgoing heat fluxes were recorded. These differences were exacerbated with the warmer temperatures in March and April.

For instance on April 2, a cold but sunny day (average temperature 37.5 F, 1637 Btu/h-ft² or 5164 Wh/m² of solar radiation) the temperature on the inside on the south wall panel at 2 p.m. was 90 F and a heat gain of 6.5 W/m² was recorded. At the same time, an almost equivalent amount of heat, namely 6.34 W/m² left the building through the north wall. For the whole day the heat loss through the south wall was only 2/3 of the heat loss through the north

wall. Figure 15 is an attempt to correlate solar radiation and the fraction of energy leaving the south wall. The higher the solar incidence, the less heat escaped through the south wall relative to the heat losses on the north wall. Despite the weak correlation ($r = .86$) a clear trend is visible. Solar gains in metal buildings should be the topic of further research.

4.6 Comparison of Field Tests with Computer Study

In section 3.4.2 a prototypical metal building was described. DOE-2 computer simulations of this building are summarized in Table 9. In the upper left corner the values for Boston, MA are printed out. With 5634 F-days, Boston comes closest to the average number of degree-days of Long Island. The first column of Table 9 details various insulation and infiltration options. The first entry represents the ceiling R-value, the second the wall R-value and the third value stands for the average infiltration rate. The second column shows the energy consumption associated with the assumptions of the previous column. The third column is the energy consumption of the whole region.

Row 1 describes a building with no insulation and an infiltration rate of 0.4. Row 4 represents a structure with ceiling R-values of R-10 and wall R-values of R-6. The BNL test building with an average R-value of about R-8 for both ceiling and walls and an infiltration rate of 0.488 ACH falls between the assumptions stated in rows 1, 2, 4, and 5. Interpolation yielded a simulated energy consumption of 421 million Btu. This value was divided by the degree-days and the area of 7500 ft²:

$$421 \text{ million Btu} / (5634 \text{ F-days} * 7500 \text{ ft}^2) = 10 \text{ Btu/F-day-ft}^2$$

As pointed out in Section 4.1 the measured overall U-value for the BNL test building amounted to 12 Btu/ft²-F-day. Considering the multitude of variables entering the computer algorithm and the complexity of the heat-flow patterns, the simulation result was deemed sufficiently accurate and the computer code was not changed further.

4.7 Qualitative Observations with Regard to Humidity and Corrosion

In Section 2.1.1 it was outlined how the vinyl sheets in the BNL metal building were not taped together but only stapled along their vertical seams. Hence, moist air and vapor can pass through the barrier into the insulation and to the wall. As a consequence, at various places insulation was found to be humid, particularly close to the floor slab. Also, close to the ground there were innumerable corrosion holes where outside air could freely enter the building. These holes seemed to occur in locations where fasteners had been installed.

Figure 15. Heat Loss Through South Wall

MEANS Table 1																							
	Boston, MA			Forth Worth, TX			Atlanta, GA			Chicago, IL			Denver, CO			Portland, OR			Los Angeles, CA			US	
Prototype	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Total Energy (1000 MBtu)	Total Cost (\$ M)
1) 0,0,0,4	1100	21,000	142.4	200	2,270	46.0																	
2) 0,0,1,0	1300	24,520	160.1	200	2,177	52.2	640	2,522	45.0	1000	15,210	60.1	1200	9,320	51.0	830	4,830	21.5	60	450	2.0	72,000	497.1
3) 0,0,2,0																							
4) 10,0,0,4	257	4,770	30.0	60	1,030	5.1	80	1,407	0.2	207	3,707	17.4	200	1,700	9.0	167	827	0.0	7	50	4	12,700	67.7
5) 10,0,1,0	404	7,400	40.0	110	2,030	10.7	150	2,520	10.0	120	4,640	27.1	175	2,700	15.3	200	7,400	10.0	10	100	1.0	22,000	141.6
6) 10,0,2,0	654	12,000	10.0	100	4,012	21.3	200	4,370	24.0	300	2,700	42.0	400	4,470	24.0	400	2,170	10.0	40	201	2.7	20,541	246.1
7) 10,10,0,4	100	2,040	20.0	50	1,240	0.0																	
8) 10,10,1,0	300	8,312	41.2	60	2,300	11.0	130	2,100	11.0	370	4,110	70.0	240	2,322	12.0	220	1,740	0.0	17	141	0	16,002	111.9
9) 10,10,2,0	507	10,502	71.2	100	4,400	24.0																	
10) 22,5,25,0,1	150	2,000	19.0	40	807	5.5																	
11) 22,5,25,1,0	200	5,544	30.0	60	2,100	11.0	100	1,047	0.5	220	2,000	20.1	310	2,041	11.2	100	1,000	7.0	10	100	0	16,704	96.1
12) 22,5,25,2,0																							

MEANS TABLE																							
	Boston, MA			Forth Worth, TX			Atlanta, GA			Chicago, IL			Denver, CO			Portland, OR			Los Angeles, CA			V-S	
Prototype	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Total Energy (1000 MBtu)	Total Cost (\$ M)
1) 0,0,0,4	5	0	2.0	10	300	0.0																	
2) 0,0,1,0	4	20	2.1	10	300	1.2	0	100	2.0	5	00	1.0	5	50	1.1	0	10	.2	5	04	0	200	10.0
3) 0,0,2,0	4	0	2.0	10	300	1.0																	
4) 10,0,0,4	2	50	1.0	0	240	4.3	0	10	1.0	5	20	0	4	31	0	2	11	1	5	20	0	400	2.0
5) 10,0,1,0	2	10	1.0	0	220	0.7	0	100	1.0	5	07	0	4	20	0	2	10	1	5	20	0	400	10.1
6) 10,0,2,0	2	10	1.0	10	200	5.2	0	101	2.0	4	20	0	4	20	0	2	0	1	2	20	4	510	10.7
7) 10,10,0,4	3	17	1.0	0	200	4.2																	
8) 10,10,1,0	2	50	1.0	0	210	4.5	0	01	1.0	5	07	0	4	20	0	2	10	1	5	20	0	400	9.0
9) 10,10,2,0	3	50	1.0	10	200	4.0																	
10) 22,5,25,0,1	3	50	1.0	0	100	0.0																	
11) 22,5,25,1,0	3	50	1.0	0	200	4.5	0	00	1.0	0	20	0	4	20	0	2	0	1	2	31	4	400	9.1
12) 22,5,25,2,0	3	00	1.0	10	200	4.0																	

COMBING MEANS TABLE																							
	Boston, MA			Forth Worth, TX			Atlanta, GA			Chicago, IL			Denver, CO			Portland, OR			Los Angeles, CA			Totals	
Prototype	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Energy (1000 MBtu)	Total Cost (\$ M)	Energy (MBtu)	Total Cost (\$ M)
1) 0,0,0,0	1100	21,000	140.1	107	5,400	52.0																	
2) 0,0,1,0	1300	24,520	162.0	400	8,570	60.4	570	6,000	40.7	1400	16,400	67.4	1270	9,301	52.0	830	4,822	24.7	60	500	2.7	72,961	146.1
3) 0,0,2,0	1500	28,100	162.2	400	11,151	70.3																	
4) 10,0,0,4	200	4,770	32.5	70	1,100	10.4	80	1,100	10.0	200	3,140	10.2	200	1,701	10.4	100	820	0.0	10	10	0	14,175	30.1
5) 10,0,1,0	407	7,400	40.1	170	2,002	20.4	100	2,020	10.0	447	4,077	27.0	310	2,700	15.0	200	1,400	10.1	22	100	1.5	23,488	111.6
6) 10,0,2,0	650	12,000	10.1	200	5,100	22.5	271	4,402	20.0	700	7,002	44.4	412	4,400	25.4	422	2,304	10.4	40	201	2.0	30,404	247.4
7) 10,10,0,4	701	2,000	25.3	50	1,400	11.1																	
8) 10,10,1,0	300	8,300	42.7	100	2,300	12.0	130	2,257	13.7	370	4,100	20.0	220	2,700	15.4	227	1,250	0.0	20	100	1.2	30,151	121.0
9) 10,10,2,0	500	10,500	72.7	100	4,700	20.0																	
10) 22,5,25,0,1	151	2,000	20.0	47	1,100	0.4																	
11) 22,5,25,1,0	200	5,540	37.5	60	2,100	10.2	127	2,047	12.2	220	2,000	20.0	317	2,000	11.7	200	1,100	7.0	10	101	1.2	30,048	107.1
12) 22,5,25,2,0	540	10,000	67.0	177	4,300	27.0																	

Table 9: DOE-2 Computer Results

5.2 Economic Considerations

The following strategies for retrofit and the approximate savings were envisioned for the BNL metal building.

1. heat losses through beams are totally eliminated through applying spray insulation;
2. heat loss through slab is reduced by half.

These retrofit strategies lead to approximate savings of 30% by reducing beam area and slab losses to about 50% of the current value:

	Current Losses	Losses after Retrofit
Infiltration	30%	30%
Beam Area	40%	20%
Ordinary Wall Areas	10%	10%
Slab	20%	10%
Total	100%	70%

With a heat loss of 12 Btu/ft²-F-day, an area of 5000 ft² and 6200 F-days, the current total annual heat loss of the BNL metal building amounts to 400 million Btu. Since the cost of heating (gas) is about \$6/million Btu, the annual heating bill for this type of metal building comes to about \$2400. With 30% savings that bill can be reduced by about \$700, which is equivalent to a net present value over a lifetime of 20 years of \$6,000, or a noteworthy 13% of the first cost of \$45,000.

The expenses to achieve these savings should be below \$5000 which can be translated to a very favorable rate of internal return (IRR) of 13%. Table 10 outlines the costs associated with the proposed options for retrofit.

On a nationwide basis, more than \$150 million could be saved by simply following some sound advice on insulation (Table 11). The Thermal Insulation Manufacturers Association, TIMA, for instance, published an Economic Systems Computer Program which determines the R-value with the lowest annualized owning cost. According to this program, which is run at no cost and as a service to the industry, the most economic R-values for many areas and building types tend to lie between R-15 and R-20.

1) Insulation of Beams:

Beams can be insulated with "K-13" cellulose spray.

3600 ft ² @ \$.50/ft ²	\$ 1800.
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2) Reduction of Slab Heat Losses:

Labor	\$ 2500
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Materials:

320 ft x 3 ft = 960 ft ²	
40 Styrofoam sheets, 8'x3'x3' @ \$ 16.—	\$ 600

4) Reduction of Infiltration:

Duct tape	
2600 ft @ \$.03/ft	\$ 100

TOTAL	\$ 5000
-------	---------

Table 10: Cost of Retrofit of BNL Metal Building

INSULATION	CONSUMPTION		SAVINGS
	10^{12} Btu	10^6 \$	10^6 \$
Current Situation:			
30 % of buildings R-0	37.7	240	
70 % of buildings R-10			100
Projected Future:			
All buildings R-10	22.5	140	
			20
All buildings R-19	19.2	120	
25 % savings due to insulation of beams and perimeter			30

			150
			=====

Table 11. Nationwide Energy Savings

REFERENCES

- [1] "Study on the National Significance of Space Conditioning Energy Consumption in Small Metal Buildings", Steven Winter Associates, Inc., New York, December 1986.
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- [3] ASHRAE HANDBOOK: 1985 FUNDAMENTALS, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 1985.
- [4] Irwin, W., T., Hays, P., "How Purlins Purloin Your Energy", Metal Buildings Review, Sept. 1978.

APPENDIX A

Nationwide Distribution of Warehouses

**REGIONAL DISTRIBUTION OF WAREHOUSE / LIGHT INDUSTRIAL
PREFABRICATED METAL BUILDINGS,
MBMA+Ten Percent Additional,
1965-1985**

ESTIMATED TOTAL NUMBER OF WAREHOUSE/LIGHT INDUSTRIAL UNITS NATIONWIDE				
Year	Total MBMA Sales In Millions of Dollars	Total Area in Millions of Sq.Ft.	Percent Warehouse	Number of Units
1965	185.0	43.6	50	1,453
1966	247.0	58.2	50	1,940
1967	232.0	54.7	50	1,825
1968	269.0	63.4	45	1,902
1969	327.0	77.0	45	2,310
1970	291.0	68.8	45	2,058
1971	335.0	79.0	45	2,370
1972	450.0	106.0	45	3,180
1973	600.0	141.4	40	4,242
1974	771.1	181.7	40	4,845
1975	564.0	133.0	40	3,547
1976	706.0	166.3	40	4,434
1977	857.1	202.0	35	4,714
1978	1,052.8	248.1	35	4,962
1979	1,214.1	286.1	35	6,675
1980	1,121.4	264.2	30	5,284
1981	1,186.2	279.5	30	5,590
1982	977.1	230.2	30	4,604
1983	1,002.4	236.2	30	4,724
1984	1,333.5	314.2	30	6,284
1985	1,408.5	331.9	30	6,638
Total(s)				83,581

APPENDIX B
DOE-2 Simulation

THE ENERGY USE SIMULATION MODEL

The energy use simulation model selected for this work was PC-DOE, the microcomputer version of DOE-2.1B. DOE-2.1B is a complete energy analysis computer program which accounts for a wide range of construction, equipment, occupant and weather parameters. This program, like all programs in its category, assumes one-dimensional heat flows in order to reduce the complexity of the code and the resulting run-time. Two and three-dimensional research programs are usually inappropriate for annual simulations and lack the capability to model the variety of interactions encountered in building operations. The authors used as input to PC-DOE, whenever possible, test data of entire metal building components in order to reduce the one-dimensional heat flow modeling problem. A brief description of the software follows.

DOE-2.1B calculates the energy consumption of a building by simulating its hour-by-hour performance for each of the 8760 hours in a year.

DOE-2.1B accounts for the building shape, the thermal properties of materials, the size and position of walls, floors, roofs, windows, and doors, and the transient effects of shading, occupancy patterns, lighting schedules, equipment operation, ambient conditions, temperature, and humidity controls. Energy consumption calculations are also affected by the operation of primary and secondary HVAC (heating, ventilation and air conditioning) systems and by the type and efficiency of the fuel conversion (plant) equipment. DOE-2.1B is organized into several interactive programs: LOADS, SYSTEMS, PLANT, ECONOMICS, REPORT and WEATHER.

The LOADS program simulator calculates hourly heating and cooling loads. Heat gains and losses through walls, roofs, floors windows and doors are calculated separately. Heat transfer by conduction and radiation through the building skin is computed using response factors. The effects of thermal mass, the placement of insulation, cloud cover, building location and orientation and architectural features are considered. Every set of response factors generated is placed in a file to be used by the LOADS and SYSTEMS programs. Infiltration loads are calculated on the basis of the difference between the inside and outside conditions and an assumed leakage area or by using the air-change method.

Internal use of energy for lighting and equipment is also computed, according to schedules assigned by the user for each piece of equipment that affects the energy balance of each space. The latent and sensible heat given off by the building occupants is calculated as an hour-by-hour function of the occupancy of the building.

All of the LOADS computations are performed on the basis of a fixed temperature for each space as specified by the user. It

provides a baseline profile of the thermal performance of a space, given a fixed internal temperature. The SYSTEMS program then modifies the output of the LOADS program to produce actual thermal loads based on an hourly variable internal temperature.

The SYSTEMS program contains algorithms for simulating the performance of the heating, ventilation, and air conditioning (HVAC) equipment used to control the temperature and humidity of each zone within the building. The SYSTEMS program uses the output information from the LOADS program and a list of user-defined system characteristics (e.g., air flow rates, thermostat settings, and schedules of equipment operation or temperature setback schedules) to calculate the hour-by-hour energy requirements of the HVAC system. The SYSTEMS program calculates thermal loads based on variable temperature conditions for each zone.

Warehouse Application

This is a one-story, rectangular-shaped building of steel frame construction comprising 8,400 sq.ft. of floor area. The structure is divided into 2 zones: a warehouse and an office located at the Southern exposure of the building. Each zone has separate space conditioning and lighting.

The architectural building description and occupancy are listed by zone as follows:

ZONE 1 - OFFICE

- o FLOOR AREA: 800 sq.ft. (30'x 30')
- o VOLUME: 9,600 cubic ft.
- o HEIGHT: 12.25 feet from finish floor to roof ridge;
9.125 feet from finish floor to eave;
slope of roof is 1:12
- o APERTURES: 160 sq.ft. of window area which equals 18% of the floor area, 2 glass doors measuring 3'x 7' each

o ROOF CONSTRUCTION:

Alternative A:

- W12 x 16 beam
- 9" x 3-1/4" 16 Ga. outside purlin
- 24 Ga. corrugated steel panel cladding
- fasteners (metallic)
- kraft-faced fiberglass batt insulation (no insulation, R10 or R19)
- acoustic tile ceiling (not suspended)

Alternative B:

- W12 x 16 beam
- 9" x 3-1/4" 16 Ga. outside purlin
- fasteners (non-metallic)
- pre-insulated roof panel, nominal 3-3/4" of isocyanurate foam (R=22.5)
- acoustic tile ceiling (not suspended)

o EXTERIOR WALL CONSTRUCTION

Alternative A:

- W8 x 15 column
- 9" x 3-1/4" 16 Ga. outside girt
- 24 Ga. steel panel cladding
- fasteners (metallic)
- kraft-faced fiberglass batt insulation (no insulation,

R8 or R10)

- 1/2" gypsum board
- double glass aluminum windows with no thermal break, 1/4" air space (U=0.827)
- double glass aluminum doors with no thermal break (U=0.827)

Alternative B:

- W8 x 15 column
- 9" x 3-1/4" 16 Ga. outside girt
- pre-insulated wall panel; nominal 4" isocyanurate foam (R=25.0)
- fasteners (non-metallic)
- 1/2" gypsum board
- double glass aluminum windows with no thermal break, 1/4" air space (U=0.827)
- double glass aluminum doors with no thermal break (U=0.827)

o INTERIOR WALL SEPARATING WAREHOUSE FROM OFFICE:

- 3-1/2" steel stud wall with glass fiber insulation
- 1/2" gypsum board on both sides of steel studs
- fasteners
- 4 pairs of hollow metal doors with urethane foam core measuring 5' x 7' each, 1-3/4" thick (R=5.26)

o FLOOR CONSTRUCTION:

- 12" concrete slab-on-grade, uninsulated
- VAT floor covering

o INFILTRATION RATE: 0.4, 1.0, 2.0 ACH

o LIGHTING: Suspended fluorescent luminaires accounting for 1.6 watts/sq.ft. Lights operate 100% of occupied hours and 5% of unoccupied hours.

o OFFICE FURNITURE AND EQUIPMENT: 2 lbs/sq.ft.

o HVAC: Gas- or oil-fired furnace for heating (AFUE=70)
Air conditioner for cooling (SEER=8.0)

o OCCUPANCY: 4 people occupy the office from 8am to 4pm, Monday through Friday, doing light office work.

o ROOM TEMPERATURE: Winter = 70F from 8am to 4pm,
setback = 60F,
Summer = 75F from 8am to 4pm

ZONE 2 - WAREHOUSE

o FLOOR AREA: 7,600 sq.ft. (100' x 75')

- o VOLUME: 103,000 cubic ft.
- o HEIGHT: 15 feet from finish floor to roof ridge;
12.25 feet from finish floor to eave;
slope of roof is 1:12
- o APERTURES: No windows;
5 hollow metal doors, 3'x7' each;
2 overhead hollow metal doors, 10' x 10' each

o ROOF CONSTRUCTION:

Alternative A:

- W12 x 16 beam
- 9" x 3-1/4" 16 Ga. outside purlin
- 24 Ga. corrugated steel panel cladding
- fasteners (metallic)
- kraft-faced fiberglass batt insulation (no insulation, R10 or R19)
- ridge vent/smoke vent along the entire length of roof

Alternative B:

- W12 x 16 beam
- 9" x 3-1/4" 16 Ga. outside purlin
- fasteners (non-metallic)
- pre-insulated roof panel, nominal 3-3/4" of isocyanurate foam (R=22.5)
- ridge vent/smoke vent along the entire length of roof

o EXTERIOR WALL CONSTRUCTION:

Alternative A:

- W8 x 15 column
- 9" x 3-1/4" 16 Ga. outside girt
- 24 Ga. steel panel cladding
- fasteners (metallic)
- kraft-faced fiberglass batt insulation (no insulation, R10 or R19)
- hollow metal door (runs will be performed with 1-3/4" thick urethane foam insulation, R=5.26, and with uninsulated doors)
- overhead hollow metal door (1-3/4" thick urethane foam insulation, R=5.26, or uninsulated)

Alternative B:

- W8 x 15 column
- 9" x 3-1/4" 16 Ga. outside girt
- pre-insulated wall panel; nominal 4" isocyanurate foam (R=26.0)
- hollow metal steel door with 1-3/4" thick urethane foam insulation, (R=5.26)

- overhead hollow metal door with 1-3/4" thick urethane foam insulation (R=5.28)
- o FLOOR CONSTRUCTION:
 - 12" concrete slab-on-grade, uninsulated
 - No floor covering
- o INFILTRATION RATE: 0.4, 1.0, 2.0 ACH
- o LIGHTING: Suspended fluorescent luminaires accounting for 1 watt/sq.ft. Lights operate 100% of occupied hours and 2.5% of unoccupied hours.
- o HVAC: Gas- or oil-fired furnace for heating (AFUE=70)
No air conditioner equipment
- o OCCUPANCY: 15 people occupy the warehouse from 8am to 4pm, Monday through Friday, doing medium intensity factory work, lifting, assembling.
- o EQUIPMENT: Process heat gain = 5.6 watts/sq.ft. during 4 hours out of the 8am to 4pm shift, Monday through Friday. The heat gain is from one 50 HP forklift.
- o ROOM TEMPERATURE: Winter = 65F from 8am to 4pm,
setback = 50
Summer = venting

Light Industrial Application

The description of the envelope of the building is the same as for the Warehouse application. The building function and occupancy changes in the production space only.

- o LIGHTING: by application - units are watts/sq.ft.

Lights operate 100% of occupied hours (8am to midnight, Monday through Friday) and 2.5% of unoccupied hours.

- Printing	- 1.9
- Machinery	- 0.9
- Electrical products	- 3.8
- Leather	- 1.2
- Knitting Mills	- 3.5
- Clothing	- 2.3
- Furniture and Fixtures	- 1.8
- o OCCUPANCY: 15 people occupy the production zone from 8am to 4pm (shift 1) and 4pm to midnight (shift 2), Monday through Friday doing medium intensity factory work, lifting, assembling.
- o EQUIPMENT: by application - units are watts/sq.ft.

The following figures represent the amount of process heat gain incurred between the hours of 8am to midnight, (two 8 hour shifts), Monday through Friday.

- Printing	- 1.1
- Machinery	- 11.1
- Electrical products	- 7.7
- Leather	- 12.1
- Knitting Mills	- 42.2
- Clothing	- 12.0
- Furniture and Fixtures	- 15.0

- o VENTILATION (make-up air): by application - units are air changes/hour (ACH)

Forced ventilation is used to replace contaminated air with clean and heated air.

- Printing	- 2.1
- Machinery	- 2.8
- Electrical products	- 4.7
- Leather	- 1.7
- Knitting Mills	- 9.0
- Clothing	- 1.2
- Furniture and Fixtures	- 3.6

COMPUTER SIMULATION MATRIX

Based on the regional distribution of SM-CALI buildings (please refer to Section 5), seven representative locations typifying basic climate zones were selected.

Boston, MA	Northeast
Atlanta, GA	Southeast
Chicago, IL	Midwest
Fort Worth, TX	Southwest
Denver, CO	North Central
Portland, OR	Northwest
Los Angeles, CA	Pacific

Preliminary PC-DOE simulations were performed in Boston, MA and Fort Worth, TX with the following insulation (ceiling R-value, wall R-value) and infiltration (air changes per hour) levels:

0,0,0.4
10,6,0.4
19,10,0.4
22.5,25,0.4
0,0,1.0
10,6,1.0
19,10,1.0
22.5,25,1.0
0,0,2.0
10,6,2.0
19,10,2.0
22.5,25,2.0

A linear regression analysis was performed for prototypes with the same ceiling and wall insulation and different air infiltration rates (0.4, 1.0 and 2.0 ACH). The correlation coefficients were all above 0.999. Since this analysis proved that infiltration rates correlate linearly with energy consumption, only the following prototypes were simulated in the remaining 5 locations:

10,6,0.4
10,6,1.0
10,6,2.0
0,0,1.0
19,10,1.0
22.5,25,1.0

Once the simulations were performed for the seven representative locations, the results were used to extrapolate the energy consumption and costs to the entire region. Boston data was extrapolated to the entire Northeast, Fort Worth data to the Southwest, Atlanta data to the Southeast, Chicago data to the Midwest, Denver data to the North Central region, Portland data to the Northwest and Los Angeles data to the Pacific region. While extrapolating the energy use for the entire US territory

from 7 data points carries a large level of uncertainty, this uncertainty is compatible with the one in the statistical estimate of the SM-CALI building stock.

Fuel costs were calculated from the 1985 Federal Energy Management Program's (FEMP) projected fuel prices. The costs in the table below are expressed in \$/MBtu:

<u>Location</u>	<u>Heating (gas)</u>	<u>Cooling (electric)</u>
Boston, MA	6.63	27.07
Atlanta, GA	5.55	20.54
Chicago, IL	5.49	18.98
Fort Worth, TX	5.60	22.06
Denver, CO	5.55	19.20
Portland, OR	6.85	9.90
Los Angeles, CA	6.13	21.02

The results of this analysis are presented in Tables 1, 2 and 3.

CONCLUSIONS

Small metal buildings have not benefited from the research activities directed over the past few years towards conventional commercial construction. However, SM-CALI buildings are demographically significant at the national level (over 1.4 billion sq.ft.) and benefit from a sustained construction level and from increased awareness and acceptance by owners and architects. These considerations indicate that small metal buildings provide an attractive target for energy conservation efforts.

Caveats on the Limitations of the Study

As explained in Section 5 of the report, the inventory data did not accurately distinguish the amount of SM-CALI construction from the larger metal building sector. The estimates of approximately 1.4 billion sq.ft. and about 92,000 buildings are considered conservative.

The energy use data was obtained by performing parametric runs on warehouse buildings only. While it is believed that the results are indicative of the the order of magnitude of energy use for both warehouse and light industrial buildings, the approximation introduced by this simplifying assumption could not be quantified.

Finally, the space conditioning energy use of warehouses was extrapolated from only 7 locations to the entire continental US, due to the difficulty of separating the statistical data on small metal buildings by discrete geographic regions. Since weather studies in "Affordable Housing through Energy Conservation" have indicated that at least 11 climate zones are needed for accurate results, it is concluded that another approximation was thus introduced.

Although the energy use and energy cost estimates for small metal buildings have to be interpreted in the light of the above caveats, it is relevant to note that absolute accuracy neither was, nor need be sought in a broad assessment of this type. Other independent factors which fluctuate widely, such as fuel prices and cost of money, reduce the desirability of a rigorous analysis. The results presented in Sections 5, 8 and 9 create the framework for quantifying the impact of SM-CALI buildings on national fuel use and could serve as the basis for more detailed analyses. The data delineate the lower and upper limits of energy expenditures in this building category and indicate the range of potential benefits to be derived from energy conservation measures. The data also point out the building components with greatest impact on energy use, thereby indicating directions of interest for future research (see also Section 10).

Space Conditioning Energy Expenditures

Yearly energy cost for SM-CALI buildings are bracketed by 73 x 10E12 BTU and \$450 million (all building stock uninsulated and with 1 air changes per hour) and 17 x 10E12 BTU and \$100 million (all building stock insulated with rigid insulation panels and 1 air changes per hour), as shown in Table 9, Cooling and Heating Section. Although no survey data were available, industry sources believe that uninsulated SM-CALI structures greatly outnumber the ones with high levels of insulation. It is reasonable to assume that some percentage (perhaps 10 to 30%) of the SM-CALI buildings are uninsulated, that most of them have relatively low insulation levels (R8/R10) and that a negligible percentage of the existing stock has high insulation levels. This calculation yields a range of 38 x 10E12 BTU and \$235 million to 27 x 10E12 BTU and \$170 million.

Another estimate can be obtained by assuming that most of the building stock has R-10 in the ceiling, R-6 in the wall and 0.4 to 2.0 air changes per hour. This approach yields a range of approximately 37 x 10E12 BTU and \$230 million to 14 x 10E12 BTU and \$90 million per year.

Although the two above ranges are not based on hard data, their relative agreement seems to point to a range for energy use of about 40 x 10E12 BTU at the high end and 15 to 25 x 10E12 BTU at the low end. This translates into \$250 million at the high end and \$90 million to \$150 million at the low end.

Of more interest, however, are the potential fuel and cost savings achievable by energy conservation measures. Table B1 summarizes energy use savings which could be obtained through energy conservation measures.

- a) If all SM-CALI buildings were uninsulated and if they were to be retrofitted to R-10 in the ceiling and R-6 in the wall, a 50 x 10E12 BTU/\$306 million savings would result.
- b) If all SM-CALI buildings were to be retrofitted from an R-10 in the ceiling to R-19 and from R-6 in the wall to R-10, a 3.5 x 10E12 BTU/\$20 million savings would result.
- c) If the insulation level was to be further increased from R-19 ceiling and R-10 wall to R-22.5 ceiling and R-25 wall, a 2.3 x 10E12 BTU/\$14 million additional savings would be incurred.

The law of diminishing returns is clearly highlighted by the rapid drop in energy use savings with increased insulation levels. Although none of the 3 hypotheses reflect the reality, it can be assessed that many buildings are covered by assumption (a), most by assumption (b) and very few by assumption (c).

Taking 3.5×10^{12} BTU/\$20 million as the lower limit for energy savings and 50×10^{12} BTU/\$306 million as absolute ceiling, the following matrix was constructed:

% uninsulated buildings	% building with R10/R6	Approximate Savings by Increasing Insulation Level	
		Energy ($\times 10^{12}$ BTU)	Cost (millions of dollars)
10	90	8	49
20	80	13	77
30	70	18	106

As illustrated above, a reasonable projection of energy savings achievable through increased insulation ranges from 18×10^{12} BTU/\$106 million to 8×10^{12} BTU/\$49 million.

Infiltration reduction measures (See Table 3, bottom) may also result in a range of 23×10^{12} BTU/\$135 million to 8×10^{12} BTU/\$50 million. This covers air infiltration reductions from 1.0 ACH to 0.4 ACH and 2.0 ACH to 0.4 ACH.

It is of interest to note at this juncture that infiltration reduction measures may result in savings approximately equal to those achievable by insulating the buildings. However, although some data are available for heat transfer through the envelope of metal buildings, no usable experimental data were found with respect to air infiltration in small metal buildings. As a result, there is no indication on whether actual infiltration rates in these structures approach the lower limit (0.4 ACH) or surpass the higher one used in this study (2.0 ACH).

Although the combined effect of insulation and infiltration energy savings should be somewhat lower than the sum of the components, it can be noted that together they account for a range of approximately 40×10^{12} BTU/\$250 million to 16×10^{12} BTU/\$100 million fuel savings per year.

It is therefore concluded that the energy consumption of small metal buildings is substantial at a national level and that the opportunities for energy savings are significant.

HEATING & COOLING COMBINED TABLE:

	Boston, MA		Forth Worth, TX		Atlanta, GA		Chicago, IL		Denver, CO		Portland, OR		Los Angeles, CA		U.S.	
Type	Energy Saving 1000 MBTU	Cost Saving (\$ M)	Energy Saving 1000 MBTU	Cost Saving (\$ M)	Energy Saving 1000 MBTU	Cost Saving (\$ M)	Energy Saving 1000 MBTU	Cost Saving (\$ M)	Energy Saving 1000 MBTU	Cost Saving (\$ M)	Energy Saving 1000 MBTU	Cost Saving (\$ M)	Energy Saving 1000 MBTU	Cost Saving (\$ M)	Energy Saving 1000 MBTU	Cost Saving (\$ M)
Insulation																
A.) 10,0,1.0 vs 0,0,1.0	17,111	112,187	8,888	40,028	8,888	38,874	18,882	88,528	8,882	38,847	3,158	21,847	816	2,247	90,883	308,588
B.) 10,10,1.0 vs 10,0,1.0	1,123	7,338	454	2,851	372	2,072	727	4,078	428	2,450	213	1,458	28	126	3,347	20,188
C.) 22.5,25,1.0 vs 10,10,1.0	800	8,227	283	1,588	245	1,378	581	2,835	312	1,754	152	1,045	12	88	2,305	14,034
Infiltration																
D.) 10,0,1.0 vs 10,0,0.4	2,718	17,725	1,218	6,988	1,085	6,724	1,732	9,883	988	5,514	533	3,645	98	554	4,325	48,848
E.) 10,0,2.0 vs 10,0,0.4	7,814	47,782	3,288	18,700	2,885	15,940	4,878	28,223	2,718	15,031	1,433	8,848	300	1,794	22,838	125,388

NOTE

Energy (MBTU), measured in million BTUs, represents the amount of energy consumed by one building in the location indicated in the heading (e.g. Boston, MA).

Total Energy (1000 MBTU), measured in billion BTUs, represents the aggregate of energy consumed by all metal buildings in one geographic area (e.g. the energy used by one metal building in Boston, MA multiplied by the number of units in the Northeast region equals the Total Energy for that region).

Total Cost (\$M), measured in millions of dollars, represents the product of energy consumed in MBTUs times the cost of that energy per MBTU.

TABLE B1