EFFECT OF RADIANT BARRIERS
IN
WALL CONSTRUCTION

FINAL REPORT

by

Mark Estes and Todd Olson
Mechanical Engineering Seniors
Mechanical Engineering Department
University of Alaska,
Fairbanks

With editorial comments by

John F. Rezek, P.E.
Sr. Research Engineer
Facilities Research

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2301 Peger Road
Fairbanks, Alaska 77909-6394

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FORWARD

The incorporated report, "Effect of Radiant Barriers in Wall Construction" is being published by DOT&PF Facilities Research essentially unedited with minor changes to clarify the text. Part of the Civil and Mechanical Engineering curricula at the University of Alaska is a course called generically, "Senior Design Project." Individual student projects are frequently sponsored by the Facilities Research Program providing the topic is consistent with our mission. Support consists primarily of advice and the use of State equipment and materials. In return, DOT&PF gains the results of the work at virtually no cost to the State. It is a very good relationship.

On occasion, as is the case with this project, the student's work is of high enough quality to publish. Normally the report would be edited before going to press. However, Mr. Estes and Mr. Olson did such an outstanding job on both their work and their report, that it was felt that it was appropriate to present it unchanged. Since this research was performed for a three credit undergraduate course, the scope of work was limited to be consistent with the requirements of that class. The results, therefore, are by no means the final word on radiant barriers. Furthermore, the student's conclusions and recommendations, while essentially correct, are somewhat simplistic. Consequently, for the purposes of this publication, I have added further analysis, conclusions, and recommendations in the "Comments" chapter.

John Rezek, P.E.
Sr. Research Engineer

ABSTRACT

The performance of radiant cardboard barriers were tested and evaluated using the DOT&PF guarded hot box. Two types of insulation were used in the testing: fiberglass bat and blown cellulose. The test procedure consisted of obtaining temperature measurements at designated positions throughout seven types of wall configurations. These tests showed, that the configuration with 5.5 inches of fiberglass bat insulation compressed to 4 inches with a radiant cardboard barrier allowed the least total heat flux through the wall section. An economic analysis indicated that the use of radiant barriers may be feasible in situations where insulation support is needed or an uninsulated gap is required for wiring or utilities.

INTRODUCTION

Our senior design project involved experimentation on the effects of radiant barriers in wall construction. The two types of insulation used were fiberglass bat and blown cellulose. The primary purpose of this project was to determine the increase or decrease in thermal resistance obtained by the addition of a radiant barrier in a wall section. Some products of this type are available on the market today, but experimental testing has not been extensively performed.

The apparatus used for testing was the DOT & PF guarded hot-box, located on first floor of the Duckering building at the University of Alaska-Fairbanks. An HP-85/3497 computer/data logger was used as the main control device. A refrigeration unit and a heater were used to maintain the temperatures desired in the cold and hot side of the guard box.

Heat loss, being a major concern in the construction of buildings, has continually lead engineers to pursue better ways to improve upon the thermal resistance of walls. Our project was to determine the feasibility of using foil-faced cardboard to increase the radiant component of thermal resistance.

OPERATIONAL TESTING

WALL SYSTEM #1 (See Fig. 1)

This wall system consisted of two 5/8 inch plywood sections, and 5.5 inches of insulation separated by 2 X 6 studs on two foot centers. The main string of thermocouples used in this setup were 9, 43, 41, and 42. The auxiliary string of thermocouples is shown towards the bottom of the figure. Thermocouples numbered 11 and 44 were located on the stud center. Thermocouples 12 and 40 were located on screw fastener heads. Two tests with this wall configuration and thermocouple setup were performed. In the first test the wall configuration was setup as shown with 5.5 inches of fiberglass bat insulation. The second test utilized blown cellulose insulation at an approximate density of three pounds per cubic foot.

WALL SYSTEM #2 (See Fig. 2)

This wall system consisted of 4 inches of insulation held in place by a cardboard or foil-faced cardboard insert. A 1.5 inch air space was present on the hot side of the cardboard inserts. Thermocouples were located at each material interface. A main string and an auxiliary string were used, as in wall system one.

Five wall configurations were tested using this type of setup. The first test utilized 5.5 inches of fiberglass which was compressed to four inches by the cardboard insert. Test number two was performed with a foil faced cardboard insert in place of the regular cardboard insert. The fiberglass insulation was then replaced with 4 inches of blown cellulose at approximately the same density as wall system one. Tests with the cardboard and foil-faced cardboard were then repeated. The final test configuration had the blown cellulose insulation with regular cardboard inserts. Aluminum foil was placed on the inside surface of the plywood on the hot side of the guard box.

Four, two hour tests were run on each of the configurations described for wall systems one and two. The guarded hot box program was set to scan the thermocouples at ten minute intervals throughout the tests. A paper printout was obtained from the HP-85 computer at the conclusion of each test. The thermocouple temperatures were then averaged to be used in our calculations. The program was equipped with a means to compile the amount of heat needed to maintain the hot side of the guard box at a constant temperature.

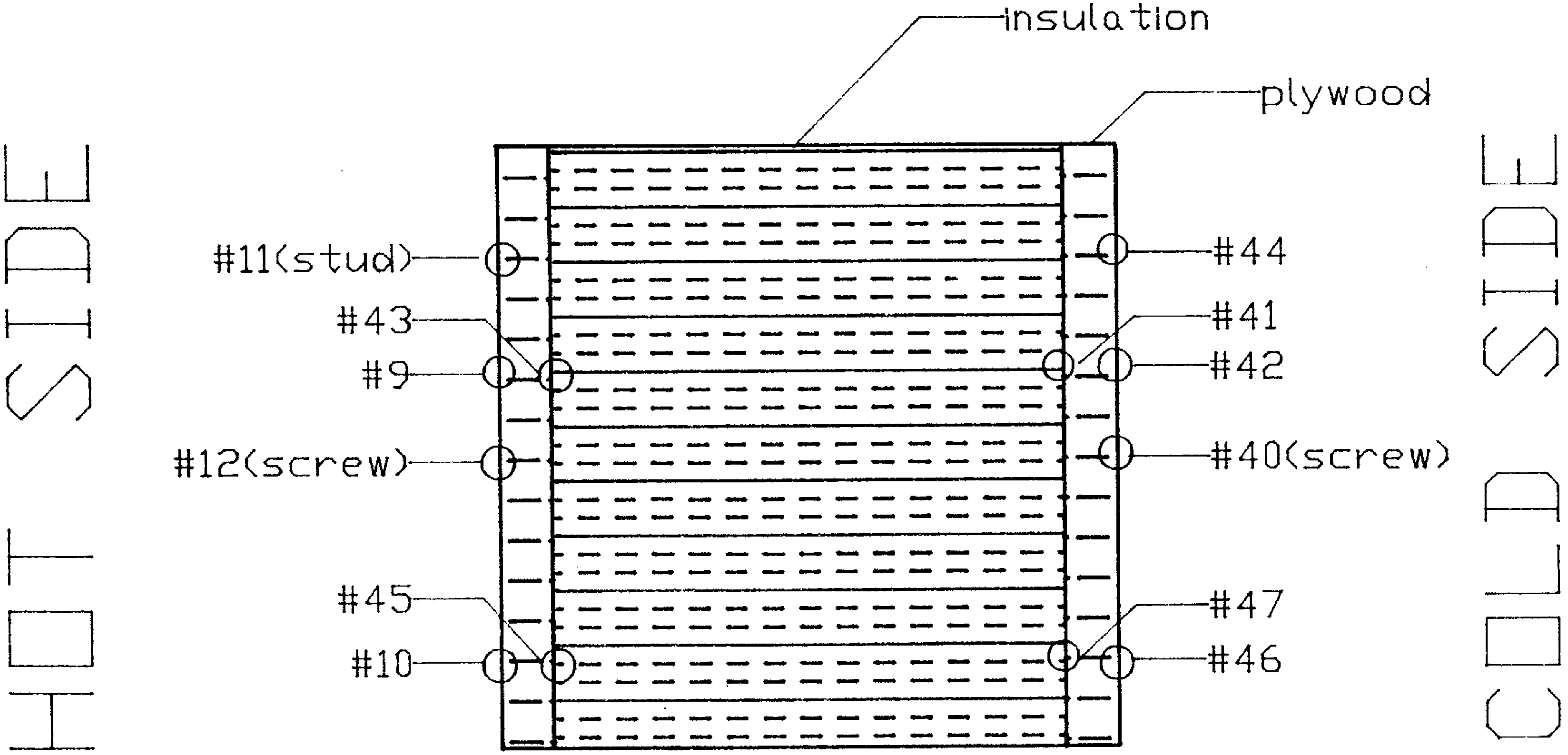


FIGURE 1

THERMOCOUPLE POSITIONS
5 1/2" INSULATION

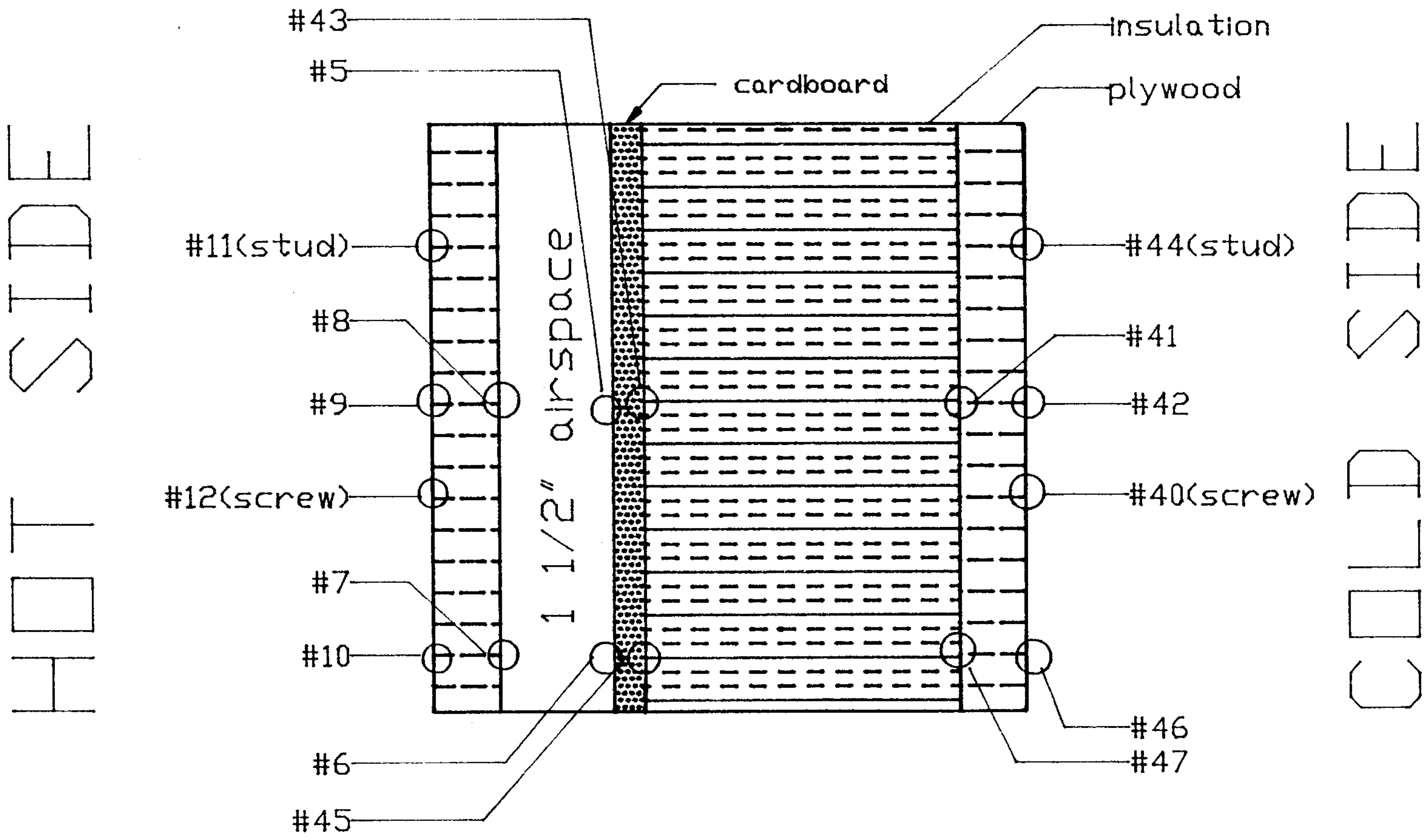


FIGURE 2

THERMOCOUPLE POSITIONS

4" INSULATION W/ 1 1/2" AIRSPACE

RESULTS

The results of heat flux calculations on each of the seven wall configurations tested are located on the following six pages. Each graph shows the increase or decrease of the heat flux through the different wall configuration as the temperature was varied. The graphs show two lines representing each of the wall configurations. The top line representing the heat flux of the whole system and the bottom line represents the heat flux when neglecting the effects of the stud area.

Fig. 3, shows the heat flux through each of the wall configurations which utilized fiberglass insulation as the insulating component. The top set of lines on the graph are the results of the wall configuration with 5.5 inches of fiberglass bat. As can be seen, this type of wall configuration was the worst fiberglass system tested in terms of heat flux. The wall configuration that used the cardboard insert with 4 inches of compressed fiberglass tested to be the second worst fiberglass configuration with a total heat flux of approximately 4.25 Btu/ft²-hr at a temperature difference of 90°F. The best fiberglass system that was tested, with a total heat flux of approximately 3.80 Btu/ft²-hr (at the same temperature difference), was the configuration which utilized the foil-faced cardboard insert in conjunction with the 4 inches of compressed fiberglass.

Fig. 4, shows the heat flux through the wall configurations that used blown cellulose insulation as the insulating material. The top line on the graph is the result for a wall configuration with a cardboard insert and 4 inches of blown cellulose insulation.

There is only one line shown on the graph for this type of setup. The reason for this is that the R-value of the stud space area of the wall section was found to be approximately equal to the R-value the stud area. So the heat loss per unit area through the studs equaled the heat loss per unit area through the stud space. The wall configuration with 5.5 inches of blown cellulose tested to be the next worst blown cellulose system. It shows a great improvement over the above case, mostly because of the fact that 1.5 inches of blown cellulose insulation has a better R-value than a 1.5 inch airspace and cardboard insert combination. The improvement of R-value due to the radiant effects can be seen by observing the next lower set of lines on the graph. This set of lines represents the configuration with a foil-faced cardboard insert and 4 inches of blown cellulose insulation. As can be seen, this type of configuration is slightly better than the 5.5 inches of cellulose, but a much better setup than the cardboard insert with 4 inches of cellulose. The difference in heat flux through the blown cellulose with a cardboard insert and the blown cellulose with a foil-faced cardboard insert, is due to the increase in thermal resistance obtained by adding the radiant barrier. The bottom set of lines are for an experimental wall configuration which consisted of a cardboard insert, 4 inches of cellulose, and aluminum foil placed on the inside surface of the hot side plywood. This type of configuration was the best blown cellulose system tested. Theoretically, this wall system should be no better than the configuration with the foil-faced cardboard insert and 4 inches of blown cellulose. The major reason for the lower heat flux with this system is thought to be that the aluminum foil has a lower emissivity value than the foil-facing surface on the cardboard.

Fig. 5 is a combination of Fig. 3 and Fig. 4, comparing the total heat flux of each configuration tested. By far, the worst system that was tested was a cardboard insert with 4 inches of blown cellulose insulation. The best configuration was found to be a foil-faced cardboard insert with 4 inches of compressed fiberglass insulation.

Located in Appendix A is a page of tabulated values that were used to generate the above plots.

Tabulated values for the increase in resistance due to compression of the fiberglass and to the addition of a radiant barrier are shown in table 1.

An economic analysis was done with a outside design temperature of -20°F and an inside design temperature of 75°F. Initial costs for the insulation and inserts were obtained from local distributors. A zero cost for installation was assumed with a 25 year life at an interest rate of 10 percent. It was found that the 4 inch compressed fiberglass system with the foil-faced insert was the most economical, with a total amortized cost of 29 cents / yr-ft^2.

The extent of experimental error in testing is somewhat hard to access. One source of error was in the heat flow (power consumption) readout from the computer. The values are given to the nearest whole watt hour. Since the average reading was about 100 watt hours, the potential error is approximately one percent. Another possible source of error was in the reading of the thermocouples. Tape was used to attach the thermocouples which may have added a small resistance, or may have let them come away from the surface slightly, resulting in a false reading. The thermocouples themselves have a ± 0.5°F accuracy, although they were calibrated to within ± 0.1°F.

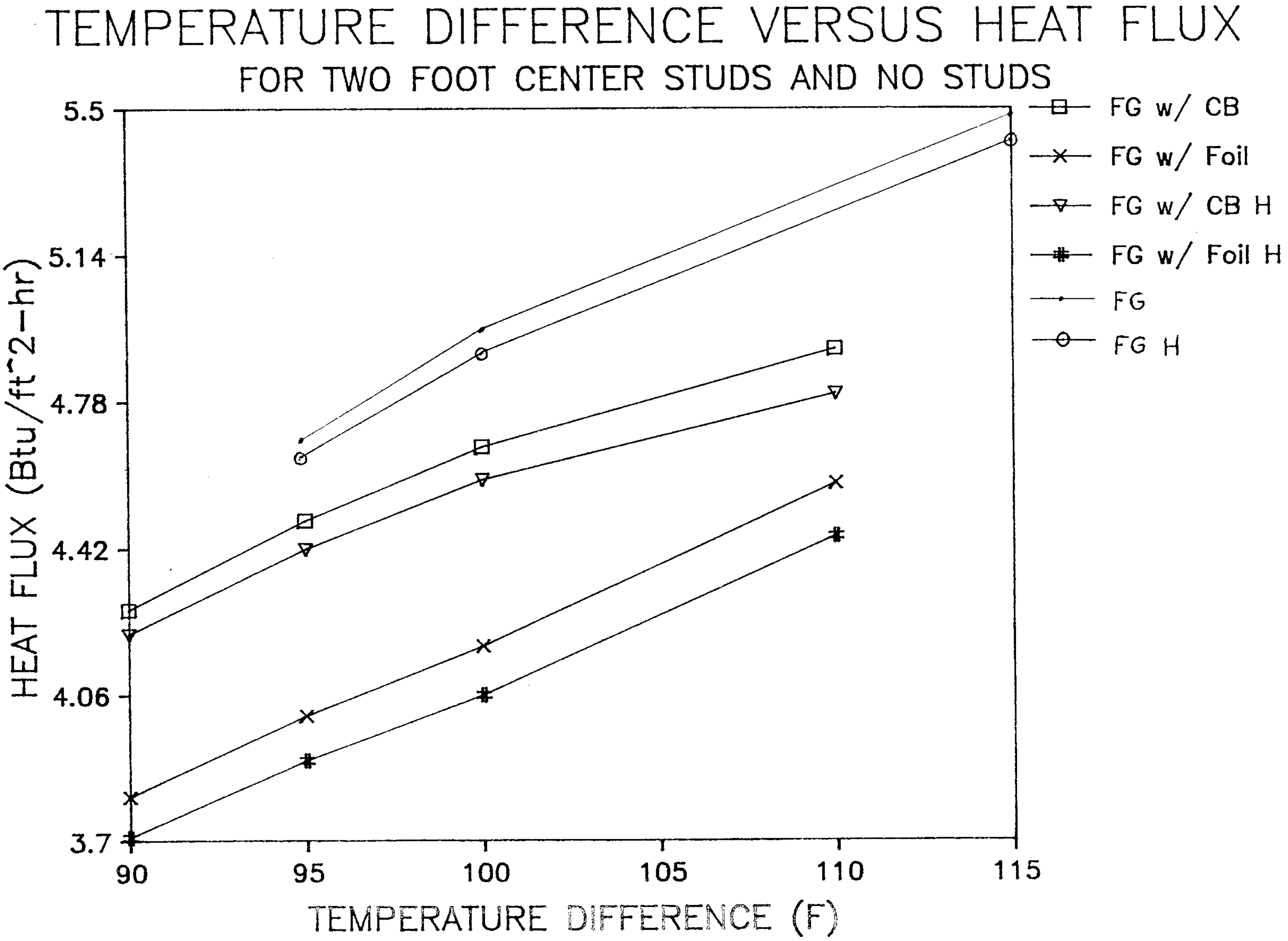
The blown cellulose density was 3.25 ± .25 lbs./cu ft. The density may have varied between the 5.5 inch and the 4 inch insulation thickness.

A small amount of heat could have escaped from around the guard box, which also may have contributed to experimental errors.

DEFINITION OF SYMBOLS

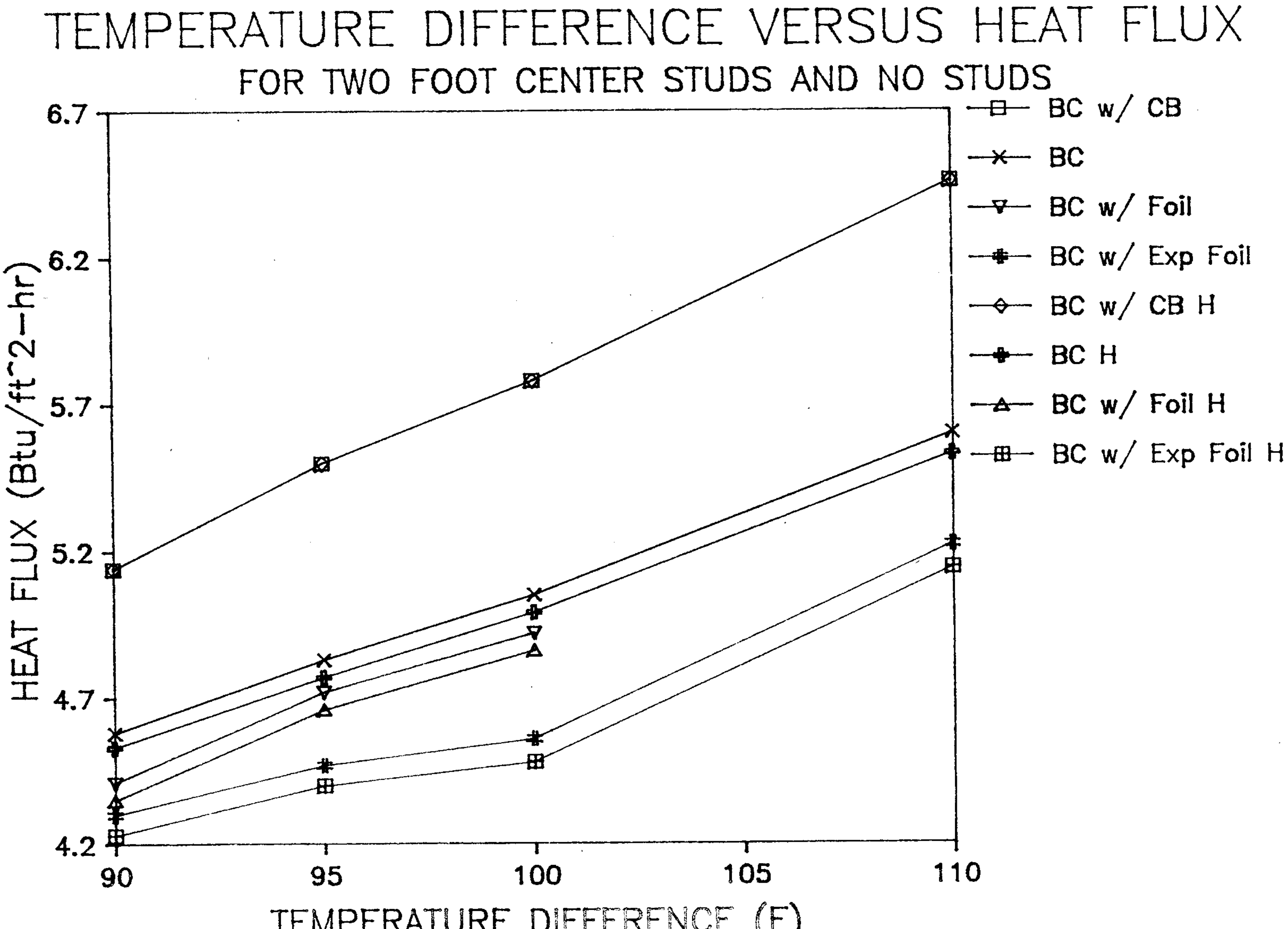
FG	Fiberglass Bat Insulation
CB	Cardboard
CBF	Foil-Faced Cardboard
BC	Blown Cellulose Insulation
EXPF	Experimental Foil W/ Cardboard
H	Homogeneous Wall System W/O Studs

FIGURE 3



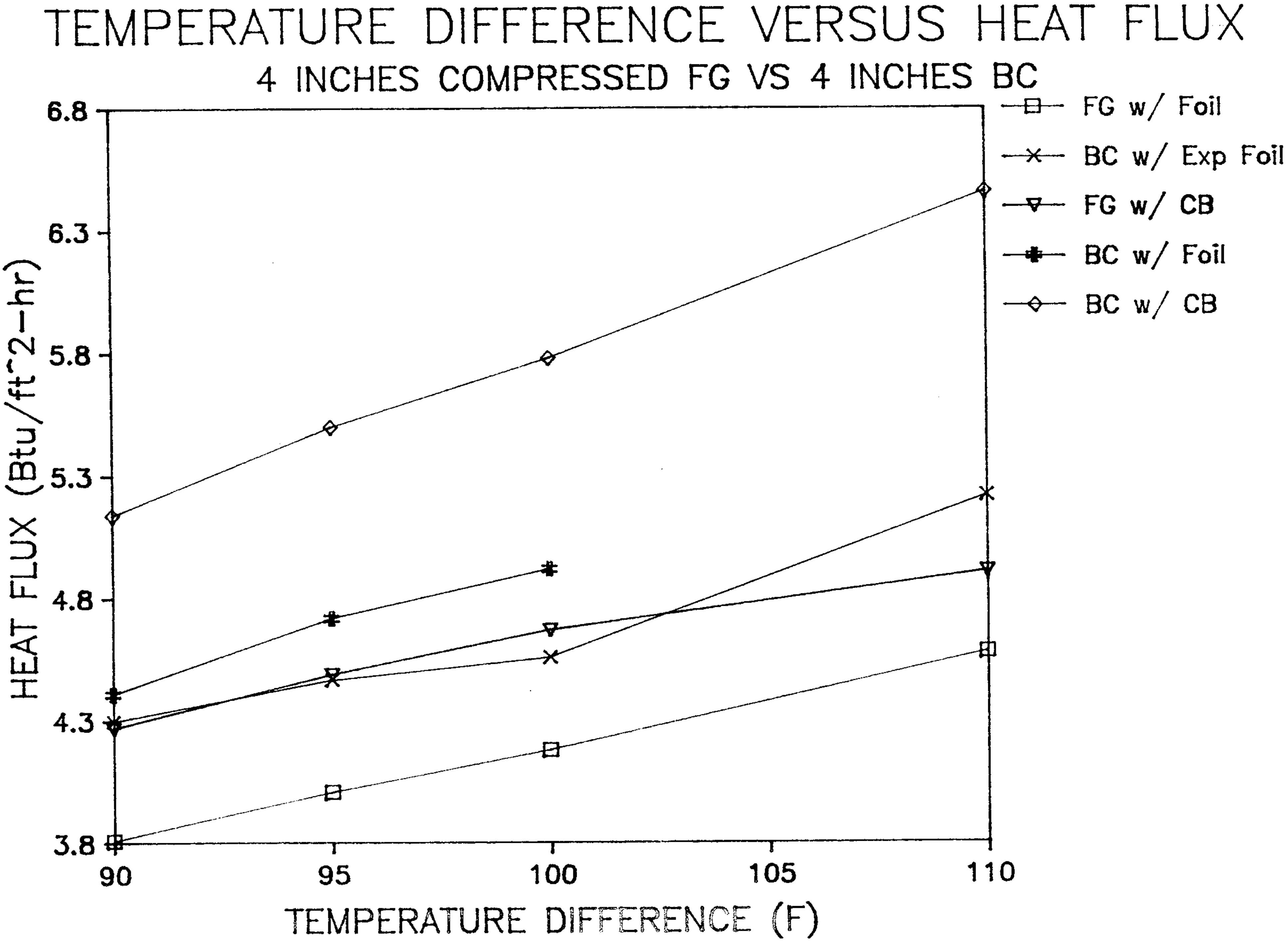
TEMPERATURE DIFFERENCE VERSUS HEAT FLUX
FOR TWO FOOT CENTER STUDS AND NO STUDS

FIGURE 4



TEMPERATURE DIFFERENCE VERSUS HEAT FLUX
FOR TWO FOOT CENTER STUDS AND NO STUDS

FIGURE 5


TEMPERATURE DIFFERENCE VERSUS HEAT FLUX

4 INCHES COMPRESSED FG VS 4 INCHES BC

TABLE 1

INCREASE IN R-VALUE DUE TO COMPRESSION OF FIBERGLASS

WALL TYPE	ORIGINAL THICKNESS (IN)	COMPRESSED THICKNESS (IN)	THEORETICAL R-VALUE hr.ft^2F/Btu	COMPRESSED R-VALUE hr.ft^2F/Btu	PERCENT INCREASE R-Value	COLD TEMP (F)
FG CB	5.5	4	16	17.9	11.9	-35
FG CB	5.5	4	16	17.1	6.9	-25
FG CB	5.5	4	16	16.9	5.6	-20
FG CB	5.5	4	16	16.7	4.4	-15
FG CBF	5.5	4	16	17.9	11.9	-35
FG CBF	5.5	4	16	17.8	11.3	-25
FG CBF	5.5	4	16	17.6	10	-20
FG CBF	5.5	4	16	17.6	10	-15

INCREASE IN R-VALUE DUE TO RADIANT WALL BARRIER

WALL TYPE	PERCENT INCREASE R-VALUE	COLD TEMP. (F)
FG CBF	9.2	-35
FG CBF	15.6	-25
FG CBF	12.5	-20
FG CBF	13.4	-15
BC CBF	15.4	-20
BC CBF	16	-15
BC EXPF	19	-20
BC EXPF	20.6	-15

ECONOMIC ANALYSIS

Design Outside Temperature = -20°F

Design Inside Temperature = 75°F

COST ESTIMATES

5.5 inch FG = \$ .35/ ft^2

4 inch BC at 3 lb./ ft^2 = \$ .24/ ft^2

5.5 inch BC at 3 lb./ ft^2 = \$ .34/ ft^2

Cardboard Inserts = \$ .14 /ft^2

Cardboard W/ Foil Facing = \$ .17 /ft^2

ASSUMED 0 COST FOR INSTALLATION
AND A 25 YEAR LIFE AT 10 % INTEREST

INSULATION	INITIAL COST (\$/FT²)	Q (BTU/YR-FT²)	HEATING COST (\$/YR-FT²)	CRF	INITIAL COST (\$/YR-FT²)	TOTAL COST (\$/YR-FT²)
5.5 " BC	.34	24343	.28	.1102	.04	.32
4 " BC CB	.38	27720	.32	.1102	.04	.36
4 " BC CBF	.41	23788	.27	.1102	.05	.32
5.5 " FG	.35	24595	.28	.1102	.04	.32
4 " CFG CB	.49	22277	.26	.1102	.05	.31
4 " CFG CBF	.52	19656	.23	.1102	.06	.29

CONCLUSIONS AND RECOMMENDATIONS

According to the results of our testing, the wall configuration consisting of 4 inches of compressed fiberglass, foil-faced cardboard, and a 1.5 inch air space had the lowest heat flux. This is due to the compression of the fiberglass insulation and to the addition of the foil facing.

The addition of the foil-facing on the cardboard increased the total resistance of the wall systems by 9.2 % to 16 %. The experimental aluminum foil increased the total resistance of the blown cellulose wall system by as much as 20.6 percent. Theoretically the 4 inch blown cellulose wall system with the foil-faced cardboard should have the same resistance as the one with the experimental foil attached to the plywood. The measured increase in resistance with the experimental foil is probably due to differing emissivities of the aluminum foil and the foil-facing, and of the cardboard and the plywood.

The blown cellulose system with the cardboard insert was found to have the same resistance through the studs as through the stud space. This explains why this wall system was found to have the highest heat flux.

The resistance of the fiberglass bat increased as it was compressed from 5.5 inches to 4 inches. The resistance increased by 4.4 % to 11.9 %. This suggests that fiberglass bat insulation is not manufactured at its optimum density.

The foil-facing cardboard with fiberglass insulation is recommended for people constructing their own home, or when there is a need to support insulation, as in a ceiling joist. Realizing that installation costs will be greater for people having their homes built by a contractor, the 5.5 inch fiberglass wall system is recommended for this case.

EDITORIAL COMMENTS

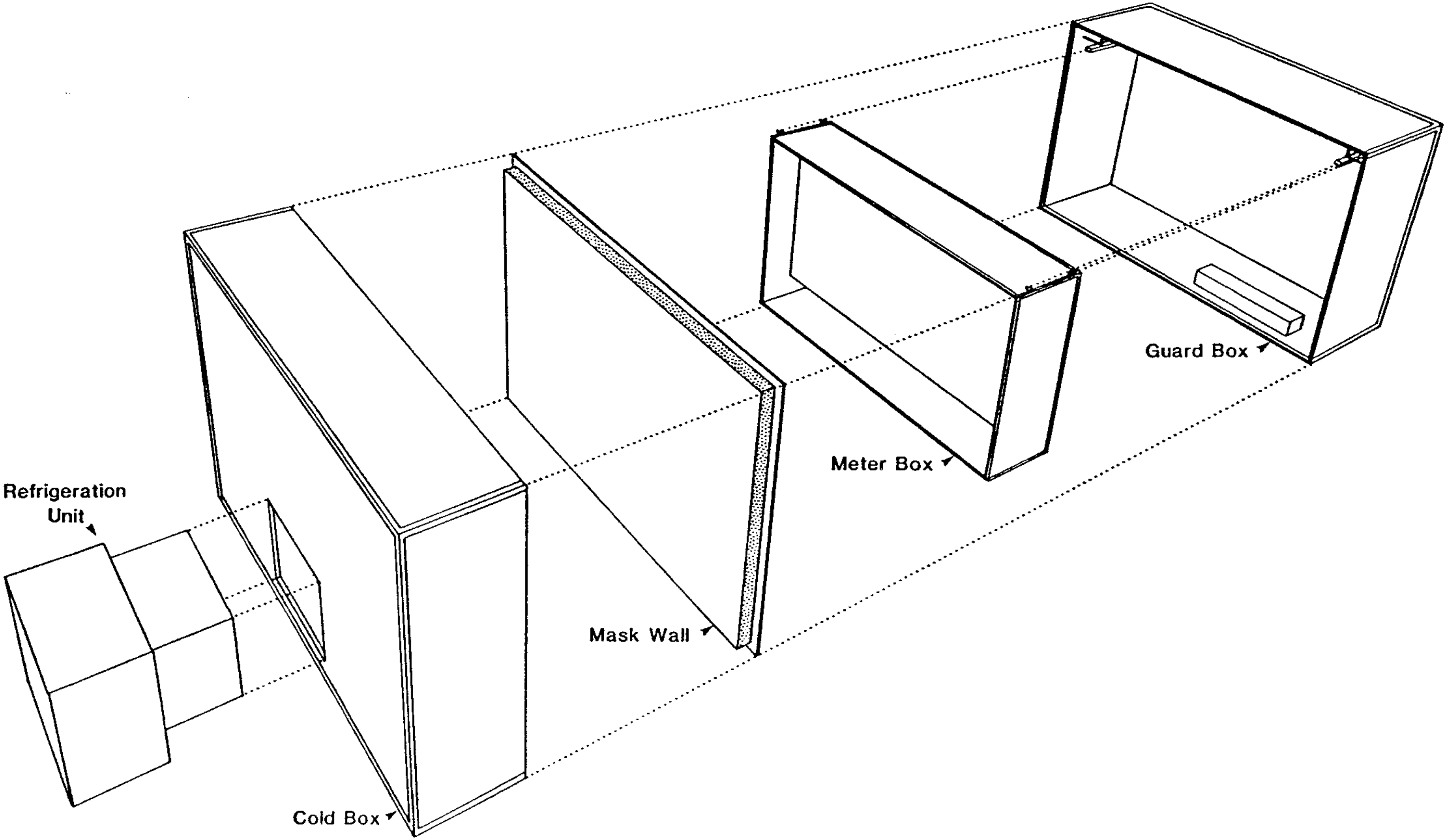
Since this investigation was conducted for a University engineering design class, not as a DOT&PF Research project, the scope of work had to be limited to be consistent with the requirements and time constraints of the class. With great dedication, the two students were able to perform tests on seven different wall configurations at four separate temperatures each. Even though tests were reduced to two hours each as a compromise to their tight schedule, they were limited to a maximum of two tests per day due to the temperature stabilization time required between different settings. There was no time to perform tests on any additional configurations (the seventh test, that of the "experimental foil", was done as a favor to me) or to do repeat tests, as would normally be done, to insure the validity of the data. However, even though the scope of work was limited and some compromises to the accuracy and confidence of the data were made, there is no reason to doubt the results. The investigative methods of the project are sound and the guarded-hot-box is capable of giving an accurate comparison of R-values even for short duration tests.

For those readers who might say " You only measured the conductive mode of heat transfer, not the radiation mode.", the guarded-hot-box does not measure thermal conductivity. It simply measures heat loss and does not distinguish between the three modes of heat transfer. The temperature of the meter box is kept within ± 0.1°F of that of the guard box. (see figure A) With no temperature difference ($\triangle T$) across those five sides of the meter box within the guard box, no heat is transferred by any mode. All heat loss from the meter box must be through the sixth side, the test

Figure A

GUARDED HOT BOX : EXPLODED VIEW

used for testing of thermal conductance



wall, into the cold box. The heat loss is determined by measuring the (electrical) energy required to maintain a constant set temperature in the meter box. It makes no difference whether the wall is a 6 inch wide, wood sided hollow chamber (high radiative and convective loses, low conductive loss) or 6 inches of solid wood (very low radiative loss, zero convective loss, high conductive loss), the apparatus measures the total heat loss through that wall. The term R-value, as applied to any system, is the summation of the reciprocals of all associated heat losses.

Another myth which this work dispels, is that the radiant barrier must be placed facing the heat to be effective. Radiant barrier proponents often try to discredit as hypothetical, the radiant heat transfer formulas used by engineers which show that it does not matter which surface has the low emissivity. In this test, the wall with the barrier facing the cold side actually out performed its "proper" counterpart by about 5% (see Fig. 5, BC w/Foil vs BC w/Exp Foil.) As stated in the report, this was most likely due to small differences in the emissivities of the materials involved. The misconception comes from confusion of the terms reflectivity and emissivity. Radiant heat flux is a function of emissivity and is not affected by reflectivity.

Although the basic contents of this investigation are valid, some analysis and qualification of the conclusions and recommendations are in order.

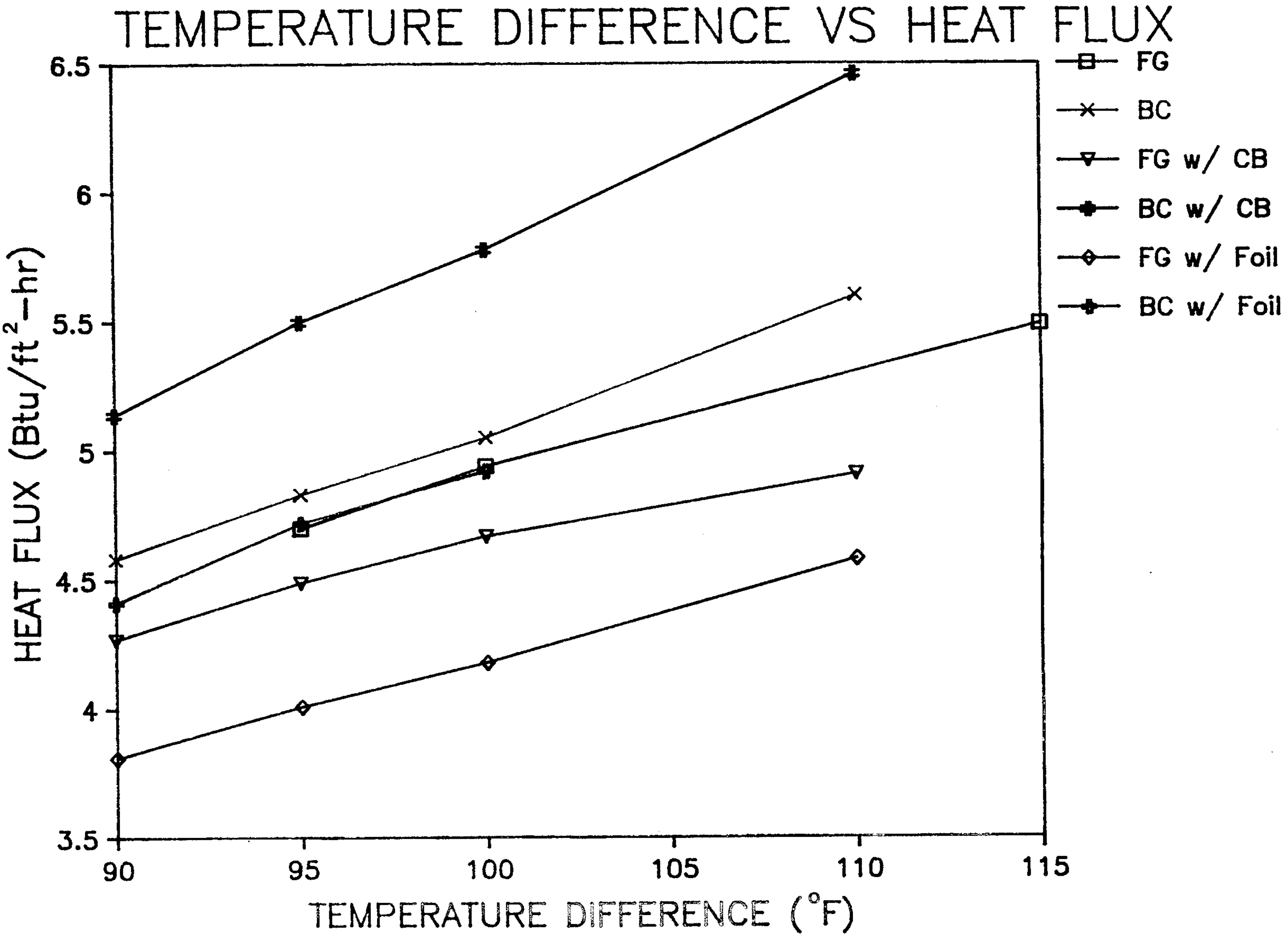
Not detailed in the student report, is an explanation of the 5°F shift of the $\triangle T$ of the fiberglass only (FG) data and of the missing 110° $\triangle T$ data from the blown cellulose with foil and experimental foil walls. The former was due to the use of a higher set point (80°F) in the meter/guard boxes, thus yielding a larger ΔT for the given cold box set points. Even though this temperature is considered above normal for occupied spaces, experience with the operation of the hot-box has shown that often, the heat generated by the freezer raises the room temperature to where the meter/guard box temperatures cannot be properly controlled at a lower point. The meter/guard box set point was lowered 5°F, to 75°F, for subsequent tests when it was determined that the room temperature was staying low enough to allow accurate control of the guard box temperature. The latter omission was due to a performance drop caused by low refrigerant pressure of the freezer: the unit was not capable of producing -35°F at the time of those tests. Time did not permit re-testing to fill these "holes" in the data after the freezer condition was remedied. Also not well defined, is the "experimental foil" was nothing more than 18" wide, heavy duty Reynolds wrap. Both the plain cardboard and foil-faced cardboard baffles used in this project were commercially available products.

To interpret the results, you must know that the larger the numeric value of the heat flux, the greater the heat loss is through the wall. To convert a heat flux value to the more familiar R-value, take the reciprocal of that number and multiply it by the ΔT associated with it. For example, the heat flux of the FG wall measured at warm side temperature of +80°F and cold side temperature of -20°F (ΔT = 100°F) is 4.94. The reciprocal is 0.202, multiplied by 100 yields R = 20.2.

Examination of the data reveals several interesting facts that are not readily apparent from the report. Because the data is plotted on different Y-axis scales (figures 3, 4, and 5) it is difficult to compare the six basic wall configurations as tested. Replotting the raw data (figure B) gives a direct comparison of each and shows that the fiberglass walls outperformed (has a lower heat flux) the cellulose walls in all equivalent configurations. In fact, the performance of the ordinary fiberglass wall was virtually identical to that of the cellulose with foil wall: the worst and best of each category respectively. It is noteworthy, that compression of the 5½" fiberglass bat, plus the addition of the cardboard and the 1½" air space, more that compensated for the loss of fiberglass thickness. Use of the air space with uncompressed fiberglass would undoubtedly result in a substantial loss in performance as it did with the blown cellulose. That configuration was not evaluated since 4" bats are not available and it was reasoned that a builder would most likely choose to compress the 6" bats rather than use 3½" bats and a 2" air space. The fairly large improvement of R-value per inch (about +17.5%) obtained by compressing the fiberglass to two thirds of its original dimension suggests that it may not be manufactured at even near it's optimum economic density. Testing of 3½" foil backed insulation in lieu of using the foil-faced cardboard was considered, but rejected because of the unlikelihood of this situation with a 5½" wall and because of the time constraints on the project.

The results of the central topic, the effect of radiant barriers, produced no surprises. Summarizing the values shown in Table 1 for cold side temperatures of -15° and -20°: the application of a "low-E" radiation

Figure B


TEMPERATURE DIFFERENCE VS HEAT FLUX
HEAT FLUX (Btu/ft^2–hr)
TEMPERATURE DIFFERENCE (°F)
6.5
6
5.5
5
4.5
4
3.5
90
95
100
105
110
115
FG
BC
FG w/ CB
BC w/ CB
FG w/ Foil
BC w/ Foil

barrier with an inch and a half air space, improved the thermal performance of the compressed fiberglass wall by 13% and blown cellulose wall by 15.7%. The greater improvement apparent with the cellulose is caused by the larger $\triangle T$ across the air space in that wall. The radiant component of the total heat loss is larger, therefore the radiant barrier is proportionally more effective. To illustrate this, the radiant component of heat loss through a hollow wall (no thermal insulation) would be in the neighborhood of 50 percent. The thermal performance of this wall could thus be improved nearly 50% by installing a radiant barrier. On the other hand, if you had a 12" wall with 10½ inches of fiberglass insulation and a 1½ inch air space, the radiant component would be quite small and so would be the improvement resulting from the addition of a radiant barrier.

The bottom line with any configuration of the thermal envelope of a building is economics. There is nothing basically wrong with the economic analysis as presented except that it is not realistic to deliberately ignore labor cost. All that was required of the students, was a demonstration of the methods of economic analysis. That they did. It is, of course, not a simple matter to accurately estimate costs, particularly for a region like Alaska which contains numerous, widely diverse, economic and climatic zones. The price of energy and money (interest) is anyone's guess over the next five years let alone twenty and to accurately estimate labor cost or the value of a specific construction task, requires experience and great insight. All that can be said for certain in criticism of the economic analysis presented, is that the initial costs would be increased if labor costs were considered. Common sense tells you that labor cost would be least for the plain fiberglass and blown cellulose walls and greater for the walls using the inserts. However, the variation between the amortized cost per square foot of each wall for the conditions given would likely remain basically unchanged.

Comparison of the amortized cost reveals that with the exception of the blown cellulose wall with cardboard insert, all configurations are essentially equal. Therefore, for the conditions given (which are acceptable for most of Alaska) the conclusions as to the viability of radiant barriers are:

1) If you have an air space in the building envelope due to the construction methods employed, consider installing a radiant barrier.

2) Do not sacrifice thermal insulation in order to create an air space for a radiant barrier.

These conclusions only apply to the particular range of circumstances covered by the tests and the economic analysis. Whether new construction or retrofit, each situation should be examined using its own particular set of parameters. However, this work does provide a general guideline for designers, engineers and builders who either may have never thought of applying radiant barriers to buildings or who have strongly considered their use.

The use of blown cellulose in some of these test wall is not an endorsement of that practice nor does it condemn it. However, if cellulose is used as thermal insulation anywhere in the building envelope, great care must be given to the integrity of the vapor barrier. The material will readily retain condensed vapor which will severely affect its thermal performance permanently. Additionally, if wet cellulose is not able to fully aspirate over the warm season, structural damage can occur. The foil-facing of the cardboard inserts cannot be substituted as a vapor barrier for the more traditional polyethylene barrier.

REFERENCES

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2. Clifford, George E., "Heating, Ventilating and Air-Conditioning," Reston Publishing Company, Inc., Reston, Virginia, 1984.

APPENDIX A

SAMPLE CALCULATION: BLOWN CELLULOSE WITH FOIL CARDBOARD

COLD SIDE AIR TEMPERATURE = -20°F

HOT SIDE AIR TEMPERATURE = 75°F

DATA EXPERIMENTALLY DETERMINED:

TOTAL HEAT FLOW = 85 W-HR
TOTAL ELAPSED TIME = 2.00 HR
TEMPERATURE OF STUD ON HOT SIDE = 71.5°F
TEMPERATURE OF STUD ON COLD SIDE = -13.1°F
AREA OF GUARD BOX = 30.75 FT^2
AREA OF STUDS = 1.80 FT^2
AREA OF INSULATION = 28.95 FT^2

$$\text{TOTAL HEAT FLOW } (Q)_{\text{Total}} = \frac{(85 \text{ W-HR} * 3.412 \text{ BTU/HR/W})}{2.00 \text{ HR}} = 145.0 \text{ BTU/HR}$$

$$\text{TOTAL HEAT FLUX } (\dot{Q})_{\text{Total}} = \frac{145.0 \text{ BTU/HR}}{30.75 \text{ FT}^2} = 4.72 \text{ BTU/FT}^2\text{-HR}$$

$$\text{TOTAL HEAT FLOW W/O STUDS} = Q_{\text{Total}} - Q_{\text{Studs}}$$

R-VALUE OF STUD SECTION = 2(.77) + 1.25(5.5) = 8.42 FT^2-HR-°F/BTU

$$\text{HEAT FLOW THROUGH STUD SECTION } (Q)_{\text{Studs}} = \frac{(71.5-(-13.1))°\text{F}}{8.42 \text{ FT}^2\text{-HR-°F/BTU}} = 10.0 \text{ BTU/HR}$$

TOTAL HEAT FLOW W/O STUDS = 145.0 - 10.0 = 135.0 BTU/HR

$$\text{TOTAL HEAT FLUX WITHOUT STUDS} = \frac{135.0 \text{ BTU/HR}}{28.95 \text{ FT}^2} = 4.66 \text{ BTU/HR-FT}^2$$

CALCULATION OF R-VALUES - COMPRESSED FIBERGLASS

ORIGINAL THICKNESS = 5.5 INCHES
COMPRESSED THICKNESS = 4.0 INCHES
R-VALUE OF FIBERGLASS PER INCH - UNCOMPRESSED = $4.0\ \frac{FT^2\text{-HR-}^\circ F}{BTU}$

AT COLD SIDE TEMPERATURE = -35°F

TEMPERATURE OF INSULATION ON COLD SURFACE = -24.0°F
TEMPERATURE OF INSULATION ON HOT SURFACE = 55.7°F
TOTAL HEAT FLOW THROUGH WALL SECTION W/O STUDS = 128.9 BTU/HR
AREA OF WALL SECTION W/O STUDS = 28.95 FT²

$$R = \frac{(55.7-(-24))^\circ F * 28.95\ FT^2}{128.9\ BTU/HR} = 17.9\ \frac{FT^2\text{-HR-}^\circ F}{BTU}$$

AT COLD SIDE TEMPERATURE = -25°F

TEMPERATURE OF INSULATION ON COLD SURFACE = -15.4°F
TEMPERATURE OF INSULATION ON HOT SURFACE = 57.1°F
TOTAL HEAT FLOW THROUGH WALL SECTION W/O STUDS = 117.6 BTU/HR

$$R = \frac{(57.1-(-15.4))^\circ F * 28.95\ FT^2}{117.6\ BTU/HR} = 17.8\ \frac{FT^2\text{-HR-}^\circ F}{BTU}$$

AT COLD SIDE TEMPERATURE = -20°F

TEMPERATURE OF INSULATION ON COLD SURFACE = -10.9°F
TEMPERATURE OF INSULATION ON HOT SURFACE = 57.8°F
TOTAL HEAT FLOW THROUGH WALL SECTION W/O STUDS = 112.8 BTU/HR

$$R = \frac{(57.8-(10.9))^\circ F * 28.95\ FT^2}{112.8\ BTU/HR} = 17.6\ \frac{FT^2\text{-HR-}^\circ F}{BTU}$$

AT COLD SIDE TEMPERATURE=-15 F

TEMPERATURE OF INSULATION ON COLD SURFACE = -6.3°F
TEMPERATURE OF INSULATION ON HOT SURFACE = 58.9°F
TOTAL HEAT FLOW THROUGH WALL SECTION W/O STUDS = 107.3 BTU/HR

$$R = \frac{(58.9-(-6.3))^\circ F * 28.95\ FT^2}{107.3\ BTU/HR} = 17.6\ \frac{FT^2\text{-HR-}^\circ F}{BTU}$$

INCREASE OF TOTAL R-VALUE DUE TO RADIANT EFFECTS

FIBERGLASS W/ CARDBOARD VS. FIBERGLASS W/ FOIL:

AT COLD SIDE AIR TEMPERATURE = -35°F

FIBERGLASS W/ CARDBOARD - $R_{\text{Total}} = 21.06 \ \frac{\text{FT}^2\text{-HR-°F}}{\text{BTU}}$

FIBERGLASS W/ FOIL - $R_{\text{Total}} = 23.19 \ \frac{\text{FT}^2\text{-HR-°F}}{\text{BTU}}$

$$\% \text{ RADIANT EFFECT} = 1 - \frac{21.06}{23.19} * (100) = \underline{9.2\%}$$

AT COLD SIDE AIR TEMPERATURE = -25°F

FIBERGLASS W/ CARDBOARD - $R_{\text{Total}} = 19.56$

FIBERGLASS W/FOIL - $R_{\text{Total}} = 23.18$

$$\% \text{ RADIANT EFFECT} = 1 - \frac{19.56}{23.18} * (100) = \underline{15.6\%}$$

AT COLD SIDE AIR TEMPERATURE = -20°F

FIBERGLASS W/ CARDBOARD - $R_{\text{Total}} = 20.05$

FIBERGLASS W/ FOIL - $R_{\text{Total}} = 22.90$

$$\% \text{ RADIANT EFFECT} = 1 - \frac{20.05}{22.90} * (100) = \underline{12.5\%}$$

AT COLD SIDE AIR TEMPERATURE = -15°F

FIBERGLASS W/ CARDBOARD - $R_{\text{Total}} = 19.81$

FIBERGLASS W/ FOIL - $R_{\text{Total}} = 22.88$

$$\% \text{ RADIANT EFFECT} = 1 - \frac{19.81}{22.88} * (100) = \underline{13.4\%}$$

BLOWN CELLULOSE W/ CARDBOARD VS. BLOWN CELLULOSE W/ FOIL:

AT COLD SIDE AIR TEMPERATURE = -20°F

BLOWN CELLULOSE W/ CARDBOARD - $R_{\text{Total}} = 15.49$

BLOWN CELLULOSE W/ FOIL - $R_{\text{Total}} = 18.30$

$$\text{\% RADIANT EFFECT} = 1 - \frac{15.49}{18.30} * (100) = \underline{15.4\ \%}$$

AT COLD SIDE AIR TEMPERATURE = -15°F

BLOWN CELLULOSE W/ CARDBOARD - $R_{\text{Total}} = 15.70$

BLOWN CELLULOSE W/FOIL - $R_{\text{Total}} = 18.69$

$$\text{\% RADIANT EFFECT} = 1 - \frac{15.70}{18.69} * (100) = \underline{16.0\%}$$

BLOWN CELLULOSE W/ CARDBOARD VS. BLOWN CELLULOSE/ EXP. FOIL:

AT COLD SIDE AIR TEMPERATURE = -20°F

BLOWN CELLULOSE W/ CARDBOARD - $R_{\text{Total}} = 15.70$

BLOWN CELLULOSE W / EXP. FOIL - $R_{\text{Total}} = 19.39$

$$\text{\% RADIANT EFFECT} = 1 - \frac{15.70}{19.39} * (100) = \underline{19.0\%}$$

AT COLD SIDE AIR TEMPERATURE = -15°F

BLOWN CELLULOSE W/ CARDBOARD - $R_{\text{Total}} = 15.49$

BLOWN CELLULOSE W/ EXP. FOIL - $R_{\text{Total}} = 19.52$

$$\text{\% RADIANT EFFECT} = 1 - \frac{15.49}{19.52} = \underline{20.6\%}$$

ECONOMIC ANALYSIS

SAMPLE CALCULATION USING BLOWN CELLULOSE WITH FOIL FACED CARDBOARD

$Q = 4.72$ Btu/hr-ft^2 * 24hr/day * 210 days heating/yr

$= 23788$ Btu/hr-ft^2

Heating value (HV) = 120000 Btu/gal

Efficiency (n) = .80

Fuel Cost = $ 1.10 / gal

$$\text{Heating Cost} = \frac{23789 * 1.10}{120{,}000 * .80} = \$\ .27\ /\text{yr-ft}^2$$

Initial Cost = .24 + .17 = $ .41 / ft^2

Initial Cost/Year = Initial Cost * CRF = .41 * .1102 = $ .05/yr-ft^2

Total Cost = Heating Cost + Initial Cost

= .27 + .05 = $ .31 /yr-ft^2

ECONOMIC ANALYSIS

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= .27 + .05 = $ .31 /yr-ft^2

AVERAGE THERMOCOUPLE READINGS

WALL TYPE	#9	#8	#5	#43	#41	#42	#11	#44	COLD TEMP
FG	77.8			72.5	-23.2	-29.2	77.8	-24.9	-35
	78.2			73.5	-9.4	-14.4	78.3	-11.1	-20
	78.3			73.8	-4.6	-9.2	78.4	-6	-15
FG CB	72.1	69.1	66.2	63	-23.1	-29	73.2	-26.4	-35
	73.2	69.5	66.8	63.9	-14.4	-16.6	73.5	-16.7	-25
	73.3	69.7	67.1	64.2	-10.4	-15.3	73.4	-12.8	-20
	73.4	70	67.5	64.8	-5.4	-10	73.5	-7.7	-15
FG CBF	73.3	69.3	63.2	55.7	-24	-29.9	73.6	-27.5	-35
	73.5	69.6	64.1	57.1	-15.4	-20.6	73.8	-18.4	-25
	73.6	69.9	64.7	57.8	-10.9	-15.7	73.9	-13.4	-20
	74.3	70.5	65.5	58.9	-6.3	-10.6	74.5	-8.4	-15
BC	71.7			68.4	-26	-31.6	73.4	-28.4	-35
	72.1			69.2	-15.5	-20.3	73.6	-18	-25
	72.3			69.5	-10	-14.8	73.7	-12.9	-20
	72.6			69.9	-6.1	-10.8	73.9	-8.9	-15
BC CB	69.5	63.6	60.6	59.5	-22.7	-29.3	70.6	-26.8	-35
	70.2	64.8	62.2	61.5	-13.4	-19.3	71.1	-17.6	-25
	70.5	64.9	63.1	62.5	-9.2	-14.7	71.3	-12.9	-20
	70.5	65.3	63.5	63.2	-5.1	-10.2	71.3	-8.2	-15
BC CBF	70.4	66	59.7	56	-12.4	-19	71.4	-17.2	-25
	70.5	66.2	60.1	56.7	-8.6	-14.8	71.5	-13.1	-20
	70.6	66.5	60.7	57.4	-5	-10.7	71.5	-9	-15
BC EXPF	70.6	59.9	53.8	52.1	-23.6	-29.4	70.8	-27.5	-35
	70.9	61.1	55.6	54.2	-15.1	-20.1	71	-17.8	-25
	71.1	61.8	56.5	55.3	-10.1	-14.8	71.2	-13.3	-20
	71.5	62.5	57.5	56.5	-5.9	-10.5	71.5	-9.2	-15