THE UNIVERSITY OF ALBERTA

A STUDY OF THE PERFORMANCE OF RESIDENTIAL NATURAL GAS FURNACES AND AN AIR TO AIR HEAT EXCHANGER

by

(C) JEROME FRANCIS KASHA

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF MECHANICAL ENGINEERING

EDMONTON, ALBERTA

FALL, 1986

ISBN 0-315-32562-3

THE UNIVERSITY OF ALBERTA

Release Form

NAME OF AUTHOR: Jerome Francis Kasha

TITLE OF THESIS: A Study of the Performance of Residential Natural Gas Furnaces and an Air to Air Heat Exchanger

DEGREE: Master of Science

YEAR THIS DEGREE GRANTED: 1986

Jerome Kasha

153 Thorncliff Place

Edmonton, Alberta.

T5T 0V5

DATE: Oct. 15, 1986.

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled A Study of the Performance of Residential Natural Gas Furnaces and an Air to Air Heat Exchanger submitted by Jerome Francis Kasha in partial fulfilment of the requirements for the degree of Master of Science in Mechanical Engineering.

Supervisor

Date: Oct 15, 1986

To my wife, Lynn
and our son, Sheldon.

ABSTRACT

This report presents the results of a two year investigation involving six residential natural gas furnaces on which tests were performed to determine their seasonal efficiency, their influence on structural air infiltration, and their economic feasibility. The furnaces were tested both in the field under typical operating conditions and in the laboratory according to the CAN1-P.1-85 seasonal efficiency test standard. The field tests were performed to determine the insitu performance of each furnace. These results were then compared to the CAN1-P.1-85 predicted values of seasonal efficiency to determine the accuracy of performance representation made by the test procedure. The laboratory test also allowed determination of the steady state efficiencies of each unit.

The report also presents the results of tests performed on a typical residential air to air heat exchanger or heat recovery ventilator in which the unit was tested to determine the level of cross contamination resulting from varying degrees of blockage in one of the flow streams.

The value of seasonal efficiency normally quoted for a standard furnace is between 50 and 60%. However, both the field and laboratory tests performed on the ICG Standard were found to deliver seasonal efficiencies which were significantly greater. Field tests produced an apparent seasonal efficiency of between 70% and 72% while laboratory

tests predicted a value of 67%. The significance of this result is that it directly reduces the economic attractiveness of a higher efficiency furnace replacement.

The operation of a free standing pilot flame was shown to contribute significantly to the rate of structural air infiltration. For the particular unit in which the standard furnace was tested, pilot operation resulted in a 25% increase over the natural infiltration level. In general, the influence of furnace operation on air infiltration was found to be closely related to the efficiency of the furnace with the lower efficiency units producing the greater effect.

Under most situations, it is more economical to purchase an upgraded standard or mid efficiency furnace than a high efficiency model. The extra investment required to purchase a high efficiency furnace is in general not compensated for by the additional cost savings.

The level of cross contamination for the air to air heat exchanger tested was shown to be typically below 1% of the air stream flowrate suggesting highly effective separation of the opposing streams.

ACKNOWLEDGMENTS

The author would wish to express his sincerest appreciation to Dr. J.D. Dale and M.Y. Ackerman for their invaluable support and assistance throughout the prepartion of this thesis.

Funding for this project was provided in part by the Alberta/Canada Energy Resources Research Fund, jointly established by the Government of Canada and the Government of Alberta and administered by Alberta Energy and Natural Resources. Financial support for the operation of the Alberta Home Heating Research Facility was obtained through the Natural Sciences and Engineering Research Council of Canada. The support of both of these groups is gratefully acknowledged.

The author would also wish to express thanks to the Inter City Gas Corperation for the donation of the ICG Ultimate furnace and to Werner's Refrigeration Company Limited for the donation of the Amana Energy Command furnace, both which were used in this study.

Finally, the author would like to acknowledge the work of Mr. F.D. Marlett of Northwestern Utilities Limited in obtaining the heating values of the natural gas used at the testing facility.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

A	surface area (m^2)
A_x	cross-sectional area (m^2)
c_p	specific heat at constant pressure (J/kg^oC)
d	diameter (m)
h	heat transfer coefficient (W/m^2 C)
K	ratio of UA between test and reference modules
L_C	energy loss corresponding to drainage of condensate at room temperature (%)
L_G	latent heat gain obtained by condensing water vapor from flue gases (%)
L_I	energy loss corresponding to increased infiltration (%)
$L_{L,A}$	latent heat loss normally accompanying uncondensed water vapor in flue gas (%)
L_S	sensible heat loss (%)
m	mass flowrate (kg/s)
Q_B	total basement heat loss (W·h)
Q_E	total electrical heat input (W·h)
Q_G	total gas heat input (W·h)
Q_I	total infiltration heat loss (W·h)
Q_R	total radiation heat gain (W·h)
Re_d	Reynolds number
T	temperature (^oC)
DT	room-ambient temperature difference (HDD)
U	overall heat transfer coefficient (W/m^2 C)
UA	overall conductance ($W/^oC$)
V	velocity (m/s)
X	percent stoichiometric flue gas CO_2 concentration (%)

e emissivity

g furnace efficiency (%)

m kinematic viscosity (m^2/s)

q density (kg/m^3)

r Stefan-Boltzmann constant

SUBSCRIPTS

on corresponds to gas furnace operation

off corresponds to gas furnace inoperation
- electric heating periods - field tests
- main burner off time - laboratory tests

ss corresponds to steady state condition

5 corresponds to reference module

CHAPTER 1

INTRODUCTION

In Canada, domestic energy usage accounts for approximately 25% of all energy consumed [1]. Of that amount, nearly 65% is used solely for the purpose of home heating [2]. Although much research has been devoted to the development of a wide variety of energy saving consumer items and appliances, it is only within the last decade that the residential gas furnace has begun to receive serious and long needed attention.

It is generally agreed that the seasonal efficiency of a typical gas-fired residential furnace is in the range of 50 to 60% [3]. Such values imply that close to one half of the total energy supplied for heating is effectively wasted. The magnitude of energy loss particularly on a national scale has become a conservation issue and as such has drawn the attention of various levels of government and has inspired interest in the development and promotion of furnace designs offering improved efficiency.

Since the early 1980's, a whole range of energy saving natural gas furnaces have become available, each claiming improved efficiency and a subsequent reprieve from the high high cost of home heating. Six typical furnace models representing a range of furnace technologies and seasonal efficiencies were chosen from this group to be used in an investigation of furnace performance and cost effectivness. Through field and laboratory testing procedures, each unit chosen was tested to determine its seasonal efficiency. Economic assessments, based on the seasonal efficiency results, were then made regarding each unit as a replacement of an existing gas furnace installation.

Reducing the rate of air infiltration has been the response of the housing industry to the demand for a more energy efficient home. Improved construction techniques, quality door and window assemblies and the employment of heavier vapor barriers have been among the measures taken to reduce the unnecessary loss of energy. This new generation of tighter house construction however has elevated concerns over indoor air quality and excessive moisture build-up. The proposed solution has been the installation of air to air heat exchangers to provide induced ventilation. One such commercially available residential ventilator was selected for testing to determine its rate of cross contamination or its effectiveness in maintaining separation of its opposing air streams. Cost limitations prevented expansion of testing to include a full assessment of its thermal effectiveness.

1.1 - DISCUSSION OF FURNACE EFFICIENCY AND LOSSES

The primary function of a residential furnace is to convert a source of potential fuel energy into usable space heating, implying both the generation and distribution of heat energy within the residence. An ideal furnace would convert all of this available fuel energy into usable energy. Certain losses, however, cause the efficiency of the conversion process to be something less than ideal (100%). For the purpose of this study, two definitions of efficiency are of importance; steady-state and seasonal efficiency.

Steady state efficiency describes the performance of the furnace during continuous operation. It is defined as the energy being delivered by the furnace, divided by the energy input rate once operational stability has been achieved.

Seasonal efficiency describes the performance of the furnace under its natural cycling mode. Because a residential furnace does not normally operate continuously, the steady state efficiency does not provide a realistic measure of true furnace performance. Certain losses which occur during the off-cycle affect the long term average performance of the unit. It is these losses which are accounted for in the measure of seasonal efficiency. Seasonal efficiency, therefore, is defined as the net amount of energy delivered during a calender year, divided by the energy input during the same calender year. It is the seasonal efficiency which is of most importance to the homeowner because it is this measure which ultimately determines the magnitude of the annual heating bill.

The most widely used residential furnace is the standard natural gas furnace. This particular style of furnace is designed for installation within the conditioned space and is characterized by three basic features:

1. Atmospheric burner - combustion occurs as an open flame under atmospheric pressure. Primary air and fuel mixture emerge from burner flame-ports and are met with secondary air supplied by natural convection.

2. Continuous pilot ignition - ignition of the main burner is provided by means of a continuously burning pilot flame.

3. Draft hood - used as a safety device to prevent backdraft from occurring through burner section. It is also used to decouple the stack draft from the natural draft set up within the heat exchanger thereby maintaining efficient combustion.

Because of its relative simplicity, both in terms of design and mode of operation, the standard furnace is safe, reliable and virtually maintenance free. Although each of the furnace's main components are tuned to offer optimum performance and efficiency, certain sources of energy loss do accompany its inherent simplicity. These losses combine to ultimately reduce both the seasonal and steady state efficiencies of the unit. Table 1.1 categorizes these various losses in terms of seasonal and steady state

TABLE 1.1 TYPICAL STANDARD FURNACE ENERGY LOSSES

STEADY STATE:	
1. Sensible	15 - 20 %
2. Latent	10 %
SEASONAL (off-cycle):	
3. Draft Relief	8 - 15 %
4. Continuous Pilot	5 - 7 %
5. Oversizing	0 - 3 %

contribution and lists the typical magnitudes of each. The losses are also illustrated in Figure 1.1.

The following are descriptions of the nature of each of the stated losses including discussions of additional losses which may occur in certain furnace installations, but which are not addressed further in this study.

1.1.1 SENSIBLE HEAT LOSS

In a space heating furnace, the furnace flame and combustion gases are maintained completely separate from the circulating room air by the surfaces of the heat exchanger. In most modern units, the room air is forced across these surfaces by a fan or blower to improve heat transfer. Because of the limited size of the heat exchanger however, all of the combustion energy is not transferred to the circulating room air. Rather, the flue gas is allowed to leave the exchanger and enter the stack at a temperature typically much higher than room temperature carrying with it a significant portion of the available fuel energy. This unused portion of heat energy contained in the hot flue gas is commonly referred to as the sensible heat loss.

Sensible heat loss may obviously be reduced by improving heat transfer at the heat exchanger, either by altering the heat exchanger design or by increasing the rate of airflow past its surface. Under most circumstances, it may also be reduced through control of excess air (required to ensure complete combustion of the fuel). Although not directly

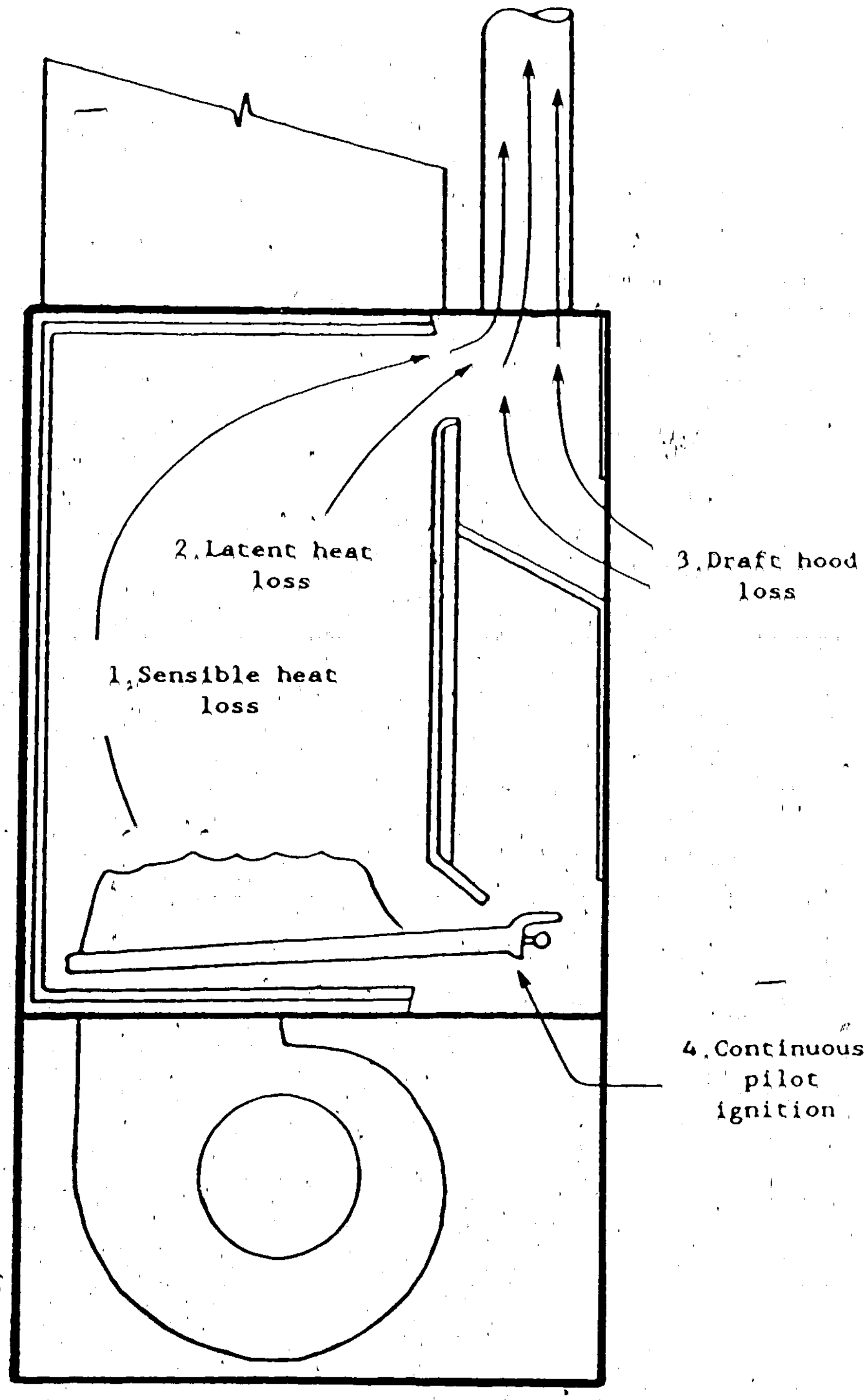

FIGURE 1.1 Standard residential gas furnace showing associated energy losses.

involved in the combustion reaction, the excess air removes energy from the system when it is heated to the furnace flue gas temperature and expelled through the furnace stack. The effectiveness of the heat exchanger is also reduced because of the transfer of energy to the excess air and the subsequent reduction in heat exchanger temperature. From an efficiency standpoint therefore it is clear that the control of excess air is desirable and that burners designed to operate efficiently with low levels of excess air are distinctly advantageous.

1.1.2 LATENT HEAT LOSS

Natural gas is rapidly becoming Canada's most popular fuel for residential heating. It provides high energy content together with ease of transport and clean (smokeless) combustion. Having methane as its main constituent however, natural gas carries a high hydrogen/carbon ratio and therefore the potential for significant latent heat loss.

Latent heat loss is the loss of energy associated with the production of water vapor in the combustion reaction. When a hydrocarbon is burned, both the carbon and the hydrogen are oxidized to form carbon dioxide (CO_2) and water (H_2O); the higher the fuel hydrogen content the greater the production of water. If this water is exhausted from the residence while still in its vapor state, it is accompanied by a significant loss of energy known as latent heat loss.

If however the water vapor is condensed from the flue gas, a portion of this latent energy may be recovered depending on the amount condensed.

1.1.3 DRAFT RELIEF

To operate safely, a furnace must have built into its design some reliable mechanism which ensures positive ventilation of combustion products. Until recently, furnaces have relied primarily on the use of a draft hood for this purpose. The draft hood is simply an open passage between the conditioned space and the stack. A difference in densities between the cool ambient air and the warmer stack gas provides a level of buoyancy which maintains a continuous positive (upward) flow of stack gases. In the event of a rare backdraft or no draft condition, the draft hood acts as a spillway ensuring that the flow reversal does not occur through the heat exchanger. Such an occurence would cause a reduction in O_2 levels in the flame zone resulting in incomplete combustion, and the introduction of toxic combustion products into the residence.

The draft hood is also used to decouple the stack draft from the normal draft set up within the furnace heat exchanger or burner area during operation. Without the use of a draft hood, a strong draft would necessarily occur within the heat exchanger section due to the the high stack gas temperature causing an increase in excess air, a reduction in exchanger temperature, and possible interference with combustion near the combustion air opening.

Seasonal efficiency is heavily taxed by the use of the draft hood. Under most conditions, heated room air is continuously lost up the stack both during furnace operation and during furnace down time. This air is then replaced by cold outside air which must either infiltrate the structure or be drawn in through ducts.

1.1.4 CONTINUOUS PILOT IGNITION

Pilot gas consumption is normally between 0.03 and 0.04 m^3/h (1 and 1.5 ft^3/h). During furnace off periods, unless the circulating blower is operating continuously, some of the heat generated by the pilot is not recovered, contributing directly to a reduction in seasonal efficiency. Clearly, some of this energy is recovered through natural convection from the heat exchanger and exposed stack surfaces. During the non-heating season however, even this contribution is considered as waste since it is no longer desired.

Besides the obvious loss of direct pilot light energy, there is an additional loss which arises due to an imposed increase in air infiltration to the structure. This infiltration increase accompanies the stack flow increase that occurs because the stand-by stack gas temperature is maintained above room temperature causing higher stack buoyancy and a stronger chimney effect.

In general, the amount of seasonal loss arising from the use of continuous pilot ignition is dependant on the pilot to main burner fuel consumption ratio and on the design of the heat exchanger, as well as on the length of the heating season and the oversizing of the unit, the latter two of which directly affect the number of stand-by hours.

1.1.5 OVERSIZING

Some percentage of furnace oversize is almost always required to ensure that the furnace is capable of sustaining the necessary load in the event of a period of particularly cold weather. It is also necessary to ensure that a reasonably short pick-up time (the time required to return the room to the comfort level) can be attained following a nightime (or daytime) temperature setback.

Gross oversizing, on the other hand, is normally undesirable. As well as providing certain disadvantages, such as short on-cycles and uneven heat distribution, it is generally agreed that oversizing reduces the seasonal efficiency of a furnace. Larger draft hood openings and stack diameters result in higher draft volume flowrates increasing the off-cycle losses. Off-cycle losses are yet further increased because of the increased fraction of down time.

Although oversizing losses are obviously unrelated to the particular design of the furnace and therefore beyond the control of the manufacturer, they are included among the losses discussed simply to demonstrate their negative affect on furnace efficiency.

1.1.6 INCOMPLETE COMBUSTION

In general, complete combustion with stoichiometric air is difficult to obtain in any combustion application. Since mixing of fuel and air is normally imperfect, some air never comes in contact with the unburned fuel. The usual indicator of incomplete combustion is the presence of combustible carbon monoxide (CO) in the flue gases. In the worst case, a certain level of unburned fuel (hydrocarbons) may also be detected. In either event, the loss which results is related to the amount of the combustible present and its respective heating value (the amount of energy released when the combustible is completely oxidized)[4]. To ensure reasonably complete combustion and the release of the maximum amount of available fuel energy, it is therefore necessary to operate a furnace with at least some excess air.

Furnace manufacturers are clearly aware of the potential losses which may result from operation with insufficient air and are therefore careful in designing their burner assemblies accordingly. As a result, losses arising from incomplete combustion in residential furnaces may be generally assumed to be zero.

1.1.7 JACKET LOSS

If a furnace is located outside of the building or in an unheated space such as an attic, the amount of energy actually supplied for heating may often be significantly less than that delivered by the furnace due to the transfer (loss) of energy to the unheated surroundings. Most residential heating systems, however, are contained entirely within the building being heated and are therefore not subject to such losses. For the purpose of this study and considering the nature of the furnaces under investigation, jacket loss will also be considered as zero.

1.2 - DESCRIPTION OF TEST FURNACES

Six different residential gas-fired furnaces were selected from the current marketplace for testing in this study. The furnaces chosen covered designs and efficiencies representing a range of current furnace technology. Table 1.2 lists the six furnace selections showing the nominal energy inputs and rated efficiencies as taken from the furnace nameplates (nameplate markings must represent steady state efficiency as determined according to the Canadian test standard CAN/CGA-2.3-M86 (5) entitled "Gas-Fired Gravity and Forced Air Central Furnaces").

TABLE 1.2 - RESIDENTIAL GAS FURNACES UNDER INVESTIGATION

FURNACE	INPUT RATING (kW)	EFFICIENCY RATING (%)	DESCRIPTION
ICG Standard	18	77	Atmospheric burner, pilot flame, draft hood.
ICG Conserver	18	77	Atmospheric burner, elect. ignition, flue damper
Airco Turbo	18	84	Induced draft, electronic ignition.
ICG Ultimate	18	92	Induced draft, electronic ignition, condensing.
Lennox Pulse	12	96	Pulse combustion, elect. ignition, condensing.
Amana Energy Command	13	96	Pressure burner, elect. ignition, circulatory water-glycol, condensing.

1.2.1 ICG STANDARD

The ICG Standard is typical of most natural gas furnaces in use in Canadian homes built within the last fifteen to twenty years. The furnace, shown in Figure 1.2, is described as a atmospheric combustion forced air design featuring a draft diverter (a built in draft hood) and continuous pilot ignition. The unit's efficiency is limited by pilot energy waste, high excess air, high temperature exhaust, and unobstructed flow of room air through the draft hood and heat exchanger during the off-cycle. Though still quite commonly used, it is considered the minimum standard in present furnace technology.

1.2.2 ICG CONSERVER

The ICG Conserver is an upgraded version of the ICG Standard. Identical in outward appearance, the upgraded unit incorporates two energy saving features: a motorized stack damper and electronic spark ignition. The stack damper is located downstream from both the flue and draft diverter opening. During the off-cycle, the damper remains closed preventing the escape of room air up the stack. Because there is no off-cycle airflow, there is no means of ventilating pilot exhaust thereby necessitating electronic spark ignition. The spark ignition system is part of a modified burner pack that replaces the complete pilot ignition burner pack assembly. Figure 1.3 is a photograph of the replacement burner pack and flue damper. The elimination of the pilot flame and the prevention of off-cycle room air loss are in theory designed to eliminate all off time losses.

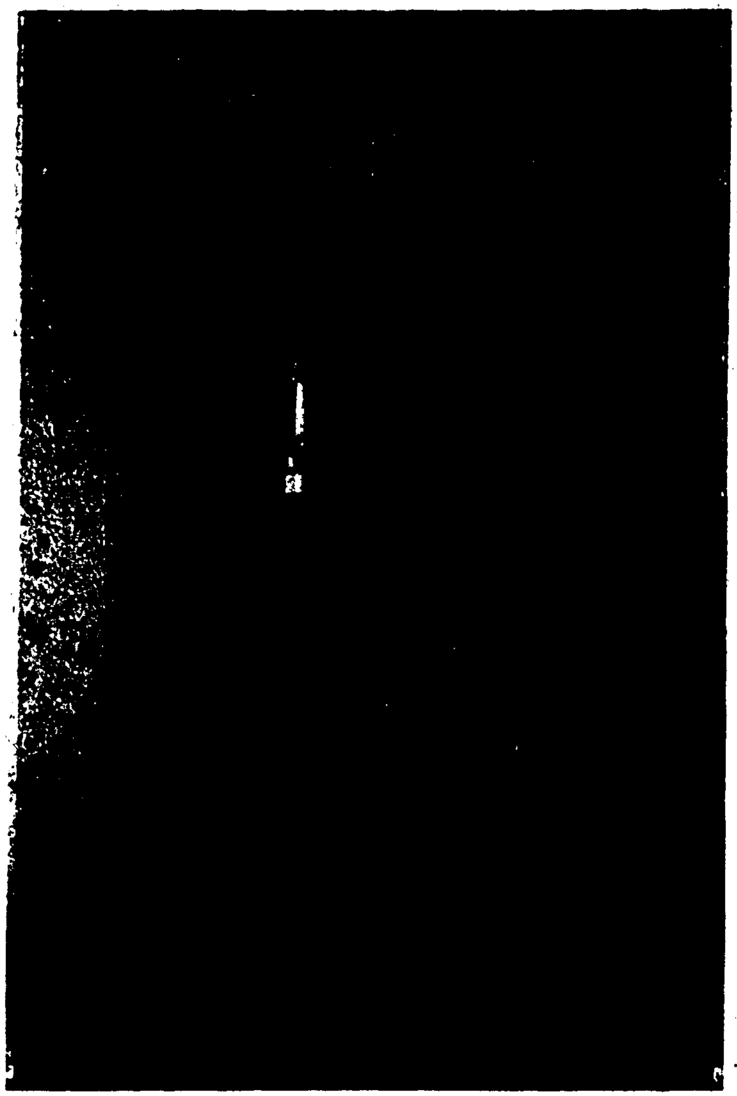

FIGURE 1.2 ICG Standard - conventional

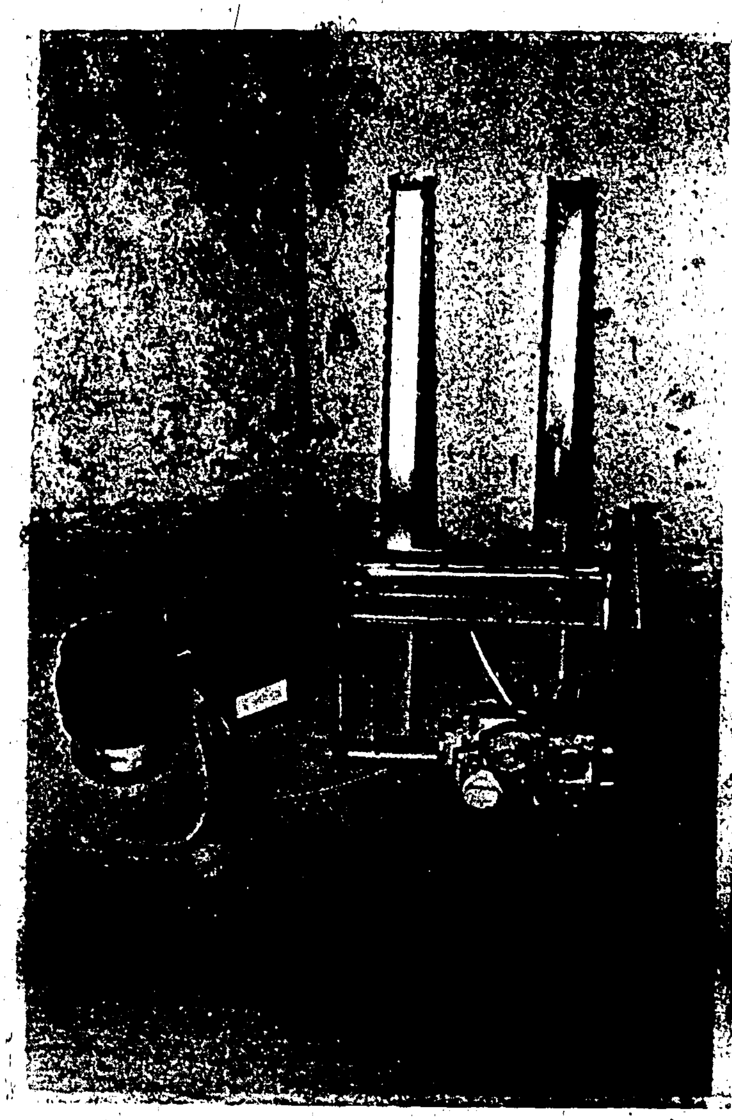

FIGURE 1.3 ICG Conserver - motorizing flue damper and electronic ignition burner pack.

1.2.3 AIRCO TURBO

The Airco Turbo is categorised among what are called mid efficiency furnaces. These are non-condensing induced draft units having seasonal efficiencies of between 80 and 90 percent.

The Airco Turbo shown in Figure 1.4 uses a small impeller type blower located at the furnace exhaust point to provide induced draft, that is, to draw combustion air into the system and to simultaneously expel exhaust gases. The Airco burner obtains efficient combustion and high flame temperature with relatively low excess air because of the controlled nature of the combustion air intake. Each of the heat exchanger heat transfer surfaces feature a matrix of 2" diameter depressions spaced approximately 4" center to center designed to enhance turbulence and improve heat transfer. The combined result of the low excess air and increased heat transfer is a significant reduction in flue gas temperature and on-cycle sensible loss. During the off-cycle, the induced draft blower does not operate providing blockage against the loss of warm room air up the stack. The Airco also features electronic ignition.

FIGURE 1.4 Airco Turbo - induced draft and electronic ignition.

1.2.4 ICG ULTIMATE

The ICG Ultimate is a high efficiency furnace. The term high efficiency usually implies that the unit is a condensing model having a seasonal efficiency greater than 90 percent. In a condensing furnace, the flue gases are cooled to below the dew point, the temperature at which the water vapor present first begins to condense. This temperature is generally around 60°C (140°F) but is dependant on the level of excess air used for combustion. This ability to dramatically cool the exhaust products eliminates the need for a standard vertical B-vent stack. A horizontal section of 2" ABS plastic pipe routed to the nearest exterior wall is all that is necessary to vent the low temperature exhaust products. This feature characterizes and readily identifies high efficiency condensing furnace installations.

The ICG Ultimate shown in Figure 1.5 uses a series of three heat exchangers to reduce its flue gas temperature to below the dew point. As in the Airco Turbo, the unit features an induced draft blower and electronic spark ignition.

The ICG Ultimate was among the first high efficiency residential furnaces to be commercially produced. Although its features were revolutionary when the model was first released, it has since been surpassed in terms of both its seasonal and steady state efficiency. Production of the furnace has been discontinued for this and for other reasons

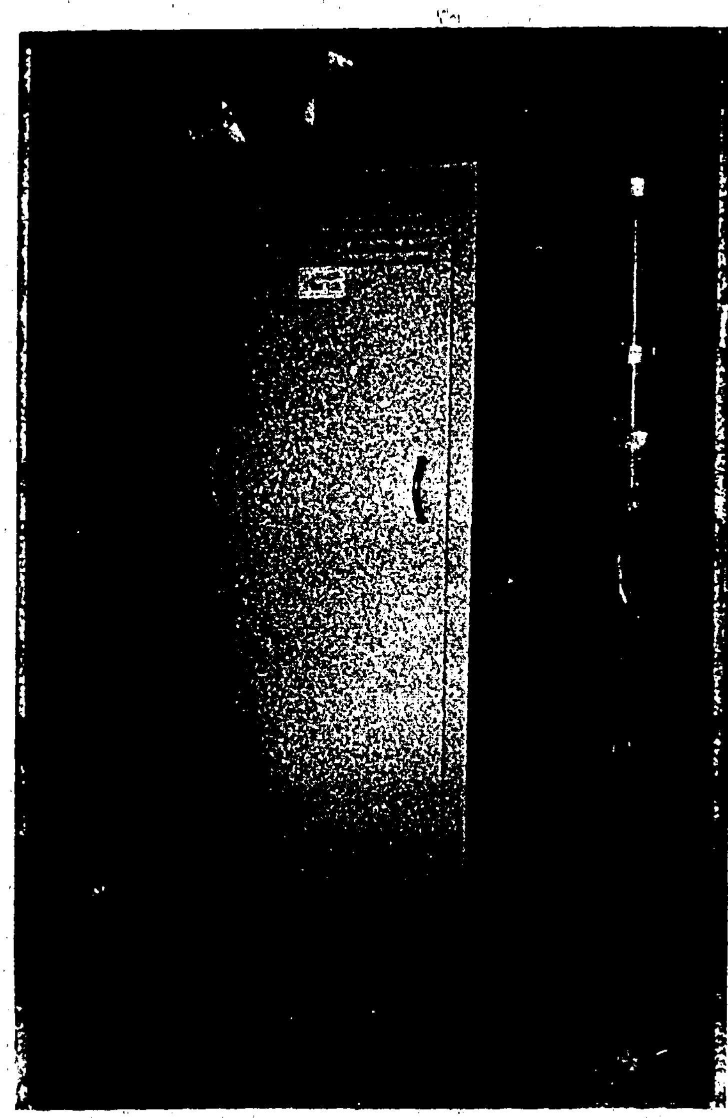

FIGURE 1.5 ICG Ultimate - induced draft, electronic ignition, and condensing.

including relatively noisy operation, inefficient circulating blower design (high electrical power consumption), and large physical size. Even though its production has been discontinued, there are still units available at reasonable cost offering favorable economics as will be discussed in later sections.

1.2.5 LENNOX PULSE

The Lennox Pulse shown in Figure 1.6(a) is a high efficiency condensing furnace featuring a unique design utilizing a phenomenon known as pulse combustion. The furnace has no conventional burner assembly. Rather, combustion occurs in a small finned chamber that is designed to generate and utilize combustion driven pulsations. The acoustic device is tuned to allow fresh charge to be drawn into the chamber, exploded and expelled in a self-sustaining cycle. The flow pulsations themselves provide the means for drawing combustion air and ventilating exhaust products, effectively eliminating the use of auxiliary electric power during operation. Electronic spark however is used, but only to initiate the self-sustained process. A second heat exchanger is used to cool the exhaust gases to below the dew point before they are vented outdoors. Figure 1.6(b) is a top view looking down into the furnace heat exchanger assembly showing the finned combustion chamber and main heat exchanger.

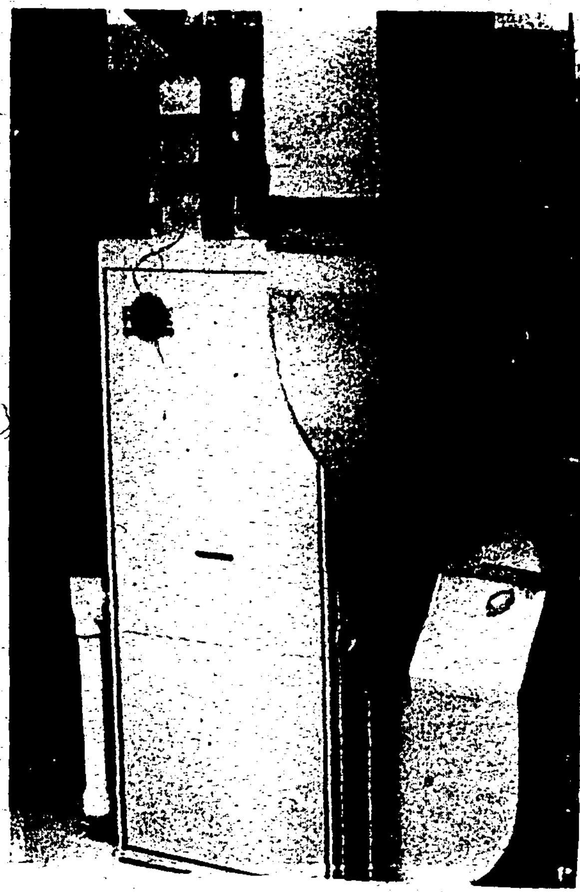

FIGURE 1.6(a)
Lennox Pulse - pulse combustion, electronic ignition and condensing.

FIGURE 1.6(b)
Top view showing combustion chamber, tail pipe and main heat exchanger.

Pulse combustion is in itself an energy saving feature of the Lennox furnace. Because pulse combustion is a constant volume process, it is accompanied by a slight increase in energy release per mass of fuel (approximately 0.5%) above that available from atmospheric or constant pressure combustion. This difference is a result of certain thermodynamic considerations, namely the difference between the constant pressure and constant volume higher heating values (HHV) for natural gas (the constant volume HHV is approximately 0.5% higher).

Because of the pulsating nature of the intake (and exhaust) flow and the potential for noise accompanying it, the Lennox Pulse draws its combustion air from outdoors and as a result does not impose any extra air infiltration load on the structure during operation. It should be noted however that this is not necessarily an energy saving feature. Computer simulation studies have shown that it is more efficient to use indoor air for combustion than outdoor air (6). The incremental loss associated with heating outdoor air for combustion is greater than that resulting from the use of indoor air.

1.2.6 AMANA ENERGY COMMAND

The Amana Energy Command shown in Figure 1.7 is a high efficiency condensing furnace. Unlike most conventional forced air furnaces, however, the Amana does not directly

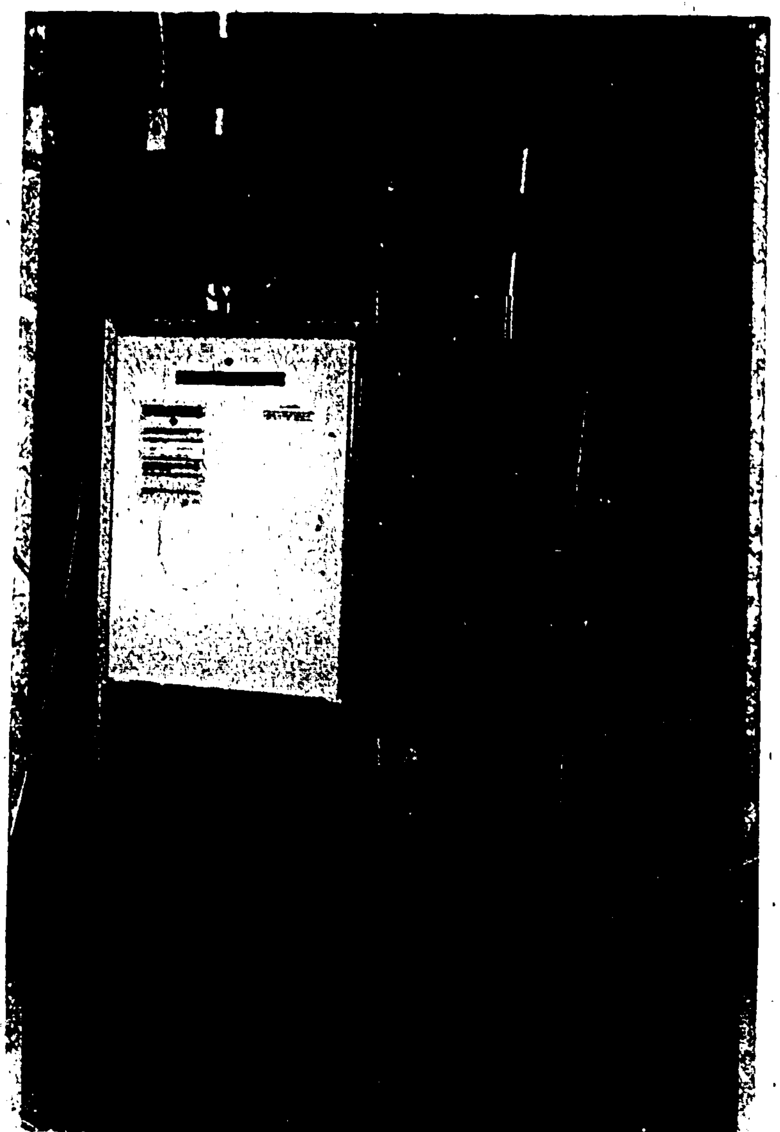

FIGURE 1.7 Amana Energy Command - induced draft, electronic ignition, circulatory water-glycol mixture and condensing.

heat the circulating room air. Rather, energy is transferred to the room air by means of a circulating water-glycol mixture. The water-glycol working fluid is first heated within the main burner/heat exchanger assembly. The heated mixture is then delivered to a second heat exchanger, similar in appearance to an automobile radiator, through which the room air is forced and subsequently heated.

Using a small blower, fuel and combustion air (room air) are driven radially through a cylindrical stainless steel mesh within the primary heat exchanger or patented Heat Transfer Module (HTM). The mixture is ignited using an electrically heated ceramic ignitor located just outside the porous mesh where the flame, once burning, is maintained. Low excess air, large flame area, and strong induced turbulence produces highly efficient combustion and energy release which is ultimately transferred to the water-glycol mixture within the HTM. Beyond the HTM, the exhaust gases are routed to another heat exchanger where they are cooled to below the dew point. Condensate is drained from this exchanger and the remaining exhaust gases are then vented outdoors using 2" ABS pipe.

CHAPTER 2

METHODS OF FURNACE TESTING

This chapter will describe the philosophies behind both the field and laboratory test procedures. It will include a description of the overall field test facility with specific reference to the modules directly involved in the furnace efficiency evaluations giving pertinent details as to their construction and relative heating performance. Also it will include a general description of a proposed federal test standard designed to allow estimation of the seasonal and steady state performance of residential gas furnaces.

2.1 FIELD TESTING

2.1.1 - DESCRIPTION OF THE FIELD TEST FACILITY

All furnace testing was done at the Alberta Home Heating Research Facility (AHHRF). The research facility was constructed in the summer of 1979 for the purpose of investigating energy consumption in residential housing. The facility is located at the University of Alberta Agricultural Farm approximately 3 kilometres west of Ellerslie, Alberta. It consists of six single-storey, double-garage sized house replicas or modules shown in Figure 2.1, each with full height walls and full concrete basements. Different construction techniques, insulation levels, and solar gain utilization schemes characterize and distinguish each of the modules enabling the study of a full range of energy consumption and utilization alternatives.

A number of exceptional features of the facility set it apart from other home heating field studies. Among these are the fact that all of the modules at the facility remain permanently unoccupied. Also, being of the same location, each of the modules is exposed to an identical climate. These two factors necessarily ensure that the thermal behavior of the modules are not complicated by inhabitant lifestyle differences and zonal climate variations. The facility uses one of its modules, Module 5, unmodified since its construction, as a reference module for comparing the thermal performance of the other units. This comparison technique greatly simplifies the assessment of the relative merits of the various module features and enables a clearer evaluation of the effects brought about by changes made to any of the other units.

All data relating to and affecting the thermal

FIGURE 2.1 The Alberta Home Heating Research Facility (Six test modules numbered in order from left to right).

performance of the facility modules is monitored on a continuous basis using two microprocessor-based data acquisition systems. The systems monitor over one hundred channels of environmental and building related measurement inputs. These include the following:

1. Environmental measurements
   - ambient air temperature
   - various ground temperatures
   - wind speed and direction
   - solar radiation
2. Building measurements
   - room, basement, and attic air temperatures
   - south-facing wall temperature
   - basement wall and floor heat loss
   - rates of air infiltration
   - electrical energy input
   - natural gas volume input (Mod.3,4)

Data from each of the inputs are recorded every 2 minutes, averaged or summed hourly as necessary, and then transferred to magnetic tape for later analysis.

2.1.2 - FIELD TEST PHILOSOPHY

Furnace field tests were performed in Modules 3 and 4 at the AHHRF. In these two modules, the six natural gas furnaces were installed and monitored over the regular heating season according to the schedule outlined in Table 2.1. During each test session, the two gas furnaces on test were cycled alternately with electric furnaces on a one week on, one week off basis. Two reasonable assumptions were used during the investigations: first, that the electric furnaces would provide 100% efficient heating, and second, that the thermal performance of the structures would remain relatively constant between successive on and off weeks. These assumptions would allow weekly comparisons of module performance data, prorated on the basis of heating degree days, to obtain estimates of in situ gas furnace efficiency. Changes in in situ efficiency over the course of each test session would be expected to occur as the result of weekly changes in climate severity. It was reasoned that these changes could be used to offer insights into the effects of furnace oversizing.

The same method of data comparison could be modified slightly to enable evaluation of efficiency in terms of the reference module, Module 5. Module 5, as discussed earlier, is used as a reference to gauge the relative performance of all other modules.

Finally, the performance data from Modules 3, 4, and 5 would be averaged over each full test session and compared, again using similar methods, to obtain long term values of in situ efficiency which would approximate the seasonal values of each unit.

TABLE 2.1 FIELD TEST SCHEDULE

TEST SESSION	MODULE #3	MODULE #4
Oct.1984 → Dec.1984	ICG Utimate	ICG Standard
Jan.1985 → Mar.1985	Lennox Pulse	ICG Conserver
Nov.1985 → Mar.1986	Amana E.C.	Airco Turbo

2.1.3 - DESCRIPTION OF TEST MODULES

The three high efficiency furnaces, namely the ICG Ultimate, the Lennox Pulse and the Amana Energy Command, were selected for testing in Module 3, the Energy Conservation Module. It was felt that this choice was consistent with the conservation scheme of the module and typical of the application of such units by the energy conservation enthusiast. The distinguishing feature of the module is its high insulation level and low natural air infiltration. The insulation level in this module represents approximately 4 times that used in conventional house construction. The low natural air infiltration, representing approximately 1/5 that of standard construction, is the result of the unit's absence of a vertical flue and its double wall construction and unperforated vapor barrier. Table 2.2 shows some of the relevant design and performance details of Module 3 as well as those of Modules 4 and 5. A more detailed description of each test module may be found in the facilities annual reports[7,8,9]. Figure 2.2 is a photograph of the three modules.

The ICG Standard, the upgraded ICG Conserver, and the mid-efficiency Airco Turbo, were selected for testing in Module 4, the Passive Solar Module. The passive solar heating which characterizes this module is obtained through two large south facing windows. The unit is fitted with an

TABLE 2.2 OVERVIEW OF TEST MODULE CHARACTERISTICS

MODULE CHARACTERISTIC	MODULE #3	MODULE #4	MODULE #5
NOMINAL INSULATION LEVEL - RSI($R_{English}$)			
Ceiling	14.80(80)	7.04(40)	3.52(20)
Walls	7.04(40)	3.52(20)	1.76(10)
Bmt.Walls*	3.52(20)	1.76(10)	1.76(10)
NATURAL AIR INFILTRATION (ACH)	0.1	0.2	0.35
SOUTH FACING WINDOW AREA (% Floor Area)	11.3	22.6	0.0
RELATIVE ENERGY** CONSUMPTION	40	61	100

* - Module 3 and 4 basement walls insulation over the full height. Module 5 is insulated to 0.61 m below grade.

** - Relative energy consumptions averaged over 1982-85.

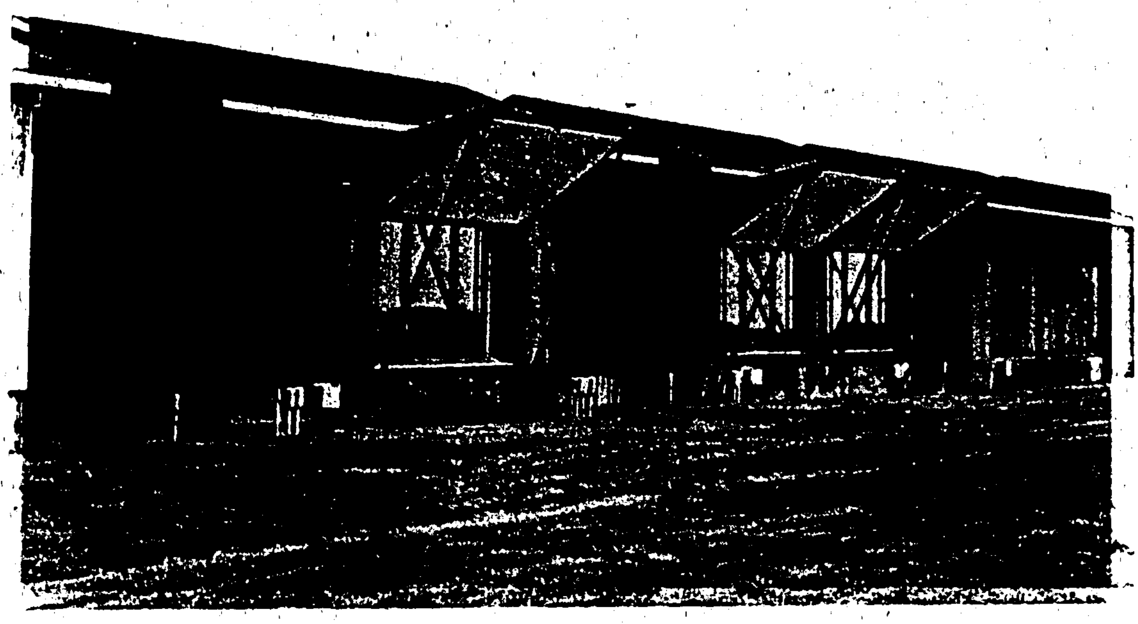

FIGURE 2.2 The Conservation Module (Module 3) and Passive Solar Module (Module 4) both used for furnace testing. The Reference Module (Module 5) also shown in background.

open vertical flue and has had no extra measures taken to reduce infiltration. This module was the best choice for testing these units since, next to Module 3, it required the lowest purchased energy input. This matching was necessary in order to ensure similar loading of all of the furnaces under investigation.

Module 5, the Reference Module, features standard construction and insulation levels and experiences rates of air infiltration typical of homes built in the 1970's. Although the module is electrically heated, it uses an open vertical flue pipe to induce envelope pressure distributions similar to those occurring in a conventional structure heated by a standard natural gas furnace. The module has no south facing windows and is thereby not greatly influenced by solar radiation.

2.2 - LABORATORY TESTING

Laboratory testing of each furnace was done on location at the AHHRF in Modules 3 and 4. Tests were performed according to the proposed Canadian Gas Association seasonal test standard CAN1-P.1-85 [10] to enable the unbiased evaluation of seasonal and steady state efficiency for each of the units.

2.2.1 BACKGROUND OF THE TEST PROCEDURE

In 1980, a Canadian Gas Association standards committee included coverage in the central furnace standard designed to encourage the purchase of energy efficient appliances. The amendment required mandatory labeling of each appliance indicating the actual output capacity (energy input minus the flue losses) as determined according to a prescribed test standard. It was felt that this marking would provide the consumer with some guidance when sizing a furnace for a particular building and that it would serve as a reference for comparing relative furnace performance.

The committee later recognized that the required marking accounted for the furnace's performance only under steady state conditions. It was therefore necessary that the existing test standard be reviewed and expanded to allow for the determination of a seasonal efficiency which would adequately account for and give credit to special features such as automatic vent dampers, spark ignition, condensation capability, and so on. The Canadian proposed test standard was developed after an extensive review of the United States Department of Energy seasonal test standard for furnaces and boilers (NBSIR 78-1543). The current revised edition of the standard is the CAN1-P.1-85 entitled Seasonal Gas Utilization Efficiency of Gas-Fired Central Furnaces.

2.2.2 - DESCRIPTION OF THE TEST PROCEDURE

At present, the CAN1-P.1-85 test procedure is offered to Canadian residential gas furnace manufacturers only as an optional procedure for use in making representation of energy consumption or energy efficiency. Unlike the steady state performance evaluation outlined in the CAN/CGA-2.3-M86 referenced earlier, the evaluation of seasonal efficiency is not a mandatory requirement.

The CAN1-P.1-85 test procedure essentially provides a method of evaluating seasonal efficiency, a figure which represents the dynamic performance of the unit and one which accounts for various energy saving features incorporated in the design. The procedure uses a flue loss method for determining first the steady-state and then seasonal efficiencies of the unit. Flue gas temperatures and CO_2 levels are measured within the furnace stack which are in turn used to determine the losses associated with the particular furnace design.

STEADY STATE TEST

During the steady state test, the furnace under investigation is operated continuously until steady-state operation is attained. The peak flue gas temperatures and CO_2 concentrations are then measured as is the rate of natural gas energy input. If the furnace happens to be a condensing model, condensate is collected for a specified amount of time and weighed to determine the rate of condensation. From these measurements are calculated the percent loss of sensible heat ($L_{S,SS,A}$), the latent heat loss ($L_{L,A}$) and, if applicable (condensing), the latent heat gains ($L_{G,SS}$). These losses are then combined to arrive at the steady-state efficiency of the furnace:

$$\eta_{ss} = 100 - L_{L,A} - L_{S,SS,A} + L_{G,SS} - L_{C,SS}$$

In addition to the normal energy loss due to the venting of high temperature flue gas, the sensible heat loss term ($L_{S.SS.A}$) also includes losses associated with excess air and dilution or draft hood air. The final term in the expression ($L_{C.SS}$) represents, for a condensing furnace, the energy lost due to condensate going down the drain at room temperature.

SEASONAL EFFICIENCY TEST

To determine the value of furnace seasonal efficiency, a test procedure must be used which accounts for system losses occurring as the result of furnace cycling. The procedure must consider the flow of room air through the heat exchanger and draft assembly during both operation and inoperation and must enable determination of the impact of these flows on air infiltration.

The seasonal performance test requires that the flue gas temperature versus time profiles be determined while warming up from a cold start and while cooling down from steady-state. From these profiles, effective flue gas temperatures may be calculated which, together with certain factors describing flue and stack flowrates (functions of furnace design), may be used to evaluate the dynamic system losses. Specifically, these losses are the sensible heat losses during the on and off periods ($L_{S,ON}$ and $L_{S,OFF}$) and the corresponding infiltration losses ($L_{I,ON}$ and $L_{I,OFF}$) imposed on the structure. If the furnace is a condensing model, a cycling test is performed in which the furnace is cycled several times under a simulated load factor of 22.5%. Following each cycle the condensate is collected and weighed to determine the latent heat gain under part load operation (L_G). These steady-state and dynamic losses are then combined with the latent loss, the latent gain (if condensing) and the pilot light loss during the nonheating season, if applicable, to yield the Seasonal Gas Utilization Efficiency (SGUE):

$$SGUE^{*} = 100 - L_{L.A} - (L_{S.ON} + L_{S.OFF} + L_{I.ON} + L_{I.OFF}) + L_G$$

* - As shown, SGUE assumes no pilot flame for simplicity.

In arriving at this value of seasonal efficiency, certain factors must be assigned such as the average annual heating degree days, the average indoor and outdoor temperatures, the infiltration parameter, and so on. The results of this test method therefore do not necessarily represent the actual efficiencies which might be realized in the field, but rather ensures the repeatability of results enabling true comparison of relative furnace performance.

CHAPTER 3

ANALYSIS AND RESULTS OF FURNACE PERFORMANCE

Seasonal efficiency, as described in Chapter 1, is the most meaningful measure of furnace efficiency from the standpoint of the consumer because it most accurately reflects the cost of home heating. Evaluation of such a parameter characterizing long term performance requires either that the furnace's operation be observed under actual field conditions over an extended period or that it be monitored according to a carefully controlled test procedure designed to simulate long term effects. The first part of this chapter will deal with the evaluation of furnace seasonal efficiency according to the first method, namely by the analysis of field data acquired from the in situ operation of each unit. The field test method will not focus on the furnace and its immediate losses but rather on the energy gains and losses associated with the heated modules within which they are installed. The second part of this chapter will look at the furnace performance evaluation according to the CAN1-P.1-85 laboratory test standard.

3.1 ANALYSIS OF FIELD DATA

Results obtained from many similar studies of in situ gas furnace performance suggest that the task of obtaining an accurate value of furnace efficiency while monitoring only the obvious affecting parameters of interior temperature, exterior temperature, and purchased energy is much more difficult than it may appear. What is often overlooked is the significance of the other climate related parameters such as radiation and infiltration. What has been discovered in this study is that, because each of these parameters does provide a measurable contribution to the overall balance of energy in the structure, they cannot be simply overlooked.

3.1.1(a) EFFICIENCY EVALUATION THROUGH DIRECT COMPARISON OF TOTAL ENERGY TRANSFERS DURING ON/OFF WEEKS

For any heated structure, the energy input necessary to maintain room temperature is dependant on the thermal characteristics of the building envelope and on the severity of the climate or ambient conditions. While the ambient conditions may be described in terms of outdoor temperature, wind velocity, solar intensity, and so on, the envelope characteristics determine the building's response to these conditions: its ability to resist loss and to utilize gain. Figure 3.1 illustrates the various energy gains and losses

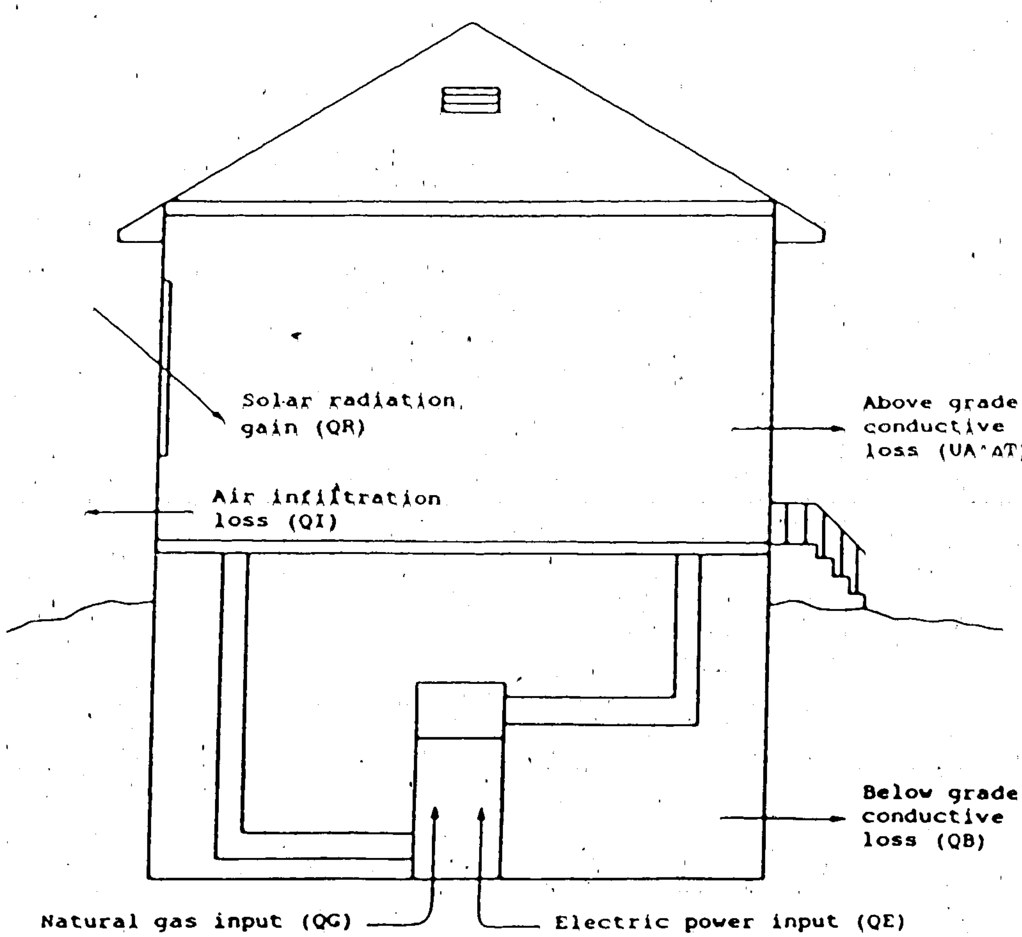

FIGURE 3.1 Energy Gains and Losses of a Typical Structure.

that are typically associated with a heated structure. What is fundamental to the analysis of field data is that the energy losses, shown as air infiltration and conductive losses, are in fact balanced on average by solar radiation and the purchased energy inputs of gas and electricity.

Above grade conductive loss, typically the major component of energy loss, is a function of the overall conductance of the structure and the indoor-outdoor temperature difference. The indoor-outdoor temperature difference, ΔT, is defined in terms of the product of the indoor-outdoor temperature difference and the duration of heating demand and is measured in units of heating degree days (HDD). The term is commonly used as the basis for defining energy consumption in houses and is of particular use when comparing energy consumption between different structures and different time frames as will be discussed shortly. The overall conductance, or UA, is a property of the physical structure which describes the building's resistance to heat loss. Because a building is normally made up of a complex assembly of materials, including doors, windows, multi-layered walls and ceilings, basements, and so on, the term UA conveniently describes the equivalent thermal resistance of the <u>entire</u> structure. If basement loss is measured separately, UA may be interpreted as representing only the above grade portion of the structure.

Because of the comprehensive nature of the term, the value of UA is not something easily measured. It may, however, be estimated though a number of techniques. One such method requires the availability of reliable data describing the structural energy gains and losses discussed earlier.

Notice in Figure 3.1 that if electrical heating is employed, UA becomes the only unknown parameter. Under such a condition, UA may easily be solved for by considering the energy balance of the structure.

$$\text{ENERGY LOSS} = \text{ENERGY GAIN}$$

$$UA*\Delta T+QI+QB = QE+QR$$

or rearranging:

$$UA = \frac{QE+QR-QI-QB}{\Delta T} \qquad (3.1)$$

Because UA is a property of the structure, its value may be assumed to remain constant with time*. Therefore if the structure is heated periodically with natural gas on a one week on - one week off cycle, the value of UA may further be assumed to be of equal value between the on and off time frames. (The terms "on" and "off" throughout the remainder of this text will refer to the gas heating and electric heating periods respectively). If comparison of module performance between the two time frames is made on the basis

* - The thermal resistance of some building insulation materials is known to vary slightly with temperature and/or age. For the purpose of this study however, these variations may be considered as negligible.

of UA similarity, the actual value of UA becomes immaterial and the comparison enables isolation of the only remaining unknown, namely η or furnace efficiency.

$$UA_{on} = UA_{off}$$

$$\frac{\eta QG_{on}+QE_{on}+QR_{on}-QI_{on}-QB_{on}}{\Delta T_{on}} = \frac{QE_{off}+QR_{off}-QI_{off}-QB_{off}}{\Delta T_{off}}$$

or rearranging:

$$\eta = \frac{1}{QG_{on}}\left(\frac{(QE_{off}+QR_{off}-QI_{off}-QB_{off})}{\Delta T_{off}}*\Delta T_{on} - (QE_{on}+QR_{on}-QI_{on}-QB_{on})\right) \qquad (3.2)$$

(summation of each term over time is assumed)

In theory, this technique may be applied to data representing any testing time interval (daily, weekly, etc.). However, when applied to the existing test data, the method did not give satisfactory results in the short term. Weekly comparisons delivered very poor results, often producing unrealistic values for furnace efficiency (between 60 and 100% for the standard furnace and between 80 and 140% for the high efficiency models). The inability to accurately measure basement heat loss and to properly quantify the overall influence of solar radiation was assumed responsible.

A long term comparison was then attempted whereby separate tallies were made of all on and off period data covering the full test session of each furnace. These long term groupings were then compared using the same relationship (Equation 3.2) and were found to give much better results. These are shown in Table 3.1.

These calculated values, approximations of seasonal efficiency, appear to be generally higher than expected for those units tested in Module 4. This result is presumed to be due to additional heat gains occurring beyond the furnace heat exchanger in the uninsulated section of flue pipe connecting the furnace to the vertical B-vent (insulated) stack. Calculations found in Appendix A with respect to the Airco Turbo show energy recovery from the 2.5 m length of 10 cm diameter pipe to be highly significant representing an apparent efficiency increase of approximately 2.5% due to sensible gains and an additional 5% due to latent recovery. (Similar calculations, not shown in the appendix, indicate apparent efficiency increases for the ICG Standard and Conserver models of approximately 3% resulting from sensible gains. Because of the higher mass flowrates however, exit temperatures from the uninsulated flue section are typically much above the local dew-point negating the possibility of latent recovery for these two furnaces). Results for the remaining high efficiency units appear somewhat scattered suggesting perhaps inaccuracy in the data and/or the improper quantification of certain parameters.

TABLE 3.1 FURNACE EFFICIENCY RESULTS FROM DIRECT COMPARISON OF ON/OFF PERIOD ENERGY TRANSFER TOTALS.*

FURNACE	OBSERVED IN SITU EFFICIENCY (%)
ICG Standard	71
ICG Conserver	80
Airco Turbo	91
ICG Ultimate	97
Lennox Pulse	98
Amana Energy Command	92

* - Calculations assume equal basement heat losses between gas furnace on and off periods thus enabling cancellation.

As indicated in Table 3.1, the given results make use of a certain assumption regarding basement heat loss. The assumption in general states that long term average basement heat losses occurring during the gas furnace on periods are of similar magnitude to those occurring during the gas furnace off periods thereby enabling them to effectively cancel each other out. It was necessary to employ such an assumption since difficulties were encountered in properly quantifying basement heat losses. The equipment used at the test site to measure basement heat loss was only capable of measuring one dimensional heat flow even though the actual flows were known to be both one and two dimensional. Measurements taken were found to be generally inaccurate and not representative of the true magnitude of the occurring losses. Furthermore, because basement heat loss data was being recorded only in Module 4 of the furnace test modules, the losses in Module 3 could only be estimated from this data on the basis of insulation similarity (refer to Table 2.2).

Justification for the treatment of basement heat loss in this manner is as follows. For a typical residential basement configuration, there is exposure of the basement's exterior surface to two separate environments, namely to ground and to atmosphere. Below grade, heat loss is dependant on the ground temperature. In the short term, because of the high thermal capacitance of the soil, random fluctuations in ambient temperatures are largely attenuated and therefore generally not observed. What is observed is a more predictable, seasonal variation closely related to the long term or average ambient behavior. As a result, the weekly change in below grade temperature and therefore basement loss may be assumed to be very small. Correspondingly, the long term totals of these on and off period losses may be viewed as being of equal magnitude, thus enabling the effective cancellation of basement heat loss from Equation 3.2.

Unlike the below grade structure, the above grade portion is directly exposed to atmospheric conditions and is highly dependant on ambient temperature change. Because of the relatively low thermal resistance of the basement wall (see Table 2.2), the above grade basement heat loss is of high significance. The actual measurement of this above grade component, however, is not strictly required since, according to the nature of the analysis, its effect may be automatically included in the value of above grade UA.

3.1.1(b) EFFICIENCY EVALUATION THROUGH COMPARISON OF ENERGY TRANSFER TOTALS WITH MODULE 5

The previous analysis essentially provided a method of comparing data between two separate time frames, namely between the weeks that the gas furnaces were in operation and the weeks that electric furnaces were in use. It is possible that certain parameters, though carefully measured, were not being properly quantified. The random differences in the ambient conditions occurring between the two time frames may not have been fully accounted for, resulting in a certain degree of error. To overcome this difficulty, comparison of data with that of a reference would be of use, enabling evaluation according to common time frames.

As described in the first chapter, Module 5 is the reference module for the test facility and is used to gauge the relative performance of all the other units. The method of comparing the energy requirements of Modules 3 and 4 with that of Module 5 is very similar to that outlined in the previous section. In this method, however, values of UA are compared between structures rather than between time frames. During the gas furnace off periods, the ratio of UA between the test modules and the reference is established.

$$K = \frac{UA_{off}}{UA_5} = \frac{(QE_{off}+QR_{off}-QI_{off}-QB_{off})/\Delta T_{off}}{(\ QE_5\ +\ QR_5\ -\ QI_5\ -\ QB_5\ )/\ \Delta T_5}$$

This ratio is then applied to the data from Module 5 which is coincident with the gas furnace on period to obtain what may be viewed as the <u>equivalent</u> off period energy utilization occurring during the on period.

$$UA_{equiv} = UA_{5.on} * K$$

Finally, this UA equivalent is compared with the actual furnace test module on period data. The resulting equation is once again manipulated to isolate the only unknown parameter, η or furnace efficiency.

$$UA_{on} = UA_{equiv}$$

$$\frac{\eta QG_{on}+QE_{on}+QR_{on}-QI_{on}-QB_{on}}{\Delta T_{on}} = UA_{equiv}$$

$$\eta = \frac{1}{QG_{on}}\left[UA_{equiv}*\Delta T_{on} - (QE_{on}+QR_{on}-QI_{on}-QB_{on})\right] \qquad (3.3)$$

One minor difficulty in applying this analysis stems from the fact that Module 5 has no south facing windows which up to this point has been the basis for estimating the solar energy input to each module. Direct beam solar radiation is among the forms of solar radiation monitored continuously at the test site. The overall solar radiation gain to each module is approximated by multiplying this radiation component, measured in units of W/m^2, by the total south facing window area. Although there is no south facing window in Module 5, there is sufficient evidence to suggest that radiation does in fact influence the heating load of the structure. Nonetheless, because of the inability to properly quantify its impact, the radiation input to Module 5 is assumed to be zero. Even so, the results, shown in Table 3.2, are reasonable and in general show agreement with anticipated values. The somewhat high values of efficiency.

TABLE 3.2 FURNACE EFFICIENCY RESULTS FROM COMPARISON OF ENERGY TRANSFER TOTALS WITH MODULE 5.*

FURNACE	OBSERVED IN SITU EFFICIENCY (%)
ICG Standard	68
ICG Conserver	78
Airco Turbo	90
ICG Ultimate	91
Lennox Pulse	96
Amana Energy Command	92

* - Calculations assume equal basement heat losses during gas furnace on and off periods thus allowing cancellation. Module 5 solar radiation input assumed to be zero.

for the units tested in Module 4 again reflect the heat gains occurring in the uninsulated flue pipe joining the furnace and B-vent stack. As in the previous analysis, cancellation of basement loss was again assumed.

3.1.2(a) FURNACE EFFICIENCY OBTAINED USING A LINEAR REGRESSION TECHNIQUE

The method of analysis up to this point has involved the direct comparison of the test session totals of data obtained during the gas furnace and electric furnace operating periods. The analysis which follows involves a more statistical approach to the solution and makes use of linear regression on the same two groupings of data.

The method of direct data comparison, as described in Section 3.1.1, is illustrated graphically in Figure 3.2. What is shown is a plot of effective energy utilization against heating degree days. The two points A and B plotted in the figure represent the test session totals of structural energy utilization during the gas furnace on and off periods, respectively. These points may be written as:

$$A = (\eta QG_{on}+QE_{on}+QR_{on}-QI_{on}-QB_{on} \text{ , } \Delta T_{on})$$

and

$$B = (QE_{off}+QR_{off}-QI_{off}-QB_{off} \text{ , } \Delta T_{off})$$

The lines extending to each point from the origin represent the theoretical or ideal progression of the cumulative totals. What is of particular importance is the slope of the electric heating line since it represents the UA of the structure according to Equation 3.1. If the value of UA is to remain constant, it is reasonable to expect the slope of the gas heating line to be of the same value. Consequently, the operation of matching the slope of the gas heating line to that of the electric heating line is analogous to the

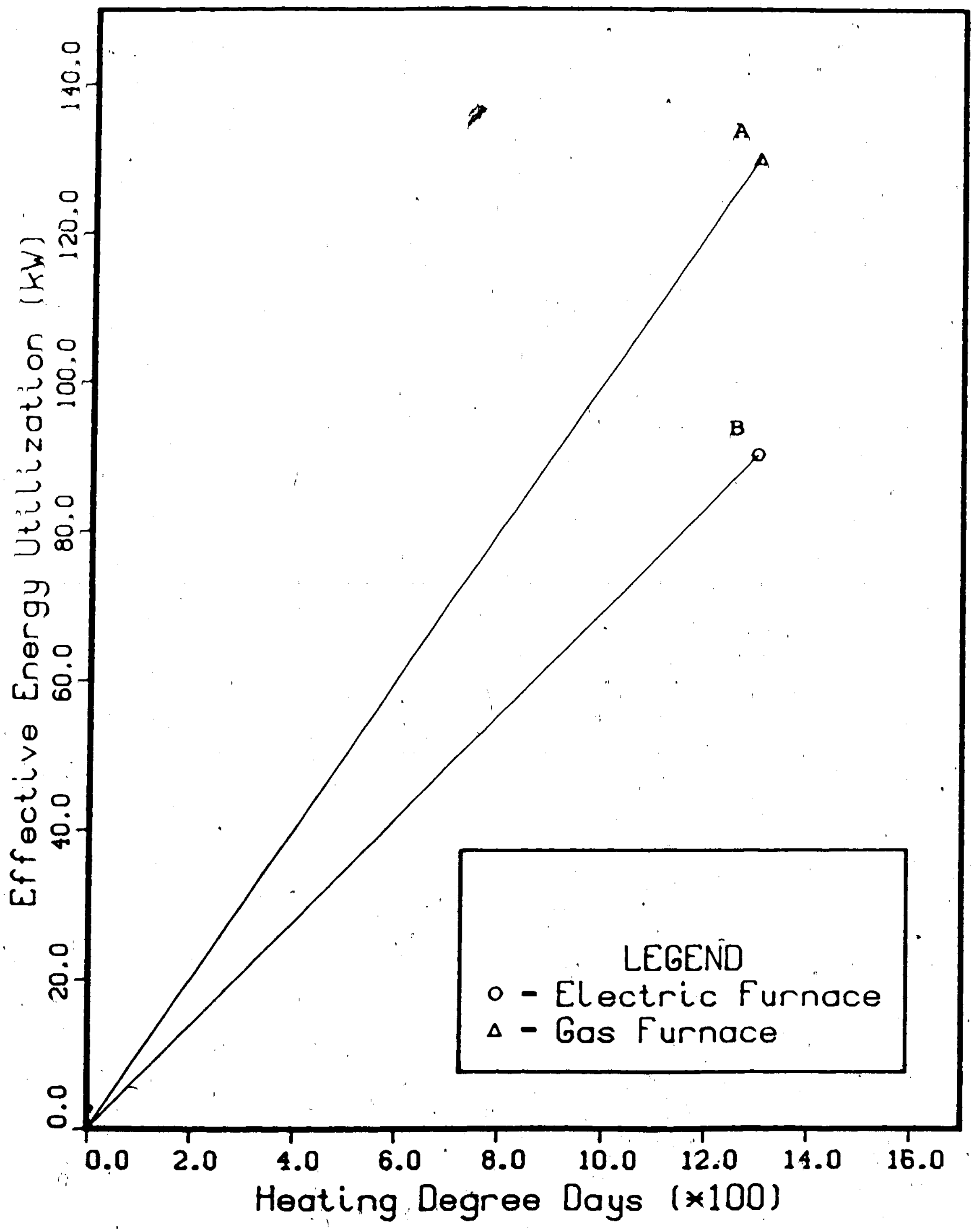

FIGURE 3.2 Graphic Illustration of the Method of Direct Comparison Showing the Test Session Totals of Structural Energy Utilization.

method of comparing UA's and the result is the identical expression for furnace efficiency, Equation 3.2.

There is, however, one inherent flaw in this analysis and that is that the slope of each line relies absolutely on the value and position of the endpoint. Because the position of each endpoint is directly affected by the contribution of every data point, it is clear that the presence of even a small amount of poor data could significantly affect the accuracy of the final result. A much better assessment of the slope of each line could be made by performing a linear regression on the same groupings of data.

Figures 3.3 through 3.8 show the actual results of linear regressions performed on the daily totals of field test data for each of the test furnaces. In each figure, the difference in slope between the gas and electrical heating lines indirectly reflects furnace efficiency; a larger difference suggesting lower efficiency and a smaller difference implying higher efficiency. By adjusting the unknown term, η, the slope of the gas heating line is altered until it is equal to that of the electric heating line. The final value of η required to obtain this match is recorded as the apparent furnace efficiency.

Results from this analysis are shown in Table 3.3. For the three high efficiency furnaces, the results show good correlation with expected values. For the remaining furnaces, those units tested in Module 4, what is again clearly observed is the large increase in apparent

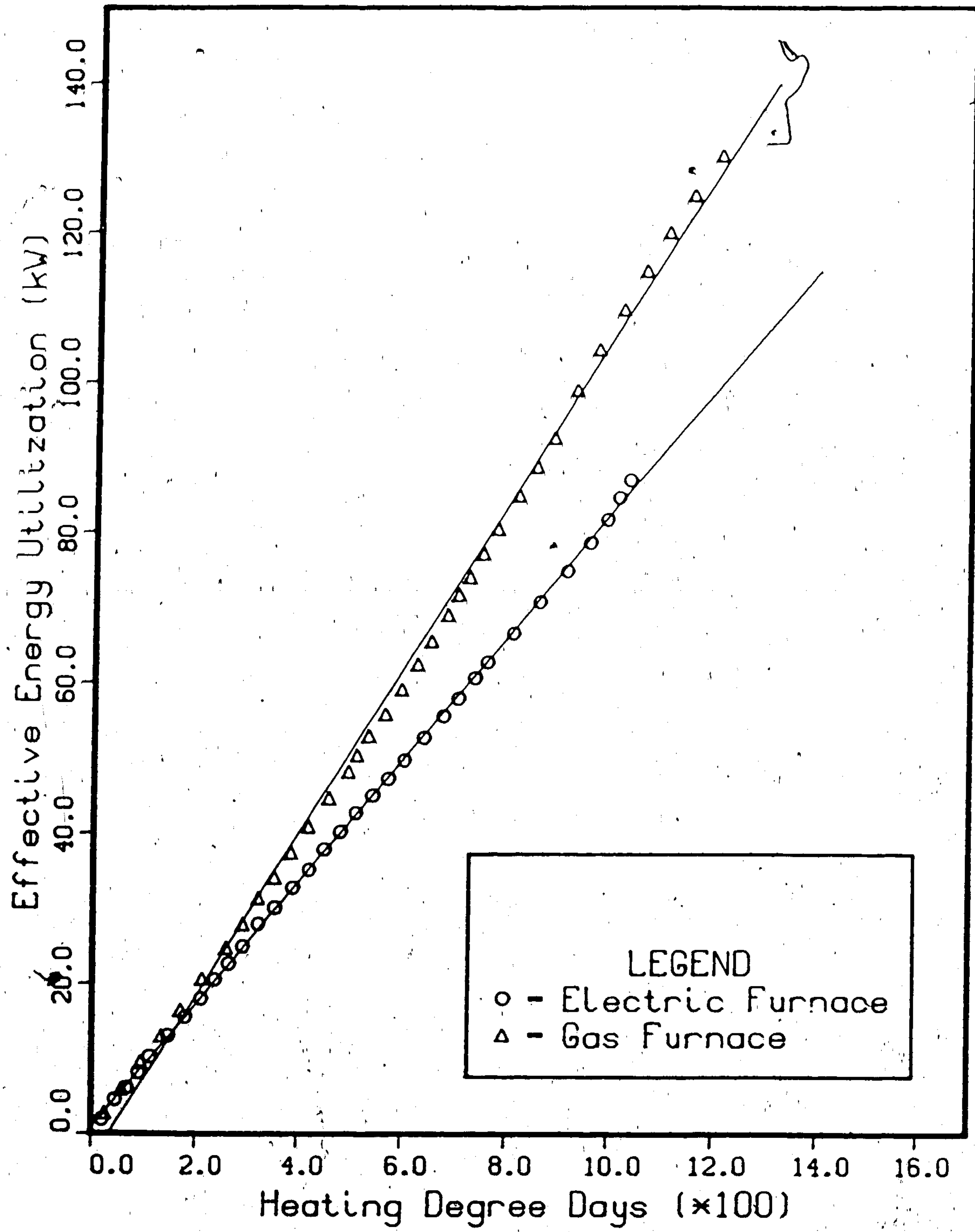

FIGURE 3.3 Module 4 Energy Utilization With ICG Standard

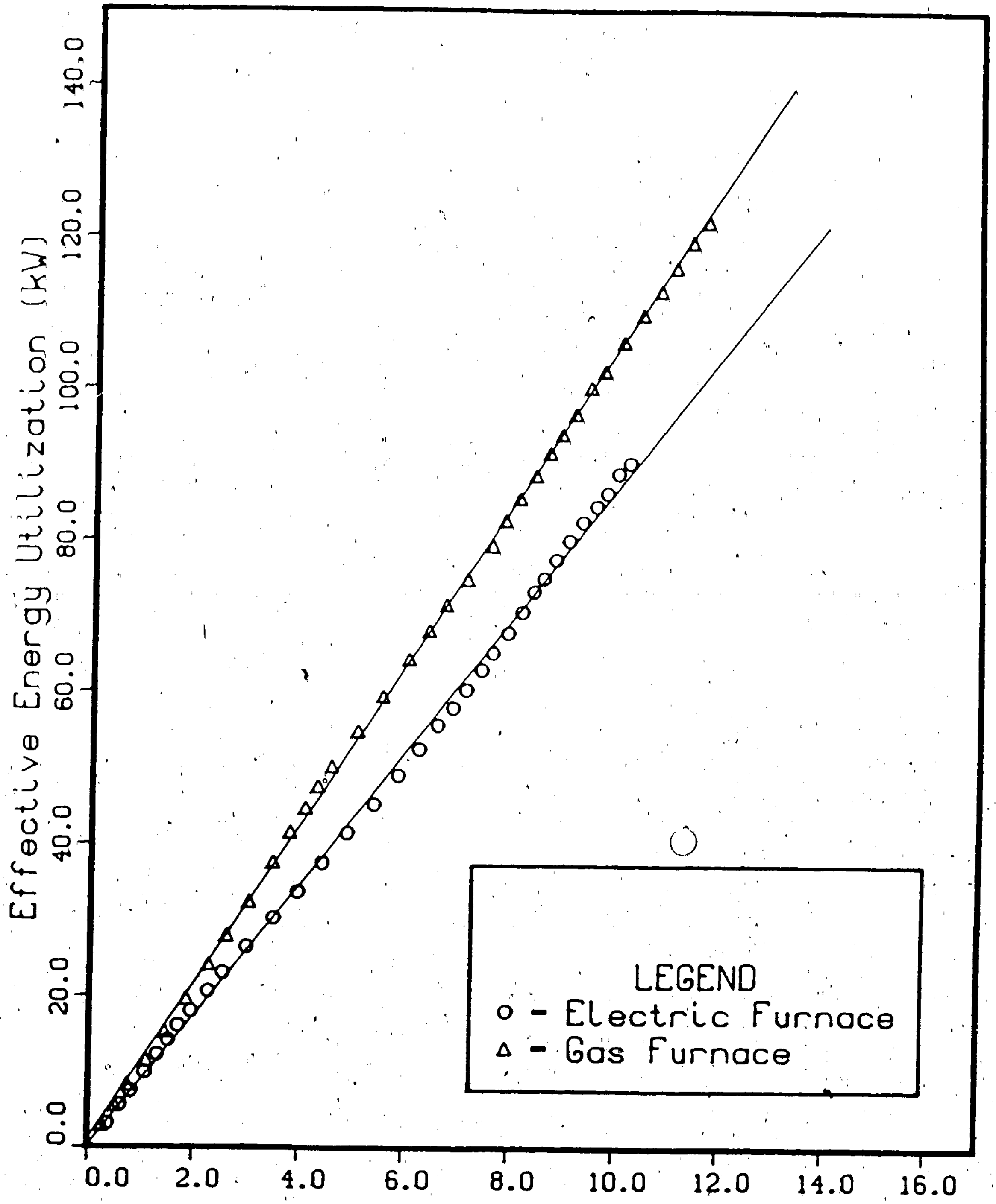

FIGURE 3.4 Module 4 Energy Utilization With ICG Conserver

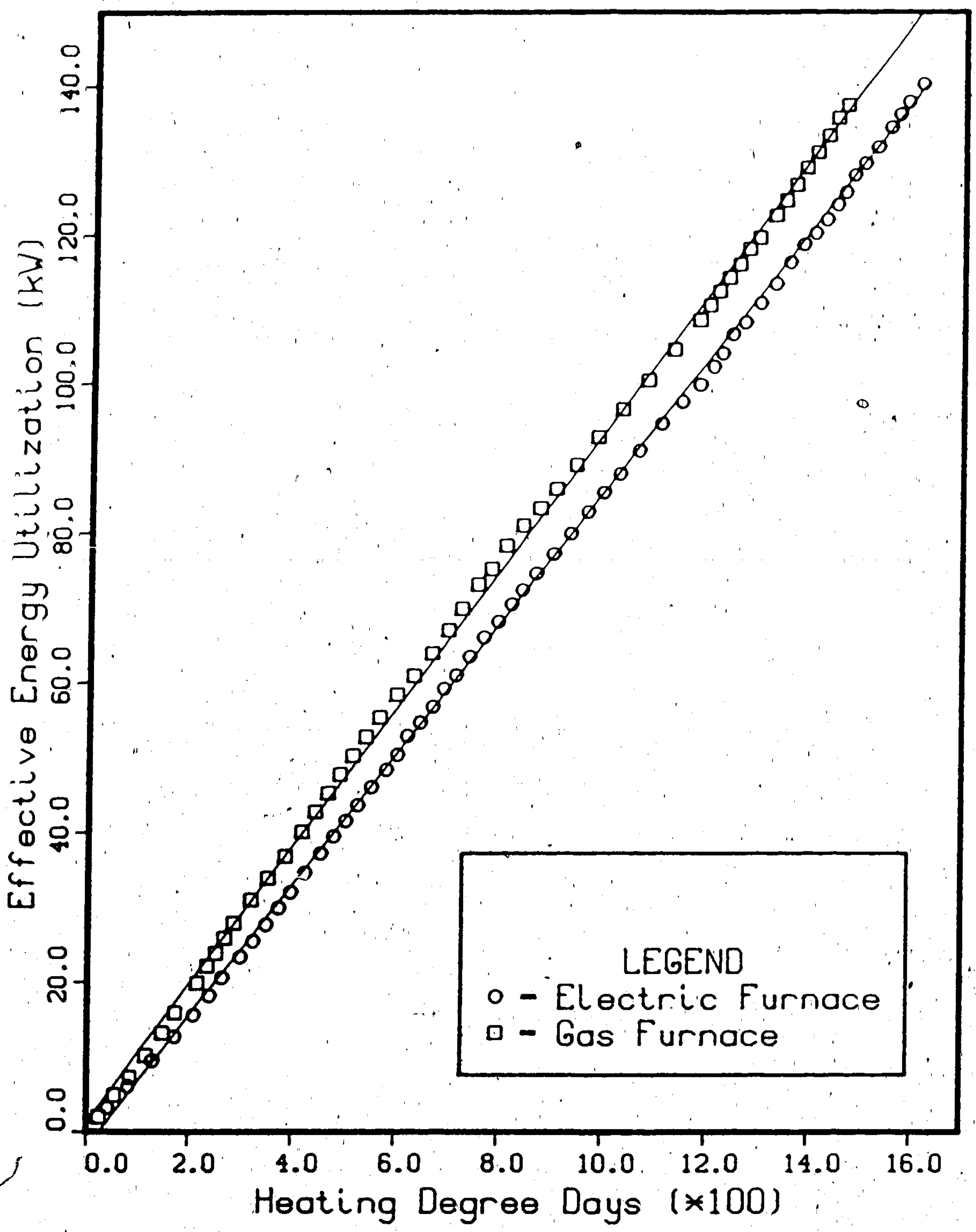

FIGURE 3.5 Module 4 Energy Utilization With Airco Turbo

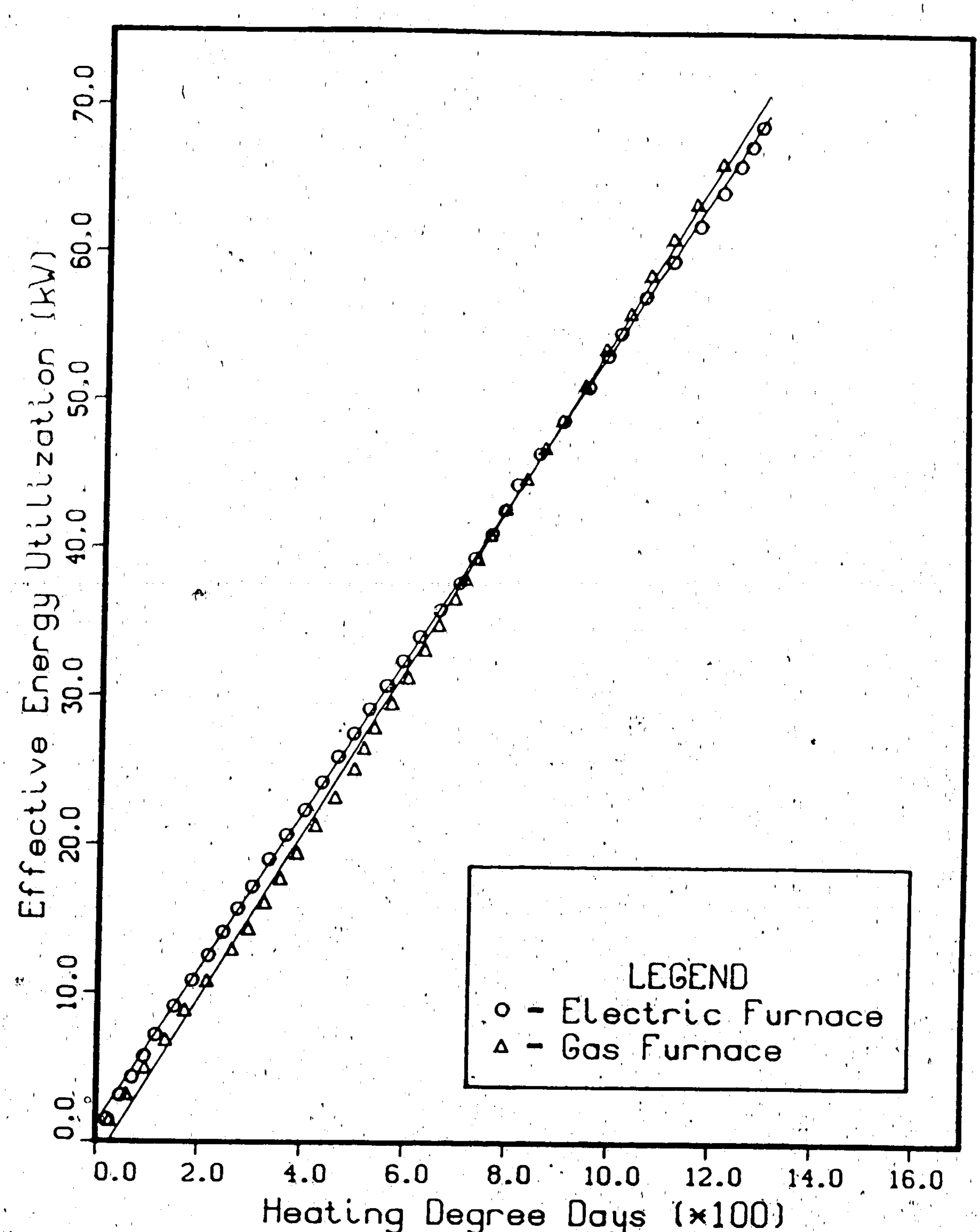

FIGURE 3.6 Module 3 Energy Utilization With ICG Ultimate

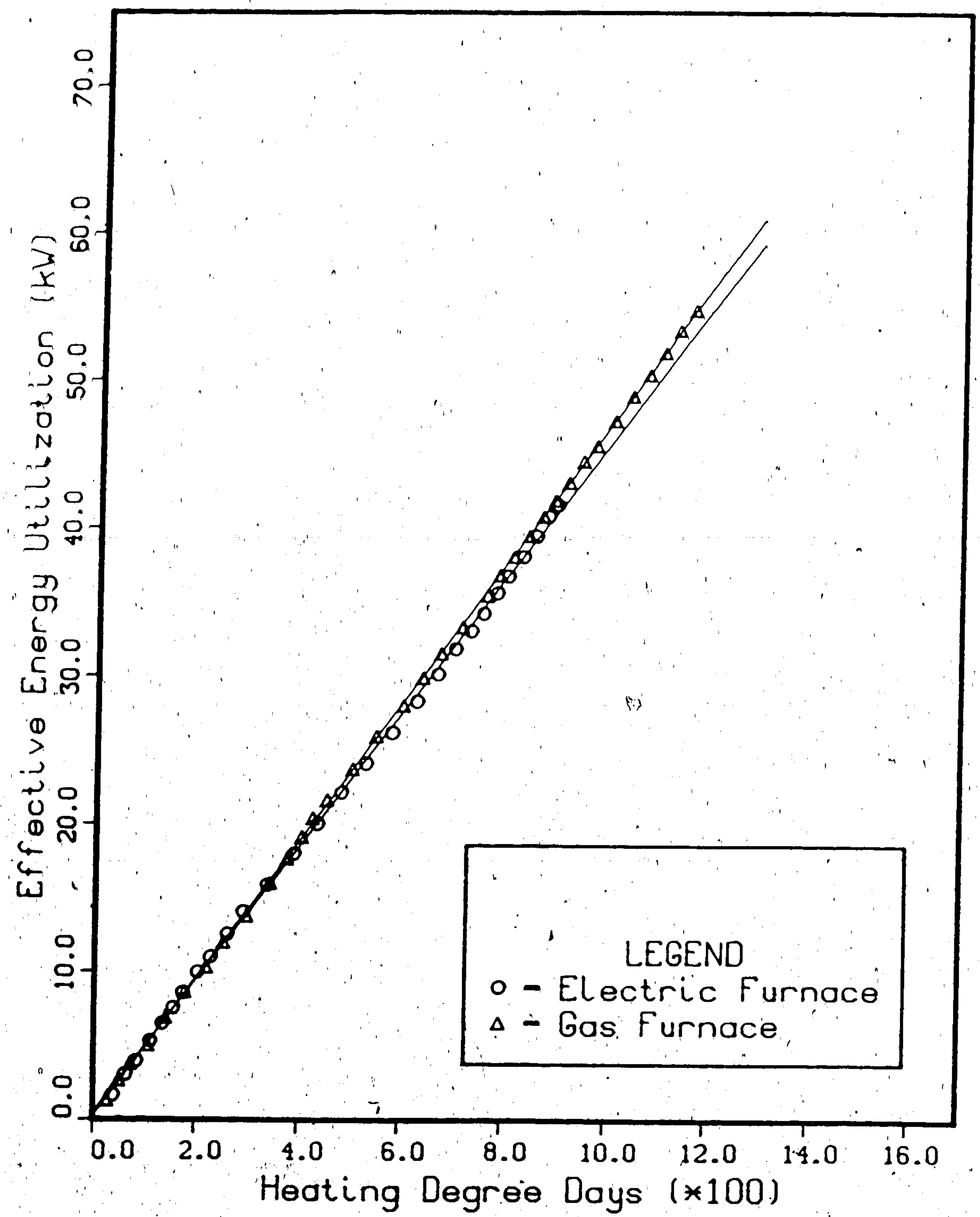

FIGURE 3.7 Module 3 Energy Utilization With Lennox Pulse

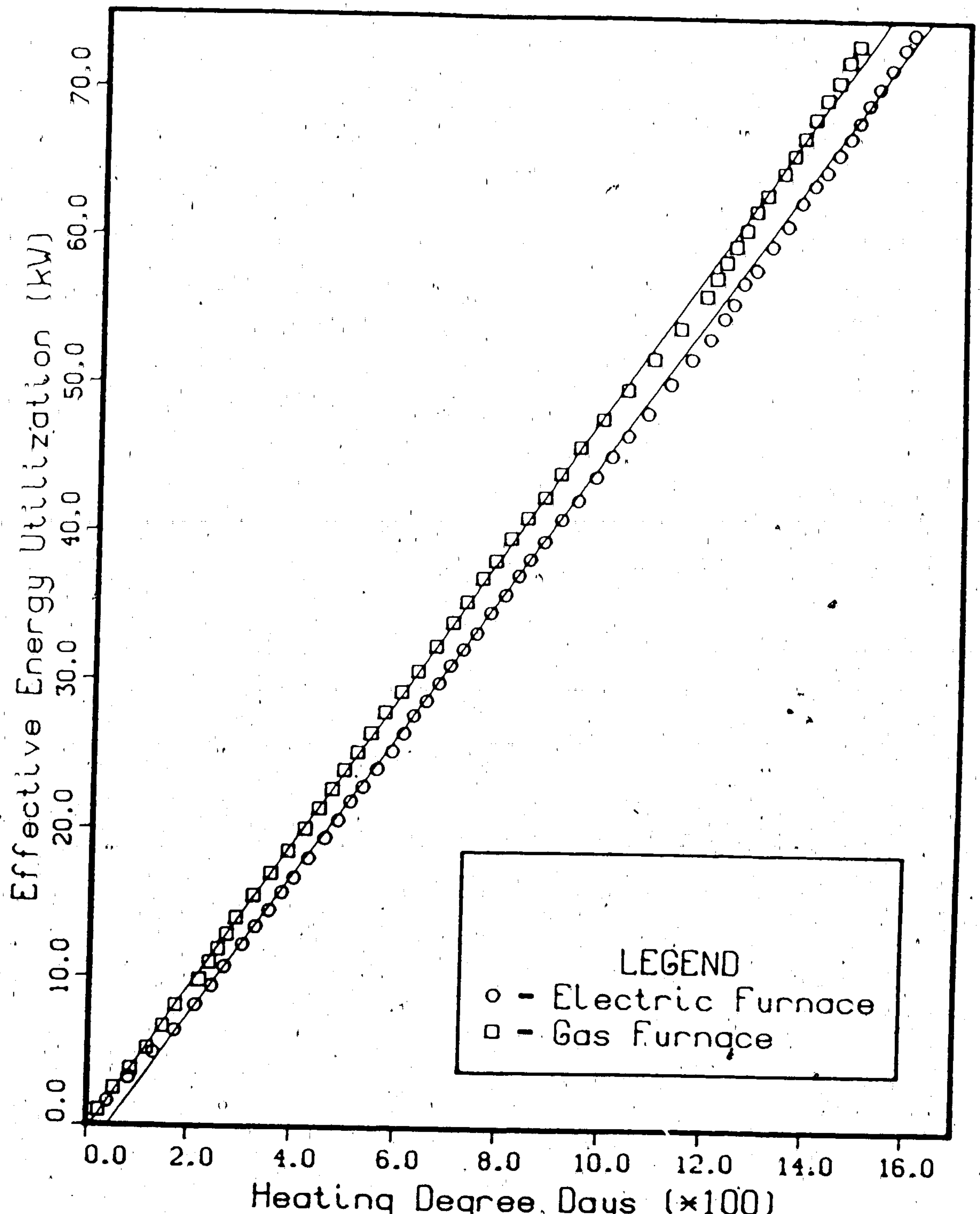

FIGURE [illegible].8 Module 3 Energy Utilization With Amana Energy Command

TABLE 3.3 FURNACE EFFICIENCY RESULTS FROM LINEAR REGRESSION ANALYSIS ON ON/OFF PERIOD ENERGY TRANSFERS.*

FURNACE	SLOPE		APPARENT IN SITU EFFICIENCY (%)
	ELECTRIC (W/HDD)	GAS (W/HDD)	
ICG Standard	81.6	109.2	72
ICG Conserver	86.8	104.4	79
Airco Turbo	87.5	92.4	93
ICG Ultimate	52.6	55.7	93
Lennox Pulse	45.3	46.8	96
Amana Energy Command	47.2	48.9	95

* - Calculations assume equal basement heat losses between gas furnace on and off periods thus enabling cancellation.

efficiency occurring as the result of the uninsulated section of flue pipe connecting the furnace to the B-vent stack. Of particular significance is the value of efficiency obtained for the standard furnace of 72%, much higher than the normally quoted seasonal value of between 50 and 60%. As well as the possible 3% efficiency increase occurring with respect to the exposed flue section, there is undoubtably an additional gain arising from the energy released by the free standing pilot flame (approximately 17% of the total average furnace output for this structure - gas plus electrical). Although some of this energy would necessarily be recovered due to the continuous operation of the circulating blower, the extent of this contribution is difficult to estimate.

3.1.2(b) FURNACE EFFICIENCY OBTAINED BY APPLYING THE LINEAR REGRESSION TECHNIQUE TO MODULE 5

This same general technique was applied to the data from Module 5 to again enable comparison of the test data between common time frames. The method that was developed is, once again essentially identical to that outlined in Section 3.1.1 except for the way in which the value of UA (slope in this case) is evaluated. During the gas furnace off periods, the ratio of slope between the test module and Module 5 is established. During the gas furnace on period, this ratio (K) is multiplied by the slope of the coincident Module 5 line to obtain a new line having a slope representing the equivalent off period UA. This is the slope to which that of the gas furnace on line is adjusted. Again, the final value of η required to obtain the match is what is recorded as the apparent furnace efficiency.

Figures representing the analysis are not included. However, the slopes of the various lines and the resulting efficiency calculations are listed in Table 3.4. These results reflect similar findings to those discussed earlier. The values of efficiency obtained for the Airco Turbo and the Amana units are somewhat questionable because of the relatively large difference in Module 5 UA observed between the on and off test periods.

TABLE 3.4 FURNACE EFFICIENCY RESULTS FROM LINEAR REGRESSION WITH MODULE 5.*

FURNACE	ELECTRIC HEATING PERIOD			GAS HEATING PERIOD			APPARENT SEASONAL EFFICIENCY (%)
	SLOPES		K	SLOPES			
	TEST MODULE (W/HDD)	REFERENCE MODULE (W/HDD)		REFERENCE MODULE (W/HDD)	EQUIVILENT ELECTRICAL (W/HDD)	GAS (W/HDD)	
ICG Standard	81.6	108.0	0.76	107.9	82.0	109.2	72
ICG Conserver	86.8	110.1	0.79	111.5	88.1	104.4	80
Airco Turbo	87.5	116.5	0.75	112.8	84.6	92.4	90
ICG Ultimate	52.6	108.0	0.49	107.9	52.7	55.7	93
Lennox Pulse	45.3	110.1	0.41	111.5	45.7	46.8	98
Amana Energy Command	47.2	116.5	0.41	112.8	46.2	48.9	92

* - Calculations assume equal basement heat loss between gas furnace on and off periods thereby enabling cancellation. Module 5 solar radiation input assumed to be zero.

3.2 LABORATORY FURNACE TESTING

The CAN1-P.1-85 laboratory test standard for furnace seasonal efficiency was described in Section 2.2.1. Essentially, the method predicts seasonal efficiency by simulating seasonal operation of the unit. The method simply requires the measurement of warm up and cool down flue gas temperature profiles, the flue gas CO_2 level, and the rate of condensate production (for high efficiency models) to enable the estimation of furnace performance as would be expected in a real use situation.

The steady state and seasonal efficiencies as predicted by the CAN1-P.1-85 test standard are shown in Table 3.5. The steady state results for the ICG Standard, the ICG Conserver and the Airco Turbo were found to be 72%, 69% and 81% respectively, significantly lower than the rated values of 77%, 77% and 84%. The 3% difference in measured efficiency between the ICG Standard and ICG Conserver (which under steady state should have been negligible) was attributed to the difference in primary air adjustment. The flue gas CO_2 levels were measured as 2.6% for the Standard and 2.2% for the Conserver. The fact that the furnaces did not achieve the level of performance indicated by their ratings was most likely due to poor burner performance under low atmospheric pressure caused by the relatively high altitude of the test site (720 m above sea level). The calculated seasonal efficiency results for the same three furnaces were found to be lower than those observed in the field. This was expected

TABLE 3.5 SEASONAL AND STEADY STATE EFFICIENCY RESULTS OBTAINED ACCORDING TO CAN1-P.1-85 LABORATORY TEST STANDARD.

FURNACE	STEADY STATE EFFICIENCY (%)	SEASONAL EFFICIENCY (%)
ICG Standard	72	67
ICG Conserver	69	76
Airco Turbo	81	83
ICG Ultimate	92	92
Lennox Pulse	97	96
Amana Energy Command	96	95

since the test standard did not reflect the external gains observed in the field measurements (uninsulated flue section). Nevertheless, the ICG Standard still performed better than expected producing a seasonal efficiency according to the test standard of 67%. The result is of particular significance since it affects the economics of the other units.

In general, the steady state results for the three high efficiency furnaces show good agreement with the ratings for each unit (refer to Table 1.2). Also, the predicted values of seasonal efficiency appear to be very similar to those values measured in the field suggesting that the CAN1-P.1-85 seasonal test procedure could in fact be used to make reasonably accurate predictions of actual furnace performance.

CHAPTER 4

EFFECTS OF FURNACE OPERATION ON AIR INFILTRATION

Most residential gas furnaces are designed for installation within the confines of the conditioned space. If combustion air ~~and~~/or draft air are not directly brought in from outdoors, these units must consume conditioned room air which must then be exhausted through the stack. To make up for the loss, outdoor air must be drawn into the residence causing an increase in the infiltration rate and a corresponding increase in the energy loss of the structure.

A standard 60,000 BTU/HR (18 kW) natural gas furnace can consume as much as 270 ft^3 (75 m^3) of indoor air per hour while operating at steady state (assuming 110% excess air and 250% dilution air). Under normal conditions however, a furnace is rarely loaded to the point of sustained steady state operation. The average seasonal load may be closer to 15% and the consumption of combustion and draft air correspondingly lower. The actual extent of reduction in infiltration however may be difficult to estimate since the imposed infiltration increase is further influenced by factors such as the sizing, the method of ignition, the tightness of the structure, and so on. Although this section will not attempt to draw any relationships between infiltration and these influencing parameters, it will present the effects on air infiltration that were observed during the testing of each furnace.

4.1 WEEKLY INFILTRATION LEVELS

Among the parameters monitored continuously at the test site are the rates of air infiltration for each module. A constant concentration of sulphur hexafluoride tracer gas is maintained within each unit by injecting known volumes of gas into the return air duct of the heating system. The rate of infiltration is then readily determined knowing the volume of tracer gas used.

Figures 4.1 through 4.6 are bar graphs showing the average weekly response of air infiltration to gas furnace operation. In each figure, gas furnace heating is represented by cross-hatched bars and electric heating by unmarked bars. The measured infiltration rates are normalized with repect to the reference module and correspond only to windspeeds of less than 2 m/s (approximately 35% of the data - structural air infiltration is a highly nonlinear function of windspeed [11]). These measures help to isolate the furnace influence by largely eliminating the effect of wind variation. What is observed

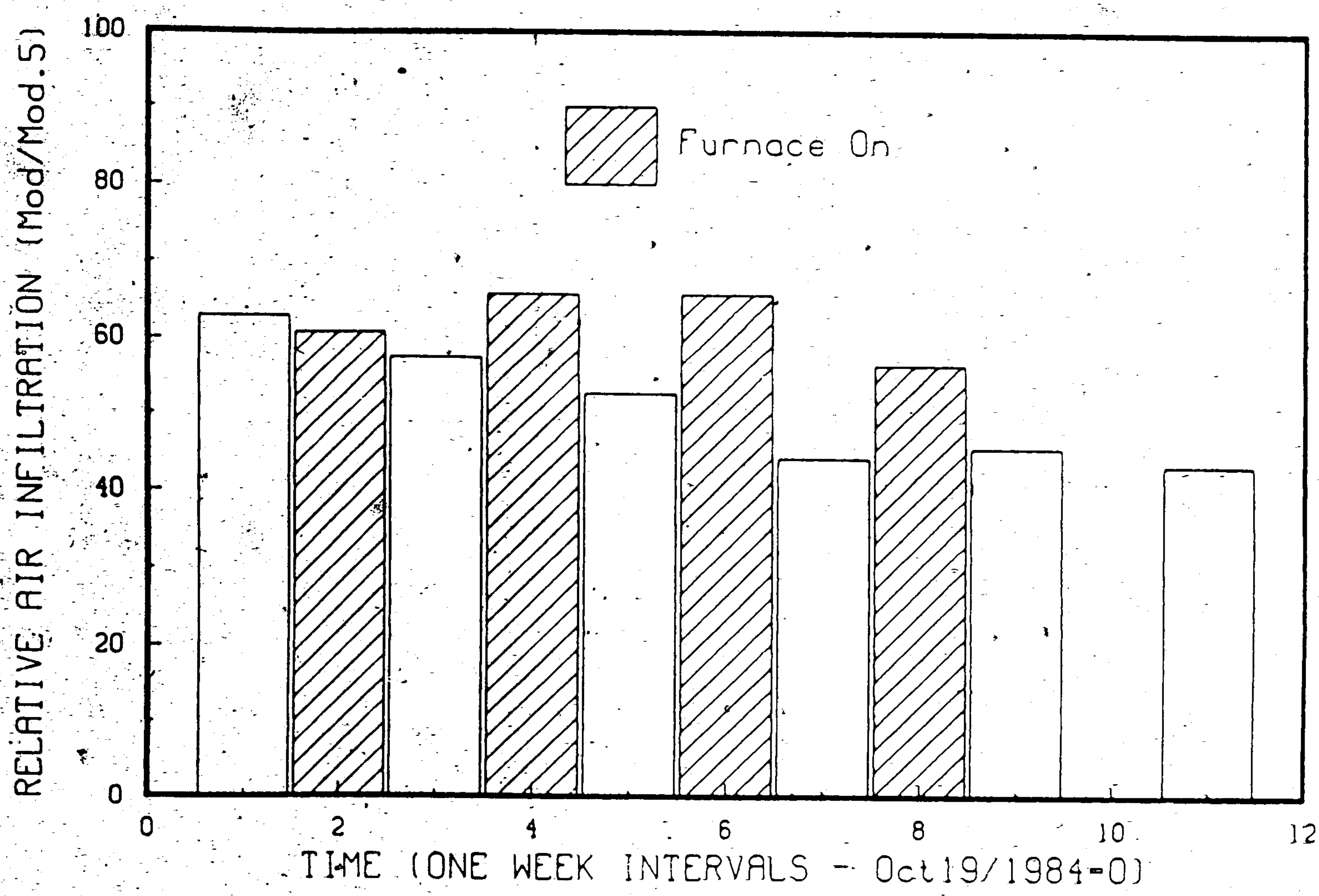

FIGURE 4.1 ICG Standard - Impact on Module 4 Infiltration.

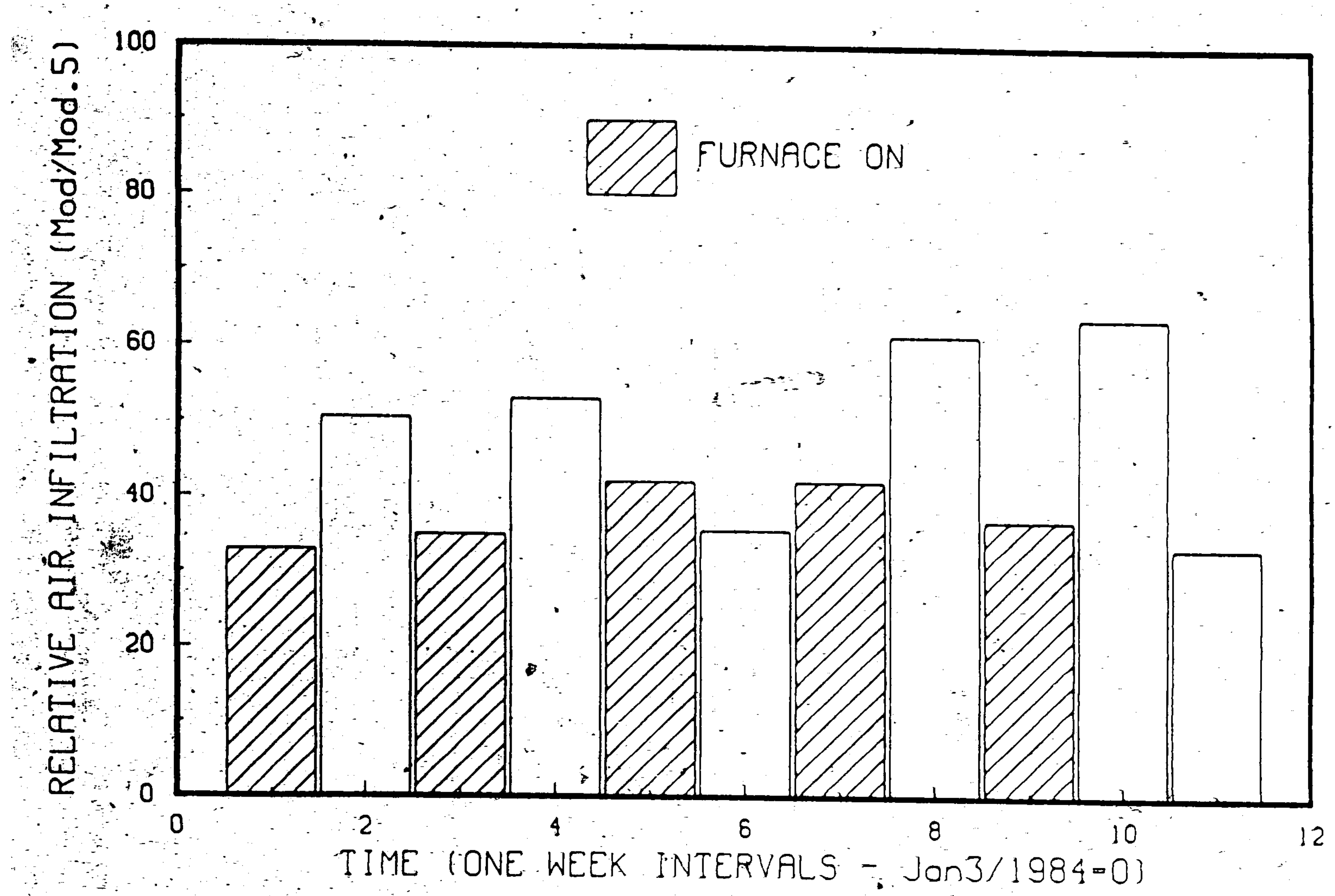

FIGURE 4.2. ICG Conserver - Impact on Module 4 Infiltration.

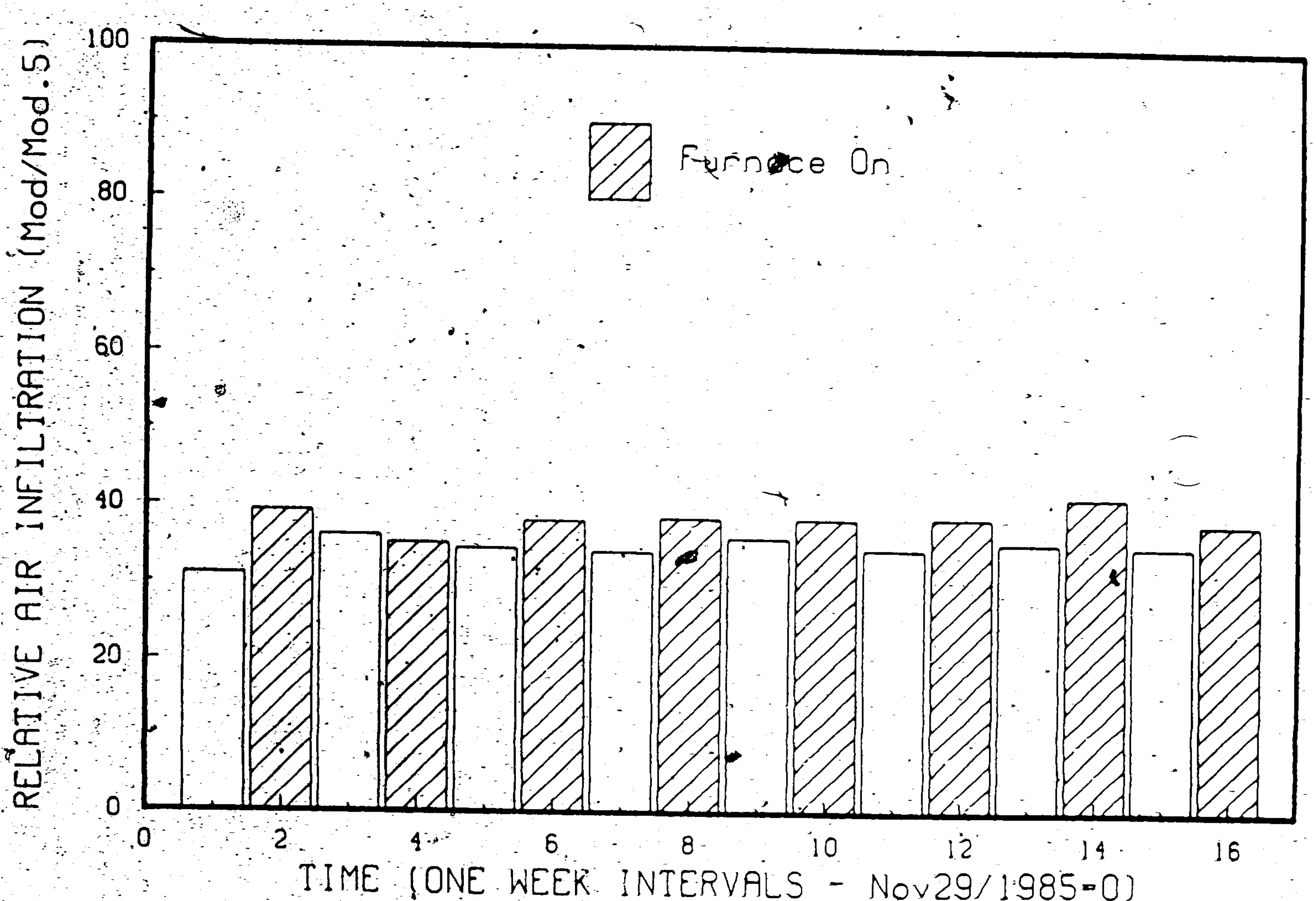

FIGURE 4.3 Airco Turbo - Impact on Module 4 Infiltration.

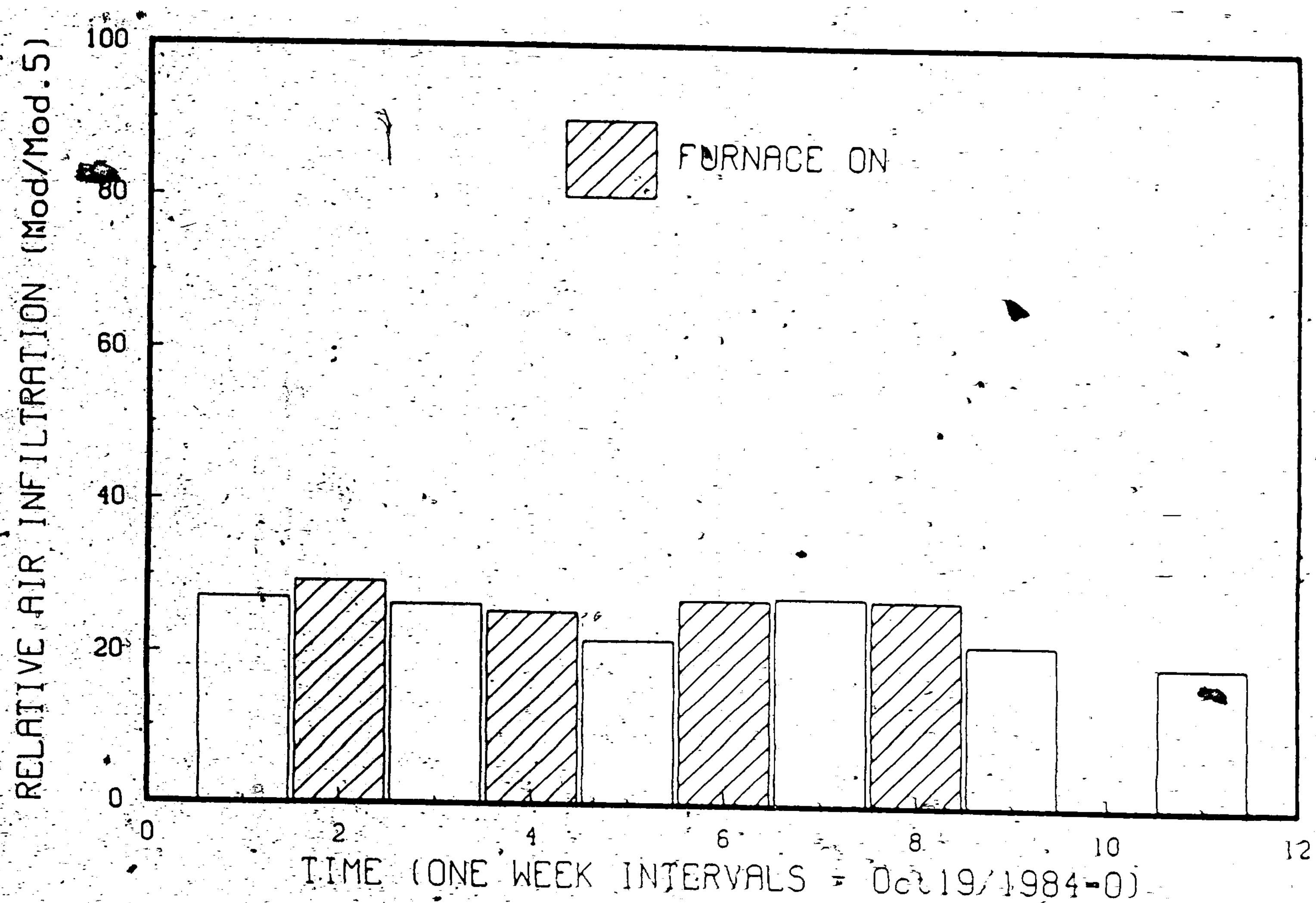

FIGURE 4.4 ICG Ultimate - Impact on Module 3 Infiltration.

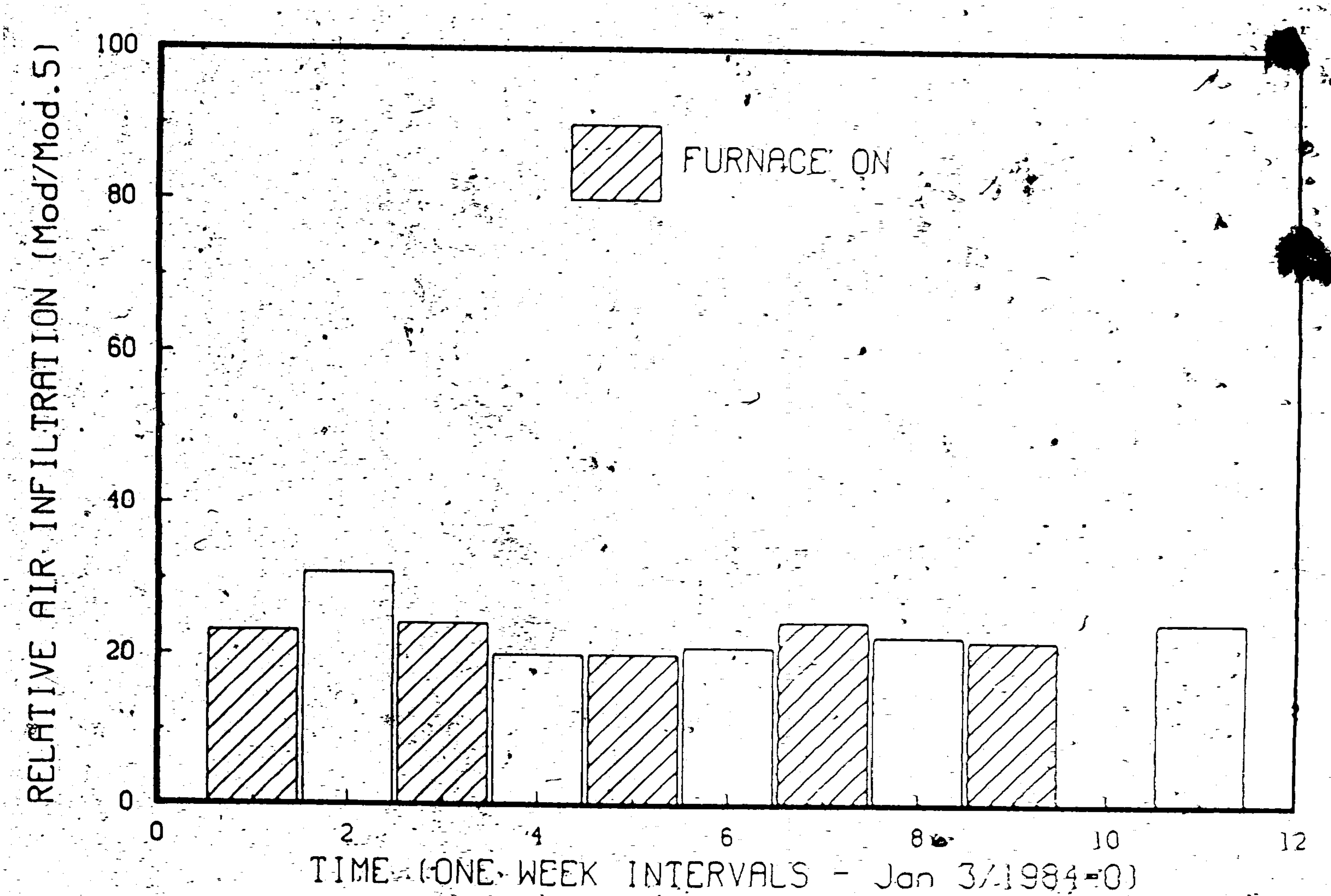

FIGURE 4.5 Lennox Pulse - Impact on Module 3 Infiltration.

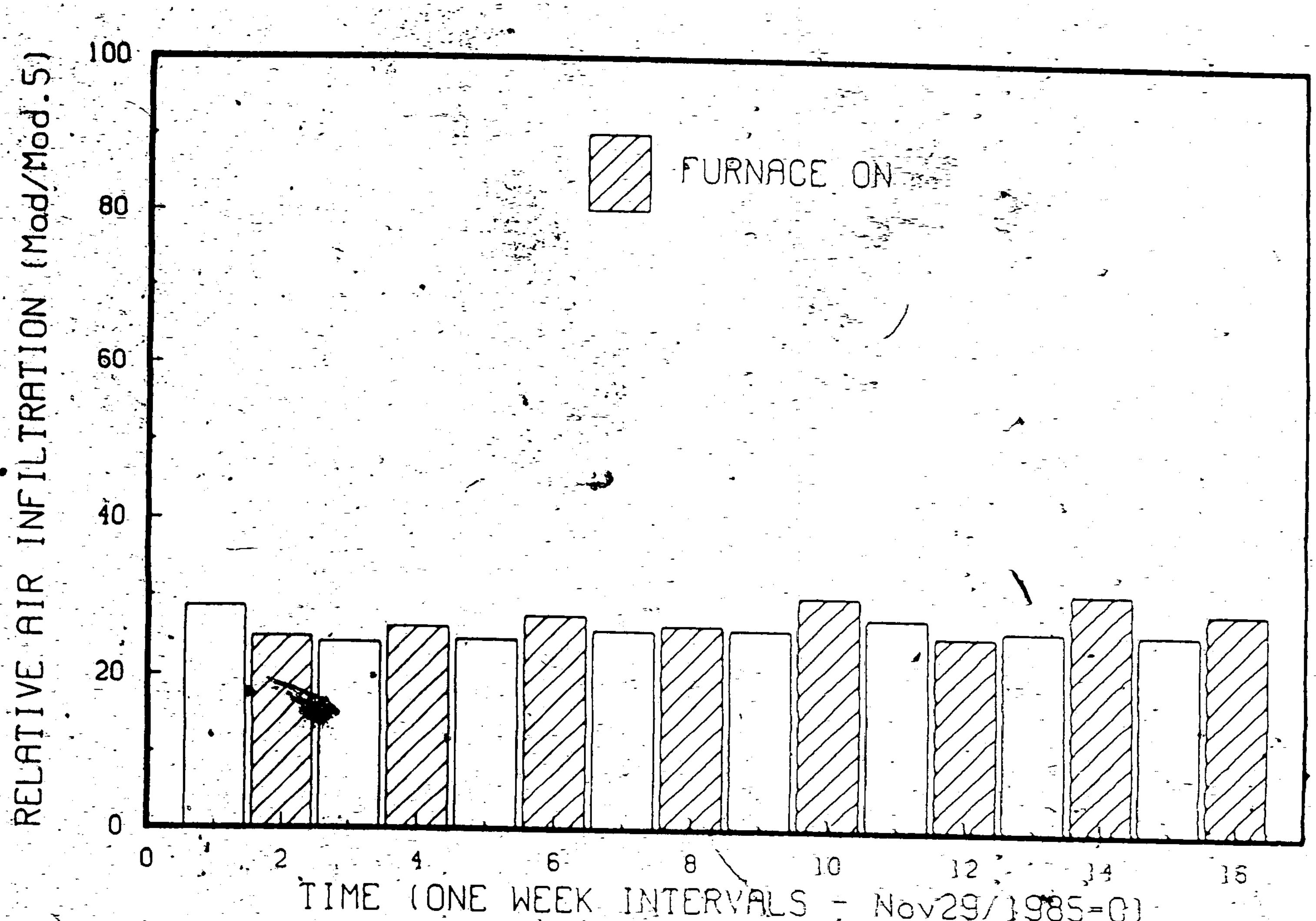

FIGURE 4.6 Amana Energy Command - Impact on Module 3 Infiltration.

from these figures is the expected result, namely that the the rates of infiltration occurring during gas furnace operation are on average higher than those corresponding to electric heating periods. This is a reasonable outcome when considering the fact that seasonal efficiency is in part related to rate of consumption of room air for combustion and draft control: the greater the rate of consumption, the lower the efficiency.

One particular observation may be made regarding Figure 4.1 for the standard furnace. During the first two weeks of electric heating, the pilot flame was allowed to remain burning. What is seen in the results of Figure 4.1 is that the rate of infiltration during this furnace off period is very similar to that occurring during the weeks of furnace operation. This would suggest that the pilot flame may contribute significantly to increasing the off-cycle stack flowrate and therefore infiltration. From the nature of this figure, one might assume this to be simply coincidental; however, re-examination of the data corresponding solely to weeks when the gas furnace was in operation suggests similar findings as will be shown later.

Notice in Figure 4.2 that the ICG Conserver displays a lower rate of infiltration during periods of gas heating than in periods of electric heating in direct contrast to the expected result. This unintentional result occurred because the flue damper was bypassed during electric heating weeks allowing it to remain continuously open. Had the damper remained closed during the electric heating periods, there would most certainly have been a reduction in infiltration during those periods as was the case during the sixth and eleventh weeks. What is demonstrated by this figure however is the dramatic reduction in air infiltration caused by the use of a flue damper or equivalent off-cycle flue obstruction. In relation to the results of the standard furnace off-cycle, the drop in infiltration resulting from the use of the flue damper is between 30 to 40%.

4.2 LONG TERM AVERAGE INFILTRATION LEVELS

The actual influence of furnace operation on air infiltration is difficult to assess on the basis of Figures 4.1 through 4.6 alone, particularly when considering those representing the high efficiency condensing furnaces, the ICG Ultimate and the Amana Energy Command. (The Lennox Pulse is expected to show no influence since it draws its combustion air from outdoors). For this reason, the infiltration data was reconsidered on an hour by hour basis and was regrouped in terms of burner operation and inoperation. Certain periods of data were excluded including the first two electric heating weeks for the standard furnace and all of the electric heating weeks for the Conserver in order to obtain an accurate assessment.. Table 4.1 shows the results of this assessment. Listed are the full test session averages of these new groupings and the

TABLE 4.1 - EFFECTS OF GAS FURNACE OPERATION ON AIR INFILTRATION.

FURNACE	RELATIVE INFILTRATION		INCREASE DUE TO FURNACE OPERATION (%)	INCREASE IN MODULE ENERGY LOAD (%)
	ELECTRIC HEATING	GAS HEATING		
MODULE 4				
ICG Standard	0.47	0.66	40	8
ICG Conserver	0.55	0.40(.36)[a]	11 (-35)[b]	2 (-7)[b]
Airco Turbo	0.35	0.39	11	2
MODULE 3				
ICG Ultimate	0.25	0.29	16	3
Lennox Pulse	0.23	0.22	-4	-1
Amana Energy Command	0.27	0.28	4	1

a - the measured value of relative infiltration occuring during gas furnace off hours within the gas heating weeks.

b - shows the measured reduction in Module 4 infiltration and energy load resulting from the blockage of the flue by the vent damper.

resulting infiltration increases calculated as the difference between the on and off-cycle test session averages divided by the off-cycle value. Also shown are the corresponding increases in module energy requirement based on the measured historic values of energy loss associated with air infiltration in each test module [9].

What is again generally observed from these results is that the lower the seasonal efficiency of the furnace, the greater the effect on the infiltration rate.

One unexpected result is the apparent reduction in Module 3 infiltration observed during the Lennox Pulse gas heating period. As mentioned earlier the Lennox Pulse does not use indoor air for combustion but rather draws its combustion air from outdoors. The observed reduction of 4% therefore is assumed to be a case of measurement error within the resolution of the monitoring system. Similarly therefore, it is recommended that the results associated with the other furnaces be viewed as representative rather than exact.

Notice also in Table 4.1 the values within brackets for the ICG Conserver. These measured results are isolated in order to illustrate the reduction in structural infiltration and energy load obtained by installing a furnace that largely reduces the off-cycle loss of room air. For Module 4, these reductions are shown to be as high as 35% and 7% respectively. It is important to realize however that these energy loss improvments are not over and above the savings made possible by the installation of a higher efficiency furnace but rather that these effects are already incorporated into the measured value of seasonal efficiency for each unit.

4.3 INFILTRATION AND FURNACE ON TIME

Perhaps a more meaningful way of illustrating the effect of furnace operation on air infiltration would be by presenting it in terms of furnace on time. It is likely that there is a relationship between infiltration increase and furnace on time when considering for example the combustion air requirement as the unit approaches steady state operation. This section will not attempt to directly quantify such a relationship but it will look at the apparent trends and will make observations complimenting the results of the previous sections.

The infiltration test data was again considered on an hourly basis with windspeeds of less than 2 m/s. For each test furnace, the relative infiltration rates were plotted against percent furnace on time where the percent furnace on time was estimated as the ratio of hourly gas consumption to the potential hourly gas consumption at steady state. The resulting plots are shown in Figures 4.7 through 4.12. In each figure, two dashed lines are used to indicate the mean infiltration rates as measured during the gas heating period (the on-cycle) and electric heating period. The numerical

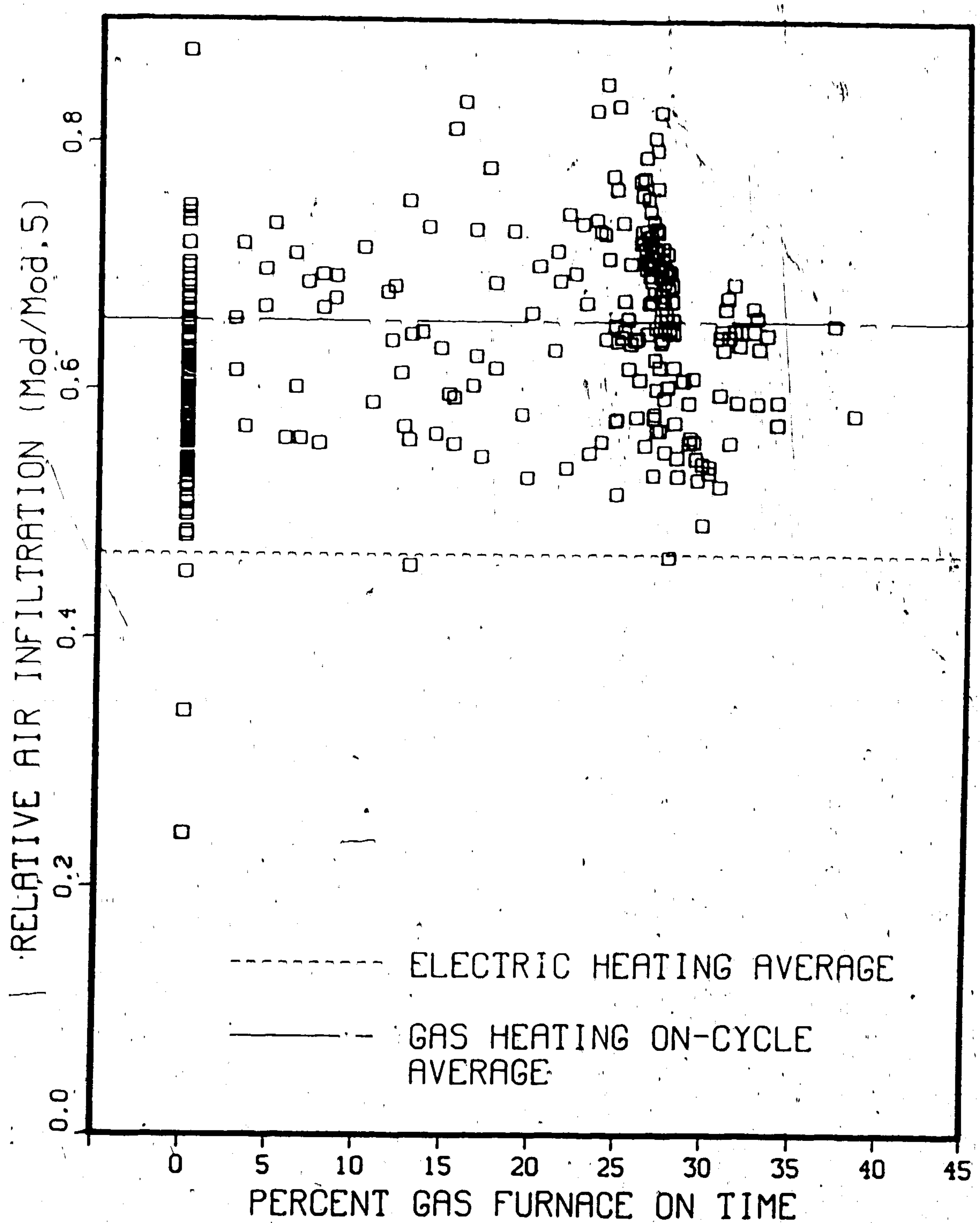

FIGURE 4.7 ICG Standard - Infiltration and Furnace On Time.

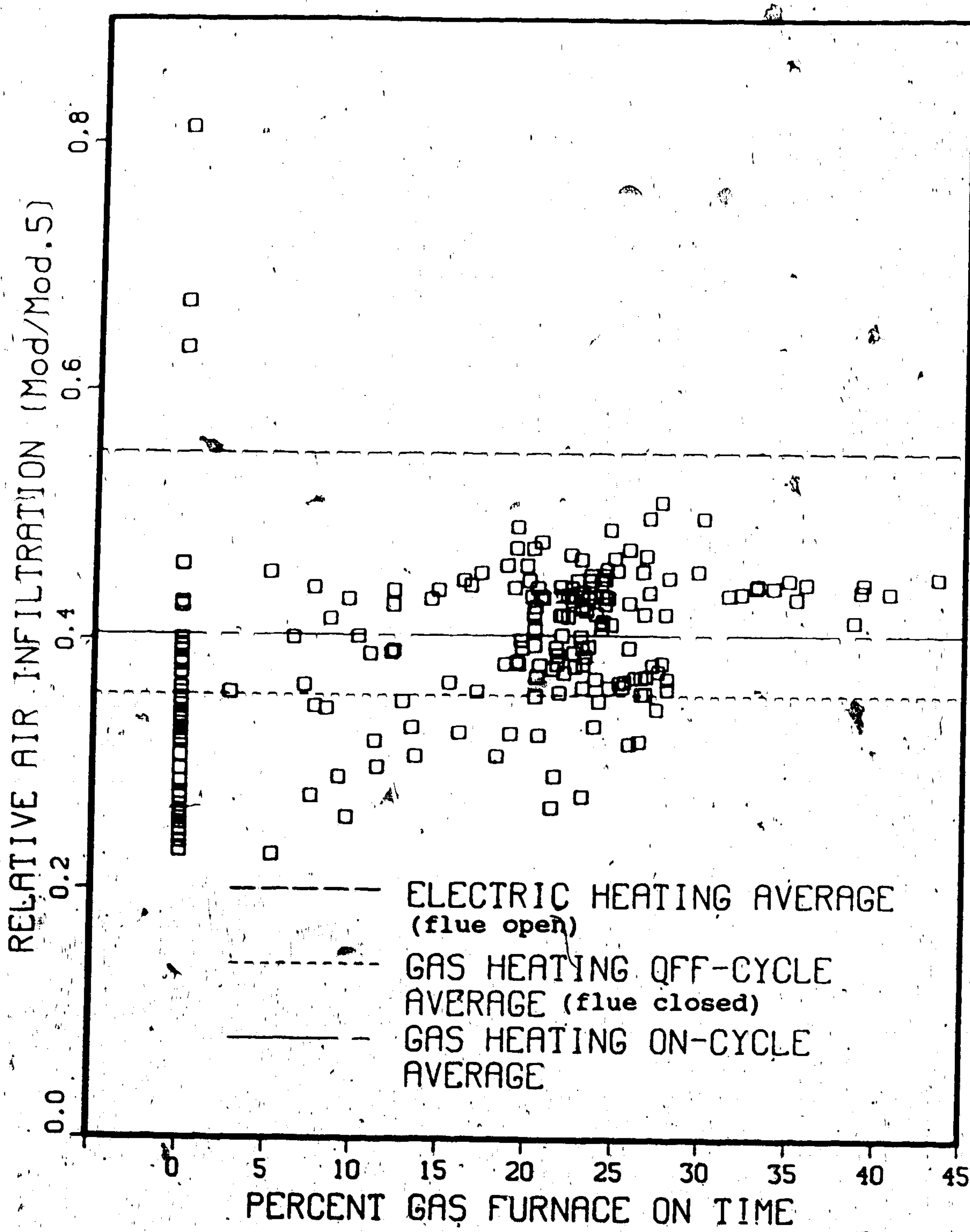

FIGURE 4.8 ICG Conserver - Infiltration and Furnace On Time.

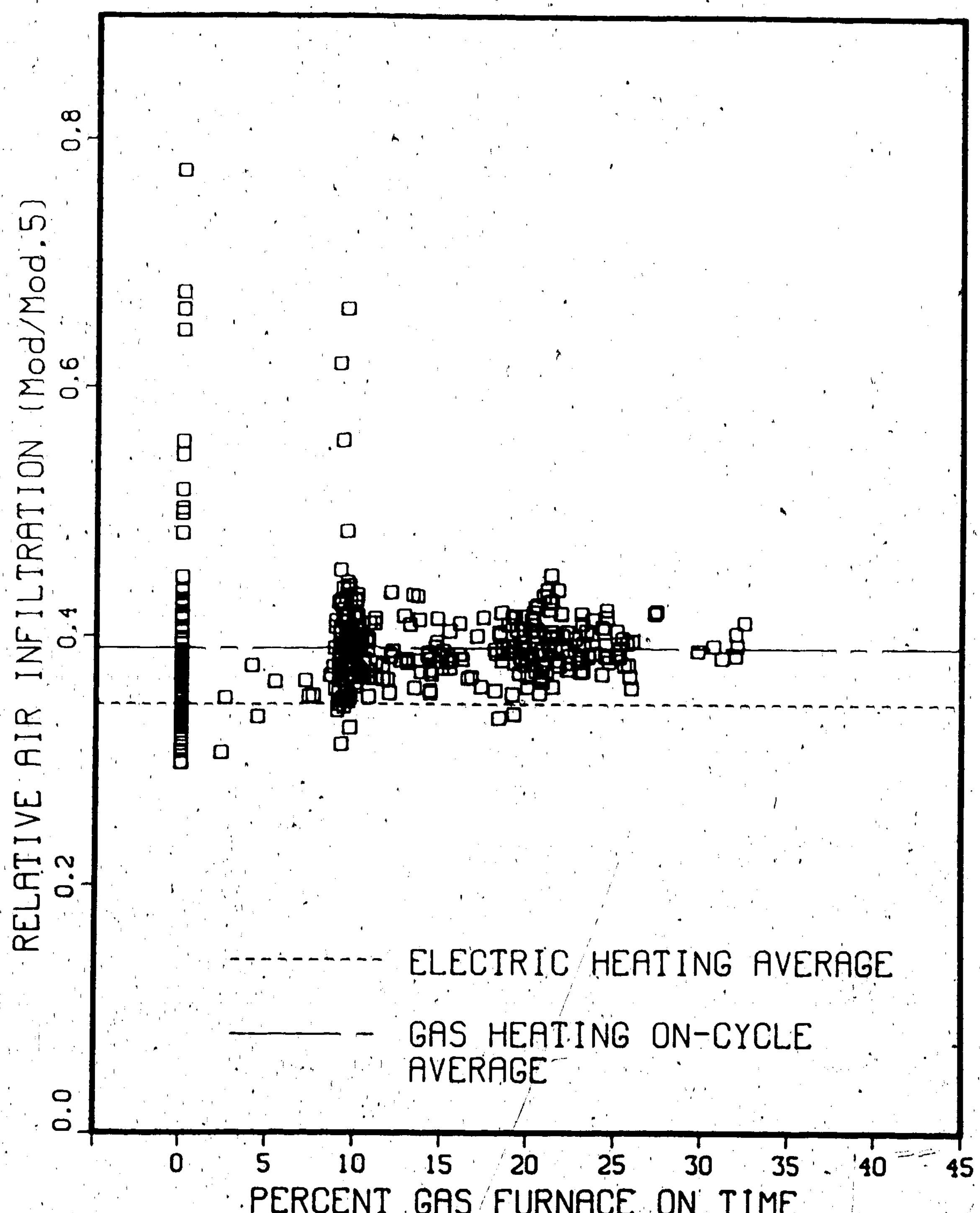

FIGURE 4.9 Airco Turbo - Infiltration and Furnace On Time.

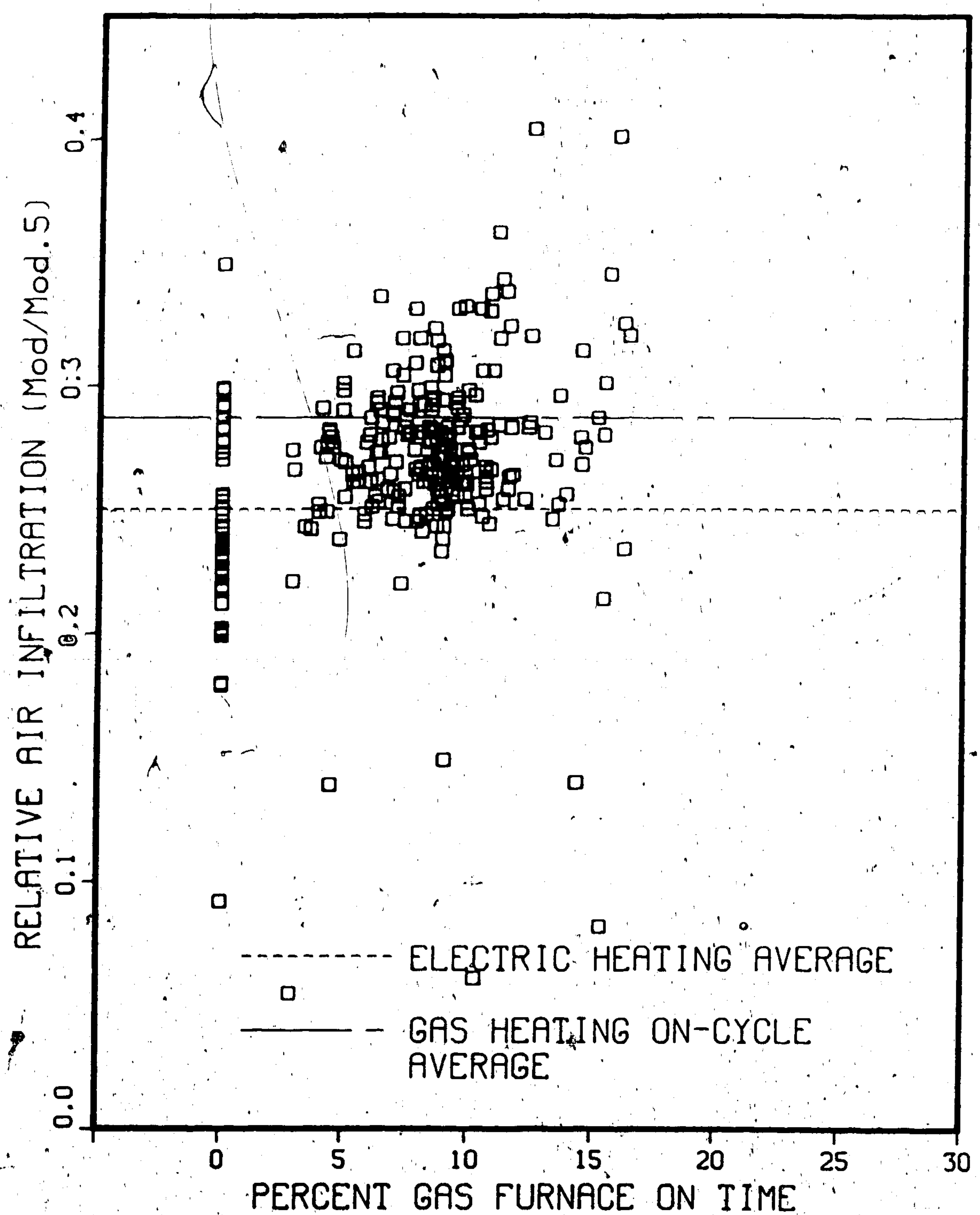

FIGURE 4.10 ICG Ultimate - Infiltration and Furnace On Time.

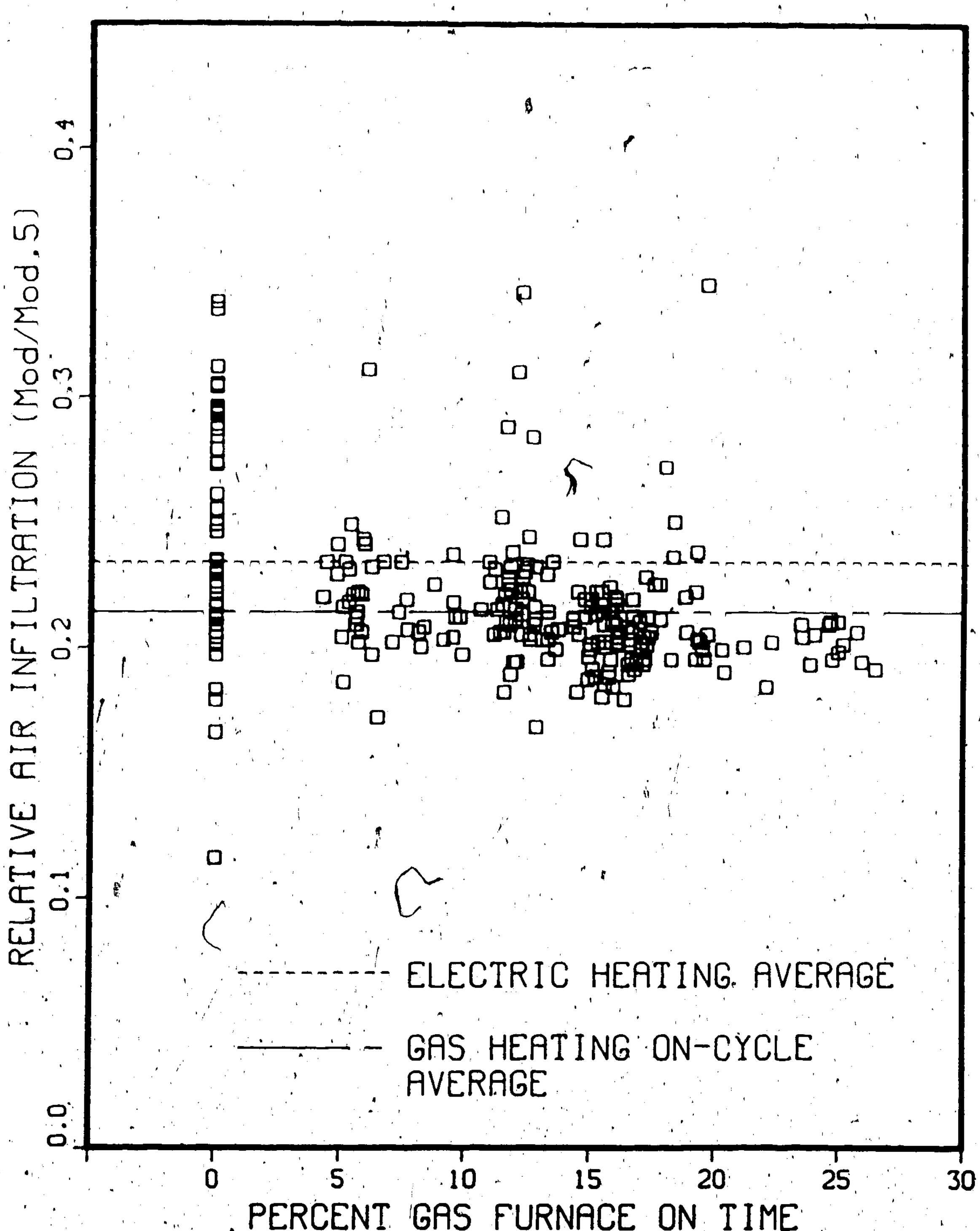

FIGURE 4.11 Lennox Pulse - Infiltration and Furnace On Time.

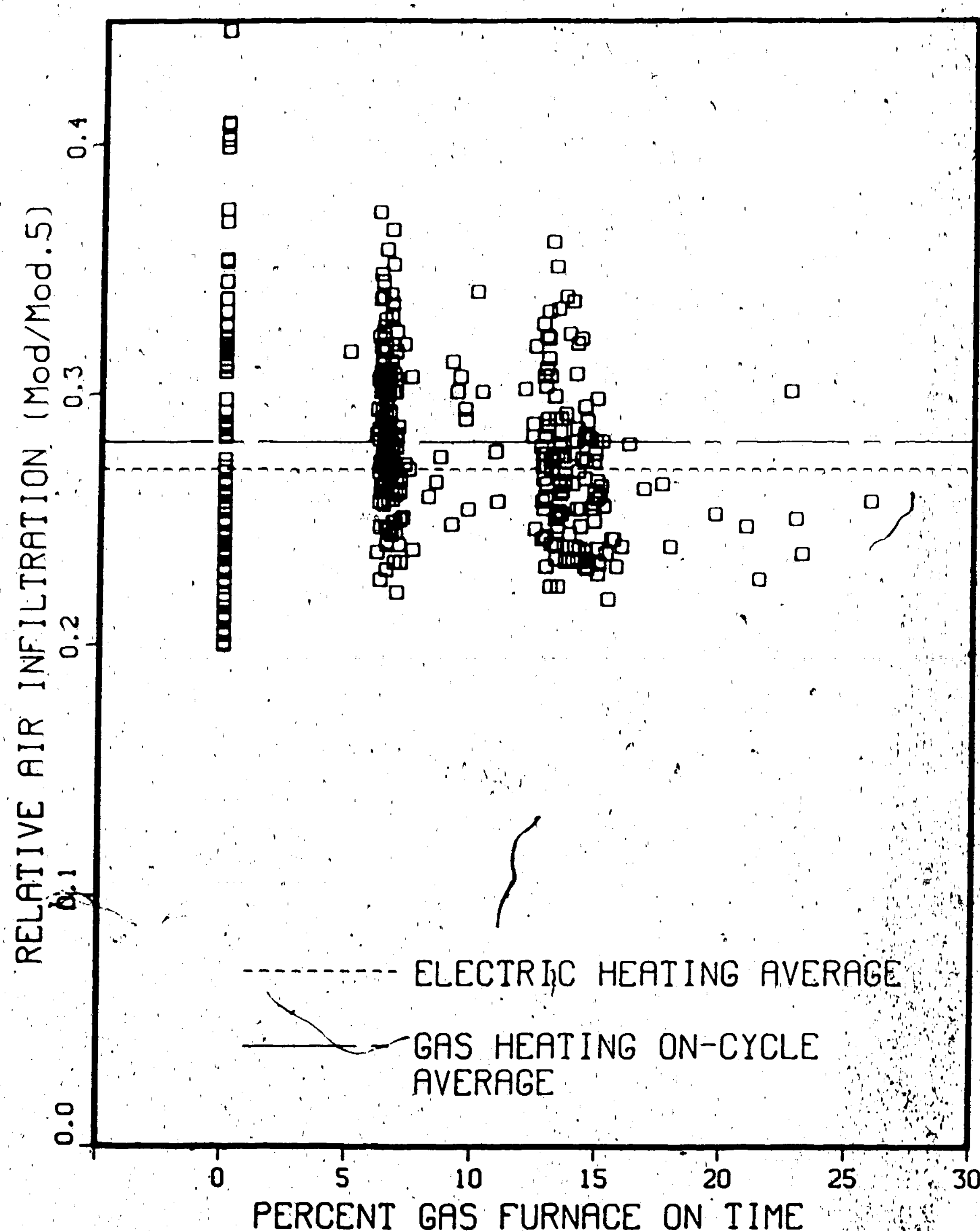

FIGURE 4.12 Amana Energy Command - Infiltration and Furnace On Time.

values of these means correspond to those given earlier in Table 4.1. Notice also the points plotted along the zero percent furnace on time. These correspond to the hours of burner inoperation during the gas heating weeks only. No data gathered during the electric heating periods are plotted in these figures.

Several significant observations may be made from these figures. Starting with Figure 4.7 for the ICG Standard, what is found is that the operation of a pilot flame greatly influences the flue or stack flowrate during the off-cycle. This corresponds to the observation made earlier regarding Figure 4.1. The average relative infiltration observed during the off-cycle, represented by the plotted data corresponding to zero furnace on time, is approximately 0.59 implying a pilot driven infiltration increase of more than 25% in this module. Little further increase is observed during furnace operation. Even during heaviest activity, the average infiltration rate does not appear to significantly increase from that of the off-cycle. There appears to be only a very mild trend towards infiltration increase with increased burner operation.

Figure 4.8 for the ICG Conserver shows that infiltration was lower during the gas heating weeks than during the electric heating weeks. The explanation as given in the previous section is that the flue damper was allowed to remain open during the electric heating periods. Unlike Figure 4.2 however, Figure 4.7 shows that there was a definite increase in infiltration from periods of burner inoperation to periods of burner operation within the gas heating weeks.

Figure 4.9 for the Airco Turbo, Figure 4.10 for the ICG Ultimate, and Figure 4.12 for the Amana Energy Command all show similar types of behavior to those demonstrated by the Standard and Conserver again with varying degrees of effect on infiltration. As discussed earlier, the greatest impact is generally demonstrated by the furnaces having the lower rated seasonal efficiencies.

Finally, Figure 4.11 for the Lennox Pulse shows an unexpected but apparently well defined trend towards decrease in relative infiltration with increasing gas furnace activity. Recall again that this particular unit does not use indoor air for combustion. It is suggested that this behavior is a function of the relative tightness of the construction between the test module and the reference module rather than of the furnace and its level of operation.

CHAPTER 5

FURNACE ECONOMICS

Conclusions regarding the economic advantage of any one furnace over another cannot simply be made on the basis of the advertised seasonal efficiency. Seasonal efficiency, while offering a means of characterizing performance, is at best a poor measure of overall economy. To properly assess the potential savings, consideration must be given, not only to the reduction in gas consumption, but also to the initial cost, maintenance costs, possible increases in electrical power consumption, and so on. Clearly, each of these sometimes 'unseen' expenses must be first recovered before a profit can be realised.

This section will look at the economics associated with the selection of any one of the study furnaces as a replacement of an existing gas furnace. The results presented will reflect the relationship between true economy and furnace efficiency and will be presented with respect to two separate Canadian cities, namely Edmonton and Toronto, in order to demonstrate the sensitivity of these results to differences in energy cost and climate severity.

5.1 PERTINANT INFORMATION AND ASSUMPTIONS

The average annual natural gas consumption figures for Edmonton and Toronto are shown in Table 5.1 both as total consumption and as the portion used for home heating. The total consumption figure for Edmonton was provided by Northwestern Utilities Limited in Edmonton. The same figure for Toronto was estimated in relation to the value given for Edmonton by considering the long term average ambient temperature relationship between the two centers. Home heating consumption was then estimated as 80% of the total gas usage with the remainder being attributed towards water heating and use in other domestic gas appliances.

For each test furnace, the initial unit costs, including both the purchase price of the furnace and its installation, were obtained by gathering estimates from five local heating contractors. The averages from these five estimates are shown in Table 5.2 rounded to the nearest $50. Also shown are the estimates of service life and maintenance cost as used in the economic evaluations. Notice that these values are fixed for each unit at 20 years and $10/year respectively. The maintenance cost figures represent only normal furnace care requirements such as filter replacement, minor burner adjustment, and so on.

TABLE 5.1 AVERAGE ANNUAL GAS CONSUMPTION FOR EDMONTON AND TORONTO

LOCATION	AVERAGE TEMPERATURE (HDD below 18 C)	AVERAGE TOTAL GAS CONSUMPTION (m^3/yr)	AVERAGE HOME HEATING CONSUMPTION (m^3/yr)
Edmonton	27.4	4270	3420
Toronto	19.9	3350	2490

TABLE 5.2 - UNIT COST AND ESTIMATES OF SERVICE RECORD FOR EACH TEST FURNACE.

FURNACE	UNIT COST ($)	SERVICE LIFE (yr)	MAINTENANCE COST ($/yr)
ICG Standard	1000	20	10
ICG Conserver	1200	20	10
Airco Turbo	1500	20	10
ICG Ultimate	1650	20	10
Lennox Pulse	2450	20	10
Amana Energy Command	3150	20	10

Similarly, the 20 year service life reflects only typical furnace longevity. Although newer furnace models are generally more complicated than the standard equipment, little information is yet available regarding the maintenance record and life expectancy of these designs. No attempt therefore was made to account for the possibility of unexpected operating expenses.

Estimates of annual furnace fuel consumption, based on furnace efficiency and the information in Table 5.1, are shown in Table 5.3. The seasonal furnace efficiencies used to estimate these values were considered to be those measured using the CAN1-P.1-85 test procedure. (Because of the influence of the uninsulated flue in Module 4, it was felt that the field test values of efficiency were not truely representative and that they would affect the economics so as to strongly favor a mid-efficiency design). Also shown in Table 5.3 are the measured average steady state electrical power consumptions for each test furnace reflecting the differences in blower/blower motor efficiency and auxiliary power usage (electronic ignition, vent blowers, etc.).

Table 5.4 lists the current (1986) natural gas and electrical power costs for Edmonton and Toronto as supplied by the local utility and power companies.

Finally, for use in the Internal Rate of Return calculations, an inflation rate of 4% was chosen as consistent with the current average in Canada.

TABLE 5.3 COMPARISON OF ENERGY CONSUMPTION ON THE BASIS OF FURNACE MODEL AND LOCATION

FURNACE	ESTIMATED ANNUAL GAS CONSUMPTION EDMONTON (m^3/yr)	ESTIMATED ANNUAL GAS CONSUMPTION TORONTO (m^3/yr)	MEASURED ELECTRICAL CONSUMPTION* (Watts)
ICG Standard	3420	2490	380
ICG Conserver	3050	2220	390
Airco Turbo	2760	2010	280
ICG Ultimate	2490	1810	510
Lennox Pulse	2390	1740	360
Amana Energy Command	2410	1750	350

* - The electrical consumptions recorded represent the steady state condition. Electricity costs which are include in the annual savings found in Tables 5.5(a) and 5.5(b) use these values and an assumed on-cycle of 25%.

TABLE 5.4 ENERGY COSTS (1986)

LOCATION	NATURAL GAS ($\$/m^3$)	ELECTRICAL POWER ($/kW)
Edmonton	0.1037	0.0458
Toronto	0.2088*	0.0510

* - Toronto uses a scaling gas pricing system. The figure recorded represents an average price when considering typical volumes used for home heating.

5.2 DESCRIPTION OF ECONOMIC EVALUATION PROCEDURES

When a homeowner is in the market for a replacement furnace, he is ultimately faced with the choice of installing either a standard furnace or one of the many mid to high efficiency models available. Assuming that the choice of manufacturer is immaterial, the decision is simply one of economy versus efficiency. Incremental economics were chosen in order to highlight the implications of such a decision where the evaluations would be made in terms of the differences in unit cost and periodic savings between the standard furnace and the remaining test furnace alternatives.

Described in the following are the two methods chosen to represent the system economics.

PAYBACK PERIOD - The payback period represents the time required for an investment to pay for itself. In terms of incremental or comparative economics, the payback period is best described as the length of time required for the differences in operating cost (cost savings) to just equal the difference in initial cost between the two investments. Payback period is calculated as:

$$\text{Payback Period (years)} = \frac{\text{Initial Cost of the Alternative} - \text{Initial Cost of the Standard}}{\text{Annual Operating Cost of the Standard} - \text{Annual Operating Cost of the Alternative}}$$

Payback period is an approximate rather than exact method of evaluating investment economics. It does not consider the time value of expenses and profits, nor does it account for the effects of inflation. It is therefore often difficult to define what is a reasonable or unreasonable payback period. A longer payback usually represents a weaker investment yet it is possible for such an alternative to provide the greatest savings over the full life of the equipment. As a backup to the payback analysis therefore a second method was chosen to present the economics of furnace investment, namely the method of rate of return.

INTERNAL RATE OF RETURN - The internal rate of return is simply the apparent interest rate earned on a particular investment. If each of the cost savings occurring over the full life of the investment are brought to an equivalent present worth, their sum has the effect of offsetting the initial cost of the investment, depending upon the choice of interest rate. The particular value of interest rate causing the adjusted savings to just equal this initial cost is known as the internal rate of return. The internal rate of return therefore is a more precise and comprehensive measure of economy which includes not only the dollar savings up to the time of 'payback' but also those beyond.

For the homeowner, knowing the internal rate of return greatly simplifies the selection process. If for example a homeowner were to borrow money to purchase a furnace, he would want the furnace to at least deliver a rate of return greater than the interest he would have to pay on the loan. Similarly, if the homeowner were to pay for it from his savings, the return would have to be something greater than the rate being earned on the bank deposit. A reasonable internal rate of return on a furnace purchase therefore would lie between approximately 6 and 14%. Anything lower would be considered a poor investment.

5.3 ECONOMIC RESULTS

Tables 5.5(a) and 5.5(b) show the results of the payback and the internal rate of return analysis for Edmonton and Toronto respectively. Overall, the results clearly suggest that the economics for furnace efficiency improvement in Toronto are much more favorable than they are for Edmonton. The large differences in both payback period and rate of return stem primarily from the corresponding differences in natural gas price between the two centers. Clearly, if the climates between the two regions were more closely matched, even greater benefits would exist under the Toronto pricing setup.

The results of the payback analysis strongly favor the purchase of a mid-efficiency furnace. The results clearly show that the differences in initial cost between the mid and high efficiency models are not at all compensated for by the extra savings. Very long payback times, as high as 12 and 18 years in Edmonton, are shown for the high cost, high

TABLE 5.5(a) - INCREMENTAL GAS FURNACE ECONOMIC RESULTS (Edmonton)

FURNACE	INITIAL COST ($)	ANNUAL SAVINGS ($)	PAYBACK PERIOD (Yrs)	INTERNAL ROR (%)
ICG Standard	1000	-	-	-
ICG Conserver	1200	37	5.5	18
Airco Turbo	1500	75	6.5	14
ICG Ultimate	1650	87	7.5	12
Lennox Pulse	2450	121	12.0	6
Amana Energy Command	3150	118	18.0	1

TABLE 5.5(b) - INCREMENTAL GAS FURNACE ECONOMIC RESULTS (Toronto).

FURNACE	INITIAL COST ($)	ANNUAL SAVINGS ($)	PAYBACK PERIOD (Yrs)	INTERNAL ROR (%)
ICG Standard	1000	-	-	-
ICG Conserver	1200	55	3.5	27
Airco Turbo	1500	107	4.5	21
ICG Ultimate	1650	132	5.0	20
Lennox Pulse	2450	172	8.5	10
Amana Energy Command	3150	167	13.0	5

efficiency Lennox and Amana units respectively, demonstrating poor economics. Though perhaps an unrealistic result, a relatively short payback period is offered by the ICG Ultimate (7.5 years for Edmonton, 5.0 years for Toronto). Discontinuation of the particular model however has caused the selling price to be artificially low and therefore not representative of most other condensing furnaces. The upgraded ICG Conserver and the mid efficiency Airco Turbo appear to display the best payback economics. Payback periods as short as 3.5 years in Toronto are possible as shown for the ICG Conserver.

Results of the rate of return analysis reflect the same general outcome as those of the payback analysis even though as discussed earlier, the rate of return analysis considers the benefits over the <u>full</u> life of the product. In Toronto, the internal rates of return are favorable for the ICG Conserver, the Airco Turbo and the ICG Ultimate, all being 20% or better. Only the ICG Conserver demonstrates reasonable economics for the Edmonton area with an internal rate of return of 18%. The Airco Turbo is marginal at 12%. The Lennox Pulse and the Amana Energy Command condensing furnaces do poorly in both Edmonton and Toronto.

5.4 LIMITATIONS OF THE ECONOMIC ANALYSIS

1. The economics presented are based on the ICG Standard measured (CAN1-P.1-85) seasonal efficiency of 67%. If a lower value of between 60 and 65% is assumed, as is most often used in such assessments, the resulting economics may appear to be somewhat better.

2. The periodic savings shown here are further based on a choice between a new standard furnace and one of the mid or high efficiency alternatives. They do not represent potential savings in terms of the performance of the "old" furnace being replaced

3. The economics presented do not attempt to include possible changes in efficiency which may occur with time as the result of the level of care and maintenance of the unit.

4. The demand placed on the furnace will certainly affect the economics. While the results presented consider only the average case, an increase in furnace load within the capability of the unit brought about for example by installation in a larger home or a poorly insulated home will enable much greater savings.

5. The use of a high efficiency furnace would effectively eliminate the cost of constructing a vertical

flue in new home construction. The economics presented do not account for such savings.

CHAPTER 6

AIR TO AIR HEAT EXCHANGER

Improved construction standards in the housing industry over the last decade have led to a significant improvement in housing comfort and energy efficiency. One aspect which has been the focus of much attention in this regard has been the potential for reduction of unnecessarily high levels of air infiltration. The result has been a new generation of what has been termed tighter house construction. While obtaining the objective of reducing energy loss, reductions in air infiltration levels have precipitated a number of clear disadvantages. Concerns over indoor air quality have been expressed suggesting that insufficient ventilation would lead to the possible build-up of unsafe levels of certain toxic gases, either naturally occurring or man-made, related to building materials. Less serious but perhaps more aggravating have been the problems associated with unpleasant odors and the excessive build-up of moisture within the residence resulting in condensation on the many 'cooler' surfaces in the home (doors, windows, etc.). The introduction of the high efficiency furnace has further compounded such problems. The reduced consumption (and subsequent expulsion) of indoor air for combustion has in many situations made critical the need to supply induced ventilation.

Such a need has led to the development and promotion of the residential air to air heat exchanger. At relatively low cost to the homeowner, the use of these units has been claimed to effectively provide the necessary ventilation requirement apart from the normally large losses of associated heat energy.

This section will briefly examine one aspect of performance of a typical residential air to air heat exchanger, namely the evaluation of the rate of cross contamination of opposing air streams as a function of flow restriction or back pressure.

6.1 DESCRIPTION OF THE HEAT EXCHANGER

The unit chosen for testing was a Canadian made VanEE 2000 Series Heat Recovery Ventilator. The unit is designed to provide ventilation and the simultaneous recovery of energy from the exhausting (indoor) air stream. The heat exchanger is of cross flow configuration utilizing a polypropylene core. The manufacturer of the unit advertises low cost, effective ventilation with as high as 82% heat recovery.

6.2 TEST APPARATUS AND METHODOLOGY

A 'double loop' test apparatus was designed and built which would accomodate and isolate the two air streams independently. The system was designed to enable operation and testing over the full range of capable flowrates (85 to 220 cfm). Each loop was made from 15 cm (6 inch) diameter ABS plastic pipe. A 10 cm (4 inch) plate orifice meter was fitted into each loop to be used for evaluating the volume flowrates. Using a tracer gas analyser, the rates of decay of a tracer gas concentration in either or both streams could be used to determine the level of system leakage and/or cross contamination between the two air streams. Figure 6.1 is a photograph of the test apparatus.

Initially, a test was performed to determine the leakage from the ventilator case. (During their manufacture, extreme care was taken to ensure that no leakage would occur from the fabricated test loops). With both loops closed and the heat exchanger in operation, an equal concentration of tracer gas was established in both loops and allowed to decay while being continuously monitored. The test was repeated at high, medium, and low speed settings

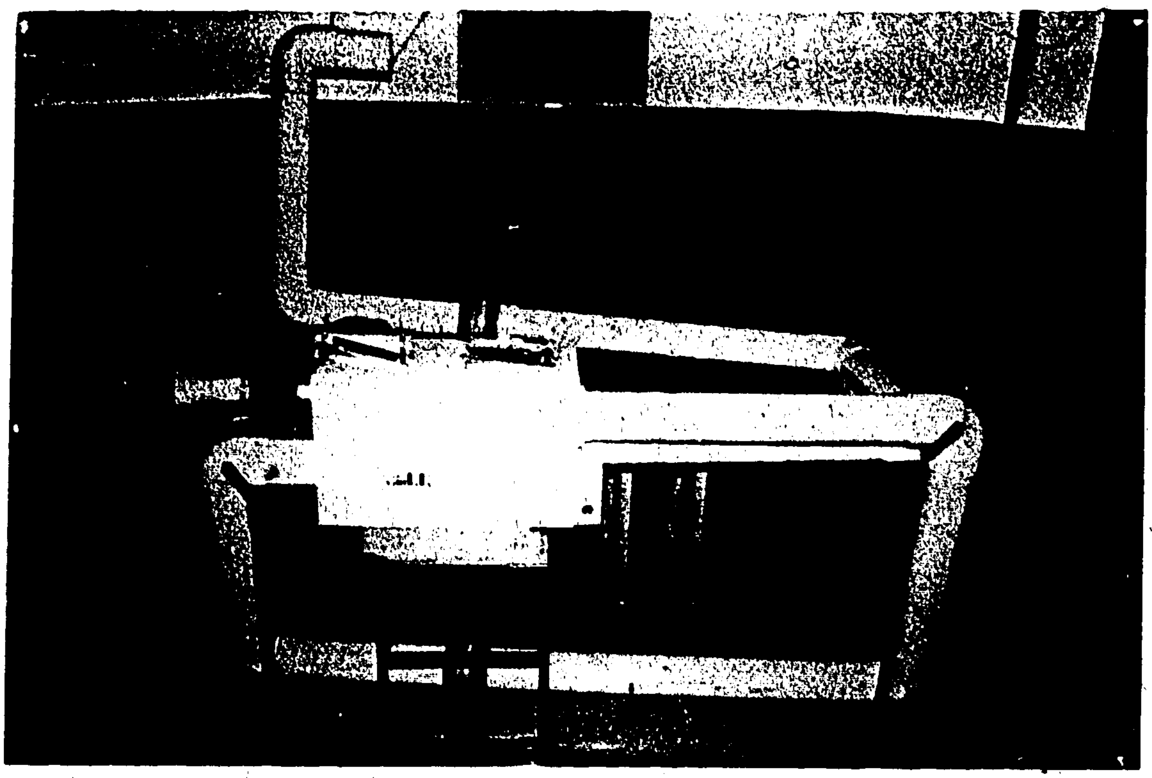

FIGURE 6.1 Heat Exchanger Testing Apparatus

corresponding to flowrates of approximately 200, 160 and 100 cfm. Decay time constants were then evaluated and used, knowing the volume of each loop, to establish the system leakage rates.

To test for cross contamination, the fresh air loop was opened up allowing it simply to circulate room air. Figure 6.1 actually shows the test apparatus with the fresh air loop open. With the heat exchanger operating, the tracer gas was introduced only into the closed exhaust loop. The rate of concentration decay was again monitored continuously. At each of the three nominal speed settings, the test was repeated while progressively blocking the intake side of the open loop thereby imposing a pressure difference across the heat exchanger core. Again the decay time constants were evaluated and later used to determine the apparent rates of cross contamination.

6.3 HEAT EXCHANGER TEST RESULTS

Table 6.1 shows the observed rates of casing leakage in conjunction with the closed loop airstream flowrate for the three nominal blower speed settings. Notice that these leakage rates are very low at 0.10, 0.07 and 0.05 cfm, consistently representing approximately 0.05% of air stream flowrate.

Figures 6.2, 6.3 and 6.4 show the relationships

TABLE 6.1 AIR-TO-AIR HEAT EXCHANGER CASING LEAKAGE RATES.

NOMINAL SPEED SETTING	FRESH AIR LOOP FLOWRATE (CFM)	EXHAUST LOOP FLOWRATE (CFM)	CASING LEAKAGE (CFM)
FULL	187	191	0.10
MEDIUM	137	150	0.07
LOW	89	94	0.05

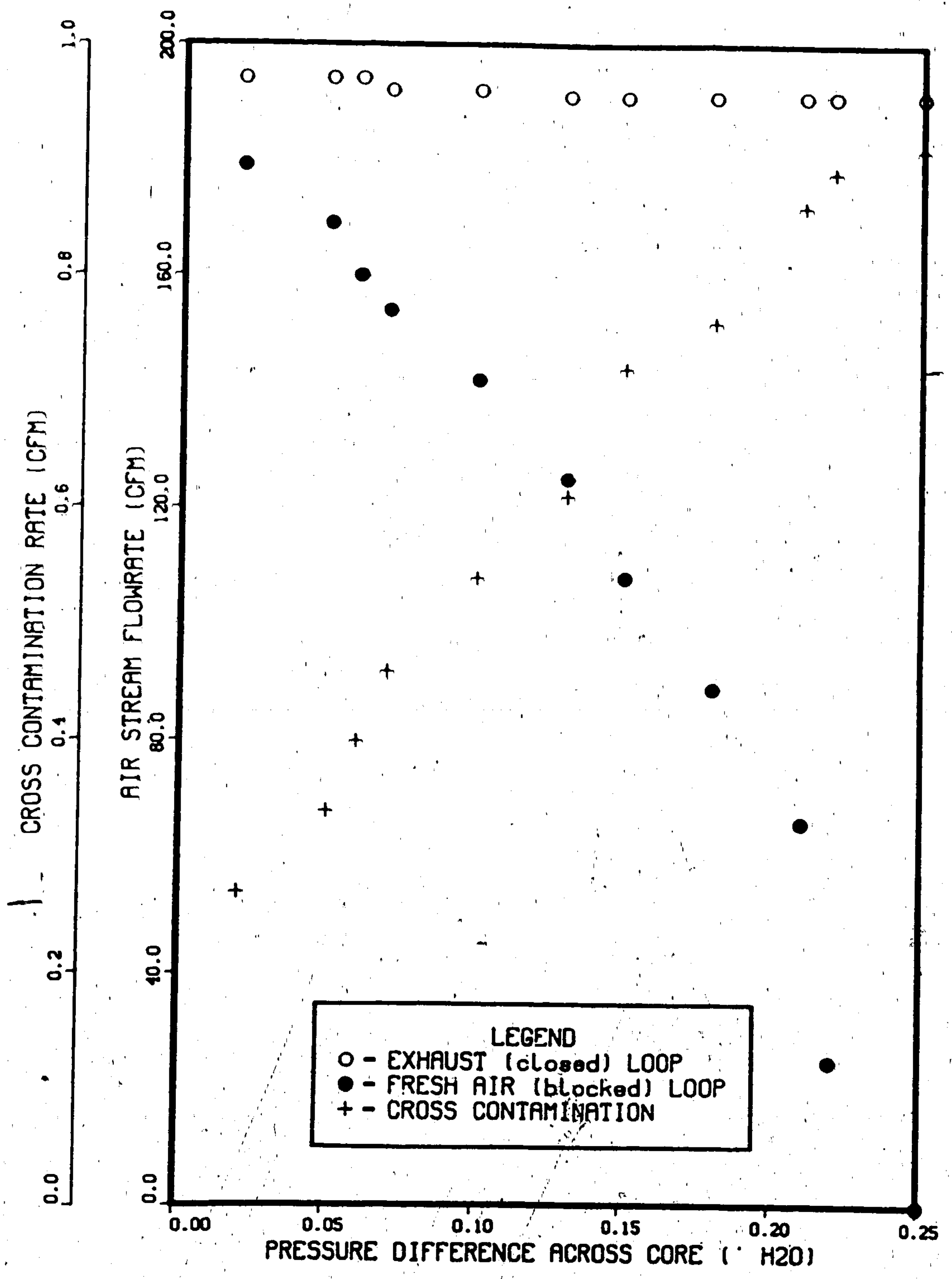

FIGURE 6.2 Cross contamination of air streams in relation to air stream flowrates and pressure differential across heat exchanger core (speed setting = HIGH)

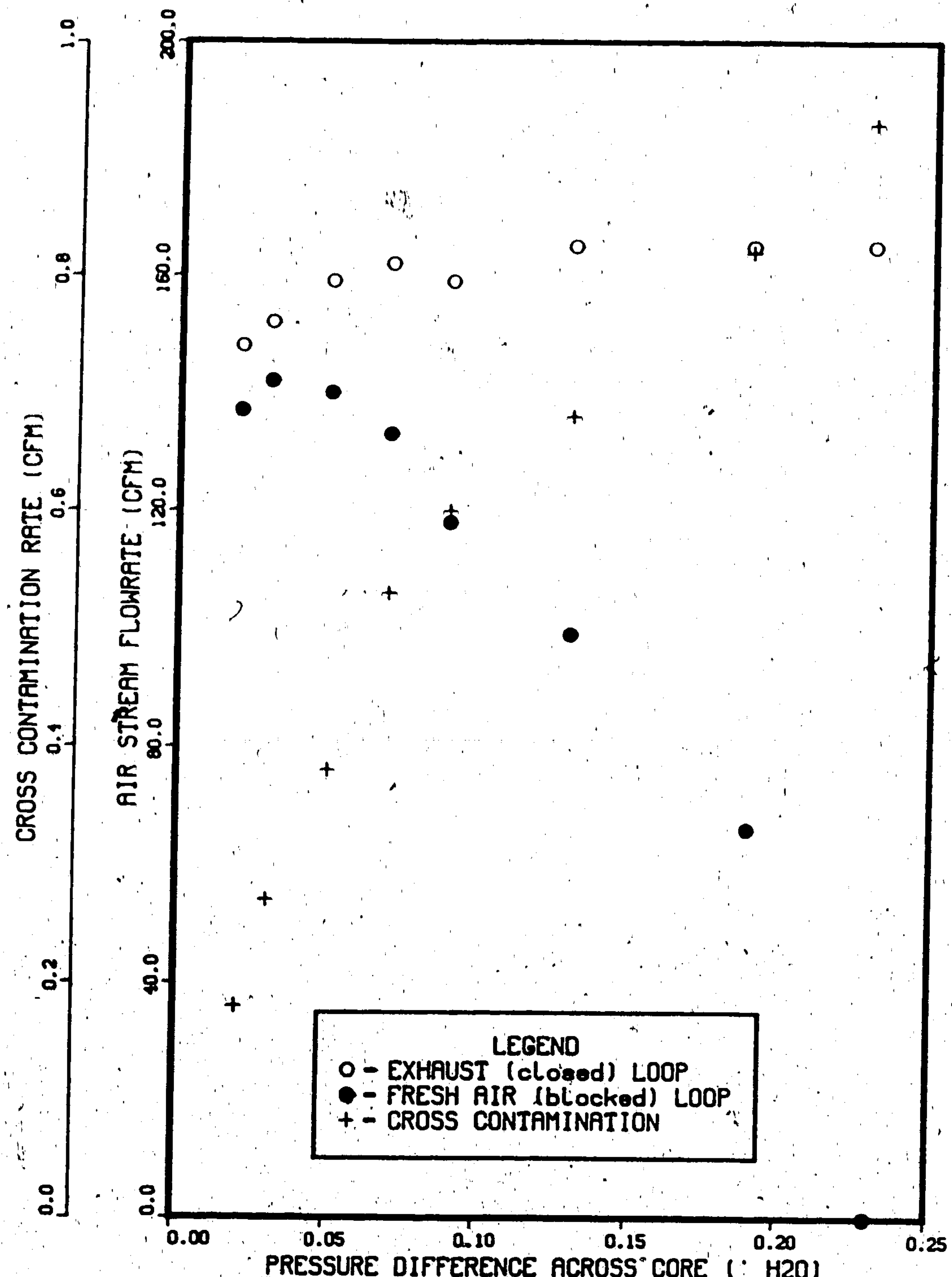

FIGURE 6.3 Cross contamination of air streams in relation to air stream flowrates and pressure differential across heat exchanger core (speed setting MEDIUM)

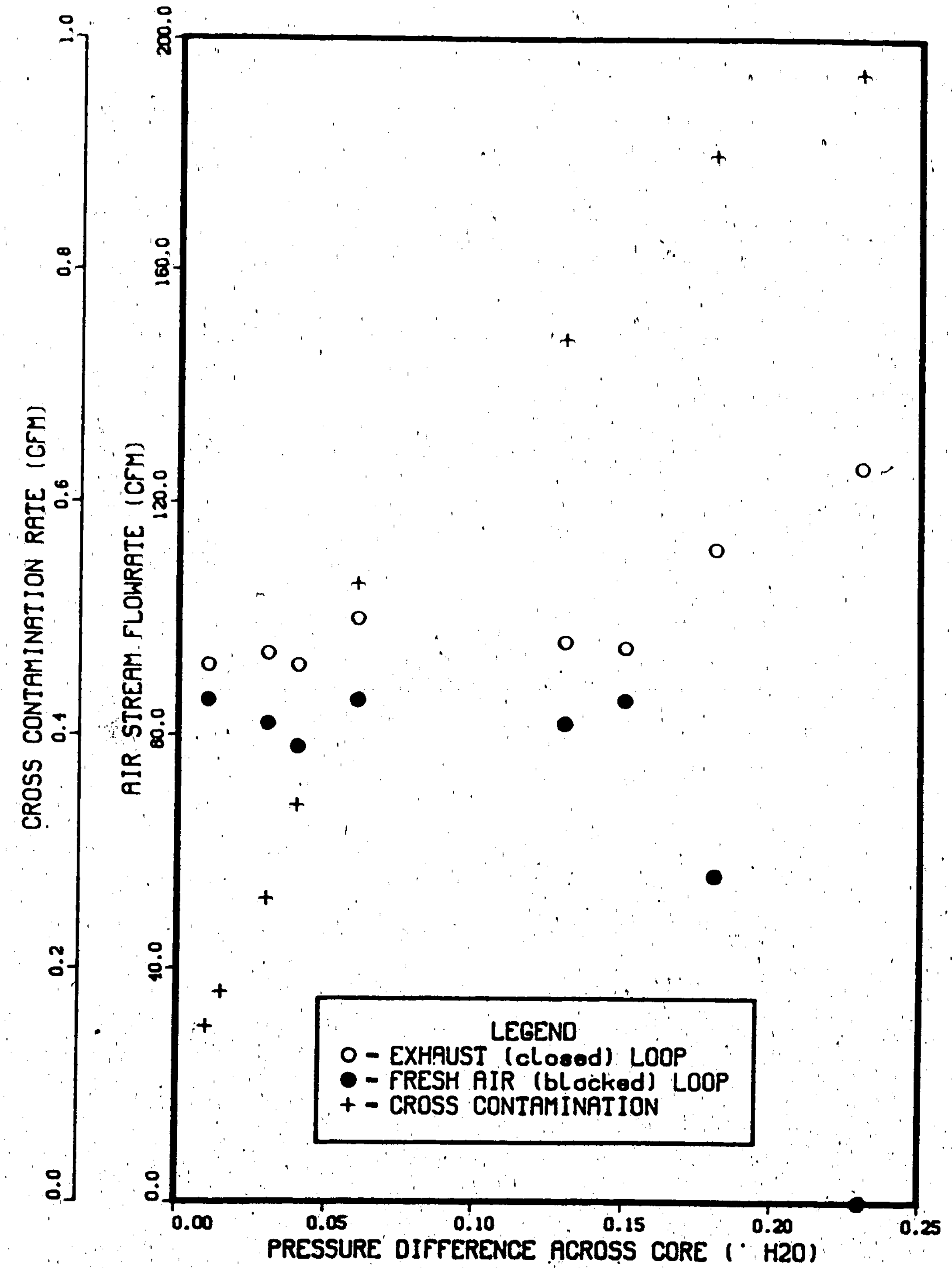

FIGURE 6.4 Cross contamination of air streams in relation to air stream flowrates and pressure differential across heat exchanger core (speed setting = LOW)

observed between cross contamination and pressure difference (flow blockage) for each of the three speed settings. The illustrated cross contamination rates are calculated as the observed leakage rates minus the system leakage rates. In each figure, as expected, the maximum rate of cross contamination is shown to occur at the maximum pressure difference imposed on the system, namely that resulting from the complete blockage of the one stream (approximately 0.25 inches of water). However, even under this condition the cross contamination rates were found to be consistently very low at approximately 1 cfm, representing 0.5% of the maximum airstream flowrate and approximately 1.0% of the minimum rate. These results would indicate highly effective separation of the two airstreams. Losses in heat exchanger effectiveness and the possibility of recirculation of airborn pollutants resulting from cross contamination rates of this magnitude would be considered negligible.

Also shown in each figure are the air stream flowrates in relation to the pressure difference and resulting cross contamination. The predictable result is that as the fresh air loop is progressively blocked off, its volumetric flowrate is reduced. Notice however the moderate increase in the closed exhaust loop at the Medium and Low settings as the blockage is imposed. As the reduction in pressure on the fresh air side reduces the load on the fresh air blower motor, the current draw is shifted to the exhaust side blower causing its speed to increase somewhat.

The fact that low levels of cross contamination were observed during testing does not negate the need to balance the system flows in a typical application. In fact, the balancing of airstream flowrates is essential for achieving efficient transfer of energy between the air streams. The installation manual accompanying the VanEE 2000, in a number of locations, stresses the importance of balancing the flows for this reason. VanEE even provides its dealers with equipment for use on a loan basis designed specifically for measuring flows and thereby assisting the balancing of the streams.

CHAPTER 7

CONCLUSIONS

Furnace Efficiency

1. The seasonal efficiency of the ICG Standard furnace as measured both in the field and in the laboratory was found to be higher than expected. The CAN1-P.1-85 laboratory test procedure predicted a seasonal efficiency of 67% while the field tests delivered an apparent seasonal value of between 70 and 72%. The value normally quoted for a standard furnace is between 50 and 60%.

While the field test value appeared to be artificially high because of additional energy gains occurring beyond the heat exchanger in the uninsulated flue pipe section, the value is perhaps typical of most standard furnace installations. In virtually all such installations, depending upon the location of the furnace with respect to the flue stack, some length of uninsulated connecting pipe is required, necessarily resulting in similar external gains. Excluding these gains, the 67% laboratory result could be viewed as an approximation to the minimum obtainable seasonal value.

The high seasonal efficiencies observed according to both the field and laboratory tests for the standard furnace are significant because they directly reduce the economic attractiveness of the higher efficiency models.

2. Because of the additional energy recovered from the uninsulated flue pipe section, the Airco Turbo appeared to perform nearly as well as the high efficiency models in the field tests. As well as the sensible gains occurring beyond the heat exchanger, latent heat was being recovered as the flue gases were cooled to below the local dewpoint. Though advantageous from an efficiency standpoint, the occurence was demonstrated to be highly undesirable. Because of the acidic nature of the condensate, significant corrosive damage was observed within the flue section after only 4 months of operation. Such damage would both increase maintenance costs and make operation hazardous. Furthermore, the potential would exist for ineffective ventilation of flue gases because of the large reduction in flue gas volume.

3. For the high efficiency furnaces, seasonal values

observed under actual field operating conditions were found to be highly consistent with those predicted by the proposed CGA seasonal efficiency test standard CAN1-P.1-85. Evidence from these results suggest that the seasonal test standard could be used to make accurate representation of real furnace performance. Assuming that no external gains would occur as the result of the particular installation, a prospective furnace buyer could justifiably use such a measured value as a dependable basis for both comparing furnace performance and assessing potential savings.

4. The steady state efficiencies measured according to the CAN1-P.1-85 seasonal test standard were found to be significantly lower than the nameplate markings for the three lower efficiency furnaces namely the ICG Standard, the ICG Conserver and the Airco Turbo. While the nameplate efficiency ratings were ~~77, 77~~ and 84% respectively, steady state efficiencies measured according to the test standard were found to be 72, 69 and 81%. This significant discrepancy was assumed to be due to reduction in burner performance because of the change in altitude. The steady state results measured for the remaining units, the ICG Ultimate, the Lennox Pulse and the Amana Energy Command, were consistent with the claims made by the manufacturers.

Influence on Air Infiltration

1. The use of a pilot flame was found to increase the natural rate of air infiltration in the test structure by approximately 25%. The infiltration rate was affected because of the higher flue gas temperature and the corresponding increase in stack buoyancy.

2. Significant reductions in air infiltration and corresponding energy loss were obtained by installing a furnace that largely reduces the off-cycle flow of room air up the stack. In the case of the ICG Conserver and its test structure, this represented a drop in infiltration of approximately 35% and a reduction in total structural energy load of approximately 7%.

Furnace Economics

1. It is more economical under most situations to purchase an upgraded standard or mid efficiency furnace than a high efficiency model. The extra investment required to purchase a high efficiency furnace is in general not adequately compensated for by the extra savings.

2. The economics surrounding furnace efficiency improvement for the Toronto area are much more favorable than those for Edmonton. This is primarily due to the difference in natural gas price between the two centers (approximately 10 and 21 cents/m^3, respectively).

3. The economic results and conclusions presented represent average home heating requirements. Under certain conditions where the heating demand is much higher, such as in a very large home or poorly insulated home, periodic savings may be significantly greater. Depending upon the level of saving, this situation would necessarily increase the attractiveness of the high efficiency alternatives.

Air to Air Heat Exchanger

1. The maximum rate of cross contamination was found be limited to approximately 1 CFM at the maximum pressure difference established across the heat exchanger core of 0.25 inches of water resulting from the complete blockage of the open fresh air stream. The rate of cross contamination represented approximately 0.5% and

1.0% of the maximum and minimum air stream flowrates respectively. Such low rates would suggest negligible influence on the thermal effectiveness of the unit and minimal likelihood of recirculation of airborne pollutants.

REFERENCES

1. Dryden, I.G.C., "The Efficient Use of Energy", 2nd. Edition, Butterworth Scientific, Butterworth and Company (Publishers) Limited, 1982.

2. Dewees, Donald N., "The Economics of Home Furnace Efficiency", Institute For Policy Analysis, University of Toronto, 1977.

3. Khoo, S.W., Schaus, O.O. and Wank, H., "The Development of Energy Efficient Domestic Gas Appliances", Canadian Gas Research Institute, Canada.

4. Van Wylen, G.J. and Sonntag, R.E., "Fundamentals of Classical Thermodynamics", SI Version 2e, Revised Printing, John Wiley and Sons Inc., 1976.

5. "CAN/CGA-2.3-M86 : Gas-Fired Gravity and Forced Air Central Furnaces", Canadian Gas Association, 55 Scarsdale Road, Don Mills, Ontario, Canada, M3B 2R3, February 1986.

6. Bonne, U. and Patani, A., "Combustion System Performance Analysis and Simulation Study", Final Report 9 November 1979 - 31 May 1982, Gas Research Institute, 8600 West Bryn Mawr Avenue, Chicago, Illinois, 60631.

7. Ackerman, M.Y., Dale, J.D., Forest, T.W., Gilpin, R.R., "Construction of the Alberta Home Heating Research Facility and Results for the 1979 - 1980 Heating Season", Department of Mechanical Engineering Report No. 23, University of Alberta, Edmonton, Alberta, Canada, 1980.

8. Ackerman, M.Y., Dale, J.D., Forest, T.W., Sadler, G.W., Wilson, J.D., Zaheeruddin, M., "Final Report On The Alberta Home Heating Research Facilily", Department of Mechanical Engineering Report No. 34, University of Alberta, Edmonton, Alberta, Canada, 1983.

9. Ackerman, M.Y., Dale, J.D., Forest, T.W., Pitman, W., Sadler, G.W., Wilson, J.D., "Fifth Annual Report on the Alberta Home Heating Research Facility", Department of Mechanical Engineering Report No.48, University of Alberta, Edmonton, Alberta, Canada, 1984.

10 "CAN1-P.1-85 : Seasonal Gas Utilization Efficiencies of Gas-Fired Central Furnaces", Canadian Gas Association, 55 Scarsdale Road, Don Mills, Ontario, Canada, M3B 2R3, March 1985.

11. Ackerman, M.Y., Dale, J.D., Forest, T.W., Sadler, G.W., Wilson, J.D., Zaheeruddin, M., "The Alberta Home Heating Research Facility - Update III - 1981-82 Heating Season", Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada, 1982.

APPENDIX A

APPENDIX A

MODULE 4 ENERGY GAIN OCCURRING FROM THE UNINSULATED SECTION OF FURNACE FLUE CONNECTING THE FURNACE TO THE B-VENT STACK.

A. SENSIBLE GAINS

Estimation of the sensible energy gains arising from the uninsulated pipe section is done by performing an energy balance on the system which equates the energy loss of the flue gases with the radiative and convective transfer to the room. The calculations which follow are based on temperatures and CO_2 levels recorded for the Airco Turbo. The pipe is galvanized steel: 10 cm diameter by 2.5 m long.

1. First determine the mass flowrate of air involved in the combustion reaction. The approximate natural gas composition (provided by Northwestern Utilities Limited, Edmonton) is:

CH_4 - 88%
C_2H_6 - 7.3%
C_3H_8 - 4.7%

The resulting stoichiometric equation is:

$$.88CH_4 + .073C_2H_6 + .047C_3H_8 + 2.25O_2 + 8.46N_2 =$$
$$1.17CO_2 + 2.17H_2O + 8.46N_2$$

Assuming zero percent CO in the flue gases of the actual reaction, the following equation applies:

$$\% \text{ Theoretical Air} = 1 + (P/A)((X - XCO_2)/XCO_2)$$

where P/A = the ratio of moles of dry constituents in the flue gas from stoichiometric combustion to the moles of air required for complete stoichiometric combustion.
= (1.17+8.46)/(2.25+8.46)
= 0.899

X = the percent stoichiometric flue gas CO2
= 1.17/(1.17+8.46)
= 12.15%

XCO_2 = the measured flue gas CO_2 concentration
= 6.7%

therefore:

$$\% \text{ Theoretical Air} = 173\%$$

Knowing the rated furnace input, the higher heating value of the fuel, the stoichiometric air/fuel ratio, and the % theoretical air, the mass flowrate of air is determined:

$$\dot{m}_{air} = 20.2 \text{ kg/h}$$

2. Perform the energy balance in order to determine the flue temperature at the exit from the uninsulated section (the thermophysical properties of the flue gas are assumed to be those of air).

$$Q_{gain} = m*c_p*(T_{inlet} - T_{outlet}) = U*A*(T_{mean} - T_{room})$$

where

Q_{gain} = heat transfer to the room

T_{inlet} = 170 ^oC (measured)

T_{outlet} ≃ 100 ^oC (measured)

T_{room} = 21 ^oC

T_{mean} = $(T_{inlet} + T_{outlet})/2$ ≃ 135 ^oC

c_p = 1015 J/kg^oC

A = 0.8 m^2

U = effective heat transfer coefficient per unit area.

$$= \left[\frac{1}{h_{\substack{inside \\ convective}}} + \frac{1}{h_{\substack{outside \\ convective}} + h_{\substack{outside \\ radiation}}} \right]^{-1}$$

i - Inside convective heat transfer coefficient:

$$V_{flue\ gas} = m_{air}/(\rho_{air} * A_x) = 0.8 \text{ m/s}$$

where A_x = pipe cross-sectional area

$$Re_d = V * d / \nu = 3000$$

On the Airco Turbo, a fan is used to expell the flue gases. This fan adds turbulence to the flow producing an estimated 100% increase in the effective Re_d. Therefore, a value of Re_d=6000 will be used to estimate the interior convection heat transfer coefficient.

$$h_{\substack{inside\\convective}} = (0.023\ Re_d^{0.8} * Pr^{0.3}) * k / d$$

$$= 7.3 \quad W/m^2\ C$$

An estimate of the radiation heat transfer from the flue gases to the inner pipe wall shows this mode to contribute only 10% of that due to convection.

ii - Outside convective heat transfer coefficient (assuming laminar free convection):

$$h_{\substack{outside\\convective}} = 1.32 * ((T_{wall} - T_{room})/d)**0.25$$

$$= 6.5\ W/m^2\ C$$

iii - Outside radiation heat transfer coefficient:

$$h_{\substack{outside\\radiation}} = \sigma\ \epsilon\ (T_{wall}^4 - T_{room}^4) / (T_{wall} - T_{room})$$

where $\sigma = 5.669(10)^{-8}\ W/m^2\ K^4$

$\epsilon = 0.3$

$$h_{\substack{outside\\radiation}} = 2.3\ W/m^2\ C$$

therefore: $U = 4\ W/m^2\ C$

Solving for T_{out}:

$$T_{out} = 100\ ^{o}C$$ (this result was confirmed during actual test runs)

3. Having determined the outlet flue gas temperature, reapply the temperature to obtain an estimate of the magnitude of energy recovered by the room:

Solving for $Q_{sensible}$:

$$Q_{sensible} = 0.4\ kW$$

The apparent increase in furnace efficiency arising from calculated sensible gains is:

$$\eta_{increase} = 0.4 / 18$$

$$= 2.5\%$$

B. There is additional recovery of latent energy due to the partial condensation of water vapor from the flue gases. To show that this is possible, knowledge of the local dew point temperature is necessary:

Knowing the natural gas composition and the theoretical air supplied, the reaction equation may be calculated as:

$$.88CH_4 + .073C_2H_6 + .047C_3H_8 + 3.89O_2 + 14.63N_2 =$$
$$1.17CO_2 + 2.17H_2O + 1.64O_2 + 14.63N_2$$

The partial pressure of the water vapor present in the flue products is:

$$\frac{2.17}{1.17+2.17+1.64+14.63} * 100 \text{ kPa} = 11 \text{ kPa}$$

The due point temperature may then be found from steam tables as:

$$T_{dew\ point} = 50\ ^{o}C$$

Measurements made at the entrance to the B-vent for the Airco Turbo showed that the flue gas temperature reached a maximum of 100°C in the 6 minutes of continuous burner operation occurring during a typical cycle. The same measurements however, indicated that the B-vent temperatures were lower than 50°C for approximately one half of the warmup time indicating that condensation was in fact occurring.

Assuming that 50% of the water vapour was condensing in the flue, the extra energy being recovered would be equal to one half of the difference between the higher and lower heating values for the fuel. For pure methane, the higher heating value is 10.6% greater than the lower heating value. This level of moisture condensation, therefore, would increase the apparent furnace efficiency by 5%.