Supplemental Information Sheet for Additional Requirements.

- For foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.
- Title vests with None proposed
SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 8/31/84

No. A-3495

Director(s) H. Z. Jackson

American Society of Heating, Refrigerating, and Air-Conditioning Engrs., Inc.

A Method of Predicting Energy Losses Due to Infiltration in Refrigerated Warehouses

Completion Date: 9/30/83 (Performance) 12/29/83 (Reports)

Contract Closeout Actions Remaining:

☐ None

☐ Final Invoice or Final Fiscal Report

☐ Closing Documents

☐ Final Report of Inventions

☐ Govt. Property Inventory & Related Certificate

☐ Classified Material Certificate

☐ Other

Project No. Continued by Project No. 

1: Newton

Library

GTRI

Research Communications (2)

Project File

Other

60:1028
June 13, 1983

Mr. H. Z. Jackson  
Georgia Tech Research Institute  
Georgia Institute of Technology  
Atlanta, Georgia  30332

Subject: ASHRAE Research Project 362-RP, "A Study To Determine A Method Of Predicting Energy Losses Due To Infiltration In Refrigerated Warehouses"

Dear Mr. Jackson:

The thirtieth of June marks the end of a reporting period on the subject project and also marks the end of the Society's fiscal year. For this reason, we would like to receive your next Progress Report as soon after the first of July as possible so that we may make the progress payment prior to closing the books on the fiscal year.

If the financial portion of your report will be delayed by your accounting department, we will be glad to accept it at a later time.

Your assistance in submitting a prompt report will be appreciated.

Yours truly,

William W. Seaton

WWS/ss
Project Number and Title: 362-RP - "A Study to Determine A Method of Predicting Energy Losses Due to Infiltration in Refrigerated Warehouses"
Research Institution: Technology Applications Laboratory, Engineering Experiment Station, Georgia Institute of Technology
Period Covered by Report: April 1, 1983 through June 30, 1983

1.0 Names of Personnel Engaged in Investigation:
   Principal Investigator: H. Z. Jackson, P.E.
   Research Assistant: Jaydeep Desai

2.0 Summary of Activity, including specific accomplishments and trends or conclusions indicated: Computerized and manual literature searches have been completed, and hard copy documents obtained. Some additional secondary references, included in bibliographies of references just obtained, are being sought to augment the material found during the literature searches. Review of the references indicates that there are some mathematical formulations for infiltration due to open doors, cracks in the building envelope, and heat and mass transfer through air curtains. But multiple solutions have not been found for all areas of interest, so computer comparisons will not be necessary for all models.

3.0 Is Original Project Time Schedule Still Valid?  x Yes  ____No.
   If not, explain.
   Have experienced about a two week slippage in project initiation, due to length of time needed to locate a suitable Graduate Research Assistant. But completion date and interim reporting dates are still valid.

4.0 Modification of Project Plan Suggested by Results to Date:
   None, other than that mentioned in Item 2.0 with respect to computer comparisons of all models.

Signature of Project Director:  [Signature]
Title: Research Engineer II
Date: 7/1/83

SEND IN TRIPlicate TO: Manager of Research
ASHRAE
1791 Tullie Circle, N.E.
Atlanta, Georgia 30329

NOTE: PLEASE NOTIFY THE MANAGER OF RESEARCH IMMEDIATELY OF ANY PROBLEM THAT COULD DELAY THE PROJECT COMPLETION OR INCREASE THE COST.
A STUDY TO DETERMINE A METHOD OF PREDICTING
ENERGY LOSSES DUE TO INFILTRATION
IN REFRIGERATED WAREHOUSES

- PHASE I -

FOR:
THE AMERICAN SOCIETY OF HEATING, REFRIGERATING AND
AIR-CONDITIONING ENGINEERS, INC.

BY:
H. Z. JACKSON
TECHNOLOGY APPLICATIONS LABORATORY
ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY

JANUARY 9, 1984
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ABSTRACT

The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) is funding an investigation of methods of predicting energy losses in refrigerated warehouses due to infiltration. This report summarizes a literature search conducted under Phase I of this program by the Technology Applications Laboratory of the Georgia Tech Engineering Experiment Station. The purpose of the literature review was to identify and document the history of research conducted to the present in the area of infiltration prediction for refrigerated warehouses. The objective of this ASHRAE program of research is to update the information contained in their various publications and handbooks, thereby improving methods used by practicing engineers in predicting infiltration.

Phase I of the research project, the literature review, has resulted in the identification of a number of published works which deal with analytical methods of predicting infiltration in cold storage facilities. The major areas of concentration are in predicting heat and mass transfer by natural convection through open doors, and in estimating the heat and mass transfer across an air curtain. Other non-analytical references include design criteria and guidelines for cold storage doors, vapor barriers, and air curtains. A total of 68 references is cited in the bibliography that accompanies this report.

Also included in this report is an outline of a field test program to be conducted during Phase II of this research project. The
field test program will verify the accuracy of two analytical solutions to infiltration encountered during the literature review, and will also amass additional field data which can be consolidated into graphs, tables, and charts to be used as design tools in ASHRAE publications.
I. Introduction

Cold storage facilities have grown in size and number in response to increased popularity of convenience foods in domestic and commercial markets. As a result, overall energy use for refrigeration by these facilities has also grown. To reduce operating costs associated with energy usage, designers and operators of cold storage buildings have a need for information that enables them to predict the heat gain of refrigerated warehouses.

Accepted practices for the design and construction of refrigerated storage facilities have been set forth by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). Design load factors have been identified, and include transmission heat gain, infiltration heat gain, internal equipment loads, and product cooling. However, there are recognized shortcomings in the prediction methods for estimating infiltration heat gain, which can account for up to 50% of the total refrigeration load.

The objective of this research project is to improve upon the current ASHRAE methods for estimating infiltration energy losses in refrigerated warehouses. Upon completion of the project, ASHRAE expects to include the findings in their various technical reference publications, such as the Fundamentals and Applications handbooks.

A two-phased workplan has been requested by ASHRAE to accomplish this objective. The first phase consists of a thorough review of the literature which deals with the prediction
of losses in refrigerated warehouses due to infiltration. The intent is not to develop new analytical approaches, but rather to consolidate and review the prior work of other researchers. Some analytical techniques are already known to ASHRAE, having been presented in some of their many technical publications. However, a comprehensive review is needed for this first phase. The findings are to be presented in a final report which summarizes the state-of-the-art.

Phase II is to consist of field measurements to verify and refine the analytical approaches encountered during Phase I. A number of warehouses of varying construction and type will be selected for use as test sites. The experimental plan will be designed to confirm the accuracy of the estimating methods, and to determine limitations to their applicability. A final report will be prepared to present the findings of Phase II.

This report summarizes the results of Phase I of the ASHRAE research project described above. A literature search has been conducted which identified pertinent technical publications from 1954 to the present. Both computerized and manual search techniques were employed. A total of 68 references is included in the bibliography; they range from complex academic works to very elementary vendors' sales publications. Generally speaking, the works encountered are sufficient to provide analytical models for verification during Phase II. If good field correlation is obtained, several of the methods for predicting infiltration can be included in ASHRAE handbooks for use by the practicing engineer.
A review of the literature reveals that two areas command the great majority of discourse related to cold storage infiltration. The first subject area is comprised of the study of natural convection through open doors in cold storage rooms. Six contributors have been found, some of which have conducted experimental programs on laboratory scale models and full-size cold stores. Both heat and mass transfer expressions have been found. Not surprisingly, the approach used by all of the researchers is similar; refinements in their consideration of non-ideal behavior and in determination of experimental constants gives rise to most of their differences.

The second area is based upon studies of the heat and mass transfer through air curtains. An air curtain is a jet or sheet of high velocity air that is directed across the door opening of a conditioned space. Theoretically, an air curtain that has the proper velocity and discharge angle can prevent the mixing of air from opposite sides of the door. In practice, some exchange does take place, and various researchers have attempted to experimentally and analytically address the phenomenon. Estimates of the effectiveness of air curtains ranges from 30% to 83%, and no consensus of opinion is evident regarding their value under field conditions.

Other subjects also were given treatment in the literature, including natural convection within wall cavities in cold storage rooms, and estimating techniques for leakage through cracks in the building structure. Noticably lacking in the literature is any current information about steady-state infiltration in closed
warehouses, such as production warehouses. But the open door infiltration component is so much greater and was obviously considered most important by the majority of the investigators.

The following sections discuss in more detail the results of Phase I of this ASHRAE research project. An annotated bibliography is found in the Appendices, as are graphs, figures, and tables encountered in the various works. A detailed test plan is also included, to be implemented during Phase II after acceptance by ASHRAE.

Conclusions reached during this project are that sufficient techniques exist for predicting infiltration in refrigerated warehouses, and that infiltration consists mainly of open door losses. Further, it is believed that good field correlation with analytical predictions can be obtained, based upon limited full-size measurements conducted to date.
II. Literature Search

The initial efforts to identify appropriate references for the research topic consisted of a computerized search for titles, authors, and abstracts. This was accomplished through the use of the Lockheed DIALOG information system which is available at the Price Gilbert Memorial Library on the Georgia Tech campus. Using this computer-based literature search system, access to over 150 data bases is possible.

In order to take advantage of the speed and flexibility of such a system, one must first select an appropriate data base, or index, and a list of keywords which are expected to be associated with the topic. A preliminary trial-and-error approach was used to probe all the logical choices of data bases, in an effort to isolate the ones which appeared to have the highest number of references related to infiltration, cold storage, or refrigeration. This procedure resulted in the selection of the on-line Engineering Index (COMPENDEX) as the data base. This base contains references from 1970 to the present.

A list of possible keywords was next compiled from the rudimentary set used in the trial search. The full list, including permutations and combinations, is shown in Table 1.

Next, a complete and thorough computerized search was made through the data base. The total number of citations encountered was far short of what had been anticipated. A second attempt using different keywords did not improve the results.
Comparing the bibliography furnished by ASHRAE (contained in the invitation to propose) to the list of references obtained revealed an interesting point. The majority of the published research related to infiltration due to the open door in cold storage warehouses and methods of controlling infiltration was done during the 1960's. Since the computerized data bases do not extend back past 1970, many published works are not resident in the file.

This discovery caused the abandonment of the computerized search in favor of the more laborious manual method. The graduate research assistant assigned to this project began to consult the indices of the various professional and trade periodicals already found to have published papers in the research area. These periodicals included the ASHRAE Journal and ASHRAE Transactions. A minimum requirement was to locate the references already furnished by ASHRAE. The overall objective was to find all references from the mid-1950's to 1970 that were not included in the computer data base, and any 1983 publications which were too recent to be on the computer data base.

This approach was found to be more successful in locating useful publications. Full length copies of the references were obtained, either by copying the original in the library or ordering through the appropriate document clearinghouse. Many of the papers contained a bibliography or reference list, which served to increase the number of authors and titles available. These additional references were also obtained if they were judged appropriate.
Several iterations of this manual search method were accomplished, in order to obtain as complete a file of references as possible. The search was concluded when examination of the bibliographies and reference lists of the papers revealed no new authors or titles.

As a final check on the adequacy of the literature search, a number of telephone calls were made to the authors of some of the references which were found. The various parties contacted are included in the bibliography in the appendices of this report. Some of the most noteworthy of these are K. R. Solvason, W. Carl Hall, W. F. Stoecker, F. C. Hayes, and J. Van Male in the Netherlands.
III. Results

In all, 68 papers for reference were located by the literature search. They range from ASHRAE handbook chapters to internal publications of equipment vendors. Topics include the theoretical determination of heat and mass transfer through an open door, heat and mass transfer calculations for air curtains, vapor trace methods for determining cold storage building infiltration, and design considerations for cold storage doors. Unfortunately, there is a shortage of field data for actual infiltration rates in modern, single-story cold storage warehouses. Hence, there are few empirical or tabular design tools available for predicting infiltration. The test program described in the appendices of this report for Phase II of the project reflects the need for such field measurements.

Surprisingly, little research seems to have been done during the energy-conscious years of 1973-1979, specifically for cold storage buildings. There is a tremendous amount of material available pertaining to residential, commercial, and industrial infiltration, but it is not transferable to cold storage facilities. This is because of the unique construction practices and temperature extremes associated with refrigerated warehouses.

The following sections describe in more detail the substance of the literature collected. The works are categorized based upon their importance to one of three applications: 1) Mathematical and Experimental Formulations or Solutions, 2) Design Considerations and Criteria, 3) Infiltration Control
Equipment and Construction. The discussion which follows is organized along the same lines, with sub-topics where necessary.

1. Mathematical and Experimental Formulations or Solutions

Natural Convection Through Openings:

The density of air is primarily a function of temperature, under naturally occurring conditions. In the case of a refrigerated storage facility, the air contained inside is much colder and denser than is outside air. If the door to the storage area is opened, this difference in density causes the forces of natural convection to be manifested in airflow through the opening. The cold, heavy air in the immediate vicinity of the door will move downward and outward, displacing the warm, lighter air on the outside. As the cold air moves out of the storage area, it is replaced with an equal volume of warm, lighter air drawn into the enclosure. The simultaneous movement of the two streams of air can be depicted as in Figure 1. Cold air moves outward through the lower half of the opening, being replaced with warm, outside air which moves inward through the upper half. Such an exchange of air in a refrigerated store facility constitutes infiltration by natural convection. For single story rooms with low ceilings, analysis and experiment by various researchers indicate that the height of the door, not the height of the room, determines the flowrate. However, no verification of this relationship has been obtained for high rise cold stores.
Six technical sources were found regarding this infiltration component. Each one is described below; results obtained by analytical means are presented in Table 2 and Figure 2.

- Brown and Solvason (1963, Reference 8)

W. G. Brown and K. R. Solvason were the first researchers to attempt to formulate an exact solution to the problem of natural convection through cold storage doors. They incorporated the concept of a neutral zone, proposed by J. E. Emshiler in 1926, as the level in the door opening at which airflow was essentially zero. Above and below this line, air moved either into or out of the cold storage room. The formulation was based upon the Bernoulli equation, the pressure difference being a function of the differing air densities caused by the temperatures on each side of the opening. The volumetric flowrate expression was obtained, corrected by a discharge coefficient as is customarily done for a sharp edged orifice, and was then used to find thermodynamic expressions for heat and mass transfer. Ultimately, these expressions were reduced to dimensionless equations using the Nusselt, Grashof, Prandtl, Schmidt, and Sherwood numbers. This was done to facilitate correlation of the solutions with laboratory scale-model tests. The general form of the equations, including the exponents a, b, c, and d, and constants A and B to be determined by experiment, is:

\[ \text{Nu} = B G r^{a} P r^{b} \quad \text{and} \quad \text{Sh} = A G r^{c} S c^{d} \]
where \[ \text{Nu} = \frac{hT H}{k} \]

\[ Gr = \frac{GAP H^3}{\rho \cdot v^2} \]

\[ Pr = \frac{C_p \mu}{k} \]

\[ Sc = \frac{\nu}{D} \]

\[ Sh = \frac{h_m H}{D} \]

For the practical range of conditions to be found in modern cold storage facilities, the relationship for heat transfer was found through experiment to be:

\[ \text{Nu} = 0.343 \, \text{Gr}^{1/2} (1 - 0.498 \, t/H) \, \text{Pr} \]

where \( t \) = doorway thickness, ft.

\( H \) = doorway height, ft.

The factor \( t/H \) is necessary to correct for viscosity effects.

Reduced to engineering terms, the heat exchange equation becomes
\[ q = 0.343 \ A \ c p \ \Delta T \ \rho_{ave} \sqrt{\frac{\rho_i - \rho_o}{\rho_{ave}}} (i - 0.498 \ t) \ \sqrt{gh} \ \text{Btu/sec} \]

where

- \( A \) = door area, width times height, \( \text{ft}^2 \)
- \( c p \) = specific heat of air at constant pressure, \( \text{Btu/°F-lb} \)
- \( g \) = gravitational acceleration, \( \text{ft/sec}^2 \)
- \( H \) = door height, \( \text{ft} \)
- \( t \) = thickness of doorway partition, \( \text{ft} \)
- \( \Delta T \) = temperature difference between opposite sides of doorway, \( °\text{F} \)
- \( \rho_i \) = density of air on inside of cold store, \( \text{lb/ft}^3 \)
- \( \rho_o \) = density of air on outside of cold store, \( \text{lb/ft}^3 \)
- \( \rho_{ave} \) = average air density, \( (\rho_i + \rho_o)/2 \)

A major shortcoming of the Brown and Solvason derivation is that the heat transfer expression considers only the sensible heat of dry air, neglecting the latent heat content of air/vapor mixtures. For conditions of low relative humidity of the outside air, this will not create a problem in application. However, for high relative humidities, the prediction of heat exchange given by this equation will result in a significant underestimate of the actual losses.
Tamm followed Brown and Solvason with a similar derivation of the air movement through a cold storage doorway. He published these findings in the German publication *Kaltetechnik-Klimatisierung* in 1966. He also assumed a neutral zone at some height $z$ in the door, and utilized the Bernoulli equation in differential form to express the air velocity at any point located vertically in the plane of the opening. By assuming equal volume flow rates into and out of the cold store room, and integrating his velocity equations to the neutral zone height $z$, he obtained the expression for the volumetric flowrate:

$$\dot{V} = \frac{2}{3} A \sqrt{gh} \left(1 - \frac{\rho_o^{1/3}}{\rho_i^{1/3}} \right) \left[\frac{1}{1 + \left(\frac{\rho_o}{\rho_i}\right)^{1/3}}\right]^{3/2} \text{ft}^3/\text{sec}$$

where

- $A$ = doorway area, width times height, ft$^2$
- $g$ = gravitational acceleration, ft/sec$^2$
- $H$ = doorway height, ft
- $\rho_i$ = density of air inside cold store, lb/ft$^3$
- $\rho_o$ = density of air outside cold store, lb/ft$^3$

This fairly simple formulation tends to overpredict infiltration rates (Longdill and Wyborn, "Performance of Air Curtains in Single Story Cold Stores", Reference 31.)

Similarly, from the thermodynamic relation for heat transfer, $q = m\Delta h = \rho V \Delta h$ he obtained the heat exchange rate:
\[
q = \frac{2}{3} A \rho_1 \sqrt{2 g H} \left(1 - \frac{\rho_1}{\rho_i}\right)^{A/2} \left(\frac{1}{1 + \left(\rho_0/\rho_i\right)^{1/3}}\right)^3 (h_0 - h_i) \text{ Btu/sec}
\]

where \( h_0 \) = enthalpy of air outside cold store, Btu/lb

\( h_i \) = enthalpy of air inside cold store, Btu/lb

Note the use here of the enthalpy term to express the heat transfer, in contrast to the approach used by Brown and Solvason. This important consideration leads to more accurate results when considering outside air with a high relative humidity.

Still, once some simplification in terms and multiplicative constants is achieved, Tamm's equation for the volume flow rate is almost equivalent to Brown and Solvason's. Tamm did not conduct an experimental program to validate his findings, relying instead upon measurements made by other researchers and correlated after the fact with his predictions. Subsequent investigators (Fritzsche and Lilienblum) were left to offer some improvement to Tamm's formulation.

- **Fritzsche and Lilienblum** (1968, Reference 16)

In 1968, Fritzsche and Lilienblum made measurements of the velocity of air moving through an open cold storage door 6 ft by 8 ft high (1.8m x 2.5m). Their objective was to provide a field correlation of the analytical solution formulated by Tamm.
The doorway was covered with a small diameter wire gridwork with large openings which did not significantly impede air flow. Cloth tufts were attached at each wire intersection, and were used as visual indicators of the direction and relative magnitude of the airflow. An anemometer was used to measure actual velocities at each point, and temperature and humidity information was recorded at selected locations. By obtaining this pointwise information concerning air velocity through the doorway, a velocity mapping of the flow field was generated (Figure 3).

Upon reducing the test data, Fritzsche and Lilienblum discovered that the experimental results did not agree with predictions found by applying Tamm's solution. By empirically fitting experimental data with predicted results, they developed a correction factor, similar to the discharge coefficient for an orifice, to be applied to Tamm's equation. However, since the correction factor is based upon measurements of only one door size, the validity of using it for other circumstances is questionable.

B. H. Shaw

According to references by other researchers, Shaw published a paper entitled "Heat and Mass Transfer by Natural Convection and Combined Natural Convection and Forced Air Flow Through Large Rectangular Openings in a Vertical Partition," in the journal of the Thermodynamics and Fluid Mechanics Group of the Institute of Mechanical Engineers in
1971. This academic group is affiliated with the University of London, England. No source of this work was encountered during either the computerized or manual literature searches, indicating that none of the document clearinghouses in the U.S. had a copy of the work. The original document has not been obtained, due to time limitations and the difficulty anticipated in tracing the author. However, the evidence in other works indicates that Shaw's contribution was essentially an experimental verification of analytical solutions of others, and offers no new important information. He is reported to have gathered anemometric data on full sized doorways at cold storage facilities, much the same as Fritzsche and Lilienblum. Although field measurements such as Shaw's are valuable for judging the accuracy and applicability of analytical techniques, this particular experimental program did not shed any new light upon the phenomenon.

- Gosney and Olama (1975, Reference 17)

H. A. L. Olama submitted a PhD thesis to the faculty of the University of London in 1975 entitled "Mass Exchange through Cold Store Doorways." Mr. Olama combined his thesis work with the assistance of W. B. Gosney (presumed to be his PhD advisor) to produce a comprehensive paper entitled "Heat and Enthalpy Gains through Cold Room Doorways." The technical paper recounted the efforts of Brown and Solvasson, Tamm, et al, and discussed the limitations of their
solutions. Gosney and Olama presented yet another analytical solution for the steady-state losses through cold storage doors, but went one step further. They proposed a transient model for the phenomenon which had been suggested from experimental results obtained during verification of the steady-state model.

Gosney and Olama began their derivation by closely paralleling the analysis of Tamm. However, instead of an expression for volume flow rates as posed by Tamm, they based their approach on a mass flow consideration. By imposing the condition of equal mass flows into and out of the cold storage room, it was found that the "neutral zone" often associated with such flows is not at the door mid-height, but at a point somewhat below H/2.

The basic formulation from first principles was next improved upon by applying heat transfer relationships based upon dimensionless parameters such as Nusselt, Grashof, and Prandtl. The exponential relationships proposed were the same as Brown and Solvason, but other constants and non-dimensional factors were derived to account for shortcomings in other formulations. In particular, a correction was applied to account for the difference in assuming equal mass flows instead of equal volume flows. The main motivation for deriving the non-dimensional representation of the problem was to allow scale-model laboratory testing to correlate the analytical findings.
Besides the steady-state model, Gosney and Olama also derived a non-dimensional transient model. The characteristics of the model are a function of the door cycle time and the ratio of viscous forces to inertia forces. Again, experimental results were used to determine the constants associated with the time-dependent relationship for the transient losses as compared to the steady-state.

Two scale models were constructed for testing. One model, made of expanded polystyrene, incorporated a 0.35 ft. by 0.25 ft. (0.107m x 0.077m) doorway equipped with a mechanically operated plastic door. This model was capable of simulating a large range of opening and closing intervals, and was used to investigate the possible time-dependency of losses through cold storage doors.

A second scale model was larger and was constructed of hardboard. An opening 2.0 ft. by 1.6 ft. (0.6m x 0.5m) was provided, covered by a polystyrene sheet in which an opening of test size was cut. This model allowed Gosney and Olama to vary the Nusselt and Grashof numbers over identical conditions of temperature and relative humidity.

Results of the laboratory testing showed good correlation. In fact, for Grashof numbers above $3.5 \times 10^6$ (practical cold storage conditions), the correlation coefficient found by linear regression techniques was 0.999 when considering the steady-state losses. Good correlation was obtained for the transient solution also.
The heat exchange expression of Gosney and Olama can be presented in engineering terms as follows, with the steady-state and transient components indicated.

\[
q = 0.221 A \frac{c_p (t_o - t_i) \rho_i (1 - \frac{\rho_o}{\rho_i})^{\frac{1}{2}} (gH)^{\frac{1}{2}} F_m}{Btu/sec}
\]

Steady State

Transient

where

- \( A \) = door area, width times height, \( ft^2 \)
- \( C_p \) = specific heat of air at constant pressure, \( Btu/°F-lb \)
- \( F_m = \left[ \frac{2}{1 + (\rho_i/\rho_0)^{1/3}} \right]^{3/2} \), density factor for equal mass flows
- \( g \) = gravitational acceleration constant, \( ft/sec^2 \)
- \( H \) = door height, \( ft \)
- \( t_o \) = outside temperature, \( °F \)
- \( t_i \) = inside temperature, \( °F \)
- \( \rho_i \) = density of inside air, \( lbm/ft^3 \)
- \( \rho_o \) = density of outside air, \( lbm/ft^3 \)
\[ \phi = (1 - 0.0112 \frac{0.0112}{0.3565} N_0) N_f^{0.1} \]

\[ N_0 = \frac{\nu T_o}{H^2} \quad \text{and} \quad N_f = \frac{T_o}{T_C} \]

\( T_o = \) Door open time in seconds

\( T_C = \) Period of each open/close cycle in seconds

\( \nu = \) Kinematic viscosity at the inside state, \( \text{ft}^2/\text{sec} \)

- W. S. Atkins and Partners for Clark Door Limited (1982, Reference 5)

In an effort to provide their customers with better estimates of the energy costs associated with infiltration through open cold store doors, Clark Door Limited commissioned an engineering firm to investigate the phenomenon. The firm, W. S. Atkins and Partners, was selected to perform a literature search to identify methods of predicting energy losses through cold storage doors. Further, they were to conduct some field experiments designed to test the correlation of calculated energy losses obtained by analytical techniques with actual measured values. In some respects, this research program conducted by Clark Door Limited is quite similar to the current ASHRAE research.

W. S. Atkins found the same principal investigators in the literature as discovered during this project: Brown and Solvason, Tamm, and Fritzsche and Lilienblum. However, through foreknowledge and immediate accessability, they were
able to obtain a PhD thesis and another little-published paper on the theme. The thesis, written by H. A. L. Olama at the University of London, is entitled "Mass Exchange Through Cold Store Doorways." It was completed in 1975. A technical paper was published in December 1975 by W. B. Gosney and Olama, and was based upon the PhD work. This reference has been previously discussed in this report.

The researchers at W. S. Atkins compiled a table which compared the results of all the analytical models they had encountered. The table is reproduced as Table 2. Note that the ASHRAE prediction comes from the 1966 Fundamentals; the 1981 Fundamentals volume has no similar prediction for the example cases used. Results using the Gosney, Fritzsche, or Brown formulations are in good agreement, except for Brown at high outside humidities. This shortcoming has been discussed earlier. However, the Berner (equipment vendor) and ASHRAE methods shown in Table 2 seem to give good "ballpark" estimates but with significant variation from point to point.

W. S. Atkins concluded that the best candidate analytical solution for field verification was that of Gosney and Olama. It might equally well be argued that the Fritzsche or Brown approaches would also give acceptable correlation of predictions, but the Gosney and Olama solution also offers a transient solution. None of the other methods incorporate this time-dependency, dealing only with a steady-state system.
The field experiments of Atkins included transient measurements of cold storage losses through an open door, as well as steady-state losses. Field data showed good correlation with Gosney and Olama predictions. The steady-state losses measured were lower than predicted, by approximately 7%. Transient heat loss measurements indicated that the predicted values at any given time were significantly lower than the actual losses, and approached the steady-state conditions much more slowly than expected. An example is shown in Figure 4. To account for the actual behavior of a more rapid approach to steady-state conditions, W. S. Atkins posed a transient behavior factor:

\[
Q_{AV} = \frac{7 \times 0.3 + (T_0 - 7)}{T_0} Q_{SS}
\]

where

- \(T_0\) = time door is open (seconds)
- \(Q_{AV}\) = average heat loss while door is open
- \(Q_{SS}\) = steady-state heat loss

Assumptions are that average heat loss over the first 7 seconds is 30% of steady-state, and that heat loss after 7 seconds is 100% of steady-state. This transient correction is based upon measurements of only one cold store and one door size. Hence, it may not extend to other cases.

The major conclusions reached by W. S. Atkins are quite valuable for the cold store designer. First of all, there are several steady-state analytical models which can predict
energy losses through cold storage doors with acceptable accuracy. Secondly, the time dependency of these losses has been verified, and an analytical approach has been devised to account for it. Thirdly, preliminary results for the single door size investigated indicated that if total door open time for traffic passage can be limited to around 7 seconds or less, 70% of the steady-state losses can be avoided. Of course, this assumes that the cold store design and operation permits such a short open door time period. Door manufacturers and cold store designers might consider adding this criterion to their specifications for cold storage doors which remain open only for pedestrian and fork lift passage.

Clark Door Limited has a computer code model available which incorporates the findings of the W. S. Atkins research program. The model uses the basic solution of Gosney/Olama, with the time dependency correction suggested by Atkins. Required inputs are inside and outside temperatures and relative humidities, height and width of the door, time door is open, minutes between each open/close cycle, and cost of electricity. Energy losses are calculated, as well as mass of water entering the store (frost loading), and financial losses. The results for the subject door are compared for continuously open doors and for doors open for only 7 seconds. A sample output is included in Appendix C, Figure 5.
Heat Transfer Through Air Curtains:

An air curtain is a jet or sheet of air directed perpendicularly across the path of the flow of air through an opening in a wall, such as a doorway. This sheet of air is designed to flow at the appropriate velocity and in the proper direction to prevent air exchange across the opening. Air is entrained by the air curtain flow and redirected back toward the side from which it originated, preventing an exchange of air through the opening.

However, air curtains are not completely effective. Some exchange of air does occur from one side to the other, accounting for a heat and mass transfer between the zones. In a refrigerated warehouse utilizing air curtains to prevent conditioned air loss, such an exchange constitutes a source of infiltration. The design engineer proposing to use air curtains in such a facility needs a method of predicting the infiltration rate attributable to air curtains.

Air curtains can be described by two different types of air flow. One is recirculatory, in which the air flows across the opening into a return grill at the other side of the opening, and is returned by ductwork to the blowers. The second type, free-flow or impingement air curtains, do not recirculate the air but rather deflect the air curtain flow to either side of the opening.

Further classification of air curtains depends upon their orientation. Vertical air curtains direct the flow either upward or downward across the face of the opening. Almost all practical
designs of vertical curtains are downflow. Horizontal air curtains flow across the opening in a direction approximately parallel to the floor. Vertical air curtains may be either recirculatory or free-flow; almost all horizontal air curtains are recirculatory.

Gravity effects make the application of a horizontal curtain quite difficult in practice. The air flow tends to sag in response to the downward gravitational force which is at right angles to the path of flow. Variable velocity from top to bottom can mitigate this effect somewhat, but such air curtains are seldom implemented in practice.

Likewise, the practical limitations of recirculatory air curtains for refrigerated storage, such as structural complexity and hygiene standards (USDA), limit their use. Hence, most air curtains found in refrigerated storage facilities are of the vertical, downflow, free-flow type.

The literature search disclosed several mathematical formulations relating the heat and mass transfer across vertical air curtains. There are also a number of references containing experimental data regarding their performance in actual installations. The references span the time period from the mid-1960's to the present.

Tamm (1963, Reference 54)
One of the first researchers to attempt to characterize the flow of an air curtain was W. Tamm of Munich, Germany. From the mathematical expression of air discharge from a plane
jet, he formulated a flow function for the air curtain using superposition and graphical techniques. While the results of this work are not useful to the practicing engineer, they did form the basis for work by subsequent researchers.

- Hetsroni and Hall (1965, Reference 25)
In 1965, G. Hetsroni and C. W. Hall of Michigan State University published a paper describing the results of experiments with three and six-nozzle vertical downflow recirculatory air curtains. The heat transfer coefficient for each curtain was determined for various air curtain velocities. Constant temperatures of 40° and 85°F were maintained on each side of the curtain by an electric heater, which was instrumented to record energy flow. Results included an empirical relationship of heat transfer to Reynolds number for the curtain, in which the overall heat transfer was found to be directly proportional to velocity and inversely proportional to curtain thickness. Since this study was somewhat specific to recirculatory curtains of a particular design, the mathematical formulation is less useful to the design engineer than are the qualitative results.

- Hayes and Stoecker (1969, References 20 and 21)
A much more practical formulation was presented by F. C. Hayes (ASHRAE member) and W. F. Stoecker (University of Illinois, ASHRAE member). Two papers were authored by these
men, the first in 1969 in the ASHRAE Transactions. The first paper contained a detailed mathematical solution of heat transfer across a high velocity, vertical downflow, free-flow air curtain. Expressions for the heat transfer were expressed in the dimensionless parameters of Nusselt, Reynolds, and Prandtl. The second paper simplified the findings into a series of relationships and graphs which were presented in engineering terms. In fact, the second paper was intended to be used as a design guide for specifying air curtains in actual installations.

The Hayes and Stoecker findings are bound by a rigid assumption that the opening under consideration is for an otherwise tightly sealed chamber. Such a restriction would not always apply in large commercial storage facilities. Therefore, the use of their findings must be accompanied with due consideration to the limitation.

- Others

A number of other investigators have reported upon the efficiency of air curtains obtained by experiment. Efficiency of an air curtain is expressed as the percentage of heat transfer avoided as compared to an unprotected opening. Trojawowski and Rubnikowicz (Poland) [Reference 57], Takahashi and Inoh (Japan) [Reference 53], and Longdill and Wyborn (New Zealand) [Reference 32] report efficiencies of up to 80% for air curtains operating under optimum conditions. However, Longdill and Wyborn report that the efficiency of horizontal or vertical air curtains can drop
to near zero under the influence of a wind of as little as 4 mph (6 m/s). They found that the use of exterior air rather than conditioned air made only a 5% or 10% difference in performance, which might be offset by the added complexity in installation. In practice, only static, properly adjusted air curtains function according to predictions.

The experimental results emphasize the difficulty of designing and operating an effective air curtain under the dynamic conditions of temperature and pressure found in refrigerated storage facilities. Such findings lead to the suggestion that air curtains are an assistance to doors and not a replacement for them.

Building Envelope Air Leakage:

Building envelopes are not completely impervious to air leakage due to construction limitations and permeability of construction materials. Modern-day use of plastic films for vapor barriers has reduced the leakage of refrigerated storage facilities due to permeability to an inconsequential amount. However, discontinuities in the structure, such as the wall-ceiling joint can still allow infiltration of outside air into the structure. All such leakage sources can be lumped into the category of building envelope leakage for purposes of discussion.

Less literature was found relating to this area of infiltration than for any other component. This seems unusual when compared to the substantial research done for residential
and commercial building infiltration during the 1970's. Only two substantive works were found which addressed directly the question of steady state infiltration in a sealed cold storage area. A third paper was found which proposed the existence of air flow within wall cavities. A fourth presented the findings of experiments in vapor trace measurements of infiltration using different tracer gases.

- Sainsbury and Gerhardt (1954, Reference 48)
The first published work is qualitative in nature, both due to the origin of the data and the passage of time since its acquisition. G. F. Sainsbury and Fisk Gerhardt measured air leakage in apple warehouses in the Pacific Northwest and reported their findings in 1954. Apples at a given storage temperature have a fairly well defined rate of respiration of carbon dioxide, ethylene, and non-ethylenic volatiles. Measurement of the concentration of these gases in a large number of warehouses allowed the calculation of an air leakage rate on a per unit volume basis. This natural production of tracer gas was a forerunner to the modern practice of using artificially-induced gases to determine air leakage rates in buildings. The results of Sainsbury and Gerhardt demonstrated a wide variation in leakage rates, from 0.6 volumes/day to 8.6 volumes/day for a closed warehouse. The variation was attributable primarily to differences in cooling delivery system design. But the designs and construction types encountered in the study are
no longer representative of modern refrigerated storage facilities. Hence, a need for more recent data exists. Telephone conversations with other researchers in the field of infiltration in refrigerated facilities (Stoecker, Howell, Sainsbury) indicate that the component of infiltration due to steady-state leakage is quite small when compared to the infiltration burden caused by open doors. Therefore, the emphasis placed upon gathering such data must be tempered by the ease with which it can be collected.

- J. Van Male (1979, Reference 58)

The second related work was a highly theoretical approach to leakage determination using a specific equivalent leak opening (selo) coefficient, posed by J. Van Male of the Delft University of Technology in Holland. The coefficient is defined as the total free cross section of a number of tubes of equal diameter yielding the same leak flow rate as the surface or building under consideration. It is straightforward in formulation, but is not useful for the practicing engineer due to the lack of any corresponding selo coefficients for refrigerated warehouse construction.

- Lorentzen and Brendeng (1960, Reference 33)

Another related paper by G. Lorentzen and E. Brendeng (Norway) discusses the possibility of free convection and forced convection within insulated, vertical walls. Such convection air flow would serve to increase the conductivity
of the wall structure, adding to the heat gain of the structure. But the significance of this phenomenon upon modern construction types and in relation to all other losses is minimal.

- Grimsrud (1980, Reference 18)

A group of five researchers, four of them ASHRAE members, conducted an intercomparison of tracer gases used for air infiltration measurements. The research was conducted under typical residential conditions to evaluate the performance of sulfur hexafluoride (SF₆), methane (CH₄), and nitrous oxide (N₂O). Experimental results indicated that, while there were some differences in measurements obtained using the different gases, they were small enough so as to be unnoticeable when compared to the error associated with measurements made with any single gas. Hence, no recommendations were made which favor the selection of one of the tracer gases over the other two.

2. Design Considerations and Criteria

As was indicated in the invitation to propose on this research project, determination of infiltration losses in refrigerated facilities has previously been left to the experience of the designer. The survey of the literature reveals that while information is available which allows for prediction of steady-state losses, dynamic conditions have not been sufficiently evaluated. As a result, given adequate design tools
and criteria by the ASHRAE Handbooks, the design engineer must still use his experience related to the operation of refrigerated storage to predict infiltration. However, some useful aids have been found through this research to improve upon the present design process. Additionally, the Phase II field test program has been designed to add greatly to the knowledge of infiltration losses associated with refrigerated storage.

Chapter 40 of the 1982 edition of the ASHRAE Applications Handbook offers several general recommendations for control of infiltration through building design and construction. Vapor barrier design, jacketed storage, door design, loading docks and vestibules, and dock door seals are all discussed as qualitative means to reduce infiltration. Only one quantitative guideline is presented, that of a typical infiltration load for a typical 100,000 ft$^2$ (10,000 m$^2$) single story freezer. The chapter on refrigeration load, Chapter 29 of the 1981 Fundamentals Handbook, offers more quantitative design information. Average air changes per 24 hours due to door openings are presented as a function of enclosed volume, based upon practical experience. It is not evident from the bibliography for the chapter whether field correlation for the tables has ever been attempted. If not, the Phase II test program should undertake such a correlation.

Beyond what is presented in the ASHRAE Handbooks, most of the other literature centers upon two aspects of infiltration control in refrigerated facilities. One of these is the optimum design and operation of doors for refrigerated storage. The other topic is the proper design of air curtains for infiltration.
control. There is more literature related to the second aspect than the first. In fact, the 1960's brought about a great deal of activity related to air curtains, which has subsequently subsided except for a few solitary authors.

• Wilder (1981, Reference 66)

Charles Wilder (deceased) wrote a very informative work on proper door design which was released as an ASHRAE publication in 1981. The brochure was a combination of two papers, one presented in the 1969 ASHRAE Symposium Bulletin, and the other at an ASHRAE seminar in Boston in 1975. The publication is an informative piece which discusses the influence of door type, door closure speed, and door controls upon infiltration losses. Much of the paper could be included in the ASHRAE Handbooks as general discussion for efficient cold storage design.

• W. S. Atkins (1982, Reference 5)

A second publication is based upon the work of W. S. Atkins, a British engineering firm, with regard to the time-dependency of infiltration rates. They found that the reduction in infiltration losses was not in direct proportion to the reduction in open door time. For example, reducing opening time from 30 seconds to 7 seconds reduces the losses by a factor of twelve. This work reinforces the need for design criteria which address the dynamic operating conditions of refrigerated warehouses. The information
presented in this paper is only a beginning to this undertaking.

Numerous authors (Kurek, Duncan, Crouse, Norton, Herndon) offer design considerations for the use of air curtains to control infiltration. Most of these discussions are in case history format and do not specifically relate to the type of facility considered by this research project. Because of the relatively low temperature differences (40°F - 50°F) considered by the applications, the representative velocities and discharge angles discussed are not directly applicable to refrigerated warehouses. In fact, most of the discussions have more applicability to heating energy conservation. Most of the papers tend to be overly optimistic with regard to air curtain performance when compared to the experimental results discussed earlier.

3. Infiltration Control Equipment and Construction

Some of the types of equipment designed to reduce infiltration in refrigerated warehouses have already been discussed in the previous sections. They are repeated here, along with several other devices not addressed by either mathematical analysis or case study results.

**Air Curtains**

The first air curtain device for which a patent was applied was designed by Thephilus Van Kennel in 1904. His was of horizontal design, and no record of an actual installation has been found. However, in 1916 an American named Caldwell did
install a vertical air curtain on a building doorway. An examination of the 1982 Thomas Register reveals 29 manufacturers or distributors of air curtain devices. Many of the companies also manufacture or distribute related products such as refrigerator doors, strip doors, and dock door seals. Operation of most of the air curtain devices is quite similar, at least for refrigerated storage.

Strip Doors

A substitute for a solid doorway might be found by suspending a large number of thin segments of some solid material across the opening, to approximate the solid coverage afforded by the door. If the segments, or strips, had a low thermal conductivity, were sufficiently flexible as to allow easy passage of personnel and materials and yet prevent air leakage, an effective door substitute would result. Such is the objective of strip doors.

Strip doors are generally constructed of clear PVC plastic strips which are suspended from the upper part of the doorway by wall or header mounting brackets. The strips are often geometrically shaped and overlapped to provide a nearly complete barrier against airflow. An added advantage of the clear strips is the safety afforded by the increased traffic visibility over that of solid doors.

However, strip doors have several drawbacks. Some materials tend to become brittle and crack at low temperatures. The passage of fork lift trucks through strip doors promotes the
build up of soil on the strips, which can be transferred to personnel or product moving through the same door. A significant pressure differential between adjacent areas separated by a strip door is often sufficient to deflect the strips, allowing airflow between the two sides. This defeats the primary purpose of the strip door. Also, the actual effectiveness of strip doors is not well established; in fact, vendor literature seldom offers any representative efficiency or performance measures.

Dock Door Seals

Standard design of loading and receiving docks for over-the-road trailers does not provide for a tight seal between the building and the back of the truck. In fact, because of driver error and curb design, a large gap often is present between the trailer walls and the building. Such an opening causes excess infiltration and the attendant energy loss.

By installing thick, flexible pads or seals around the dock door opening, some of this infiltration can be avoided. These dock door seals allow the trailer to be backed up far enough to compress the pads and obtain a tight seal, but avoid contact with the building wall. Proper selection of the size and spacing of the seals will allow most truck sizes to be accommodated, but an occasional odd-sized trailer might still allow for some leakage. However, standardized trailer sizes and judicious use of loading docks can all but eliminate this problem.
Doors for Refrigerated Storage

Perhaps overlooked during warehouse design, the proper selection of doors for refrigerated storage can make the most difference in infiltration losses. The open door time and closed door sealing capacity of a proposed door are two factors which must be considered. Related to the open door time are the controls and drive mechanism used to move the door, and their reliability in use. Operator confidence in the door operation can also directly affect door losses, since the operator must close the door for it to be of any use at all.

Vestibules for Loading Docks

In cases where product shipping requires an extended period with doors open, a vestibule arrangement for the loading dock can prevent excess infiltration. The vestibule is usually maintained at about 50°F, and must have positive humidity control to avoid frost and freezing problems. Optimum designs employ at least four doors to allow for one-way traffic. Vestibule construction adds appreciably to the total cost for refrigerated storage, but can sometimes be justified.
IV. Conclusions and Recommendations

Efforts during this project to identify methods for predicting infiltration in refrigerated warehouses have resulted in the collection of a substantial amount of literature. References include analytical approaches for estimating energy losses through open doorways, and guidelines for proper cold storage design. By and large, the available design information is qualitative in nature, with the possible exclusion of that related to heat and mass transfer through open doors and through air curtains. Hence, some of the design considerations the practicing engineer must face during the design of a facility will still be addressed based upon experience. But there are some quantitative design tools and data available to make the job easier, and other data will be obtained during the Phase II test program.

An insufficient amount of data exists regarding the steady-state infiltration rates of closed refrigerated warehouses. The only tabular data characteristic of such losses was compiled and published in 1954. Obviously, these data are outdated because of modern refrigeration systems and building construction techniques. While it can be argued that these losses are but a small percentage of the daily infiltration rate in modern facilities, the ability to accurately estimate closed, steady-state losses could lead to more efficient design and operation. For instance, a production warehouse which remains closed for many hours each day might utilize a cascaded or staged refrigeration system designed to more efficiently operate during
off-production hours. Knowledge of typical closed, steady-state losses would assist the practicing engineer in the design of such systems.

Little or no analytical or experimental data are available to measure the comparative advantages of different door types. For example, one might wish to know whether a single horizontal sliding door was more energy-efficient than a double horizontal sliding door with respect to infiltration. No data are available to support either design's advantage over the other. Similarly, four-door vestible design has not been shown to be substantially more efficient than the use of dock door seals. Intuitively, the design engineer is apt to recognize distinct advantages in some designs, but is not able to substantiate his beliefs. Unfortunately, the results of this research project will not improve the lot of the designer in this regard. While every attempt will be made to measure and record the influence of these design features upon infiltration rates, it is felt that too little data and too many variables exist to expect the development of an accurate analytical tool.

Several quantitative methods for predicting infiltration by natural convection through cold storage doorways have been found. The two best procedures are those of Gosney and Olama, and Fritzsche and Lilienblum. These two analytical approaches correlate quite closely for typical cases encountered in practice, and are fairly easy to apply. Some simplification can be done, and design tables or nomographs can be developed from
the equations. A computer program is already available based upon the Gosney and Olama method.

Further, the Gosney and Olama technique allows for prediction of transient door losses (modified by the W. S. Atkins study) which should give good results for cold storages with high traffic. The field measurements proposed in the test plan for Phase II include portions devoted to verifying these two analytical solutions.

Results from at least two experimental programs which investigated infiltration through open doors indicated a time-dependency for energy losses. Pham and Oliver observed a decrease in losses for door-open times of long duration; this characteristic was also suggested by W. F. Stoecker in a personal communication. This long term phenomenon is attributed to the establishment of isotherms within the cold store, which originate at the door opening. The warmest of these is near the open door. The decrease in temperature difference would then result in less driving force to promote air exchange through the door. For a door open only for a short time, W. S. Atkins found a transient behavior which resulted in losses much lower than predicted for the steady-state. Both these phenomena, short term transient losses and long term decaying losses, should be investigated through field measurements in full size cold storage facilities. An attempt should be made to model the infiltration losses occurring under both circumstances. Design engineers and building operators could use the models to predict infiltration losses associated with particular cold storage facilities.
While the existence of steady-state and transient models for predicting infiltration simplify the design process, the stochastic process of opening and closing doors found in a working cold storage facility can be difficult to estimate. The statistical treatment required to model a real-life facility with respect to door usage frequency would likely be quite complicated. For this reason, it would be beneficial to measure the gross infiltration behavior of several diverse facilities, to obtain a range of infiltration rates. These data would enable the design engineer, faced with a discouragingly complex door usage pattern, to obtain a "rule of thumb" estimate which could be used as a starting point for refinement by other analytical techniques. In the Phase II test plan, several gross infiltration measurement experiments are suggested to obtain these data. A vapor trace technique is suggested, due to its ease of implementation and relatively good accuracy.

A Phase II field test program based upon these conclusions is recommended. It is believed that ASHRAE can expect to considerably improve its design methods for predicting infiltration in cold storage facilities through the conduct of the Phase II research program. Further, an effort should be made to reduce the appropriate analytical models to working graphs, tables, and nomographs, to be incorporated into the design handbooks. At present, only the mathematical equations are available. The combination of these two achievements during Phase II will result in a much improved design guide for the Fundamentals and Applications handbooks.
ACKNOWLEDGEMENTS

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A special thanks is due Mr. Steve Vickroy of St. Louis, Missouri for volunteering his time to come to Atlanta and discuss the research project and offer additional reference material.

And finally, for the many hours of labor devoted to getting the results of this work down on paper, I thank my secretary, Ms. Marguerite Osborne.
APPENDIX A

WORK STATEMENT
WORK STATEMENT FOR PHASE II
TEST PROGRAM

A paragraph outline has been developed to describe the test program recommended for Phase II of the research project. Each component is assigned a task number. Each task represents an investigation of one of the four research areas suggested in the conclusion of this report. The tasks are presented in the most logical order of conduct, to take advantage of a learning curve as more complex experiments are conducted. However, because of the need to experience variable ambient conditions, several iterations through each task may be required during the course of a calendar year. But the logical sequencing will be maintained where possible.

Task No. 1: Study of Steady-State Open Door Natural Convection

Objective
Verify the steady-state infiltration rates predicted by the analytical solutions of Gosney and Olama, and Fritzsche and Lilienblum. Investigate any effects due to room height of single story buildings, and effects due to room volume. Also investigate influence of door traffic (personnel, fork lifts) upon infiltration.

Activity
Attach a wire gridwork to an exterior door opening for the purpose of making point measurements of air velocity. Attach cloth tufts at each point to indicate direction and
relative velocity of airflow. Conduct anemometric measurements of air velocities, and thermocouple temperature measurement, at selected points in the plane of the door opening under steady-state condition of interior and exterior temperature differential. Use electronic hygrometer to measure interior and exterior dewpoint temperature. Photograph array of tufts to provide visual record of airflow pattern and relative velocities. Without gridwork, make spot measurements of airflow while traffic passes through doorway.

Parameters to be varied

Height of warehouse, 25 ft to 35 ft (7.6 m to 10.7 m). Volume of Warehouse, 500,000 ft$^3$ (14,150 m$^3$ to 141,500 m$^3$). Door size, 8 ft x 10 ft (2.4 m x 3.0 m) and 10 ft x 14 ft (3.0 m x 4.3 m). Temperature difference between interior space and ambient, six differences of 50°F, 60°F, 70°F, 80°F, and 100°F (10°C, 16°C, 21°C, 27°C, 32°C, and 38°C).

Parameters to be measured

Air velocity and temperature at points in the plane of the door opening. Interior and exterior dewpoint temperatures.

Desired Results

Acceptable experimental correlation of analytical predictions of volume flow rates, mass flow rates, and energy losses due to steady-state natural convection through open doors. An error of $\pm 10\%$ will be judged acceptable correlation. Water vapor transmission rates will be calculated from measured parameters.
No. 2: Study of Short Term Transient Natural Convection

Objective

Determine the short-term transient behavior of airflow through an open door due to the forces of natural convection. Determine if door geometry, temperature differential, or room volume affect the transient behavior.

Activity

Attach a wire gridwork to an exterior door opening for the purpose of making point measurements of air velocity over the transient period. Attach cloth tufts at each point to indicate direction and relative velocity of airflow. Obtain anemometric measurements of air velocities at points in the plane of the door opening at closely spaced time intervals following a sudden opening of the door. Photograph array of tufts in small increments of the time sequences, to provide visual record of airflow pattern and relative velocities. Conduct simultaneous carbon dioxide vapor trace experiments to confirm total losses with time found by integrating the transient loss rate curve.

Parameters to be varied

Warehouse volume, 500,000 ft$^3$ to 5,000,000 ft$^3$ (14,150 m$^3$ to 141,500 m$^3$). Door geometry, especially height. Desirable heights are 6 ft, 8 ft, 10 ft, and 12 ft (1.8 m, 2.4 m, 3.0 m, and 3.7 m). Temperature difference between interior space and ambient, four differences of 50°F, 70°F, 90°F, and 100°F (10°C, 21°C, 32°C, and 38°C) from an interior
temperature of -10°F (-23°C). Total test conditions = 4 x 4 = 16.

Parameters to be measured

Air velocities at points in the plane of the door opening, at closely spaced time intervals. Interior and exterior temperatures before opening door and allowing air exchange to begin. Concentration of carbon dioxide tracer gas before and after test, to evaluate total integrated losses during time transient. Building interior dimensions.

Desired results

Provide a mathematical expression relating time to the short-term transient infiltration losses through an open cold storage door. Identify any dependency upon temperature differential or door geometry. Show that transient losses for short time intervals are significantly less than steady-state losses.

Task No. 3: Study of Long Term Decay of Infiltration Losses

Objective

Determine the long term behavior of infiltration rates from natural convection through open cold storage doors.

Activity

Conduct carbon dioxide gas vapor-trace experiments to measure long term exchange of air within a cold storage facility. Obtain limited anemometric measurements to characterize the nature of the airflow through the doorway over time. Measure temperatures at multiple points in a
grid designed to allow isotherms to be drawn for the room at various time intervals.

**Parameters to be varied**

Volume of cold storage room under investigation, two significantly different volumes at two separate temperature differences between interior space and ambient of 60°F and 100°F (10°C and 38°C). Degree of volume occupied by stored goods, at least three conditions: 1/3, 2/3, full. Number of doors open simultaneously, one door and multiple doors. Total test conditions = 2 x 3 x 2 = 12.

**Parameters to be measured**

Concentration of carbon dioxide gas within the cold storage room. Interior temperatures at a variety of points within the enclosure at intervals during the tests. Exterior temperature and wind direction and velocity. Air velocity at three points in the plane of the open door, at intervals during the tests. Dimensions, volume of stored goods.

**Desired Results**

Confirm or refute theory of long term decay of infiltration rates through open cold storage doors. If decay does occur, identify contributing causes, such as per cent capacity of stored goods, multiple openings, or increase in temperature in vicinity of door. Characterize the magnitude of the reduction.
Task No. 4: Study of Gross Energy Losses Due to Infiltration in Working Cold Storage Facilities

Objective
Obtain a measure of the comparative losses associated with a diverse group of facilities, under actual working conditions.

Activity
Obtain continuous measurements of refrigeration electric energy consumption, during working and quiescent periods. Isolate and quantify infiltration load as closely as possible by such measurements. Observe several days of operation, recording such parameters as number of door openings, goods moved, and type of facility. Correlate power measurements with carbon dioxide vapor-trace measurements.

Parameters to be varied
Type of facility, production and public storage of various construction types, twelve facilities. Door types and infiltration control devices, such as air curtains or strip doors. Loading door configuration, such as vestibule or enclosed dock, or exterior door seals. Total test conditions = 12.

Parameters to be measured
Electric energy consumed by refrigeration equipment, continuous recording. Concentration of carbon dioxide tracer gas within enclosure. Building dimensions. Ambient
conditions of temperature, wind velocity and direction, and relative humidity.

Desired results

From the recorded data, produce a table of comparative energy losses due to infiltration for a range of typical facilities. Present "rule-of-thumb" characteristic energy losses to allow designers to have a starting point from which to proceed with further refinements in predicting infiltration losses.
APPENDIX B

BIBLIOGRAPHY
BIBLIOGRAPHY


Case study of an air curtain installation at a 150,000 sq.ft. manufacturing facility, on a 12' by 12' exterior overhead door.

(2) "Air Curtain Machines For Food Service Facilities," Air Force research document, 1975.

Air Force study conducted to develop literature base and guidelines for use of air curtains for insect control at military facilities.


Very informative qualitative paper on air curtain design considerations. Includes engineering design data for an installation in a freezer room at -10°F.


Literature review of methods of predicting infiltration in cold storage through open doors. Outlined results of major contributors: Brown and Solvason, Tamm, Fritzschke and Lilienblum, Gosney and Olama, and older ASHRAE Handbooks. Performed measurements on a full size cold store and compared results to predictions obtained by applying Gosney and Olama solution. Steady state results agreed to within 7%. Transient measurements were also performed, and indicate that the Gosney and Olama transient model will underpredict losses for long open-door times. W. S. Atkins has a computer model which incorporates the findings of this project, and which can be used to predict heat and moisture transfer through open doors under steady state and transient conditions. This study, undertaken independently by Clark Door Limited, is very significant and closely parallels the objectives of this ASHRAE research project.

Case study of a large industrial air curtain installation, used for heating application in a manufacturing bay.


Economic consideration of eight different facilities, in an attempt to show how energy costs affect some differently than others. Three specific cases of construction details were discussed: doorway design, amount of insulation, and proper selection of refrigeration system.


Analogous to Part 1, for horizontal partitions instead of vertical ones.


Combinations of two previous papers and simplification of data presentation. Tables and nomographs suitable for use in ASHRAE design manuals.


Description of a thermistor-based tracer gas sensor, using helium as the gas. Electronic equipment now outdated.

Short case history of hot air curtain installed on the receiving door of a metalworking plant.


Comprehensive discussion of the history, advantages, applications, and field results of air curtains. Some empirical energy cost estimating formulas are posed, as well as heat transfer rates for standard door sizes.


Revised draft of final report covering a broad range of concerns regarding estimation and measurement techniques. Directed toward multiple-opening buildings at ambient interior conditions, of typical construction.


Case study of a horizontal air curtain used to prevent infiltration through a foundry doorway. Graphical presentations of air speed, temperature recovery, and noise measurements are included.


Measurements were made of air movement through an open door using tufts and thermometers, and heat loss calculated. The results were compared with the solution suggested by W. Tamm, and a correction factor to the Tamm solution derived. The empirical correction factor was based on a doorway 1.5m high by 2.5m wide, and caution was noted in extending the results to other door sizes.

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A major paper on analysis of infiltration losses through cold storage doors. Includes a review of the analytical approaches used by other researchers: Brown and Solvason, Tamm, Fritzsche and Lilienblum. Experimental correlation very good for door size studied, 1.6 ft. wide 2 ft. high (0.5m x 0.6m). Also includes an expression for the time dependency of infiltration through openings. In a simplified form, could be used in ASHRAE handbook as design tool. Forms the basis for the field testing done by W. S. Atkins for Clark Door Limited.


Results of the comparison of SF$_6$, CH$_4$, N$_2$O, and C$_2$H$_6$ used as tracer gases for infiltration measurements. While some differences were noted, the tests were not conclusive in determining the nature of the discrepancies. Therefore, no recommendation was made as to the relative merits of using any single gas.


Case history discussion of air curtain installations on retail facilities. No engineering analysis tools presented.


Detailed mathematical formulation of the problem of heat transfer across an air curtain. Results are in terms of Grashof, Nusselt, Reynolds, and Prandtl numbers. Foundation for subsequent paper on design data, which is more useful.


Contains useful design criteria and design tables for air curtain installations. Based upon earlier thesis work.

Generally informative article on air curtains and applications.


General discussion of the history and application of air curtains. Taken from information acquired in 1964 study by same author.


Results of an experimental approach to derive a semi-theoretical expression for heat transfer through a recirculatory air curtain. The empirical relation is found to be a function of Reynolds number of the jet, and the ratio of door height to nozzle width.


Experimental results of tests using three and six-nozzle air curtains indicate that heat transfer through an air curtain is proportional to air velocity and inversely proportional to the thickness of the curtain. Not particularly useful as general design information.


Relationship of Nusselt, Reynolds, and Prandtl numbers to the deflection modulus of an air curtain. The deflection modulus is found to be a function of the initial velocity of the jet, air densities on either side of the curtain, the door height, and nozzle width. The results are similar to those presented by Haynes and Stoecker, for low values of initial turbulence. The paper goes further to relate the influence of turbulence on this type of air curtain heat transfer. Useful for designers of air curtains, but not particularly helpful for cold storage designers.

Relates the experimental investigation of the effect of turbulence upon the heat transfer across air curtains. It was found that for values of initial turbulence levels above 8% to 10%, little effect upon heat transfer was noticed.


Discusses a method of cold storage construction utilizing wall, ceiling, and floor plenums to circulate cooling air and intercept infiltrating moisture; also air curtains.


ASHAE-sponsored research project which addresses the problem of moisture infiltration through openings and duct seams where ducts pass through unconditioned space. A mathematical expression for natural convection through a doorway is derived, following the same general approach as Tamm. However, the emphasis is on the solution for moisture transport only, and not sensible heat transfer by dry air.


Contrasts traditional methods of predicting infiltration with computer simulation using pressure equilization. Useful only for multiple openings with wind effects.


Effects of outside air pressure, building pressurization, leaky and tight construction, and architectural treatment are discussed. Mostly applicable to commercial buildings.

Presentation of a design optimization procedure for air curtains based upon empirically determined relationships for optimum jet velocity and discharge angle. Also demonstrates the deleterious effects of wind or drafts, which can render the air curtain completely ineffective. Some tables might be useful for ASHRAE design references.


Original paper on the subject of free and forced convection in insulated walls.


Qualitative description of the possible presence of convection within wall cavities. Both natural and forced convection is discussed. Some laboratory tests are described, in which theoretical static heat conductivity was exceeded substantially by walls which permitted convection. No quantitative design information is presented.


Results of a nine year field study of heat transfer effects due to natural convection within cold storage walls. While the data indicated a negligible increase in conductivity due to convection, it was found that the absence of an impermeable vapor barrier on the outside surface allowed a significant amount of deleterious infiltration.


Results of tests on permeability of various vapor barrier materials are presented. Some discussion of recommended materials and installation methods is included.

Design and installation suggestions for the vapor barrier for a cold storage room. Based upon a construction technique presented in a booklet published by the Building Research Advisory Board are used to illustrate the technique.


Description of a prototype controller designed to vary the discharge angle of an air curtain in response to wind pressure. Company did not pursue the development of the device.


Discusses a variety of design considerations, including the possibility of natural convection within wall cavities having loose fill insulation. Emphasizes importance of vapor barrier, cooling air distribution.


Newspaper article containing case histories and comments from buyers of strip doors. Savings estimates range from 3% to 35%, although no controlled testing is indicated.


Case study of 129,600 sq. ft. manufacturing facility designed with air curtains for fresh air make-up and ventilation.


Another discussion of the air curtain design for the Pan American Airways terminal building in New York.

Early investigation of the use of air curtains for cold storage. Very rudimentary in scope and conclusions.


Simulated and actual truck bodies were instrumented for tracer gas measurement of air leakage due to open doors. Empirical relations for air exchange and cooling load derived; not suitable for warehouses due to dependence upon unoccupied volume, small volume effects.

(45) Pham, Q. T. and Oliver, D. W., "Infiltration of Air into Cold Stores," preliminary proceedings from XVIth International Congress of Refrigeration, 1983.

Results of a variety of field measurements of cold storage warehouses are presented. Includes measurements of air exchange through open doors, and through doors equipped with air curtains and strip curtains. When compared against predictions (Tamm), the measured values were lower and tended to decrease as doors were left open for longer periods of time. From this they proposed a partitioning effect due to stored goods near the opening. Also investigated the effects of forklift truck passage and internal circulation fans upon door air exchange. In all, the results are informative, but not conclusive.


Pacific Northwest investigation of amounts of respired CO2 and fruit volatiles in apple storage, and air leakage as determined by measurement of concentrations in thirty storage rooms.

Description of air curtains in general and American Air Curtain products in particular.


Design guidelines for specification of various details of cold storage facilities, such as door size and mounting hardware, and construction details.


Case study of Jamison vertical sliding door installation at a Stouffer Foods Corporation freezer warehouse. No infiltration data included.


Optical CO2 gas detector measurements of efficiency of air curtains in field installations, giving results ranging from 60% to 80% compared to an open doorway.


Using superposition techniques, combined the free plane jet velocity and horizontal air velocities due to an open doorway to obtain flow functions. Formed basis for subsequent work by other researchers to characterize the heat and mass transfer through a vertical air curtain.
Tamm, W., "Kalteverluste Durch Kuhlralumoffnungen" (Cold Losses Through Openings in Rooms), Kaltetechnik-Klimatisierung, 142-144, 1966.

Includes the derivation of a formula for the velocity of airflow through an opening. The formula is combined with an expression for heat transfer based on enthalpy difference to yield an expression for energy losses associated with the open door.

An improvement over the Brown and Solvason solution.


Results of research conducted by W. S. Atkins to determine the effects of door height and open time upon energy loss due to infiltration. Relative measures of the importance of each are presented in graphical form.


Laboratory simulation of openings equipped with air curtains, and measurement of air curtain efficiencies. Highest efficiency found was 86%; only interior openings simulated, i.e., no wind.


Derivation of a leakage coefficient based upon a "specific equivalent leak opening," se/o coefficient. Not applicable to practical engineering problems, as se/o is not characterized for modern cold storage facilities.


Describes a new design of air curtain which employs two jets contained in a tunnel-like doorway. Efficiencies near 90% have been measured for rooms with no other openings. Cost of fabrication and installation is said to be considerably higher than conventional designs.

Discussion of an analytical approach to predicting the mass exchange across an air curtain based upon the exit velocity of the jet, and height of the doorway. A deflection modulus related to the differences in air density on either side of the doorway is defined, and optimized with respect to discharge angle and exit velocity to yield the minimum mass exchange. Highly theoretical and applicable only to steady-state conditions.


Theoretical and experimental investigation of the influence of initial turbulence upon the velocity and temperature profiles of a recirculating air curtain. Provides the basis for similar paper by Van and Howell which describes heat transfer across air curtains.


Extension of an infiltration predicting technique to relate interroom air movements. Airflow through building envelope openings is computed from the ASHRAE crack method together with a mass balance in each room. Airflow through door openings is computed after the method of Brown and Solvason. Simultaneous solution of the mass balances in all rooms yields predicted values of ±20% when compared to experimental results.


Discussion on changes in design approach to cold storage, with regard to various components such as truck loading platforms, ceiling height, and automated materials handling.

   Discusses the importance of selecting the proper vapor barrier material and method of installation to minimize infiltration. Cites the wall-ceiling/roof juncture as most critical area and most susceptible to leakage.


   General design considerations for efficient doors for refrigerated warehouses. Good practical discussion, perhaps suitable for Applications handbook.


   Discusses door control systems, air curtains, vestibules and enclosed docks for cold storage facilities.


   Design description of an air curtain system for the Pan American Airways Terminal at Idlewild Airport (Kennedy International) in New York. Design process included the use of wind tunnel tests on scale model to develop wind screen placement positions.
PERSONAL COMMUNICATIONS


Burnett, Eric F. P., Building Engineering Group, Waterloo, Ontario, Canada, telephone communication, August 1983.

Frick, R. J., Sysco Corporation, Houston, Texas, telephone communication, August 1983.

Hall, C. W., National Science Foundation, Washington, D. C., telephone communication, August 1983.

Hayes, F. C., Trane Company, LaCrosse, Wisconsin, telephone communication, August 1983.

Howell, R. H., Department of Aerospace and Mechanical Engineering, University of Missouri, Rolla, Missouri, telephone communication, August 1983.

Kennon, Michael, The King Company, Owatonna, Minnesota, telephone communication, August 1983.

Nemes, George, George Nemes and Associates, Ferndale, Michigan, telephone communication, August 1983.


Schlachter, D. C., The Kroger Company, Cincinnati, Ohio, telephone communication, August 1983.

Solvason, K. R., Building Services Section, National Research Council, Ottawa, Canada, telephone communication, August 1983.

Stoecker, W. F., Department of Mechanical Engineering, University of Illinois, Urbana, telephone communication, August 1983.

Van Male, J., Delft University of Technology, Delft, Holland, telephone communication, August 1983.

Vickroy, S., Mesker/Clark, Inc., St. Louis, Missouri, personal conversation in Atlanta, September 9, 1983.


xxiv
<table>
<thead>
<tr>
<th></th>
<th>Keywords and Combinations, Permutations</th>
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<tbody>
<tr>
<td>1.</td>
<td>Cold Storage</td>
</tr>
<tr>
<td>2.</td>
<td>Refrigerating</td>
</tr>
<tr>
<td>3.</td>
<td>Cold Storage or Refrigerating</td>
</tr>
<tr>
<td>4.</td>
<td>Commercial Buildings</td>
</tr>
<tr>
<td>5.</td>
<td>Industrial Buildings</td>
</tr>
<tr>
<td>6.</td>
<td>Warehouses</td>
</tr>
<tr>
<td>7.</td>
<td>Commercial Buildings or Industrial Buildings or Warehouses</td>
</tr>
<tr>
<td>8.</td>
<td>Infiltration</td>
</tr>
<tr>
<td>9.</td>
<td>Modelling</td>
</tr>
<tr>
<td>10.</td>
<td>Measurements</td>
</tr>
<tr>
<td>11.</td>
<td>Natural Convection</td>
</tr>
<tr>
<td>12.</td>
<td>Heat Flow</td>
</tr>
<tr>
<td>13.</td>
<td>Moisture Flow</td>
</tr>
<tr>
<td>14.</td>
<td>Air Curtains</td>
</tr>
<tr>
<td>15.</td>
<td>Infiltration or Modelling or Measurements or Natural Convection or Heat Flow or Cold Storage</td>
</tr>
<tr>
<td>16.</td>
<td>Energy Conservation</td>
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<tr>
<td>17.</td>
<td>Equipment</td>
</tr>
<tr>
<td>18.</td>
<td>Methods</td>
</tr>
<tr>
<td>19.</td>
<td>Energy Conservation and Equipment or Methods</td>
</tr>
<tr>
<td>20.</td>
<td>Cold Storage or Refrigerating and Energy Conservation and Equipment or Methods</td>
</tr>
<tr>
<td>21.</td>
<td>Cold Storage or Refrigerating and Infiltration or Modelling or Measurements or Natural Convection or Heat Flow</td>
</tr>
<tr>
<td>22.</td>
<td>Cold Storage or Refrigerating or Refrigeration and Infiltration or Modelling or Measurements or Natural Convection of Heat Flow.</td>
</tr>
<tr>
<td>TEMP INSIDE °F (°C)</td>
<td>RH INSIDE %</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>0 (-18)</td>
<td>90</td>
</tr>
<tr>
<td>-22 (-30)</td>
<td>85</td>
</tr>
<tr>
<td>-22 (-30)</td>
<td>90</td>
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<td>-22 (-30)</td>
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</tr>
<tr>
<td>32 (0)</td>
<td>90</td>
</tr>
<tr>
<td>32 (0)</td>
<td>90</td>
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TABLE 2. Comparison Of Heat Loss Calculations
<table>
<thead>
<tr>
<th>Storage</th>
<th>Date of Sample</th>
<th>Gross Room Vol.</th>
<th>Relative Activity</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(cu. ft.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F (BSMT)</td>
<td>12/29/52</td>
<td>46,200</td>
<td>1.7</td>
<td>CARBON UNIT IN ROOM</td>
</tr>
<tr>
<td>G (2ND FL)</td>
<td>1/22/52</td>
<td>249,760</td>
<td>2.7</td>
<td>LARGE PORTION OF FRUIT BOXES IN CARBOARD CARTONS</td>
</tr>
<tr>
<td>H</td>
<td>2/20/33</td>
<td>32,000</td>
<td>2.53</td>
<td>CARBON UNIT IN ROOM OF ANJOU Pears</td>
</tr>
<tr>
<td>H</td>
<td>3/5/53</td>
<td>32,000</td>
<td>0.56</td>
<td>NO PURIFIER IN THIS ROOM OF ANJOU Pears</td>
</tr>
</tbody>
</table>

**Central Station Cooling Systems with Fans Located in Exterior Rooms**

| I                | 11/6/51        | 77,000          | 3.52             | A                                                                        |
| I                | 1/20/52        | 77,000          | 3.74             | I, CARBON UNIT IN ROOM                                                   |
| I                | 1/19/53        | 513,930         | 3.64             | A                                                                        |

**Central Station Cooling Systems with Fans Located within Storage Room**

| L (BRICK BLDG)   | 2/4/53         | 253,450         | 7.81             | I, THIS SAMPLE TAKEN 8:30 AM AFTER PLANT CLOSED UP OVER WEEKEND          |
| M (N BLDG)       | 11/6/51        | 524,600         | 3.12             | A                                                                        |
| M (N BLDG)       | 1/21/52        | 524,600         | 4.40             | A                                                                        |

| M (S BLDG)       | 11/6/51        | 261,800         | 1.91             | A                                                                        |
| M (S BLDG)       | 7/21/53        | 261,800         | 1.38             | A, CARBON UNITS IN THIS STAGE                                           |
| N                | 11/21/50       | 431,000         | 0.94             | A, CARBON UNITS IN THIS STAGE                                           |
| N                | 12/15/50       | 431,000         | 0.98             | A, DURING THIS AND ABOVE PERIOD FRUIT IN STORAGE WAS AT 35 TO 37°F       |
| N                | 2/5/53         | 431,000         | 2.04             | I                                                                        |
| O                | 10/29/51       | 1,046,200       | 1                |                                                                           |

Table 3.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Room Vol.</th>
<th>Air CH Rate when Sampled</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>12/1/50</td>
<td>1,047,000</td>
<td>3.05 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MOVING FRUIT OUT TO PACKING LINE AND NORMAL SHIPPING ACTIVITY</td>
</tr>
<tr>
<td>Q (2 PM)</td>
<td>3/4/53</td>
<td>353,500</td>
<td>8.00 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PALLET STORAGE OPERATED WITH DOORS WIDE OPEN</td>
</tr>
<tr>
<td>Q (8:30 AM)</td>
<td>3/17/53</td>
<td>353,500</td>
<td>2.00 I</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>STORAGE HAD BEEN SHUT UP ALL NIGHT</td>
</tr>
<tr>
<td>Q (4:30 PM)</td>
<td>3/17/53</td>
<td>353,500</td>
<td>6.57 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OPERATED WITH DOORS OPEN THRU DAY</td>
</tr>
<tr>
<td>S (2 PM)</td>
<td>2/13/53</td>
<td>1,607,300</td>
<td>2.05 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>THIS SAMPLE TAKEN AFTER PLANT CLOSED UP OVER WEEKEND AND FANS OFF SINCE 9 PM 2/15</td>
</tr>
<tr>
<td>S (9 PM)</td>
<td>2/16/53</td>
<td>1,607,300</td>
<td>1.25 I</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Storage Cooled by Unit in Room Circulating to One Room Only</td>
</tr>
<tr>
<td>S (4 PM)</td>
<td>2/16/53</td>
<td>1,607,300</td>
<td>1.86 A</td>
</tr>
<tr>
<td>T</td>
<td>1/29/52</td>
<td>240,000</td>
<td>1.66 I</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>.98 I</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>.21 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>en Storage Room</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>... A</td>
</tr>
</tbody>
</table>

TRAFFIC ACTIVITY.

Table 3.

From Sainsbury and Gerhardt, Reference 48
Air Flow Through an Open Door
As a Result of Natural Convection

Figure 1.

From Herndon, Reference 23
Computer Comparison of Analytical Models

H = 10 ft, B = 7 ft, T1 = -20°F
- BROWN and SOLVASON S MODEL
- TAMM S MODEL
- FRITZSCHE and LILIENBLUM S MODEL
+ GOSNEY and OLAMA S MODEL

Heat Transfer Rate Through Cold Store Doors

Figure 2.
<table>
<thead>
<tr>
<th>VERT. AXIS</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.845</td>
<td>2.845</td>
<td>2.845</td>
<td>2.953</td>
<td>3.009</td>
<td>2.90</td>
<td>2.845</td>
<td>2.845</td>
<td>2.736</td>
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<tr>
<td>3</td>
<td>2.188</td>
<td>2.188</td>
<td>2.188</td>
<td>1.913</td>
<td>1.913</td>
<td>1.805</td>
<td>1.805</td>
<td>1.805</td>
<td>1.86</td>
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<tr>
<td>4</td>
<td>1.641</td>
<td>1.641</td>
<td>1.532</td>
<td>1.477</td>
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<td>1.532</td>
<td>1.585</td>
<td>1.641</td>
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<tr>
<td>5</td>
<td>0.82</td>
<td>0.932</td>
<td>0.932</td>
<td>1.04</td>
<td>1.204</td>
<td>1.093</td>
<td>1.04</td>
<td>1.04</td>
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<tr>
<td>6</td>
<td>0.056</td>
<td>0.272</td>
<td>0.384</td>
<td>0.548</td>
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<td>0.436</td>
<td>0.548</td>
<td>0.436</td>
<td>0.164</td>
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<tr>
<td>7</td>
<td>1.148</td>
<td>1.421</td>
<td>1.805</td>
<td>1.148</td>
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<td>0.932</td>
<td>1.093</td>
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<tr>
<td>8</td>
<td>1.86</td>
<td>1.913</td>
<td>2.35</td>
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<td>1.86</td>
<td>1.913</td>
<td>1.696</td>
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<td>9</td>
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<td>2.461</td>
<td>2.35</td>
<td>2.405</td>
<td>2.405</td>
<td>2.077</td>
<td>2.077</td>
<td>1.913</td>
<td>1.913</td>
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<td>10</td>
<td>2.953</td>
<td>3.009</td>
<td>3.117</td>
<td>3.009</td>
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<td>2.517</td>
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<td>11</td>
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<td>2.625</td>
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<td>2.517</td>
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<td>3.009</td>
<td>2.845</td>
<td>2.953</td>
<td>2.953</td>
</tr>
</tbody>
</table>

Measurement of Air Exchange Through Open Door-English Units

Figure 3.
<table>
<thead>
<tr>
<th>VERT. AXIS</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>J</th>
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</thead>
<tbody>
<tr>
<td>HORIZ. AXIS</td>
<td>1</td>
<td>1.166</td>
<td>1.05</td>
<td>1.0</td>
<td>0.967</td>
<td>0.934</td>
<td>0.967</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>0.867</td>
<td>0.867</td>
<td>0.867</td>
<td>0.9</td>
<td>0.917</td>
<td>0.884</td>
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<td>0.867</td>
<td>0.834</td>
</tr>
<tr>
<td>3</td>
<td>0.667</td>
<td>0.667</td>
<td>0.667</td>
<td>0.583</td>
<td>0.583</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
<td>0.567</td>
</tr>
<tr>
<td>4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.467</td>
<td>0.45</td>
<td>0.433</td>
<td>0.467</td>
<td>0.483</td>
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<td>0.5</td>
</tr>
<tr>
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<td>0.284</td>
<td>0.317</td>
<td>0.367</td>
<td>0.333</td>
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<td>0.017</td>
<td>0.083</td>
<td>0.117</td>
<td>0.167</td>
<td>0.167</td>
<td>0.133</td>
<td>0.167</td>
<td>0.133</td>
<td>0.05</td>
</tr>
<tr>
<td>7</td>
<td>0.35</td>
<td>0.433</td>
<td>0.55</td>
<td>0.35</td>
<td>0.35</td>
<td>0.317</td>
<td>0.284</td>
<td>0.333</td>
<td>0.333</td>
</tr>
<tr>
<td>8</td>
<td>0.567</td>
<td>0.583</td>
<td>0.717</td>
<td>0.633</td>
<td>0.567</td>
<td>0.567</td>
<td>0.583</td>
<td>0.517</td>
<td>0.517</td>
</tr>
<tr>
<td>9</td>
<td>0.783</td>
<td>0.75</td>
<td>0.717</td>
<td>0.733</td>
<td>0.633</td>
<td>0.633</td>
<td>0.633</td>
<td>0.583</td>
<td>0.583</td>
</tr>
<tr>
<td>10</td>
<td>0.9</td>
<td>0.917</td>
<td>0.95</td>
<td>0.917</td>
<td>0.833</td>
<td>0.783</td>
<td>0.767</td>
<td>0.733</td>
<td>0.717</td>
</tr>
<tr>
<td>11</td>
<td>0.934</td>
<td>0.9</td>
<td>0.9</td>
<td>0.867</td>
<td>0.85</td>
<td>0.867</td>
<td>0.9</td>
<td>0.833</td>
<td>0.8</td>
</tr>
<tr>
<td>12</td>
<td>0.833</td>
<td>0.817</td>
<td>0.767</td>
<td>0.917</td>
<td>0.967</td>
<td>0.917</td>
<td>0.867</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Measurement of Air Exchange Through Open Door-SI Units
Figure 3.
Steady State vs. Transient Heat Gain Through Open Door

Figure 4.

From W. S. Atkins, Reference 5
This program calculates the energy loss through coldstore doorways as a result of the cyclic door operation. It further provides a comparison of energy costs based on this operation assuming a reduction in the number of seconds per cycle.

It compares costs on a month by month basis using the monthly averages of temperature and relative humidity at the location of the facility.

Finally it calculates and displays an annual cost savings which would be realized with the installation of doorways that operate at a reduced cycle time.

Figure 5.
LOCATION OF DOOR:
FREEZER
ATLANTA GA

INSIDE STORE: -18.8 DEG. C  95 % RH
DOOR HEIGHT (M): 3.02  DOOR WIDTH (M): 2.43

TIME OPEN PER CYCLE (secs): 16
TIME OF CYCLE (minutes): 2

ELECTRICITY COST: .06 $/kwh
REFRIGERATION COP: 2.12

ENERGY COSTS ARE BASED ON COLDSTORE OPERATION:
8 HOURS/DAY  5 DAYS/WEEK  DAY SHIFT
NUMBER OF DOORS = 1

*** STEADY STATE COSTS ASSUME THE TIME OPEN IS CONTINUOUS ***
*** ACTUAL COSTS ASSUME THE TIME OPEN PER CYCLE (secs) IS: 16 ***
*** PROJECTED COSTS ASSUME THE TIME OPEN PER CYCLE (secs) IS: 7 ***

ENERGY COSTS FOR CYCLIC DOOR OPERATION

<table>
<thead>
<tr>
<th>MONTH</th>
<th># OF DAYS</th>
<th>STEADY STATE COST</th>
<th>ACTUAL COST</th>
<th>PROJECTED COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>22</td>
<td>758.55</td>
<td>71.09</td>
<td>13.45</td>
</tr>
<tr>
<td>February</td>
<td>20</td>
<td>807.15</td>
<td>74.66</td>
<td>14.13</td>
</tr>
<tr>
<td>March</td>
<td>22</td>
<td>1319.05</td>
<td>122.01</td>
<td>23.08</td>
</tr>
<tr>
<td>April</td>
<td>21</td>
<td>1906.81</td>
<td>176.57</td>
<td>33.40</td>
</tr>
<tr>
<td>May</td>
<td>22</td>
<td>3392.53</td>
<td>313.81</td>
<td>59.37</td>
</tr>
</tbody>
</table>

Figure 5.
THE FOLLOWING AVERAGE TEMPERATURES, AS ADJUSTED (see below),
AND AVERAGE RELATIVE HUMIDITY DURING THE VARIOUS MONTHS WERE
USED TO CALCULATE THE COSTS ILLUSTRATED ON THE PRECEDING PAGE.

<table>
<thead>
<tr>
<th>MONTH</th>
<th>AVERAGE TEMPERATURE</th>
<th>% RELATIVE HUMIDITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>45.0</td>
<td>60.0</td>
</tr>
<tr>
<td>February</td>
<td>49.0</td>
<td>55.0</td>
</tr>
<tr>
<td>March</td>
<td>59.0</td>
<td>52.0</td>
</tr>
<tr>
<td>April</td>
<td>69.0</td>
<td>55.0</td>
</tr>
<tr>
<td>May</td>
<td>79.0</td>
<td>71.0</td>
</tr>
<tr>
<td>June</td>
<td>84.0</td>
<td>53.0</td>
</tr>
<tr>
<td>July</td>
<td>84.0</td>
<td>60.0</td>
</tr>
<tr>
<td>August</td>
<td>84.0</td>
<td>53.0</td>
</tr>
<tr>
<td>September</td>
<td>84.0</td>
<td>50.0</td>
</tr>
<tr>
<td>October</td>
<td>69.0</td>
<td>60.0</td>
</tr>
<tr>
<td>November</td>
<td>59.0</td>
<td>53.0</td>
</tr>
<tr>
<td>December</td>
<td>49.0</td>
<td>52.0</td>
</tr>
</tbody>
</table>

IN PERFORMING THE COMPUTATIONS, AVERAGE TEMPERATURES
<table>
<thead>
<tr>
<th></th>
<th>HOURLY COSTS</th>
<th>REFRIGERATION COP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>STEADY STATE</td>
<td>ACTUAL</td>
</tr>
<tr>
<td>January</td>
<td>4.37</td>
<td>2.65</td>
</tr>
<tr>
<td>February</td>
<td>5.04</td>
<td>2.53</td>
</tr>
<tr>
<td>March</td>
<td>7.49</td>
<td>2.27</td>
</tr>
<tr>
<td>April</td>
<td>11.36</td>
<td>2.06</td>
</tr>
<tr>
<td>May</td>
<td>19.28</td>
<td>1.80</td>
</tr>
<tr>
<td>June</td>
<td>19.80</td>
<td>1.80</td>
</tr>
<tr>
<td>July</td>
<td>20.74</td>
<td>1.80</td>
</tr>
<tr>
<td>August</td>
<td>19.20</td>
<td>1.80</td>
</tr>
<tr>
<td>September</td>
<td>18.54</td>
<td>1.80</td>
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<tr>
<td>October</td>
<td>11.91</td>
<td>2.06</td>
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<tr>
<td>November</td>
<td>7.56</td>
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<tr>
<td>December</td>
<td>4.93</td>
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<td>MONTHLY AVERAGE</td>
<td>12.47</td>
<td>2.12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>MASS WATER IN (kg/s)</th>
<th>HEAT LOSS (kw)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>STEADY STATE</td>
<td>ACTUAL</td>
</tr>
<tr>
<td>January</td>
<td>0.0168</td>
<td>0.0117</td>
</tr>
<tr>
<td>February</td>
<td>0.0186</td>
<td>0.0129</td>
</tr>
<tr>
<td>March</td>
<td>0.0200</td>
<td>0.0134</td>
</tr>
<tr>
<td>April</td>
<td>0.0461</td>
<td>0.0350</td>
</tr>
<tr>
<td>May</td>
<td>0.0923</td>
<td>0.0640</td>
</tr>
<tr>
<td>June</td>
<td>0.0807</td>
<td>0.0560</td>
</tr>
<tr>
<td>July</td>
<td>0.0688</td>
<td>0.0444</td>
</tr>
<tr>
<td>August</td>
<td>0.0807</td>
<td>0.0550</td>
</tr>
<tr>
<td>September</td>
<td>0.0756</td>
<td>0.0525</td>
</tr>
<tr>
<td>October</td>
<td>0.0509</td>
<td>0.0353</td>
</tr>
<tr>
<td>November</td>
<td>0.0266</td>
<td>0.0198</td>
</tr>
<tr>
<td>December</td>
<td>0.0174</td>
<td>0.0121</td>
</tr>
<tr>
<td>MONTHLY AVERAGE</td>
<td>0.0524</td>
<td>0.0363</td>
</tr>
</tbody>
</table>

Figure 5.
IR CURTAINS RESTRICT CONDITIONED AIR LOSS

Each time the door to a cooler or to a cold storage area is opened, a portion of the cold dense air inside is replaced by warmer outside air. The driving force behind this air movement is the temperature difference between the warm and cool air. This phenomenon occurs not only in cold storage rooms, but any time a door between two masses of different temperatures is opened. The chart on the back can be used to determine the amount of air that is exchanged for each minute that the door is opened.

Air curtains are devices which inhibit the penetration of unconditioned air into a conditioned space by forcing a layer of air over the entire opening. Without restricting traffic, the air layer moves at an angle such that air trying to penetrate the “curtain” is entrained and redirected. Manufacturers of the devices claim that, properly adjusted, air curtains have an effectiveness of about 60-80%.

EXAMPLE

A poultry processing plant maintains its storage freezer at —20° F. The adjacent production area has an average year round temperature of 65° F. The dimensions of the cooler door are 6’W x 8’H, and this door is open an average of 5 hours each day, 5 days per week.

From the chart, the air exchange is 1150 cfm per ft. width of the door opening.

\[
1150 \text{ cfm/ft.} \times 6 \text{ ft.} \times 300 \text{ min./day} \times 250 \text{ days/year} = 517.5 \times 10^6 \text{ cu. ft./yr.}
\]

Assuming an overall C.O.P. of 2.4 for the refrigeration system and an electrical cost of 5.0¢ per KWH, the cost to cool 10,000 cu. ft. of air from 65° F to —20° F is 12.0¢. The annual cost to cool the air entering the freezer is:

\[
517.5 \times 10^6 \text{ cu. ft./yr.} \times \$0.12/10^4 \text{ cu. ft.} = \$6,210
\]

A 2hp air curtain is installed at a cost of $1,000. The effectiveness of this installation is 60%. The cost to operate the air curtain is $61.55/yr.

\[
0.6 \times \$6210 - \$61.55 = \$3664/\text{yr. net annual savings}
\]

\[
\frac{\$1000}{\$3664/\text{year}} = 3.2 \text{ month payback}
\]

SUGGESTED ACTION

Estimate the air exchange for a specific case from the graph and then determine the annual cooling loss. Make an economic evaluation to determine if an air curtain can be justified.
AIR EXCHANGE THROUGH A VERTICAL RECTANGULAR OPENING DUE TO TEMPERATURE DIFFERENCE

TEMPE RA TURE D IFF ERE NCE, °F

CFM/FT WIDTH OF OPENING

Door Height, ft.
Nomograph for Determining Heat Transfer Coefficient for Open Door

\( T(°F) \) = average temperature between warm and cold side

\( F \) = density difference/average density

From Brown and Solvason, Reference 8
Heat Transfer Coefficient vs. Exit Velocity for Vertical Air Curtain

Calculated From Van Male, Reference 60
Heat Transfer Coefficient vs. Exit Velocity for Vertical Air Curtain

Calculated From Hayes and Stoecker, Reference 21
Efficiency vs. Exit Velocity for Horizontal Air Curtains, Cold Side Temperature 32°F (0°C)

From Longdill and Wyborn, Reference 32.
Efficiency vs. Exit Velocity for Horizontal Air Curtains,
Cold Side Temperature -4°F (-20°C)

From Longdill and Wyborn, Reference 32
Efficiency vs. Exit Velocity for Vertical Air Curtains

From Longdill and Wyborn, Reference 32
THE EFFECT OF SIDE AND DIRECT WIND (6.7 m/sec) ON OPTIMIZED CURTAINS

<table>
<thead>
<tr>
<th>CURTAIN NUMBER</th>
<th>CURTAIN EFFICIENCY, %</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>NO WIND</td>
</tr>
<tr>
<td>1</td>
<td>77</td>
</tr>
<tr>
<td>2</td>
<td>82</td>
</tr>
<tr>
<td>3</td>
<td>83</td>
</tr>
<tr>
<td>4</td>
<td>79</td>
</tr>
<tr>
<td>5</td>
<td>68</td>
</tr>
</tbody>
</table>

THE EFFECT OF DRAFT ON OPTIMIZED CURTAINS

<table>
<thead>
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<th>CURTAIN NUMBER</th>
<th>CURTAIN EFFICIENCY, %</th>
</tr>
</thead>
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<td>NO DRAFT</td>
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<tr>
<td>1</td>
<td>77</td>
</tr>
<tr>
<td>2</td>
<td>82</td>
</tr>
<tr>
<td>3</td>
<td>83</td>
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<tr>
<td>4</td>
<td>79</td>
</tr>
<tr>
<td>5</td>
<td>69</td>
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</table>

Figure 15.

From Longdill and Wyborn, Reference 32
# The Effect of Wind on Interchange and Horizontal Curtain Performance

<table>
<thead>
<tr>
<th></th>
<th>Air Interchange</th>
<th>Curtain Efficiency (%)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$Q$ (m$^3$/s)</td>
<td>$Q_{op}$ (m$^3$/s)</td>
</tr>
<tr>
<td>No wind</td>
<td>1.18</td>
<td>0.24</td>
</tr>
<tr>
<td>Direct wind (5.2 m/s)</td>
<td>1.29</td>
<td>1.28</td>
</tr>
<tr>
<td>(2.6 m/s)</td>
<td>1.24</td>
<td>1.22</td>
</tr>
<tr>
<td>Side wind (5.2 m/s)</td>
<td>0.34</td>
<td>0.30</td>
</tr>
<tr>
<td>(2.6 m/s)</td>
<td>0.42</td>
<td>0.27</td>
</tr>
</tbody>
</table>

* $Q_{op}$ was the loss while an optimum curtain was operating with:

$$U_{op} = 6.1 \text{ m/s}, B = 63 \text{ mm}, \theta = 25^\circ, T_I = 20^\circ\text{C}$$

Figure 16.

From Longdill and Wyborn, Reference 32
Figure 17.

From Wilder, Clark Door Co., Reference 66
APPENDIX D

AIR CURTAIN MANUFACTURERS/DISTRIBUTORS
Aerovent, Inc.  
Ash & Bauer Streets, Piqua, OH 45356  
(513) 773-4611

Air Economy  
Post Office Box 29-T, Flemington, NJ 08822  
(201) 782-8888

AIS Equipment Corporation  
156-B, Parisppany Road, P. O. Box 178-T  
Parsippany, NJ 07054  
(201) 884-2121

Allied Environmental Systems Atlanta  
(404) 493-1440

Arenberg Sage, Inc.  
Post Office Box 250A, Jamaica Plain, MA 02130  
(617) 522-7800

Bacu Refrigeration Supply Company  
37 High Street, Poughkeepsie, NY 12601  
(914) 454-3500

Bacu West  
Phoenix, AR 85021  
(602) 861-1858

Berner International Corporation  
Post Office Box 5205, New Castle, PA 16105  
(412) 658-3551

Cambridge Engineering, Inc.  
2783 Chesterfield Airport Road, P. O. Box 1010  
Chesterfield, MO 63017  
(314) 532-2233

Chalfant Sewing Fabricators, Inc.  
11525-7 Madison Avenue, Cleveland, OH 44102  
(216) 521-7922

Chase Industries, Inc.  
8102 Reading Road, Cincinnati, OH 45222  
(513) 821-3939

Curtainaire of California, Inc.  
1714 E. Albion Street, Los Angeles, CA 90031  
(213) 227-1877

Custom Industries, Inc., Dept. T  
Post Office Box 18547, 6106 W. Market Street  
Greensboro, N.C. 27419  
(919) 299-2885

Daco Group, The Air Door Inc.  
Post Office Box 177-T, Twinsburg, OH 44087  
(216) 425-3831

Dynaforce Corporation  
195-T, Sweet Hollow Road, Old Bethpage, NY 11804  
(516) 420-8787
HCH Associates, Inc.  
Post Office Box 87-T, Robbinsville, NJ 08691  
(609) 259-9722

Insul-Aids Products, Inc.  
73-T Atlantic Avenue, Matawab, NJ 07747  
(201) 583-6872

King Company of Owatonna  
Travis Street, Industrial Park  
Owatonna, MI 55060  
(507) 451-3770

Mac-Lee Company, Inc.  
Post Office Box 553, Decatur, AL 35601  
(205) 353-8600

Mars Air Doors  
114-16 Sheldon Street, El Segundo, CA 90245  
(213) 772-3321

Necor Corporation  
Post Office Drawer 2367, Menlo Park, CA 94025  
(415) 321-3750

Nortel Machinery, Inc.  
1051-T Clinton Street, Buffalo, NY 14206  
(716) 852-2685

Peabody International Corporation  
722 Post Road, Darien, CT 06820  
(203) 327-7000

Spencer Turbine Company  
The Windsor Industrial Park, Windsor, CT 06095  
(800) 243-8160

Spendrup Fan Company  
746 Quray Avenue, Grand Junction, CO 81501  
(303) 243-3429

Stancase Equipment Company  
121-A Spring Street, New York, NY 10012  
(212) 925-5614

Universal Jet Industries, Inc., Dept T  
Post Office Box 70, Hialeah, FL 33011  
(305) 887-4378

Vortec Corporation  
10125-T Carver Road, Cincinnati, OH 45242  
(515) 891-7474
STRIP DOOR MANUFACTURERS/DISTRIBUTORS

A & D Fabricating Company, Inc.
Post Office Box 980T, Lawrence, MA 01843 (617) 685-4301

Able Sewing Fabricators
3470 Saint Rocco Court, Cleveland, OH 44109 (216) 961-4440

Aleco, Clear-Flex Strip Doors
Post Office Box 589, Dept T, Tuscumbia, AL 35674 (205) 381-4970

Allied Canvas Products Corporation
160-T S 2nd Street, Milwaukee, WI 53204 (414) 347-1580

Atlas Industries, Inc.
2952 W. Chicago Avenue, Chicago, IL 60622 (312) 384-7444

C.A.H. Industries, Inc.
1597 Brummel Ave., Elk Grove Village, IL 60007 (312) 593-0727

Clark Caster Company
7312 W Roosevelt Road, Forest Park, IL 60130 (312) 366-1913

Clark Door Company
71 Myrtle Street, Cranford, NJ 07016 (201) 27-5100

Continental Plastic Company, Div., CIP, Inc.
425-T Diems Drive, Wheeling, IL 60090 (312) 541-1960

Conveyor Components Company
Dept T, Post Office Box 236, Croswell, MI 48422 (313) 679-4211

Cool Curtain, Inc.
4701-B Arrow Highway, Dept, T, Montclair, CA 91763 (714) 626-3531

Curton Industries, Inc.
42 W Bridge Street, Catskill, NY 12414 (518) 943-6931 (800) 833-5005

Environmental Products Company
701-T W Illinois Avenue, Aurora, IL 60506 (312) 893-2414

Equipment Company of America
1077 Hialeah Drive, Hialeah, FL 33010 (305) 887-1772

Flex-Strip Products, Inc.
Dept 3-A, 3139 Oakcliff Industrial Street
Atlanta, GA 30340 (404) 457-1503

F. R. Industries, Inc.
556-T Long Road, Pittsburg, PA 15235 (412) 242-4902

Frommelt Industries, Inc.
(319) 556-2020
465 Huff Street, Dubuque, IA 52001

Industrial ESP Company
709 Gilman Avenue, Marietta, OH 45750 (614) 373-0022

Johnston Environmental, Inc.
1503-T E Chestnut, Santa Ana, CA 92701 (714) 547-8288

Kelly Company, Inc.
6770 N Teutonia Avenue, Milwaukee, WI 53209 (414) 352-1000

McGuire Company, Inc.
The Hudson Avenue & Union Street, Hudson, NY 12534 (518) 828-7652

Manufacturing Warehouse, Inc.
1730 NW 29th Street, Miami, FL 33142 (305) 635-8886

Material Control, Inc.
719 Morton Avenue, Aurora, IL 60506 (312) 892-0962

Randall Industries
685 Executive Drive, Dept T, Hinsdale, IL 60521 (312) 920-9290

Singer Safety Company
3800 N Wilwaukee Avenue, Dept 82-T Ext. 223
Chicago, IL 60641 (312) 258-1000

Solem Industries, Inc.
Equipment Div., Dept ATH, 3400 Oakcliff Road
Atlanta, GA 30340 (404) 458-9107

T & S Equipment Company
103 N Albion Street, Albion, MI 49224 (517) 629-3908

Transeal LTD
55 Dott Avenue, Albany, NY 12205 (518) 489-1422

Vestill Manufacturing Company
Cass & Albion Streets, Albion, MI 49224 (517) 629-5507