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REFRIGERATION REQUIREMENTS FOR TRUCK BODIES EFFECTS OF DOOR USAGE
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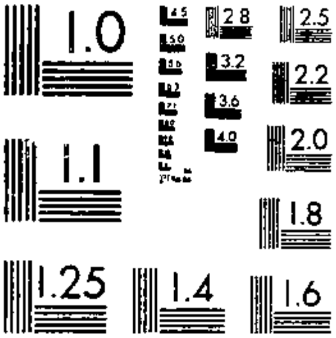

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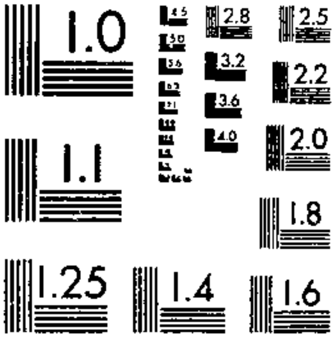

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REFRIGERATION REQUIREMENTS FOR TRUCK BODIES—EFFECTS OF DOOR USAGE

Technical Bulletin No. 1375

Agricultural Research Service
UNITED STATES DEPARTMENT OF AGRICULTURE

In Cooperation with

National Bureau of Standards
UNITED STATES DEPARTMENT OF COMMERCE

CONTENTS

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REFRIGERATION REQUIREMENTS FOR TRUCK BODIES—EFFECTS OF DOOR USAGE

By R. W. PENNEY, *Transportation and Facilities Research Division, Agricultural Research Service, U.S. Department of Agriculture* and C. W. PHILLIPS, *Building Research Division, Institute of Applied Technology, National Bureau of Standards*

SUMMARY

Three refrigerated truck bodies and a simulated truck body were used in laboratory tests to determine the cooling loads caused by opening the door of refrigerated trucks. The cooling load caused by door opening can be the predominant factor in the selection of a refrigeration unit for such vehicles. Experiments were conducted under controlled conditions of 0° F. temperature in the truck body and 100° F. temperature and 50 percent relative humidity in the test room. A brine refrigeration system was used to obtain steady-state temperature in the truck body, and liquid nitrogen was used to determine increases in cooling loads caused by opening the door. Helium gas was used as a tracer to measure the air exchange resulting from door usage.

Tests showed that a 1-minute door opening can cause air temperature inside the truck body to rise as much as 60 degrees and that more than one complete air change can occur during the same period. Formulas were developed to estimate the amount of air exchange and the cooling load caused by door opening.

INTRODUCTION

A frozen food delivery truck must have a refrigeration unit of sufficient cooling capacity to match the combined cooling loads imposed by the truck body and by door usage. Standard test methods now are available to measure the cooling capacity of mechanical refrigeration units,[1] and the cooling load of refrigerated truck bodies.[2]

These two methods make it possible for a truck operator to buy a truck with a refrigerating unit that closely matches the cooling load of the truck body in service. However, in local delivery operations, heat

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[1] Air Conditioning and Refrigeration Institute Standard 1110–64, for Speed-Governed Transport Refrigeration Units Employing Forced-Circulation Air-Coolers, and Standard 1120–61, for Variable-Speed Transport Refrigeration Units Employing Forced-Circulation Air-Coolers.

[2] PHILLIPS, C. W., and PENNEY, R. W. "Development of a Method for Testing and Rating Refrigerated Truck Bodies." U.S. Dept. Agr. Tech. Bul. 1376, 36 pp., illus. 1967.

that enters the cargo space when the door is opened may require more refrigerating capacity than the heat that enters by direct transmission through the truck body. A method of determining the cooling load caused by door usage is needed to enable firms engaged in local delivery of refrigerated products to select equipment with adequate capacity.

This study was undertaken to develop a practical method of calculating the cooling load caused by door usage in local delivery of frozen foods. It should be noted that the cooling load due to door usage as estimated by this method assumes that the interior air and cargo temperature is restored to the original temperature between sucessive door openings. In practical operation such temperature recovery may not occur and, in some cases, may not be necessary. All factors relating to required cargo temperature, such as body cooling load, cargo time-temperature tolerance, loading arrangement, packaging, subcooling, delivery schedule time, and number of door openings per hour, should be considered in determining the required refrigerating capacity.

METHODOLOGY

Test Facilities

Three truck bodies (A, B, and C) and a simulated truck body (D) were used in the door-opening tests. Interior volume, door dimensions, and insulation of these bodies are shown in table 1.

Tests were conducted under controlled ambient conditions of 100° F. temperature and 50 percent relative humidity in the test room and 0° F. temperature inside the truck body. A brine refrigeration system was used to chill the interior of the bodies to obtain steady-state conditions before the door opening tests. Liquid nitrogen expanded into the cargo space was then used to measure the cooling load caused by opening the door.

Thermocouples were used to measure temperatures. Exterior and interior temperatures were taken near each of the eight corners of the truck body. Interior air temperatures also were taken at the midlength of the body near the floor and ceiling at the four angles formed with the walls. In addition, temperatures were taken at the inside top and bottom of body B near the door, using thermocouples placed at the surface, one-fourth inch behind the surface, and in the air 1 inch from the surface. Body B was selected for these temperature measure-

TABLE 1.—*Description of truck bodies used in the tests*

Truck body	Interior volume	Kind of door	Size of door		Insulation
			Width	Height	
	Cubic feet		*Inches*	*Inches*	
A	432	Reach-in	22½	44	Foamed-in-place urethane.
B	333	do	22½	44½	Preformed urethane.
C	388	Walk-in	26	59	Glass fiber.
D	560	do	29	70	Foamed-in-place urethane.

ments because it was the one with most nearly homogeneous material in the floor, wall, and ceiling.

Fiberboard boxes, containing a mixture of sand and sawdust with density and specific heat approximating those of frozen foods, were used to simulate a load in body D. Enough boxes were placed in the body to occupy half the inside cargo space. A half load was used to represent the average size of the load in a truck body during a day's delivery operation. The temperature of the top surface of one box in the top layer of the load was measured by a thermocouple.

Air Exchange Measurement

Three methods were tried for use in measuring the amount of air exchanged, or replaced, inside the vehicle during a door opening. One method used multiple heated thermocouples to measure air velocity through the door, but this method was not successful because of difficulties encountered with high-speed switching. The second method was based upon changing the ambient humidity and measuring the resulting change in the cooling load. That method was unsuited for measurement of low air-exchange rates. A third method, using helium as a tracer gas, was selected as the most practical.

Helium gas has been used successfully by Coblentz [3] to measure air leakage of buildings. In this method, helium gas is added to an enclosed space, and the subsequent reduction in concentration is an index of the air infiltration or exchange. The relative concentration measurements are dependent upon the thermal conductivity of the air-helium mixture. The thermal conductivity of the mixture is approximately linear with helium concentration below about 5 percent. The method was modified for the door-opening tests to give more rapid response and to permit its use with below-freezing temperatures.

To establish whether the relation between helium concentration and instrument readings remained linear, helium in measured amounts was added to one of the bodies and meter readings were taken of the thermal conductivity of the air-helium mixtures after each addition. The relation between helium added and meter readings was linear, as shown in figure 1.

The rate of air flow, or air leakage, into the body was calculated according to the following formula when using the helium-trace method:

$$\text{Air leakage, } q=\frac{V}{t}A_c, \text{ cubic feet per minute}$$

Where:

V=internal volume, cubic feet

t=time, minutes

$A_c=\ln C_1/C_2$

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[3] COBLENTZ, C. W., and ACHENBACH, P. R. "Design and Performance of a Portable Infiltration Meter." American Society of Heating and Air-Conditioning Engineers, Inc., Transactions, vol. 63, 1957.

Where:

C_1=concentration index (meter reading) at start of time period, microvolts

C_2=concentration index (meter reading) at end of time period, microvolts

To test the suitability of the formula for air leakage, an airflow of 17 cubic feet per minute was introduced into the body through a calibrated orifice. The helium-trace measurement of the same flow gave a value of 17.3 cubic feet per minute. A graph of the helium meter readings for this test is shown in figure 2.

The total amount of air exchanged during a door opening was measured by using the helium-trace method. Because this method measured the air leakage through the truck body before and after door openings, no correction for that leakage was needed.

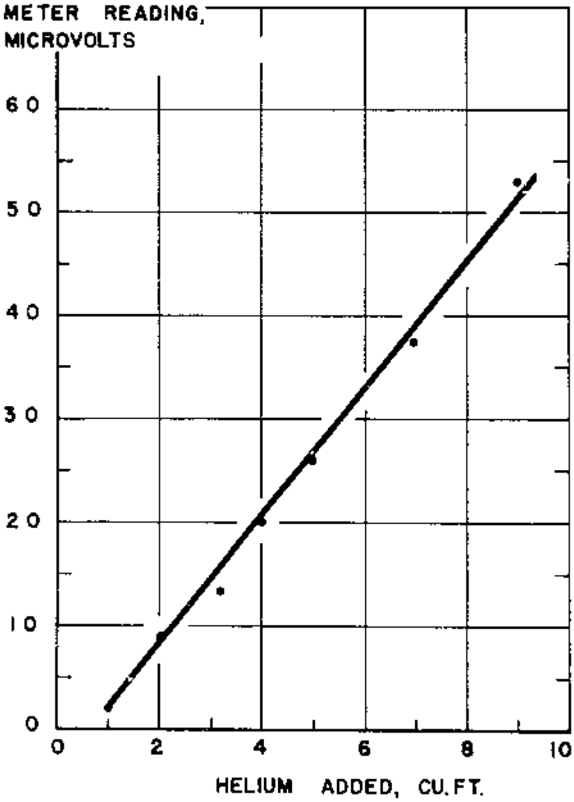

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FIGURE 1.—Linear relation between meter readings and helium gas added to the interior of the truck body.

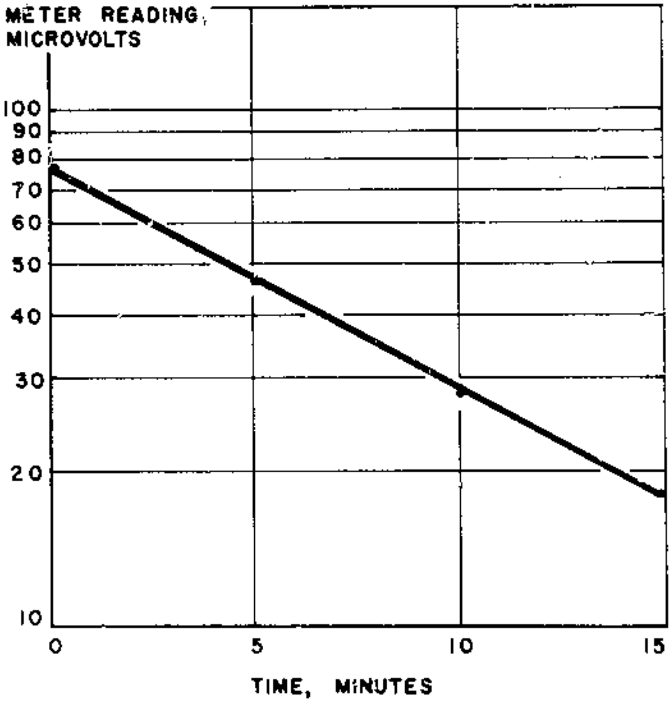

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FIGURE 2.—Helium meter readings when an airflow of 17 cubic feet per minute was introduced into a truck body.

To measure air change (A_c) caused by opening the door, a quantity of helium gas was introduced into the truck body, and concentration readings were then taken until a peak was reached. No further helium was added, and readings were taken for about 10 minutes to establish the slope of the concentration curve plotted against time on a semilog scale. The door then was opened for a given number of minutes and closed. Concentration readings again were taken to reestablish the slope of the concentration curve. Both concentration curves then were extended in a straight line to the period of door opening. The air change was calculated from the concentration at door opening (C_1) and closing (C_2). A limitation of this technique is that the range of the upper and lower meter readings limits accurate measurement to a maximum of about three air changes, and the accuracy of the calculated value of air change using this method is dependent on the degree of mixing of the leakage air in the cargo space. Figure 3 shows a typical semilogarithmic graph of relative helium concentrations for a 2-minute door opening.

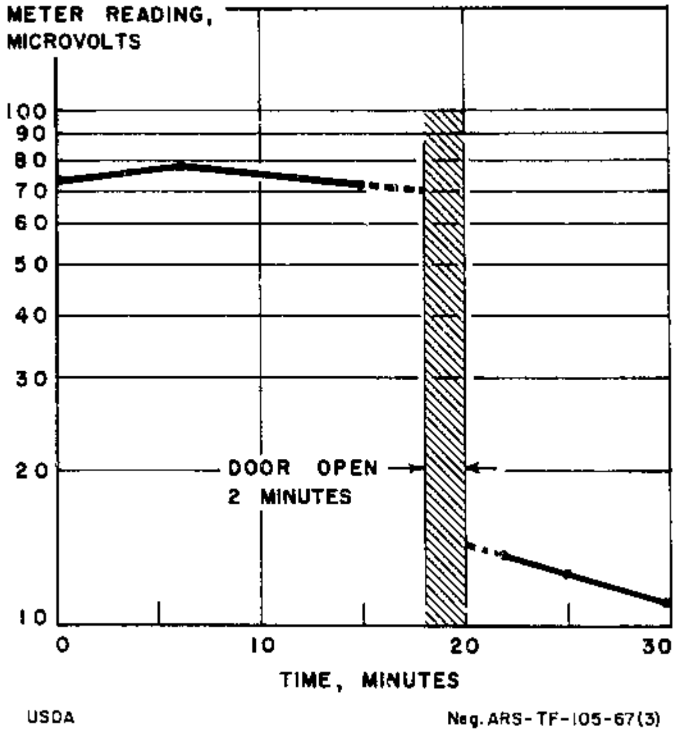

FIGURE 3.—Changes in relative helium concentration for a typical 2-minute door opening.

Cooling-Load Measurement

The steady-state cooling load of the truck body was obtained by measuring the temperature change of a metered cold brine flowing through a coil used to cool the truck interior. The cooling load was found by subtracting the power supplied to a control heater and fans in the truck body from the total heat pickup of the coil.

A tank of liquid nitrogen was placed inside the truck body before beginning a test to measure the cooling load caused by opening the door. When the desired steady-state temperature condition was attained, the brine system was turned off and the liquid nitrogen system was turned on. The rate of use of liquid nitrogen at the steady-state condition was determined by weight. The nitrogen system was then turned off and the door opened. After the door was closed, the nitrogen was turned on again and the amount of nitrogen needed to reestablish the steady-state condition was determined. The amount of nitrogen above that required to maintain the steady-state condition was used to calculate the cooling load caused by opening the door.

RESULTS

Temperature

Test body B was used to measure the temperature effects on the structure near the door caused by opening the door. Figures 4 and 5 show the temperature changes caused by a 3-minute door opening, in a test using the brine coil for cooling. The fan was turned off during the period of door opening. As might be expected, higher temperatures were found at the ceiling than at the floor. With the capacity of the particular brine coil used, the time for the air to return to its initial temperature after the door was closed approximated 30 minutes. The inside surface temperature recovered more slowly than the air temperature, and the temperature of the structure one-quarter inch below the surface lagged behind the surface temperature.

In one test of body D, air temperature was recovered in 3 minutes following a 2-minute door opening when liquid nitrogen, expanded directly into the cargo space, was used as the refrigerant. As indicated by the rate of liquid nitrogen usage, an additional 25 minutes was required for the structure to return to the same steady-state heat transfer rate observed before the 2-minute door opening.

When the door of truck body D was opened, the average interior air temperature rose rapidly during the first minute, leveled off,

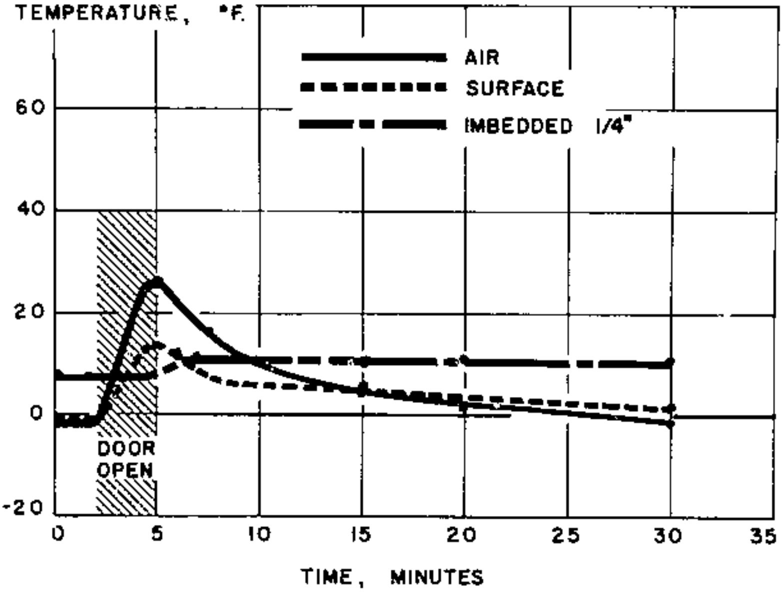

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FIGURE 4.—Changes in interior temperatures at the floor of a refrigerated truck body caused by a 3-minute door opening.

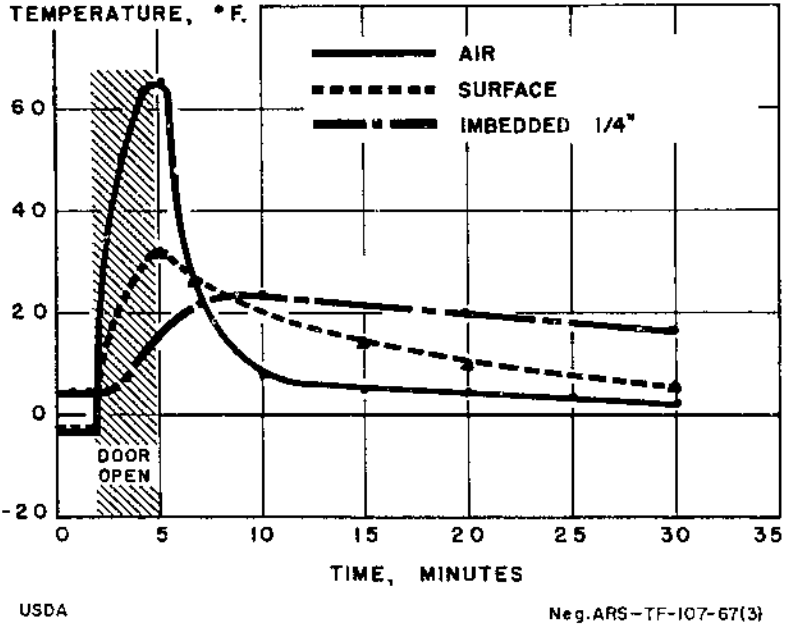

FIGURE 5.—Changes in interior temperatures at the ceiling of a refrigerated truck body caused by a 3-minute door opening.

and then rose only slightly when the door was kept open for 2 or 3 minutes. Following the initial rapid temperature rise, caused by the exchange of warm exterior air and cold interior air, a heat flow between the warm entering air and the cold structure and cargo tended to hold the temperature constant. The effect of 1-, 2-, and 3-minute door openings on average interior air temperature in truck body D, half filled with simulated cargo, is shown in figure 6.

The temperature of the top surface of one of the boxes in the top layer of the simulated frozen food load increased to 13° F. for a 1-minute door opening, 28° for a 2-minute door opening, and 41° F. for a 3-minute door opening (fig. 7).

Air Exchange

Figure 8 shows the curves of air change with time of door openings for the four truck bodies tested. The door size, height of door, and interior volume of the body affect the relative positions of the curves. For example, body D, when empty, had a rapid air exchange, but when it was half filled, the air exchange was reduced to approach the curve of body C.

The following formula was developed for calculating the air changes which would occur as a result of door usage in a truck body, taking into account the variables of door size, door height, unoccupied

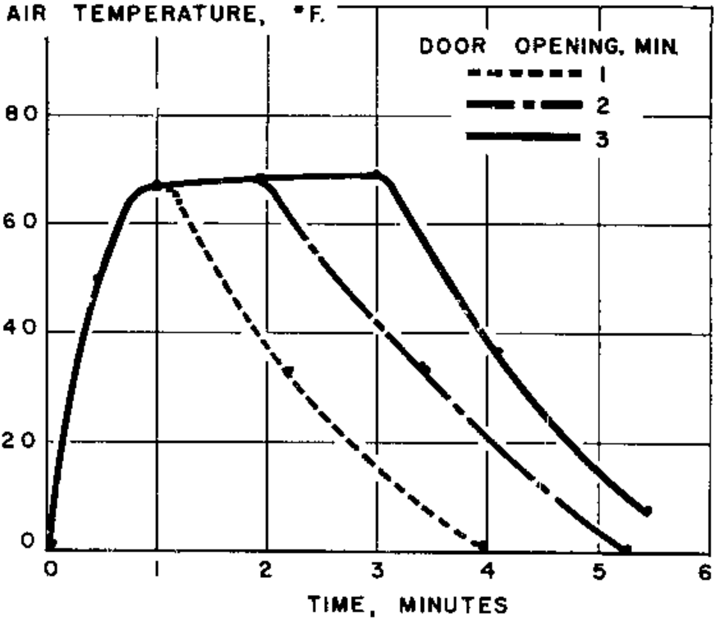

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FIGURE 6.—Effect of 1-, 2-, and 3-minute door openings on average air temperture inside truck body D, half filled with simulated cargo. Liquid nitrogen was used for air temperature recovery.

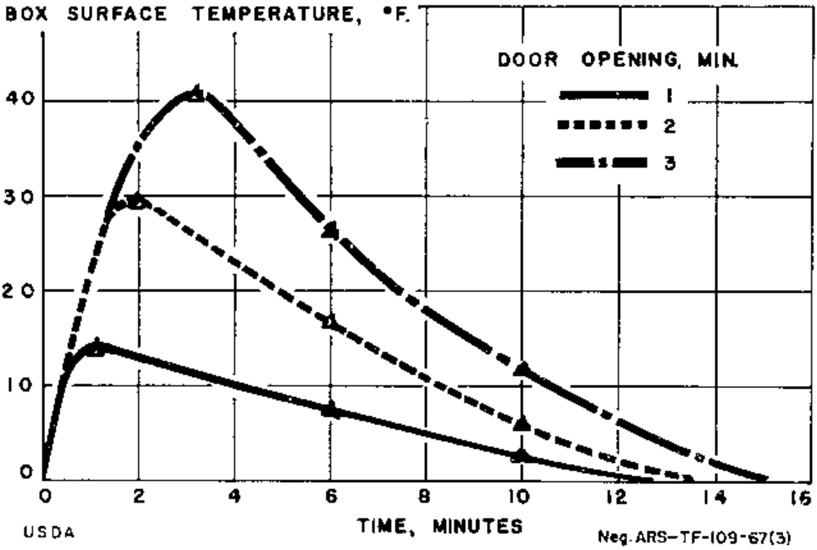

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FIGURE 7.—Surface temperatures of a simulated frozen food box for door-opening times of 1, 2, and 3 minutes. Liquid nitrogen was used for air temperature recovery.

interior volume, interior and exterior temperatures, and door opening time:

$$A_c = 2\ ln\ (1 + X)$$

Where:

$$X = \frac{1}{2} \frac{3{,}700\, A_d\, C \sqrt{H}}{V_i T_m} \sqrt{t_o\text{-}t_i}\ \theta$$

A_d=effective door area, square feet (area not blocked by cargo)
C=discharge coefficient for a rectangular opening $= 0.7$
H=one-half the effective door height, feet
V_i=interior volume of vehicle not occupied by cargo, cubic feet
T_m=mean temperature of inside and ambient air, degrees Rankine
t_o=ambient air temperature, ° F.
t_i=initial inside temperature, ° F.
θ=door-opening time, minutes

The derivation of this theoretical formula may be obtained from the authors.

To show the relation between calculated and observed values, the experimental data of figure 8, plotted as individual points, are compared in figure 9 with the theoretical number of air changes, A_c, calculated by the above formula and shown as a solid line.

For ambient temperature of 100° F. and interior temperature of 0° F., calculation of X becomes:

$$X = 25.4 \frac{A_d \sqrt{H}\ \theta}{V_i}$$

If the doorway size, internal volume not occupied by cargo, and duration of door opening are known for a truck body, X can be calculated and the number of air changes, A_c, obtained from figure 9.

Cooling Load

The cooling load, in B.t.u. per door opening, is shown in figure 10 for truck body D when empty and when half filled with boxes of simulated frozen food. The following equation for a door-opening cooling load was developed from theoretical equations and from test results:

Q=the cooling load in B.t.u. per door opening

$$= K\, A_c\, V_i \left(\frac{h_o}{v_o} - \frac{h_i}{v_o}\right)$$

Where:

K=the ratio of actual enthalpy change to maximum theoretical available enthalpy change
V_i=volume inside body not occupied by cargo, cubic feet
A_c=number of air changes
h_o=enthalpy of ambient air, B.t.u. per pound dry air
h_i=initial enthalpy of interior air, B.t.u. per pound dry air
v_o=specific volume of ambient air, cubic feet per pound dry air
v_i=initial specific volume of interior air, cubic feet per pound dry air

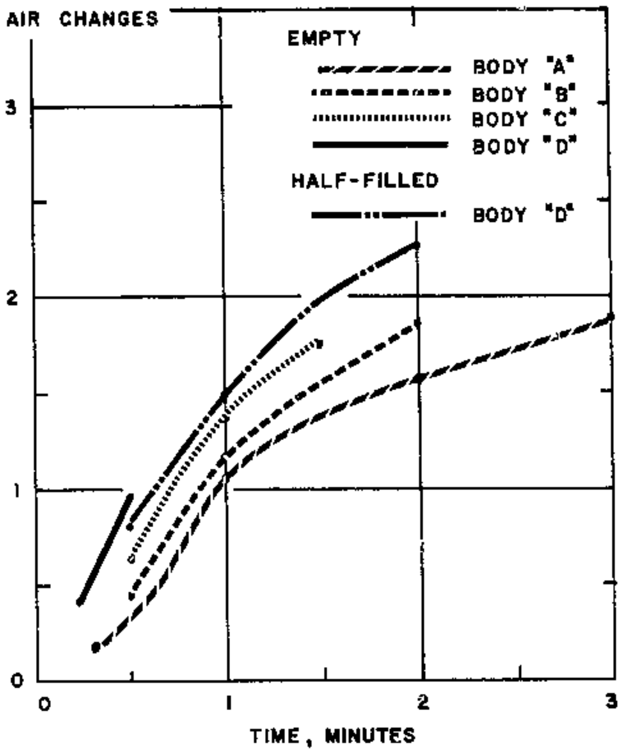

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FIGURE 8.—Air changes which occurred in the four truck bodies for various door-opening times.

Values of K computed from tests on body D for empty and half-filled conditions were 0.53 and 0.91, respectively.

An approximate value of K based on tests of body D is given numerically by the empirical, dimensionally inconsistent, relation

$$K \approx \left(\frac{A_t}{V_t}\right)^2$$

Where:

A_t = area of exposed surface inside body, square feet. The approximate values of K found by $\left(\frac{A_t}{V_t}\right)^2$ for body D are 0.54 and 0.93, respectively, for empty and half-filled conditions.

It should be noted that values of $K > 1$ are not realistic and should not be used.

For ambient conditions of 100° F. temperature and 50 percent relative humidity, and 0° F. interior temperature, the above equation for Q becomes:

$$Q=3.08\,K\,A_c\,V_t$$

Actual test values and calculated values for door-opening cooling loads with body D are shown in table 2.

Sample Calculations

The total cooling load for a refrigerated truck body consists of at least the following elements: (1) Body cooling load, usually determined by test or rating, (2) cooling load caused by opening the door, as discussed in this report, (3) cooling loads caused by loading cargo at temperatures higher than desired, (4) cooling load from other sources such as lights and fans in the cargo space.

Two examples are given to show the approximate effects of door usage on the total cooling load for a frozen food truck body. In these examples, the door-usage cooling loads are calculated, and three additional factors relating to total cooling load are assumed: (1) A

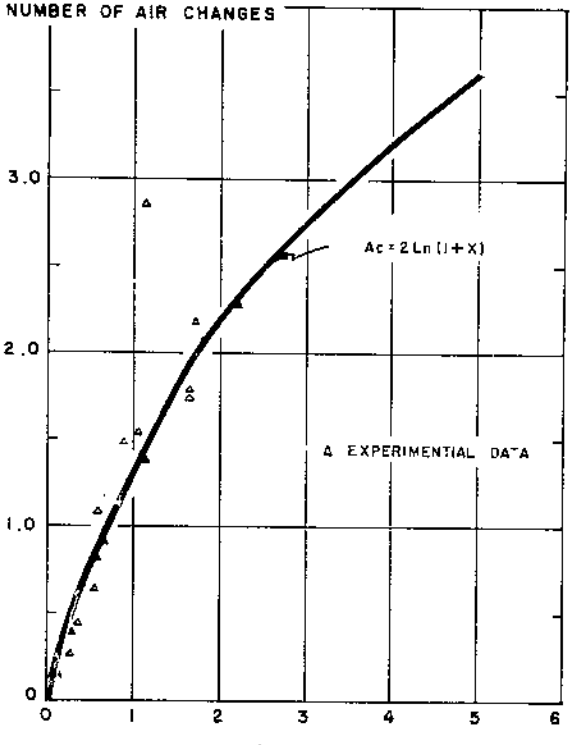

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FIGURE 9.—Observed and theoretical air changes versus factor X in the formula for air changes.

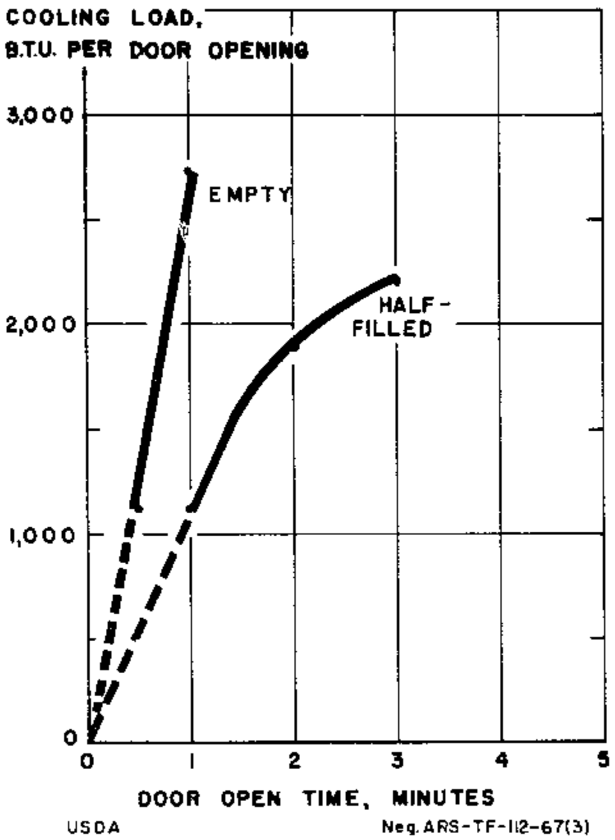

FIGURE 10.—Cooling loads caused by opening the door of truck body D when empty and when half filled with boxes of simulated frozen food.

known body cooling load, (2) a refrigerating system capable of temperature recovery in the cargo space between periods of door opening, and (3) no warm cargo or other cooling load.

Example 1

Assume a reach-in truck body of the following size: Internal volume, empty, 500 cubic feet; door size, 22 inches wide by 24 inches high; and internal dimensions, 5 feet high, 5.6 feet wide, and 17.8 feet long.

The truck will be operated in a maximum ambient condition of 100° F. temperature and 50 percent relative humidity, and at 0° F. interior temperature. The truck body cooling load is 2,000 B.t.u. per hour, with a 100-degree temperature difference. The service in which the truck is to be used calls for it to be loaded three-fourths full at the beginning of a nominal 8-hour day, and to make 32 deliveries, each requiring a 1-minute door opening. The truck

TABLE 2.—*Cooling loads in truck body D caused by opening the door*

Empty or filled truck body and door-open period	By test	As calculated
Empty:	*B.t.u.*	*B.t.u.*
½ minute	1, 240	850
1 minute	2, 710	2, 690
Half-filled:		
1 minute	1, 210	1, 170
2 minutes	1, 900	2, 060
3 minutes	2, 210	2, 500

returns with one-eighth of the volume of the interior occupied by the load. Since the door-opening cooling load increases as the truck is emptied, the door-opening cooling load should be calculated on the basis of a load occupying one-eighth of the interior volume.

With ambient conditions of 100° F. temperature and 50 percent relative humidity, and an interior temperature of 0° F. the short equation for air exchange, A_c, may be used as follows:

$$A_c = 2\ ln\ (1+X)$$

Where:

$$X = \frac{25.4 A_d \sqrt{H}}{V_t}\,\theta$$

Since:

$$A_d = \frac{22 \times 24}{144} = 3.66 \text{ square feet, door area}$$

$H = 1$ foot (one-half height of door)

$V_t = 7/8 \times 500 = 437$ cubic feet (volume of interior not occupied by load)

$\theta = 1$ (duration of door opening, minutes)

Substituting:

$$X = \frac{25.4(3.66)\sqrt{1}(1)}{437}$$

$$= 0.213$$

Then:

$$A_c = 2\ ln\ (1+0.213)$$

$$= 0.38 \text{ air change per door opening.}$$

The cooling load from one door opening at the one-eighth filled condition may be calculated by the short equation:

$$Q = 3.08 K A_c V_t \text{ B.t.u.}$$

Where:

$$K = \left(\frac{A_t}{V_t}\right)^2$$

Since:

A_t=exposed internal area, square feet

$=5.6\times17.8=99.7$ square feet, truck ceiling area

$+5.6\times17.8=99.7$ square feet, cargo top surface area

$+7/8[2(5.6)+2(17.8)]5=204.7$ square feet, side wall area

$=404.1$ square feet

$V_t=500\times7/8=437$ cubic feet (volume of interior not occupied by load)

Substituting:

$$K=\left(\frac{404.1}{437}\right)^2=0.85$$

Then:

$$Q=3.08(0.85)(0.38)(437)$$

$$=433 \text{ B.t.u.}$$

The average time between door openings is 14.5 minutes.

The rate of removal of the 433 B.t.u. is $\frac{433}{14.5}\times60=1{,}800$ B.t.u. per hour.

Therefore, the total heat load to be removed is the sum of the body cooling load, 2,000, and the door cooling load, 1,800, or 3,800 B.t.u. per hour.

Example 2

Assume a frozen food delivery truck, with internal volume of 257 cubic feet and internal dimensions of 5.8 feet high, 5.5 feet wide, and 8 feet long.

A rear walk-in door 24 inches wide and 70 inches high is provided. The truck is to be operated in a maximum ambient condition of 100° F. temperature and 50 percent relative humidity, with a 0° F. interior temperature. The body cooling load is 1,300 B.t.u. per hour for 100° F. temperature difference. The operating schedule calls for a 2-minute door opening every 20 minutes. The frozen food is to be protected at the most severe conditions (that is, when the body is almost empty).

As in the first example, the selected maximum ambient conditions of 100° F. temperature and 50 percent relative humidity, and 0° F. interior temperature, permit the curve in figure 9, or the short equation for air exchange, A_c, to be used:

$$A_c=2\ ln\ (1+X)$$

Where:

$$X=\frac{25.4A_d\sqrt{H}}{V_t}\ \theta$$

Since:

$$A_d=\frac{24\times 70}{144}=11.6 \text{ square feet}$$

$H=3$ feet (approximately)

$V_t=250$ cubic feet (with truck almost empty)

$\theta=2$ minutes

$$X=\frac{25.4(11.6)\sqrt{3}(2)}{250}$$

$$=4.07$$

In this example the curve in figure 9 will be used to find the number of air changes. For an X value of 4.07, the air change, A_c, is 3.2.

The short equation for the door-opening cooling load also may be used as follows:

$$Q=3.08KA_cV_t \text{ B.t.u.}$$

Where:

A_i=internal exposed area, square feet

$=2(8+5)(5.8)+2(8\times 5.5)$

$=157+88$

$=245$ square feet

$V_t=250$ cubic feet, (inside unoccupied volume)

$$K=\left(\frac{A_i}{V_t}\right)^2=\left(\frac{245}{250}\right)^2=0.96$$

Therefore:

$$Q=3.08(0.96)(3.2)(250)$$

$$=2{,}390 \text{ B.t.u.}$$

The average rate of heat removal for a 2-minute door opening every 20 minutes is $\frac{2{,}390}{20}\times 60=7{,}170$ B.t.u. per hour.

Therefore, the total heat load to be removed is the sum of the body cooling load, 1,300, and the door cooling load, 7,170, or 8,470 B.t.u. per hour.

CONCLUSIONS

The formulas developed in this study provide a means of calculating the approximate cooling load caused by opening the door of a refrigerated truck for periods up to 3 minutes in duration. It is not a purpose of this paper to describe recommended procedures for truck usage or the degree of cargo temperature recovery required between door openings. If the frequency of door usage is known, and if full temperature recovery of the cargo and truck interior is obtained between successive openings,[4] the product of the number of openings and the calculated cooling load per opening will give the total cooling load caused by door usage. The magnitude of the door-usage cooling load is a principal factor needed by operators and manufacturers of refrigerated trucks to determine the required capacity of the refrigerating means for such vehicles.

The use of the curve developed for air changes (fig. 9) should be limited to the ranges given. Also, no attempt should be made to use multiples of cooling loads for a given door-opening time to obtain cooling loads for longer door-opening times.

Additional studies are needed to determine the effects of successive door openings when there are variations in the door-opening schedule and the interval between openings is less than the temperature recovery time. Cooling loads for long door openings, such as those required to completely load or unload trucks, also need to be studied.

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[4] In some operations, full temperature recovery may not be required between successive door openings and the resulting cooling load will be less than for full recovery.

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