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Heat-Transmission Tests on Sheet Steel Walls

by W.C. Brown

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RÉSUMÉ

On a réalisé un programme de 27 essais de transmission de la chaleur sur 14 configurations différentes de parois en tôle d'acier. Le but recherché était de quantifier les transferts de chaleur par les profilés en Z et d'évaluer les effets de l'écoulement d'air de convection sur le flux de chaleur qui traverse les parois métalliques. Les essais ont été effectués sur des parois de 2,44 m x 2,44 m (8 pi x 8 pi) dans une enceinte chauffée protégée.

Les résultats ont révélé que le flux de chaleur à travers les profilés pouvait représenter un pourcentage important (35 %) du flux de chaleur total traversant la paroi. Environ la moitié de la résistance à ce flux de chaleur provenait des profilés et l'autre moitié de la résistance effective entre les profilés et les surfaces des parois. Le flux de chaleur des profilés n'a pas été réduit de façon importante par l'enlèvement de la moitié des vis de fixation du revêtement extérieur, mais il a pu être réduit grâce à l'amélioration thermique des profilés.

Les résultats ont aussi démontré que le courant de convection pouvait transporter autant de chaleur à travers une paroi d'acier qu'il pouvait en passer par conduction à travers l'isolant. On peut empêcher presque complètement ce transfert de chaleur en ajoutant un pare-air à la paroi d'acier.

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HEAT-TRANSMISSION TESTS ON SHEET STEEL WALLS

W.C. Brown
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ABSTRACT

A program of 27 thermal transmission tests was conducted on 14 different configurations of sheet steel wall. The purpose of the test program was to quantify the heat transfer through the sheet steel wall Z-girts and to evaluate the effects of convective airflow on the heat flow through sheet steel walls. The test walls were 2.44 m × 2.44 m (8 ft × 8 ft) and the tests were conducted in a guarded hot box test apparatus.

The test results showed that the heat flow through the Z-girts could be a significant percentage (35%) of the total heat flow through the sheet steel wall. Approximately half of the resistance to this heat flow was contributed by the Z-girt while the other half was contributed by the effective resistance between the Z-girt and the wall faces. The Z-girt heat flow was not significantly reduced by removing half of the screws holding the exterior cladding to the Z-girt but could be reduced if the Z-girt was thermally designed.

The test results also indicated that convective airflow could transport as much heat through a sheet steel wall as was transported by conduction through the insulation. This mechanism of heat transport could be controlled by the addition of an air barrier to the sheet steel wall.

INTRODUCTION

Sheet steel walls are used extensively in the construction of industrial buildings. They are typically constructed from a sheet steel V-rib inner liner, a layer of insulation, and a corrugated sheet steel exterior cladding. Figure 1 shows details of a typical sheet steel wall as used in this study. Normally the inner liner is fastened directly to the steel frame of the building; the exterior cladding is attached to the inner liner and the structural steel of the building through cold formed sheet steel elements called Z-girts. The Z-girts are designed to be strong enough to support the exterior cladding but small enough to minimize the heat transfer through them. The insulation, typically batt type glass fiber insulation, is sandwiched between the inner liner and the exterior cladding.

The Canadian Sheet Steel Building Institute (CSSBI) asked the Division of Building Research (now the Institute for Research in Construction) of the National Research Council of Canada to evaluate the heat transfer through insulated sheet steel walls. The objectives of the study were:

1. to measure the heat transfer through walls with a number of different Z-girts installed;

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2. to evaluate the effects of convective airflow within the wall on the heat transfer through the wall;

3. to evaluate the potential for reducing the heat transfer through sheet steel walls by reducing the heat transfer through the Z-girts.

THEORY

Heat is transferred through sheet steel walls by conduction through the insulation and conduction through the Z-girt. It can also be transferred by convective airflow around the insulation if measures are not taken to control this mechanism of heat transfer. The total heat transfer through a sheet steel wall under steady state conditions, Q_t, can be expressed by

$$Q_t = Q_i + Q_z + Q_c \tag{1}$$

where

Q_i = heat transfer by conduction through the insulation;
Q_z = heat transfer by conduction through the Z-girt;
Q_c = heat transfer by convective airflow.

Heat Transfer Through Insulation

Assuming one-dimensional heat flow, the heat transfer by conduction through the insulation under steady-state conditions, Q_i, can be expressed as

$$Q_i = (T_1-T_2)\cdot(A_i/R_i) \tag{2}$$

where

T_1 = average hot wall surface temperature;
T_2 = average cold wall surface temperature;
A_i = area of the insulation;
R_i = resistance of the insulation.

Heat Transfer Through Z-girt

The heat transfer by conduction through the Z-girt under steady- state conditions, Q_z, can be expressed as

$$Q_z = (T_1-T_2)\cdot(A_z/R_z) \tag{3}$$

where

A_z = cross-sectional area of Z-girt;
R_z = effective resistance of the Z-girt and sheet steel surfaces.

As with the heat transfer through the insulation, it is assumed that the temperature difference driving the heat transfer through the Z-girt is the average surface-to-surface temperature difference, T_1-T_2. However, it is also assumed that the heat transfer area is equivalent to the cross-sectional area of the Z-girt, A_z. Further, it is assumed that the resistance to Z-girt heat flow can be reduced to a single value, R_z. The last point assumes that the resistance to heat transfer of the inner liner and exterior cladding, the contact resistances between the inner liner, exterior cladding, and Z-girt, and the resistance of the Z-girt itself can be combined into a single value.

The ratio of A_z to R_z can theoretically be determined from the following expression

$$R_z/A_z = r_1/A_1 + r_z/A_z + r_2/A_2 \tag{4}$$

where

r_1 = a combination of resistance of inner liner to Z-girt heat flow and contact resistance between inner liner and Z-girt;
A_1 = effective heat transfer area of inner liner;
r_z = resistance of Z-girt;
A_z = cross-sectional area of Z-girt;
r_2 = a combination of resistance of exterior cladding to Z-girt heat flow and contact resistance between Z-girt and exterior cladding;
A_2 = effective heat transfer area of exterior cladding.

All of the areas contained in Equation 4 can be assumed to be products of the width of the Z-girt heat transfer area (length of Z-girt)*, w_z, times the height of the appropriate heat transfer area, h. Since w_z is common to all areas, it can be factored out of Equation 4 and the equation becomes

$$R_z/h_z = r_1/h_1 + r_z/h_z + r_2/h_2 \tag{5}$$

where

h_1 = effective height of inner liner heat transfer area;
h_z = height of Z-girt heat transfer area (thickness of Z-girt);
h_2 = effective height of exterior-cladding heat transfer area.

The resistance of the Z-girt, r_z, can be determined analytically from the thermal conductivity of the Z-girt, k_z, and from its geometry. The height of the Z-girt heat transfer area, h_z, is the thickness (gauge) of the Z-girt and can be measured. However, given the three-dimensional heat flow path between the Z-girt and the inner liner and exterior cladding and the uncertainty in determining contact resistance, values of r_1/h_1 and r_2/h_2 are difficult to determine analytically. They can, however, be determined by experiment and from the following expressions

$$r_1/h_1 = w_z \cdot (T_1 - T_{z_1})/Q_z \tag{6a}$$

$$r_1/h_2 = w_z \cdot (T_{z_2} - T_2)/Q_z \tag{6b}$$

$T_1-T_{z_1}$ is the temperature difference between the average inner liner temperature, T_1, and the hot edge of the Z-girt, T_{z_1} and $T_{z_2} - T_2$ is the temperature difference between the cold edge of the Z-girt, T_{z_2} and the average exterior cladding temperature, T_2. Q_z is the heat flow through the Z-girt and w_z is the width of the Z-girt heat transfer area. Values for r_1/h_1 and r_2/h_2 for a given inner liner and exterior cladding can be determined from measured values of temperature difference and heat flow.

Convective Airflow

Previous work (Schuyler and Solvason 1983) has shown that convective airflow can transfer as much heat through a sheet steel wall as that transferred by conduction through the insulation. Convective airflow is defined as air movement within a wall that is driven by a temperature difference across the wall rather than by an external pressure difference. It will exist to some extent in any vertical enclosure that is filled with a porous medium and has a temperature difference across it. Buoyancy forces generated by the temperature difference cause the air to circulate up the hot surface of the wall cavity and down the cold surface of the wall cavity. The circulation path is completed through the porous medium at the top and bottom of the wall cavity.

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*In the discussion that follows, all dimensions are labeled according to the relationship to the heat flow path and not to the physical dimensions of the component that forms that path. Thus, the width of the heat transfer area is the horizontal dimension across the face of the sample. This is physically equivalent to the length of the Z-girt. See Figure 1 for the axis labels as used in the discussion.

Convective airflow can have a minor effect on the heat flow through a wall that is completely filled with insulation because the insulation will restrict the airflow. However, a sheet steel wall has unobstructed columns of air on both sides of the insulation because the V-ribs on the inner liner and the corrugations on the exterior cladding do not permit the insulation to conform exactly to the wall surfaces (Figure 2). As a result of these air columns, a sheet steel wall can have significantly less resistance to convective airflow than a wall that is completely filled with insulation.

A complete air barrier, located within the wall in such a way as to disconnect the columns of air on the hot and cold surfaces of the wall cavity, has been shown to reduce the heat flow by convective airflow, Q_c, to a negligible value (Schuyler and Solvason 1983). Further examples of the effects of convective air flow and the effectiveness of air barriers are reported in this paper.

EXPERIMENTAL APPARATUS

The thermal transmission tests were performed in the Environmental Test Facility of the Division of Building Research, National Research Council of Canada (Figure 3). This facility conforms to ASTM Standard C236 (ASTM 1984) and consists of a cold side chamber (test temperatures as low as -40°C), a guarded hot box (test temperatures between 15°C and 25°C), and a room side chamber that performs as the thermal guard for the hot box. The hot box, with a 2.44 m square test area (5.946 m^2), is used to measure the heat flow through a 2.44 m square test wall. The wall to be tested is mounted in a well-insulated test frame. The test frame is mounted to the open side of the cold side chamber and the hot box is mounted on the room side surface of the test wall. The room side chamber is then mounted to the cold side chamber, surrounding the hot box.

For control purposes, the temperatures of the cold side chamber and the hot box are sensed with RTDs. The cold side chamber temperature is controlled, through electric reheat, by an industrial three-mode controller. Cooling in the cold side chamber is provided by refrigerant from a central refrigeration plant. The hot box temperature is also controlled, through a DC power supply and convection heater, by an industrial three-mode controller. No cooling, other than the heat loss through the test wall, is provided in the hot box.

The room side chamber acts as a thermal guard for the hot box by having its temperature controlled to maintain zero temperature difference across the walls of the hot box. The temperature difference across the hot box walls is sensed by an equal-area 64-junction thermopile. The room side chamber temperature is controlled, through electric reheat, by an industrial three-mode null voltage controller. Cooling in the room side chamber is provided by process chilled water.

The DC power supplied to the hot box convection heater is measured by a precision current shunt and voltage divider. Test temperatures are sensed with 30-gauge copper-constantan thermocouples. All power and temperature readings are taken with a computer-based data acquisition system. It is estimated that heat flow is measured by the hot box with an accuracy of 3% and that temperatures are measured with an accuracy of ±0.1°C.

TEST SPECIMEN

The test specimens used in the study (Figure 1) were 2.44 m square sheet steel walls constructed with four sections of 0.7 mm steel V-rib inner liner and three sections of 0.7 mm corrugated exterior cladding. The test walls were constructed by mounting the inner liner and exterior cladding to a wood frame, which was constructed from 19-mm thick pine lumber. The depth of the wood frame corresponded to the thickness of the wall (two wall thicknesses were tested). The test walls were insulated with 16.6 kg/m^3 glass-fiber friction-fit batt insulation, which had a reference thickness approximately equal to the thickness of the wall. The vertical joints of the inner liner and the perimeter of the inner liner were caulked and taped to the pine frame to prevent air leakage through the test specimen.

Three 2.39 m long by 6.4 mm thick angle-iron pieces (51 mm × 51 mm) were attached to the hot box side of the inner liner at the 1/4, 1/2, and 3/4 height points to simulate attachment to a structural frame. The angle-iron pieces were attached to the inner liner using 5.5 mm × 19 mm Type A hex-head self-tapping screws, which were centered between the V-ribs of the liner (approximately 152 mm apart).

For those test walls that contained Z-girts, the Z-girts were attached to the inner liner with the same screws and at the same location as the angle-iron pieces. The exterior cladding was attached to the Z-girts using 6.3 mm × 19 mm Type AB hex-head self-tapping screws located in each valley of the cladding (approximately 133 mm apart). Tests were conducted with one and three rows of Z-girts. Those with one row had the row located at the mid-height point.

TEST RESULTS

A program of 27 thermal transmission tests were run on 14 different configurations of sheet steel wall. Details of the test walls are listed in Table 1. The order of listing shown in Table 1 is for reporting purposes only; in general, the testing order was designed to minimize the number of changes between tests and is not the order shown in Table 1. All walls were tested at nominally 21°C hot side air temperature and -35°C cold side air temperature. All walls, except Wall 13, were also tested at nominally -7°C cold side air temperature. Tests with -7°C cold side air temperature are labeled with an 'A' in the tables listing the test results.

Variables in the test program included wall thickness (159 mm and 260 mm), total length of Z-girt (2.232 m and 6.696 m), thickness of Z-girt (1.6 mm and 2.7 mm), and Z-girt design. Most walls contained a complete air barrier to control convective airflow. The effectiveness of air barriers was checked by testing two walls without air barriers.

Resistance of Insulation (R_i)

The resistance of the base walls used in the test series, i.e., walls with cladding, insulation, and pine frame but without Z-girts, was determined in Tests 1 to 3. The 159 mm thick wall in Test 1 contained one layer of 152 mm reference thickness (172 mm relaxed thickness) insulation, while the 260 mm wall in Tests 2 and 3 contained two layers of 127 mm reference thickness (140 mm relaxed thickness) insulation. The wood support frame was either 159 mm or 260 mm thick depending on the wall being tested.

The walls in these three tests contained a 2.44 m square sheet of kraft paper to act as an air barrier. This paper sheet was taped to the edge of the pine frame on the cold side. In addition, the 260 mm wall of Test 3 contained a second sheet of kraft paper that was located between the two layers of insulation. It was also taped to the pine frame.

The resistance of the base wall, hereafter referred to as the resistance of the insulation, was calculated from the test results and the following expression for R_i derived from Equation 2

$$R_i = A_i \cdot (T_1 - T_2)/Q_i \qquad (2)$$

In this expression, A_i equals the test area of the hot box (5.946 m^2), T_1 and T_2 are the average hot and cold surface temperatures measured for the test, and Q_i equals the total heat flow measured for the test (= Q_t).

The results of Tests 1 to 3 are given in Table 2. The addition of the second air barrier to the 260 mm wall (Test 3) did not significantly change the measured resistance (<4%). Therefore, it can be concluded that one air barrier is sufficent to control convective airflow in sheet steel walls. The values measured for base wall resistance were used to determine Q_i in subsequent tests. An average of the values measured in Tests 2 and 3 was used as the resistance for the 260 mm walls.

Convective Airflow

The effect of convective airflow on the resistance of sheet steel walls was measured in Tests 4 and 5. Tests 4 and 5 measured the heat flow through test walls without air barriers and without Z-girts. The wall in Test 4 was 159 mm thick, whereas the wall in Test 5 was 260 mm thick. The insulation batts from Tests 1 and 2 were used in these tests.

Table 3 compares the resistance measured for these walls without air barriers with the resistance measured for similar walls with full air barriers (Tests 1 to 3). The resistance of the walls without air barriers is less than half the resistance of the walls with air barriers at a 55 K temperature difference. A comparison of the resistances measured at a 27 K temperature difference shows that the difference is less but still quite significant (25% for the 159 mm wall and 41% for the 260 mm wall).

The trend of lower resistance with increasing temperature difference indicates that convective airflow is occurring in the walls without air barriers. It is apparent from these test results that, in those walls with unobstructed and connected vertical air passages on the warm and cold sides of a wall, convective airflow can exist and this convective airflow can transfer a significant quantity of heat through the wall. The addition of a simple air barrier to separate the columns of air is sufficent to eliminate convective airflow. Elimination of one or the other air columns should also eliminate convective airflow. One way to accomplish this would be to use a flat, rather than a V-rib, inner liner, which would allow the insulation to conform exactly to the surface of the inner liner.

Z-Girt Thermal Conductivity (k_z)

The thermal conductivity of solid Z-girts was determined from Tests 6 to 8. The walls in these tests contained one row of three solid Z-girts with a total length of 2.232 m. The thickness of the walls in Tests 6 and 7 was 159 mm, and the thickness of the wall in Test 8 was 260 mm. The thickness of Z-girts in Tests 6 and 8 was 1.6 mm and the thickness of Z-girt in Test 7 was 2.7 mm.

All Z-girts were attached at the mid-height point as described in the section, "Test Specimen". The insulation batts from Test 1 were used in Tests 6 and 7, and the batts from Test 2 were used in Test 8. An air barrier, similar to that in Test 1, was installed in the walls for Tests 6 and 7, and two air barriers, similar to those in Test 3, were installed in the wall for Test 8.

The thermal conductivity of the Z-girts can be determined from the following expression for k_z:

$$k_z = Q_z \cdot x_z / (A_z \cdot (T_a - T_b)) \tag{7}$$

The heat flow through the Z-girts, Q_z, was determined from the difference between the total heat flow measured through the test wall, Q_t, and the heat flow through the insulation, Q_i. Q_i was determined from Equation 2, with R_i determined from Tests 1 to 3. The area of the Z-girt heat transfer path, A_z, was the product of w_z and h_z, the width and height of the heat transfer area of the Z-girts (physically the length and thickness of the Z-girt). Twelve pairs of thermocouples were taped at various points along the width of the Z-girts (Figure 4) to measure the temperature difference (T_a-T_b) across a measured depth of Z-girt (x_z). The distance between the paired thermocouples was 102±1 mm in Tests 6 and 7 and 178±1 mm in Test 8.

The average value determined for the thermal conductivity of the Z-girts in Tests 6 to 8 was 68 W/(m•K) (Table 4). This value differs by 50% from the ASHRAE (1985) tabulated value for 'mild' steel - 45.3 W/(m•K). The carbon content of the Z-girts used in these tests was determined to be 0.07%**, and the thermal conductivity of steel at this carbon content is reported to be between 60 and 65 W/(m•K) (Smithells 1975), a value very close to that measured for the Z-girts in these tests. The Z-girts were galvanized with a total thickness of zinc of 0.05 mm. If the heat flow through the zinc, with a thermal conductivity of 110 W/(m•K), is taken into account, the thermal conductivity of the steel will be about 3% less than that measured for the Z-girt.

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Resistance Between Z-girt and Surface of Wall

The resistance between a Z-girt and the faces of a wall cannot be easily determined analytically. However, the ratio of this resistance to the height of heat transfer area can be determined by experiment for the connection between the inner liner and Z-girt, r_1/h_1, and between the Z-girt and exterior cladding, r_2/h_2. Data from Tests 6 to 8 were used to determine values of r_1/h_1 and r_2/h_2. The walls in these tests contained one row of Z-girts and were described in the previous section, "Z-Girt Thermal Conductivity".

Experimentally determined values of temperature difference and heat flux were used to calculate r_1/h_1 and r_2/h_2 using Equations 6a and 6b, which are repeated here for convenience

$$r_1/h_1 = w_z \cdot (T_1 - T_{z_1})/Q_z \tag{6a}$$

$$r_2/h_2 = w_z \cdot (T_{z_2} - T_2)/Q_z \tag{6b}$$

The width of the Z-girt heat flow path, w_z, was determined by measurement. The temperatures of the hot and cold surfaces of the test wall, T_1 and T_2, and of the hot and cold edge of the Z-girt, T_{z_1} and T_{z_2}, were determined by measurement with thermocouples. T_{z_1} and T_{z_2} are the temperatures occurring at the inside of the bends in the Z-girt (see Figures 5 and 6). The heat flow through the Z-girt, Q_z, was determined as noted above (in the section "Z-Girt Thermal Conductivity").

Table 5 lists the values of r_1/h_1 and r_2/h_2 determined from Tests 6 to 8 for solid Z-girts and the inner liner and exterior cladding used in these tests. Table 5A also lists measured and calculated values of r_z/h_z for the three Z-girts tested. The measured values of r_z/h_z compare favorably with the calculated values, indicating that the temperatures and heat fluxes measured in the tests are correct. The resistance of the Z-girt, r_z, was calculated from the dimensions of the Z-girt heat flow path and the measured Z-girt thermal conductivity, k_z. Figures 5 and 6 show the dimensions of the Z-girts used in Tests 6 to 8 and the calculation of Z-girt resistance.

The values of r_1/h_1 tabulated in Table 5A indicate that the resistance between the Z-girt and inner liner is about 60% of that between the Z-girt and exterior cladding. The values also indicate that the total effective resistance between the Z-girt and the faces of the wall is of the same order of magnitude as the resistance of the Z-girt. The exact ratio will depend on the resistance of the Z-girt. However, these values do indicate that efforts directed at reducing Z-girt heat flow should be directed at the resistance between the Z-girt and the wall faces as well as at the resistance of the Z-girt alone.

Tests 9 to 11 were used to check the accuracy of prediction of Z-girt heat flow, which could be obtained with the experimentally determined values of r_1/h_1 and r_2/h_2 and calculated values of r_z/h_z. These tests were similar to Tests 6 to 8 but differed in that each test wall had three rows of Z-girts rather than one row. The measured values of r_1/h_1 and r_2/h_2, along with the calculated values of r_z/h_z, were used to calculate the Z-girt heat flow.

Table 6 compares measured and calculated values of Z-girt heat flow. Heat flows calculated from the experimentally determined values of r_1/h_1 and r_2/h_2 are within 10% of measured Z-girt heat flow. The average values of r_1/h_1 and r_2/h_2 that were determined from these tests can therefore be used to calculate the heat flow through solid Z-girts with an error of no more than 10%.

Variations in Z-Girt Thermal Design

Tests 6 to 8 (Table 5) show that the heat flow through the Z-girt, Q_z, is a large percentage of the heat flow through a sheet steel wall. Typically, Z-girts are installed every 2.4 m in a building (as in Tests 6 to 8) and these tests show that the heat flow through the Z-girts can be as much as 35% of the heat flow through the wall.

Tests 12 and 13 were run to determine whether contact resistance would be increased (and heat flow through the Z-girt decreased) if the number of screws fastening the exterior cladding to the Z-girts were reduced. These tests were respectively equivalent to Tests 9 and 11 in that the same wall thickness, Z-girts, insulation, and air barriers were used. However, they differ from Tests 9 and 11 in that half the screws fastening the exterior cladding to the Z-girt were removed.

Table 7A compares the heat flows measured for Tests 12 and 13 with the heat flows measured for Tests 9 and 11. The removal of half the screws from the exterior cladding produced only a marginal reduction in the heat flow through the Z-girt. It can be assumed, therefore, that the removal of the screws had little effect on the contact resistance. This is not an unexpected finding since the strength of the Z-girt and the exterior cladding is sufficent to maintain good thermal contact even with a screw at only every second contact point. It can be concluded that the heat flow through the Z-girt will not be significantly reduced by reducing the number of fasteners by 50%. Further reductions in the number of screws will eventually produce an effect on the Z-girt heat flow, but this will also obviously affect the structural integrity of the wall.

Test 14 was run to measure the heat flow through a thermally improved Z-girt. This test was equivalent to Test 9 in that the same wall thickness, insulation, and air barriers were used. However, the three rows of solid Z-girts in Test 9 were replaced by three rows of thermal Z-girts in Test 14. The thermal performance of the Z-girts was improved by removing metal from the Z-girt, thus increasing the length of the heat flow path and reducing the heat flow area. The profile of the thermal Z-girts is shown in Figure 7.

Table 7B compares the normalized Z-girt heat flow measured in Test 14 with the normalized heat flow measured in Test 9. The heat flow through the thermal Z-girt is 61% less than the heat flow through the solid Z-girt. The corresponding reduction in heat flow through a sheet steel wall will depend on the wall design, but for a wall with Z-girts on 2.4 m centers it will be on the order of 20%.

CONCLUSION

Thermal transmission tests were run on a number of different configurations of sheet steel walls. In general, the tests showed that the thermal performance of sheet steel walls can be seriously affected by the heat transferred by convective airflow and by the heat transferred through the Z-girts. The following specific conclusions can be drawn from the results of the tests:

1. Heat transfer by convective airflow can reduce the effective resistance of a sheet steel wall with fibrous insulation by as much as 50%. It can be virtually eliminated by a complete air barrier properly located in the wall.

2. For the sheet steel walls tested in this study, the heat flow through the Z-girts was as much as 35% of the total heat flow through the test walls. It is believed that this figure is representative of sheet steel walls in general.

3. The thermal conductivity of steel Z-girts measured 33% higher (68 W/(m•K) vs 45.3 W/(m•K)) than the ASHRAE book value for mild steel. Z-girt heat flow calculated using the "book value" would be in error by 33%.

4. A parameter that is useful as a measure of the effective resistance between Z-grits and the faces of a sheet steel wall can be determined from thermal transmission tests. This parameter indicated that the effective resistance between the Z-girt and faces of the wall was of the same order of magnitude as that of the Z-girt. It predicted the heat transfer through the Z-girts used in this study with an accuracy of 10%.

5. Removing half of the fasteners holding the exterior cladding to the Z-girt did not significantly reduce the heat flow through the Z-girt. However, the heat transfer through the Z-girt can be significantly reduced (61%) by improving the thermal design of the Z-girt.

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TABLE 1

Details of Test Wall Configurations

Wall No.	Wall Thickness mm	Air Barriers	Z-Girts Type	Z-Girts Height mm	Z-Girts Width m
1	159	YES	no Z-girts installed		
2	260	YES	no Z-girts installed		
3	260	YES	no Z-girts installed		
4	159	NO	no Z-girts installed		
5	260	NO	no Z-girts installed		
6	159	YES	1 * S	1.6	2.232
7	159	YES	1 * S	2.7	2.232
8	260	YES	1 * S	1.6	2.232
9	159	YES	3 * S	1.6	6.696
10	159	YES	3 * S	2.7	6.696
11	260	YES	3 * S	1.6	6.696
12	159	YES	3 * S'	1.6	6.696
13	260	YES	3 * S'	1.6	6.696
14	159	YES	3 * T	1.6	6.783

NOTE: The legend for 'Z-Girts - Type' is as follows:
1 * S - one row of solid Z-girts
3 * S - three rows of solid Z-girts
3 * S' - three rows of solid Z-girts mounted to the exterior cladding with half the regular number of screws
3 * T - three rows of thermal Z-girts

TABLE 2

Resistance of Base Walls (R_i) Used in Sheet Steel Wall Tests

Test	Thickness (mm)	T_1 (°C)	T_2 (°C)	$Q_i(=Q_t)$ (W)	R_i ($m^2 \cdot K/W$)
1	159	19.7	-34.8	77.2	4.20
1A		20.3	-7.2	39.7	4.12
2	260	20.0	-35.3	53.8	6.11
2A		20.8	-6.9	25.9	6.36
3	260	19.9	-34.8	51.4	6.33
3A		20.8	-7.0	26.5	6.24

NOTE: Tests 1 and 2 had one air barrier, while Test 3 had two air barriers.

TABLE 3

Measured Resistance of Sheet Steel Walls with and without Air Barriers

Wall Thickness (mm)	Wall without air barrier					Wall with air barrier	
	Test	T_1 (°C)	T_2 (°C)	Q_t (W)	R_w ($m^2 \cdot K/W$)	Test	R_w ($m^2 \cdot K/W$)
159	4	18.1	-34.7	161.2	1.95	1	4.20
	4A	20.2	-7.0	52.4	3.09	1A	4.12
260	5	17.9	-35.0	146.2	2.15	2 & 3	6.22
	5A	20.2	-6.9	43.2	3.73	2A & 3A	6.30

TABLE 4

Measured Thermal Conductivity of Solid Z-girts

Test	T_1 (°C)	T_2 (°C)	Q_t (W)	Q_i (W)	Q_z (W)	l_z (mm)	h_z (mm)	T_a-T_b (K)	k_z ($W/(m \cdot K)$)
6	19.3	-34.9	110.5	76.7	33.8	159	1.6	13.5	71.5
6A	20.1	-7.0	55.7	39.1	16.6	159	1.6	6.8	69.7
7	19.2	-34.8	118.7	76.4	42.3	159	2.7	10.7	66.9
7A	20.1	-7.1	60.4	39.3	21.1	159	2.7	5.4	66.1
8	19.7	-35.1	78.4	52.4	26.0	260	1.6	18.8	68.9
8A	20.3	-7.1	37.9	25.9	12.0	260	1.6	9.2	65.0
								Average k_z =	68.0

NOTE: Z-girts in these tests were 2.232 m long, i.e. w_z = 2.232 m.

TABLE 5

Measured Values of Contact Resistance for Various Z-Girts

Test	T_1 (°C)	T_{z_1} (°C)	T_{z_2} (°C)	T_2 (°C)	Q_t (W)	Q_i (W)	Q_z (W)	r_1/h_1 (K/W)	r_2/h_2 (K/W)	Meas. r_z/h_z (K/W)	Calc. r_z/h_z (K/W)
6	19.3	7.6	-14.9	-34.9	110.5	76.7	33.8	0.77	1.32	1.49	1.56
6A	20.1	14.1	3.0	-7.0	55.7	39.1	16.6	0.81	1.34	1.49	
7	19.2	5.2	-12.5	-34.8	118.7	76.4	42.3	0.74	1.18	0.93	0.93
7A	20.1	12.9	4.0	-7.1	60.4	39.3	21.1	0.76	1.17	0.94	
8	19.7	9.8	-18.1	-35.1	78.4	52.4	26.0	0.85	1.46	2.40	2.50
8A	20.3	15.2	1.4	-7.1	38.0	25.9	12.1	0.94	1.57	2.55	
							Average r_n/h_n	0.81	1.34		

R_i(159 mm) = 4.20 4.12 ; h_z(6 & 8) = 0.0016 ; r_z(159 mm) = 0.0025
R_i(260 mm) = 6.22 6.30 ; h_z(7) = 0.0027 ; r_z(260 mm) = 0.0040

TABLE 6

Calculated Z-Girt Heat Flow for Three-Row Z-Girt Tests

Test	T_1 (°C)	T_2 (°C)	Q_t (W)	Q_i (W)	Q_z (W)	Q_z' (W)	$Q_z - Q_z'$ (W)	% diff.
9	18.2	-34.6	173.9	74.8	99.1	95.3	3.8	3.8
9A	19.2	-6.8	86.3	37.5	48.8	46.9	1.9	3.9
10	17.2	-34.6	199.4	73.3	126.1	112.6	13.5	10.7
10A	19.4	-6.8	101.1	37.8	63.3	57.0	6.3	10.0
11	18.7	-34.3	128.7	50.7	78.0	76.3	1.7	2.2
11A	20.1	-6.8	64.4	25.4	39.0	38.7	0.3	0.8

NOTE: Q_z = measured Z-girt heat flow
Q_z' = calculated Z-girt heat flow

TABLE 7

Measured Heat Flow

Test	T_1 (°C)	T_2 (°C)	Q_t (W)	Q_i (W)	Q_z (W)	w_z (m)	$Q_z/w_z/\Delta T$ (W/(m•K))	Test	Q_z (W)	$Q_z/w_z/\Delta T$ (W/(m•K))
				A. Through Z-Girts With Screws Removed						
12	18.5	-34.8	173.8	75.5	98.3	6.696	0.28	9	99.1	0.28
12A	19.5	-6.8	84.9	37.2	47.7	6.696	0.27	9A	48.8	0.28
13	18.9	-34.6	126.6	51.1	75.5	6.696	0.21	11	78.0	0.22
				B. Through Thermal Z-Girts						
14	18.9	-34.6	107.5	75.7	31.8	6.783	0.09	9	99.1	0.28
14A	20.1	-6.9	56.1	38.2	17.9	6.783	0.10	9A	48.8	0.28

NOTE: Test 13 run at one temperature difference only.

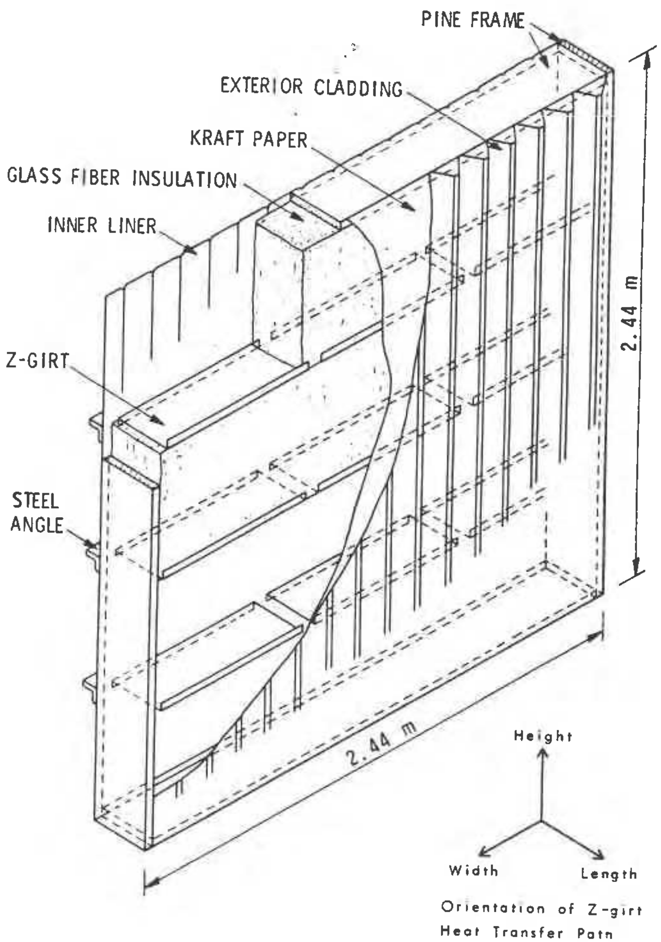


Figure 1. Details of typical sheet steel test wall

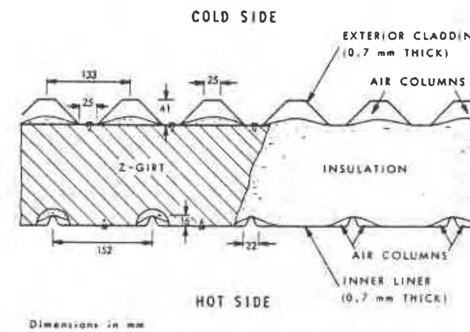


Figure 2. Top view of inner liner and exterior cladding, and conformance of insulation to profile of liner and cladding

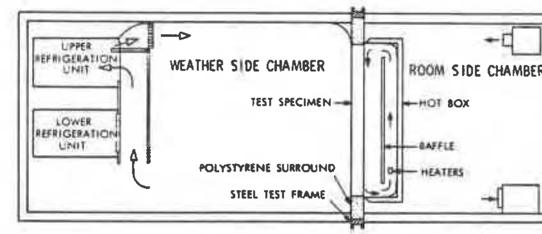


Figure 3. Schematic of IRC/NRCC large-scale environmental test facility

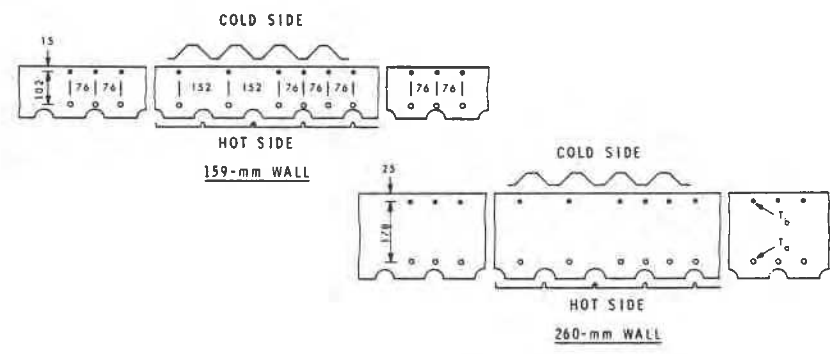
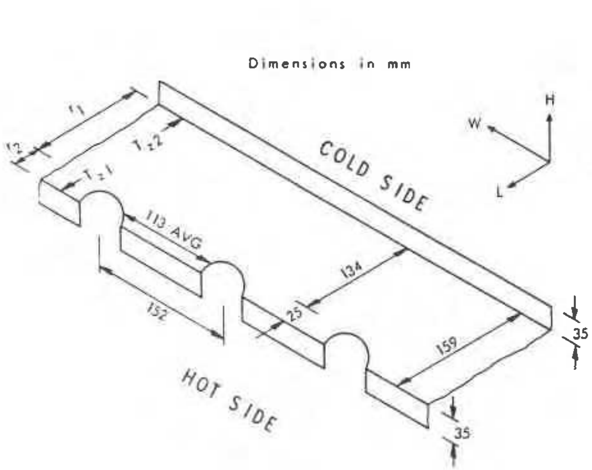


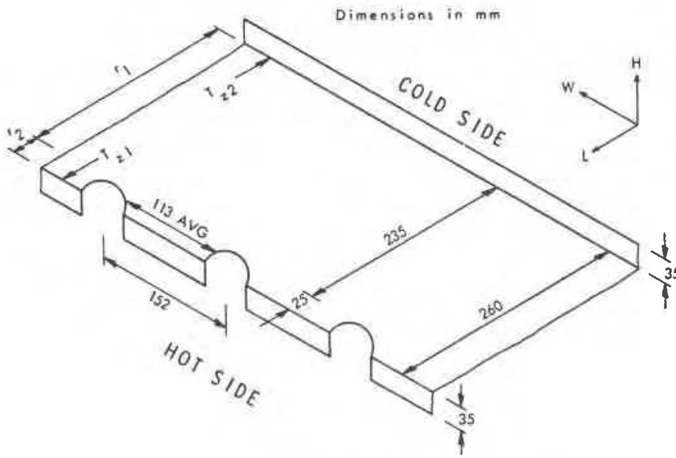
Figure 4. Location of thermocouples on Z-girts for determination of Z-girt thermal conductivity



CALCULATION OF r_z FOR 159-mm SOLID Z-GIRTS

$$\begin{aligned} r_z &= r_1 + r_2 \\ &= L_1/k_z + W_1/W_2 \cdot L_2/k_z \\ &= (L_1 + W_1/W_2 \cdot L_2)/k_z \\ &= (0.134 + 0.152/0.113 \cdot 0.025)/68 \\ &= 0.0025\ m^2 \cdot K/W \end{aligned}$$

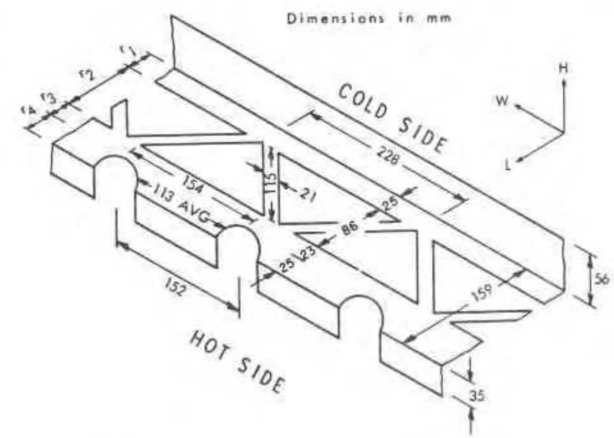
Figure 5. Profile of 159-mm Z-girts and calculation of thermal resistance



CALCULATION OF r_z FOR 260-mm SOLID Z-GIRTS

$$\begin{aligned} r_z &= r_1 + r_2 \\ &= L_1/k_z + W_1/W_2 \cdot L_2/k_z \\ &= (L_1 + W_1/W_2 \cdot L_2)/k_z \\ &= (0.235 + 0.152/0.113 \cdot 0.025)/68 \\ &= 0.0040\ m^2 \cdot K/W \end{aligned}$$

Figure 6. Profile of 260-mm solid Z-girts and calculation of thermal resistance



CALCULATION OF r_z FOR THERMAL Z-GIRTS

$$\begin{aligned} r_z &= r_1 + r_2 + r_3 + r_4 \\ &= L_1/k_z + W_1/W_2 \cdot L_2/k_z + L_3/k_z + W_4/W_3 \cdot L_4/k_z \\ &= ((L_1 + L_3) + W_1/W_2 \cdot L_2 + W_4/W_3 \cdot L_4)/k_z \\ &= (0.048 + 0.228/0.042 \cdot 0.115 + 0.152/0.113 \cdot 0.025)/68 \\ &= 0.0104\ m^2 \cdot K/W \end{aligned}$$

Figure 7. Profile of 159-mm thermal Z-girts and calculation of thermal resistance

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