THERMAL CONDUCTIVITY OF ALUMINIUM FOIL

By

ROBERT M. KELLY

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Signature of Author

Professor in Charge of Research
PREFACE

The purpose of this thesis was to investigate the insulation properties of aluminium foil. The use of aluminium foil as a heat insulator, though used in the British Isles and on the continent particularly in Germany where it was first developed commercially, is comparatively unknown in this country.

This is due to two principal reasons. First, a psychological one, namely the natural inertia of the users of heat insulating materials to adopt any new material which differs radically both in action and appearance to the common insulating materials on the market.

The second reason, a practical one is that there is little knowledge of its insulation value in this country.

 Practically all of the data on aluminium foil as insulation has heretofore come almost entirely from German sources. This is undoubtedly an additional reason why insulation users shy at the use of aluminium foil.
To meet this condition this thesis was undertaken at the suggestion of the Alfol Insulation Company, Inc., which holds the American rights to the original German patents. The work was carried out at the Applied Heat Laboratory at M.I.T. by the writer under the guidance of Professor Gordon B. Wilkes.

In conclusion I would like to express my appreciation to Professor Wilkes whose practical direction of the work did much to expedite it and bring out the significant importance of the material, and to Mr. O. K. Bates and T. C. Patton also of the Applied Heat Department for their many timely suggestions.

To Mr. Max Breitung, President of the Alfol Company, Mr. Putnam, treasurer of the Company, and Mr. F. C. Clarke, vice-president of the Company, I am indebted. They maintained the best possible cooperation in the work, supplying the foil used in the tests and all the data of previous work done on the foil which otherwise would have been very difficult to obtain.

Cambridge, Mass.
May 1931
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>PART I</th>
<th>General Theory</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Preliminary Remarks</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Methods of Heat Transfer</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Use of Air Layers as Insulation</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Use of Air Layers in Connection with Aluminium Foil</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PART II</th>
<th>Tests</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Description of Tests Made With Aluminium Foil</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Theory of Conduction</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Typical Data Sheet on 6&quot; Pipe Runs</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Results of Tests on 6&quot; Pipe</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Description of Tests on 4&quot; Pipe</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Typical Data Sheet on 4&quot; pipe Runs</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Results of Tests on 4&quot; pipe</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Plate Test</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Bare Pipe Loss</td>
<td>36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part III</th>
<th>Discussion</th>
<th>37</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conclusions</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>Recommendations</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>Bibliography</td>
<td>47</td>
</tr>
</tbody>
</table>
PART I

GENERAL THEORY

The phenomenon of Heat is one which has been studied from the very earliest times. It is unquestionably one of the oldest of the physical sciences. It has been used for metallurgical purposes since antiquity. So too is the study of heat flow and insulation though undoubtedly in a very crude form. The main reason for insulation until very recent times was more to attain higher temperatures rather than to use insulation for heat economy. Fuel, until the advent of the World War was always cheap and in sufficient quantity. Since then, however, fuel costs have gone up considerably. This has put the engineer on the track of conserving the Btu's intrusted to him. To offset in some degree the rising fuel costs and growing scarcity, he has devised more efficient power plants and heat machines and has come to the realization that proper insulation is a not insignificant aid in cutting down his fuel costs as well as aiding in the more efficient operation of his machines.

While all this is concerned with the insulation of pipe surfaces, furnaces, etc., from the loss of heat outward, notice should also be taken of
insulation of cold bodies from the flow of heat in from hotter conditions outside or refrigeration. This field has had a considerable growth in the last ten years.

The laws of heat flow are few and have been investigated for considerably more than a century. Heat flows from the hot body to the cold body, that is, there must be a temperature differential. Some are of the opinion that the cold body also transfers heat back to the hot body though in smaller amount. This in no way invalidates our assumption, however, since there is in any case a net heat motion from the hot body to the cold body until the cold body attains the temperature of the hot body. No attempt will be made here to clear up or take sides with any of the controversial theories of heat flow since it is not pertinent to the subject at hand.

**METHODS OF HEAT TRANSFER**

Heat may be transferred in any one of three ways:

1. By conduction
2. By convection

By conduction we mean the heat transferred by contact of adjacent particles of matter from the hot body to the cold body. Conduction is made evident when we thrust a poker in a hot fire. The heat travels
through the solid poker by virtue of the fact that the metal of which it is composed is a good conductor of heat. Hence, the poker will get appreciably hotter even though the hand may be a foot away from the hot body, e.g., the fire.

By convection we imply the motion of fluids under the combined action of gravity and temperature difference between the fluid particles in different regions between the hot body and the cold body. Almost all substances expand when heated, hence, increase in specific volume. Thus if air, for example, is between the hot body and the cold body the air in contact with the hot body will get heated and will be displaced by the heavier cooler air in contact with the cold body. The hot air in coming in contact with the cold body will give up its acquired heat by conduction.

Hence, the action of convection currents is to move the hot body closer to the cold body insofar as the transfer of heat goes. However, convection is not thought of as playing any considerable part in the transfer of heat in spaces of less than one and one-half inches in the case of small temperature differences.

We now come to the third cause of heat
transfer namely radiation. This very interesting method of transfer of energy occurs without the heating of the medium through which it passes, or to avoid a controversial point the heat arrives at the same intensity that it left. Whether we accept the undulatory theory of wave propagation of classical mechanics as enunciated by Maxwell or the quantum hypothesis as put forth by Planck is beside the point in this thesis. It should be remarked, however, that a combination of Planck's and Maxwell's theories, namely, waves radiated as quanta appears to offer at least a working hypothesis to explain physical phenomena. All bodies radiating energy are referred to the "black body" which by definition is a prefectly radiating body. Lamp black very nearly approaches this condition, hence, the name "black body."

Stefan's Law expresses the net energy radiated by a body as:

\[ E = S(T_1^4 - T_0^4) \]

where \( E \) is in watts /sq.cu.

\( T_1 \) - absolute temperature °C of hot surface

\( T_0 \) - absolute Temperature °C of surroundings

\( S \) - a constant depending on the body for black body \( S = 5.7 \times 10^{-12} \)
The ratio of the value of \( S \) of a body to that of the value of \( S_0 \) for a black body is known as the emissivity.

\[
\frac{S}{S_0} = e
\]

It has been found experimentally that most ordinary insulators approach black body conditions and that smooth shiny metallic surfaces are much removed from this condition as is seen from the following.

A table of emissivities is given below:

<table>
<thead>
<tr>
<th>Material</th>
<th>Emissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical black body</td>
<td>1.00</td>
</tr>
<tr>
<td>Paper, wood, quartz, clay,</td>
<td></td>
</tr>
<tr>
<td>porcelain, glass, etc.</td>
<td>0.85 to 0.95</td>
</tr>
<tr>
<td>Turned cast iron</td>
<td>0.44</td>
</tr>
<tr>
<td>Polished sheet iron</td>
<td>0.25</td>
</tr>
<tr>
<td>Cast aluminium</td>
<td>0.07</td>
</tr>
<tr>
<td>Polished Aluminium</td>
<td>0.05</td>
</tr>
<tr>
<td>Polished Copper</td>
<td>0.04</td>
</tr>
<tr>
<td>Polished Silver</td>
<td>0.04</td>
</tr>
</tbody>
</table>

It is now of interest to discuss the interaction of conduction, convection, and radiation, in so far as they affect the thermal conductivity of an insulator.

Still air is the best insulator known exclusive of the radiation factor. Although other gases may manifest an even lower conductivity they are relatively rare and obviously out of the question as far as practicability is concerned.

**USE OF AIR LAYERS AS INSULATION**

The obvious method of insulating a hot body
would be to enclose it by a dead air space. A metallic jacket could be used to cover the whole and could be at a distance of 2" from the hot body. Such an arrangement would be excellent in an ideal case; however, it has serious drawbacks as we shall try to point out.

First there would undoubtedly be considerable convection loss due to the large temperature differential between the hot body and the metal jacket which would also be reflected in a large radiation loss.

Secondly, it would be difficult to prevent leaks, which would result in additional heat transfer. We shall now investigate the effect of interposing additional air spaces or subdividing the original 2" space.

If we have such an arrangement, the net radiation of two surfaces will be given by the following:

$$\text{net radiation} = S(T_1^4 - T_0^4) \left( \frac{1}{e_1} + \frac{1}{e_2 - 1} \right)$$

where $e_1$ and $e_2$ are the emission coefficients of the two surfaces.

It is readily seen that if $e_1$, $e_2$, are small as is met with in polished metal, the net
radiation will be cut down considerably. It has been found experimentally that the interposition of one surface between the hot body and the cold body cut down the radiation to \( \frac{1}{2} \), 2 sheets \( \frac{1}{3} \), 3 sheets \( \frac{1}{4} \), etc.

We shall now see how convection is affected. The temperature differential between layers will be reduced so much so that if four layers are equidistantly spaced and the hot body is in the neighborhood of 500°F, the convection between layers may be safely neglected.

As far as leaks are concerned the transfer could only affect the top layers and the air leaking in would not come into direct contact with the hot body. Hence, leaks though important are certainly of no such significance as with no subdivision of the air space.

All this discussion has assumed that the intervening surfaces are not in thermal contact with each other or better are separated by excellent insulating materials and the supported area is small compared to the total area enclosing the hot body.

Such an arrangement should result in excellent insulation and in the hypothetical case with maximum subdivision the resultant conductivity of heat would be a minimum. Hence the coefficient of conductivity
of this setup considered as a material would be less than any solid material obtainable.

The first man who recognized the value of this idea and tried to apply it practically as heat insulation was the Frenchman Péclet, as long ago as 1850.

It found no practical application, however, because of the cost of the many sheet jackets and the difficulty of application in the case of the various pipe diameters.

Another difficulty was experienced in the varying amount of the thermal expansion of the various sheets due to the temperature gradient in passing from the hot surface to the outer shell. This resulted in loosening of the joints and the resultant introduction of leaks.

The idea was then taken under consideration by Professor Ernest Schmidt of Danzig. He departed considerably from Péclet's method as will be shown in the following lines, although the basic principles were still operative. Dr. Dychenhoff an associate of Schmidt got away from the concentric shell idea by using aluminium foil paper thin of 0".00028 to 0".0005 in
thickness crumpled and laid loosely on each other and in contact. The reader is here referred to the photographs toward the end of the thesis.

He laid the crumpled sheets of aluminium foil on top of one another until the desired thickness was attained. It may be stated that when a sheet of foil is thus crumpled it has an average thickness of $\frac{3}{8}"$. Hence five or six layers may be placed in a 2" space. After applying the aluminium foil, it was covered by a protective sheet of aluminium which was supported by small blocks of solid insulating material between the hot surface and the outside sheathing. In the case of pipe insulation, fabricated sheet iron supports were used. The outside sheathing was fastened to the supports by soldering or other means and was of such gage to provide sufficient mechanical security against damage - about 27 gage (0.014).

It would be appropriate now to discuss the reasons why crumpled aluminium foil has the
heat insulating properties that it possesses despite the fact that the crumpled sheets are in contact with one another.

It is quite obvious that if sheets of smooth foil were piled on top of each other there would be virtually no insulation. This is because aluminium is one of the best conductors of heat and the individual sheets would have very good thermal contact with one another. Also the air space would be cut down to almost nothing.

The effect of laying crumpled sheets of foil on top of each other is to provide air spaces and reduce the contact of the layers of the foil to each other.

This can be seen from the photographs towards the end of the thesis. The drawings below will, however, give a rather idealized picture of the principle.
The effect of direct conduction by the aluminium is reduced to a minimum not only by the poor thermal contact but also by the thinness of the foil. The crumpling further subdivides the air spaces so that convection can be safely considered to be negligible.

According to H. Nieman (0".00028) thick foil 16 cu. (4") long and 1 cu. (3/8") wide only conducts (122.5 millionth Kcal/hr/°C (270 millionth Btu one hour 1°F). He also found that at refrigerating temperatures the plain foil with nonconducting separators had about the same value as crumpled foil of the same thickness with the individual layers crumpled to 10 millimeters (3/8") in width.

Nieman also observed that the foil crumpled to 8-10 millimeters in thickness afforded the best insulation value at refrigerating temperatures. This corresponds to five to six layers of foil in a two inch space.
Description of tests made with Aluminium Foil.

The foil used in tests was of two types:

1. 0".00028 aluminium foil 16" wide manufactured in Germany and embossed with a diamond shaped design, the significance of which will be explained further along.

2. 0".001 aluminium foil 16" wide manufactured by the Aluminium Company of America.

The tests made on the 0".00028 foil, known by the trade name of Alfol, were by using the crumpled method as mentioned in the previous pages. In the second method the 0".001 foil was used smooth and the various layers separated by strips of flexible insulation.

All the tests both with the crumpled and straight foil were made by the pipe cover method. In addition a run was made on the standard plate tester with the crumpled foil.

A 6" inside diameter pipe was first used with one inch of insulation. The pipe was 34" long and had an outside diameter of 6"5/8.

Tests were made with 2 layers of crumpled
foil in the one inch space at three different watt inputs. The three layers were used at one imput. This was followed by putting on another layer of crumpled foil in the same space as before, making four layers of foil to the inch. Three runs of different watt input were made with this setup. Then another layer was put on making five layers in all and at one imput.

Tests were then made on a four inch inside diameter pipe with a two inch space of insulation. Both smooth foil (0.001) and crumpled foil were used. The crumpled foil was applied in much the same manner as the two inch pipe except that runs were made with three to eight layers in a two inch space. The test with the smooth foil was made as mentioned before with strips of insulation separating the various layers.

After the tests of the insulation on the four inch pipe a run was made to determine the bare pipe loss of that pipe. At that time a run was made on the plate tests with six layers of crumpled foil in a two inch space.

This describes in general the tests made. A more detailed discussion will follow in connection with each test.
When the matter came up as to how the tests on aluminium foil were to be made, it was first decided to conduct the various runs on the standard plate tester used in the Laboratory of Applied Heat. It was soon evident, however, that the tests would take too long using the plate tester, and since it had to be used for other purposes at times—for industrial tests of other insulating materials as well as for laboratory instruction in Heat Measurements, an alternative method was adopted. This was to make the tests by the pipe cover method and to make one run on the plate tester. The pipe cover method, it was recognized, would not give the same accuracy as the standard plate method, but would be sufficiently accurate for the purpose and since the pipe method did not involve the time consuming balancing that is met with in the plate method, more runs could be made than otherwise. Also the relative values would be the same in both cases and the final plate test could be used to estimate the actual values of thermal conductivity more accurately.

There were several electrically heated pipes available in the Applied Heat Laboratory. A standard 6" pipe was first selected, having a maximum
watt input of 550 watts at 110 volts A.C. The pipe was suspended by a wire at either end and secured to an iron pipe standard as is shown in accompanying drawing. It was decided to put one inch of aluminium foil on the pipe. Instead, however, of putting the one inch thickness of aluminium foil over the ends of the pipe as well as the pipe surface proper, two blocks of two inch thick Carey Alumino Hi-Temp insulation were used - cut to the proper shape and secured by guy wires as shown in drawing. The aluminium foil was then wrapped around the pipe surface. The value of the thermal conductivity of this material was known at different temperatures, it having been tested in the laboratory of Applied Heat and hence the losses through the ends could be calculated. The losses converted to watts could be subtracted from the total watt input to obtain the watts converted to heat passing directly through the aluminium foil insulation around the pipe proper. A curve showing the conductivity plotted against temperature of hot surface is given at the end of the thesis.

After the pipe was set up and the end blocks in place, holes were drilled diametrically opposite each other, half way up the pipe to accommodate the thermocouples for measuring the temperature of the hot surface. The thermocouples were of the copper
constantan type and had their hot junctions silver soldered and were put into the holes mentioned above, drilled with a No. 28 drill and about 3/16" deep. The junctions were then jammed tight by hammering in a short copper brad alongside the junction. The wires were then enclosed in asbestos sleeving and run along the surface of the pipe as is seen in drawing.

The crumpled foil was then wrapped around the pipe, each layer being independent and tied by string to hold it in place. The aluminium sheeting which was in three pieces was then put on, the end pieces of which lapped over the end blocks as can be seen by the drawing. The outside couples for measuring the surface temperature were likewise copper constantan and were placed half way up and diametrically opposite in between the laps of the center piece of aluminium sheeting. The wires were then run along the top guy wire and connected to the appropriate places.

All the cold junctions were run into glass tubes which were immersed in ice in a thermos bottle. The cold junction hence was kept at 32°F.

A Leeds and Northrop potentiometer indicator was used to measure the voltage generated between the hot and cold junctions of the thermocouples. The couples were standardized in the Applied Heat Laboratory under
the direction of Professor Wilkes and from the curve of millivolts plotted against temperature, the temperature corresponding to the millivolt reading of the potentiometer could be determined.

By means of switches the same potentiometer was used for the readings of all the four couples.

A thermometer set in close contact to the outer surface of one of the end blocks was used to obtain the outside temperature of the blocks.

The potentiometer was capable of being read to the nearest two hundredth millivolt.

The first run on the 6" pipe with one inch of insulation was made with two layers of crumpled foil. Since the two layers of foil as ordinarily crumpled would only take up $2 \times \frac{3}{8} = \frac{3}{4}"$ space, the foil was crumpled more in order to fill up the one inch space as much as possible. The foil was tied by means of string around it. The two end pieces of aluminium sheeting were then put on by lapping the ends about $\frac{1}{2}"$ on the circular end blocks and then tied by cord with a clove hitch to ensure as little leakage as possible. The middle piece of sheeting was then put on by lapping the edges about $\frac{1}{4}"$ over the ends of the outside sheets. The junctions for measuring the surface temperature were inserted half way up and between the laps of the
middle and outside sheeting. After this was completed and the couples/connected through switches to the then potentiometer, the power was/turned on for the runs.

For the six inch pipe three runs were made with different watt inputs in order to obtain the conductivity at different temperatures. Three watt inputs on this pipe were used, namely 100, 250, and 550 which gave nearly equally varying temperatures. The latter input, namely 550 watts was the maximum power possible, that is all the series resistance was cut out. The run was first made with an input of 100 watts, followed by 250 watts, and finally 550 watts.

It took a day to make one run. That is, the pipe temperatures would reach equilibrium in about twenty-four hours after a change was made in the power supplied. The power was put on about 4-5 o'clock in the afternoon and left on overnight. In the morning a reading would be taken about 9-10 o'clock. Again a reading was taken about 11-12 o'clock. About 2-3 o'clock another was taken, at which time the pipe would usually reach equilibrium. Equilibrium was judged to have been reached when after two hours no variation of pipe surface temperature was indicated by potentiometer or an oscillation about a mean of not more than ± .03 milli-volt which corresponded to a fraction of a degree
Fahrenheit. The averages of the readings over this period were made and from these the necessary data was obtained.

After the last run on the two layers in one inch was completed, the outside junctions were removed and the sheeting taken off. Then another layer of crumpled foil was wrapped around and the sheeting and outside junctions replaced. This time, however, only one run at 100 watts was made since the values at other watt inputs could be estimated from the values obtained from the two layer runs. For the four layers to the inch, the foil had to be compressed lightly by hand in order not to overfill the given space. Three runs were made with the four layers to the inch. When five layers were used, however, a considerable amount of compressing had to be resorted to in order to restrict the foil to the one inch space. This reflected in a higher value of conductivity than either the three or four layers to the inch arrangement.
THEORY OF CONDUCTION

The amount of heat per unit time conducted through a uniform place of material may be expressed as follows:

\[ q = \frac{KA(t_2-t_1)}{L} \]

where

- \( A \) = Area
- \( t_2 \) = temperature of hot surface
- \( t_1 \) = temperature of cold surface
- \( L \) = thickness of plate
- \( K \) = a constant for the particular material that is known as the coefficient of thermal conductivity

\( K_f = \text{Btu/hr/sq.ft./in/ } ^\circ\text{F} \)

For a cylinder of unit length, we have from (1)

\[ q = K\frac{\theta}{dr} \]

For differential arc of width \( dr \) and the temperature differential \( dt \) for both sides

or \( q \frac{dr}{r} = K\theta \ dt \)

Integrating between the limits \( r_2 \) and \( r_1 \) and \( t_2 \) and \( t_1 \) and substituting \( 2\pi \) for \( \theta \) we have
\[
q \int_{r_1}^{r_2} \frac{dr}{r} = K_2 \int_{t_1}^{t_2} dt
\]

since \( \int \frac{dr}{r} = \log r \) and \( \int dt = t \)

therefore \( q \log (r_2 - r_1) = K_2 \gamma (t_2 - t_1) \)

or \( q \log \frac{r_2}{r_1} = K_2 \gamma (t_2 - t_1) \)

and \( q = \frac{2 \pi K (t_2 - t_1)}{\log \frac{r_2}{r_1}} \)

mean area = \( \frac{2 \pi (r_2 - r_1)}{\log \frac{r_2}{r_1}} \)

mean radius = \( \frac{r_2 - r_1}{\log r_2} \frac{r_1}{r_2} \)

We will now apply this demonstration to a typical run on the six inch pipe in order to show how the value of the coefficient of conductivity was arrived at. The value of heat loss per unit area (\( H \)) will also be given. This will be worked out on the next page.

For 6" pipe

\[
\log \text{mean radius} = \frac{r_2 - r_1}{\log \frac{r_2}{r_1}} = \frac{4 \frac{5}{16} - 3 \frac{5}{16}}{0.2638} = 1 = 3.80
\]

\[
= \frac{4 \frac{5}{16}}{3 \frac{5}{16}}
\]
log mean area of insulation = \frac{3.8 \pi x 34}{144} = 5.65 \text{ sq.ft.}

log mean area of the two end blocks = 2 \left( \pi x \frac{3.80 + 2.80}{2} \right) = .965 \text{ sq.ft.}

watts \times 3.41 = \text{Btu/hr.}

Two Layers of Crumpled Aluminium Foil in one inch space

<table>
<thead>
<tr>
<th>Time</th>
<th>Pipe Surface Couples</th>
<th>Outside Casing Couples</th>
<th>Watts</th>
<th>Room Input Temp.</th>
<th>Temp. of Block Ends</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.00</td>
<td>5.36 5.52</td>
<td>1.91 2.08</td>
<td>109</td>
<td>25.0</td>
<td>37.0</td>
</tr>
<tr>
<td>9.30</td>
<td>5.39 5.55</td>
<td>1.91 2.08</td>
<td>112</td>
<td>25.0</td>
<td>37.0</td>
</tr>
<tr>
<td>9.50</td>
<td>5.42 5.60</td>
<td>1.90 2.08</td>
<td>112</td>
<td>25.0</td>
<td>37.0</td>
</tr>
<tr>
<td>12.30</td>
<td>5.56 5.76</td>
<td>1.95 2.15</td>
<td>110</td>
<td>25.0</td>
<td>37.0</td>
</tr>
<tr>
<td>1.00</td>
<td>5.58 5.82</td>
<td>1.94 2.16</td>
<td>110</td>
<td>25.0</td>
<td>37.0</td>
</tr>
<tr>
<td>3.00</td>
<td>5.58 5.80</td>
<td>1.92 2.14</td>
<td>110</td>
<td>23.6</td>
<td>36.9</td>
</tr>
<tr>
<td>3.30</td>
<td>5.57 5.81</td>
<td>1.94 2.15</td>
<td>112</td>
<td>23.2</td>
<td>36.8</td>
</tr>
<tr>
<td>4.00</td>
<td>5.58 5.81</td>
<td>1.94 2.16</td>
<td>110</td>
<td>23.2</td>
<td>36.8</td>
</tr>
</tbody>
</table>

Considered balanced beginning at 1.00 P.M. and if readings are averaged the following results.

5.70 M.V.  2.05 M.V.  111 Watts  23.6°C  36.8°C
from plot of couples of millivolts and °C.

5.70 M.V. = 127°C  2.05 M.V. = 48°C
from plot of end blocks $K_f$ of ends at 127°C = 0.88
watts lost through end blocks $= K_f A \frac{T_f}{3.41} = 0.203 K_f T_c$

\[
K_f = \frac{(W_0-W_e) 3.41}{A T_f} = \frac{(W_0-W_e) x 3.41}{5.65 x 1.8} = \frac{(W_0-W_e) 3.36}{T_c}
\]

\[
= \frac{(111-20) 3.36}{(127-48)} = 0.386 \text{ Btu/hr/sq.ft/in/°F}
\]
\[ H = \frac{(W_0 - W_e)^{3.41}}{A \frac{T_f}{T}} - (\frac{W_0 + W_e}{3.41})^{3.41} - \frac{(111 - 20)^{3.85}}{4.97 \times T \times 1.8} (127 - 23.6) = 0.336 \text{ Btu/hr/ft}^2/\text{F} \]

The other runs on the six inch pipe were made and the results calculated using the constants obtained in order to facilitate the calculations.

The mean temperature of the half way up points of the outside casing was found to be nearly the mean temperature of the top and bottom of the casing. The runs on the four inch pipe with two inches of insulation were made in a similar manner. Obviously, however, new constants had to be calculated, but they were applied in the same way.

On the following page will be given the results of the tests on the six inch pipe.

It will be seen that four layers to the inch represented the optimum condition. With five layers the reduction in radiation losses was more than counter balanced by the increased loss by the conductivity of the aluminium foil itself.
Results of Tests on Six Inch Pipe - One Inch of Crumpled Aluminium Foil

<table>
<thead>
<tr>
<th>Input</th>
<th>Mean Temp.</th>
<th>K_f</th>
<th>Temp. Difference</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pipe Surface to Air</td>
<td></td>
</tr>
<tr>
<td>111</td>
<td>190°F</td>
<td>0.386</td>
<td>187°F</td>
<td>0.336</td>
</tr>
<tr>
<td>247</td>
<td>362</td>
<td>0.445</td>
<td>385</td>
<td>0.386</td>
</tr>
<tr>
<td>555</td>
<td>668</td>
<td>0.564</td>
<td>681</td>
<td>0.469</td>
</tr>
</tbody>
</table>

3 Layers

<table>
<thead>
<tr>
<th>Input</th>
<th>Mean Temp.</th>
<th>K_f</th>
<th>Temp. Difference</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>113.3</td>
<td>199</td>
<td>0.352</td>
<td>200</td>
<td>0.317</td>
</tr>
</tbody>
</table>

4 Layers

<table>
<thead>
<tr>
<th>Input</th>
<th>Mean Temp.</th>
<th>K_f</th>
<th>Temp. Difference</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>109.2</td>
<td>198</td>
<td>0.336</td>
<td>200</td>
<td>0.303</td>
</tr>
<tr>
<td>238</td>
<td>317</td>
<td>0.385</td>
<td>385</td>
<td>0.340</td>
</tr>
<tr>
<td>547</td>
<td>503</td>
<td>0.518</td>
<td>681</td>
<td>0.460</td>
</tr>
</tbody>
</table>

5 Layers

<table>
<thead>
<tr>
<th>Input</th>
<th>Mean Temp.</th>
<th>K_f</th>
<th>Temp. Difference</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>106</td>
<td>191</td>
<td>0.373</td>
<td>186</td>
<td>0.320</td>
</tr>
</tbody>
</table>
The tests made on the four inch pipe were made with the same end blocks. Since, however, the blocks were 8
5/8 in diameter and the four inch pipe had an outside diameter of 4
1/2, there were 2
1/16 left for insulation on the pipe surface.

The tests were made with both crumpled foil and smooth foil. The crumpled foil was put on in a manner exactly like that applied with the six inch pipe, namely, having each layer cut and tied on with string individually. With the practice attained with the six inch pipe, the foil was applied with much greater ease and certainly more neatly and uniformly. The effect of the better technique will be discussed later when we come to make a comparison of the results obtained from the both pipes.

The tests with the smooth foil presented rather interesting features. First, it was necessary to choose proper insulators and secondly, the proper method to applying them in order to make as practical a setup as possible. It was also thought desirable to cut down on the amount of spacing insulation as much as possible for apparent reasons.

It was first decided to use celotex cubes 3/8" on edge, stringing them on wire about the circumference of the pipe and having four to the length of
the pipe. After the second layer was applied, it was appreciated that it was anything but stable principally due to the uneveness of the cubes of celotex, their readiness to split, and particularly the difficulty of placing the cubes of an upper layer such as to exactly cover the cubes of a lower layer.

It was then decided that a flexible strip running continuously around the pipe for each layer would be more practical than the chopped up piece idea. Though there would be more insulation used, the amount would still be small in comparison to the total area. Stripes of hair felt one-half inch thick, one inch wide and running four to the thirty-four inch length of the pipe was found satisfactory. The volume of the insulation space of the pipe being 1452 cubic inches, and the volume of the hair felt strips being 170.4 cubic inches. The ratio of 1452 to 170.4 is 8.5 to 1. If, therefore, the value of the thermal conductivity of the separator is of approximately the same magnitude as the aluminium foil, little error can result. In the tests on the four inch pipe with hair felt as a separator, the combined coefficient of conductivity was very close to that of hair felt alone.

Hair felt though a very excellent insulator cannot be used at temperatures above that of boiling water 100°C (212°F) for the reason that it will begin smoking at temperatures much above that mentioned. It was, therefore,
necessary to find a suitable insulator that could be applied with the ease that distinguished the use of hair felt and yet could be used at temperatures of the order of 1000°F. Asbestos belting appeared to fill the bill and was accordingly used.

The asbestos belting available was one inch wide and nearly 7/16" thick, hence whereas four strips of 1/2" hair felt nicely suited the 2"1/16 available, four strips of the asbestos belting left a gap about 5/16" between the last layer of foil and the outside casing. On the other hand, five layers would obviously exceed the limitation of 2"1/16. Another disadvantage of the asbestos belting as compared to the hair felt lay in the fact that its coefficient of thermal conductivity was much greater than that of the aluminium foil. Its value $K_f$ at 306°F mean Temperature was 1.63 as compared to $K_f = 0.425$ for three layers per inch of aluminium foil at the same mean temperature. However, as mentioned above, the amount of spacing insulation being small in comparison to the total amount of insulation, no great deleterious effect could be evident by the use of the greatly inferior insulating value of the asbestos belting as compared to aluminium foil. Some such insulator had to be used and since all high temperature insulators have relatively high coefficients of conductivity as compared to low temperature insulators,
the use of the belting is justified. In using both the hair felt and asbestos belting as separators as mentioned before 0.001 aluminium foil was used. Also a layer was wrapped about and in close contact to the bare pipe. Hence, five layers of foil were used in all, counting the foil in direct contact with the pipe as one layer. To be sure it was not so effective as it would be with an air space between it and the pipe but it undoubtedly helped reduce the coefficient of conductivity of the setup.

Therefore, in making any comparison between the plain and crumpled foil, the basis of comparison should be on five layers in a two inch space. As a matter of fact the outside casing being of aluminium and bright is as much a part of the insulating system as any one layer. That the use of asbestos belting did make a difference in conductivity value as compared to hair felt may be seen by comparing the values obtained with each. The way the strips of hair felt and asbestos belting were arranged as well as the abandoned cubes of celotex idea will be shown in an accompanying drawing.

The results of the tests on the four inch pipe using from three to eight layers of crumpled foil 0.00028 thick in a 2\(\frac{1}{16}\) space and those using five layers of smooth 0.001 thick with hair felt and asbestos belting spacers will be given on the next pages.

The aluminium foil in the run made with
three layers in the 2\"1/16 space though crumpled as much as practically possible, did not fill up the allotted space by about five eighths inches.

A typical data sheet with constants figured out will also be given.
Typical Data Sheet for Four Inch Pipe Run.

Three layers of crumpled Aluminium foil in 2"1/16 space at 100 watts.

Cold Junction at 0°C (32°F)

<table>
<thead>
<tr>
<th>Time</th>
<th>Pipe Surface Couples</th>
<th>Outside Casing Couples</th>
<th>Watts</th>
<th>Room Input Temp. °C</th>
<th>Outside Temp. of End Blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.20</td>
<td>7.52 7.52</td>
<td>1.75 1.75</td>
<td>107</td>
<td>21.0</td>
<td>38.0</td>
</tr>
<tr>
<td>1.00</td>
<td>7.90 7.90</td>
<td>1.81 1.82</td>
<td>108</td>
<td>21.4</td>
<td>43.0</td>
</tr>
<tr>
<td>3.00</td>
<td>7.96 7.94</td>
<td>1.76 1.75</td>
<td>105</td>
<td>19.0</td>
<td>42.0</td>
</tr>
<tr>
<td>3.30</td>
<td>7.94 7.92</td>
<td>1.72 1.71</td>
<td>108</td>
<td>18.8</td>
<td>41.1</td>
</tr>
<tr>
<td>4.00</td>
<td>7.92 7.91</td>
<td>1.70 1.69</td>
<td>106</td>
<td>18.0</td>
<td>40.2</td>
</tr>
<tr>
<td>4.30</td>
<td>7.92 7.92</td>
<td>1.72 1.72</td>
<td>106</td>
<td>19.0</td>
<td>41.0</td>
</tr>
<tr>
<td>5.00</td>
<td>7.92 7.91</td>
<td>1.72 1.72</td>
<td>106</td>
<td>19.6</td>
<td>40.8</td>
</tr>
<tr>
<td>Average</td>
<td>7.92</td>
<td>1.74 1.72</td>
<td>107</td>
<td>19.3</td>
<td>41.4C</td>
</tr>
<tr>
<td>Temp.</td>
<td>171°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Considered balanced at 1.00 P.M.

\[
\log \text{mean radius of ends}; \quad D_2 = 8\frac{5}{8}; D_1 = 4\frac{1}{2}''
\]

\[
= \frac{r_2 - r_1}{\log e} = \frac{4.3125 - 2.25}{\log e \frac{4.3125}{2.25}} = 3.17
\]

\[
\log \text{mean area of ends} = \frac{2(3.17)^2\pi + 2\pi x 3.17}{144} = 0.716 \text{ sq.ft.}
\]

\[
\log \text{mean area of insulation} = \frac{3.17 \times 2\pi x 3^4}{144} = 4.70 \text{ sq.ft}
\]

\[
\text{Area of pipe surface} = \frac{\pi x 4\frac{1}{2} x 3^4}{144} = 3.34 \text{ sq.ft.}
\]

\[
K_f \text{ of block ends at } 171°C = 0.94
\]

\[
W \text{atts lost through ends} = \frac{K_f A \Delta T_f}{L x 3.41} = \frac{K_f x 0.716 x \Delta T_c x 1.8}{2x3.41}
\]

\[
= 0.189 K_f \Delta T_c
\]
\[ K_f = \frac{(W_o - W_e)x3.41xL}{A \Delta T_f} = \frac{(W_o - W_e)x3.41x2^{\frac{1}{15}}}{4.70x \Delta T_c x1.8} = 0.833(W_o - W_e) \]

\[ H = \frac{(W_o - W_e)x3.41}{(\text{Area of Pipe Surface})(T_f - \text{Pipe Surface to room})} = \frac{(W_o - W_e)3.41}{3.34x4 \Delta T_c x1.8} = \frac{(W_o - W_e)0.567}{4 T_c} \]

For three layers in 2"1/16 at 100 watt run

Watts lost through ends = 0.189x0.94(171-41.4) = 23.1 watts

\[ K_f = \frac{0.833(107-23.1)}{(171-42)} = 0.543 \text{ Btu/hr/sq.ft/in}^{\circ}\text{F}. \]

\[ H = \frac{0.567(107-23.1)}{(171-19.3)} = 0.313 \text{ Btu/hr/sq.ft./}^{\circ}\text{F}. \]

Mean Temperature = \[ \frac{(171x1.8+32)+(42x1.8+32)}{2} = 244^{\circ}\text{F} \]

Temperature Difference - Pipe surface to Room = (171-19.3)x1.8 = 273^{\circ}\text{F}
Results of Test on four inch pipe using 2\textsuperscript{nd} 1/16 of crumpled foil. From three to eight layers in the given space.

### 3 Layers

<table>
<thead>
<tr>
<th>Input Watts</th>
<th>Mean Temp of Insul.</th>
<th>$K_f$ Btu/hr. per sq.ft./ Pipe Surface to in./(^{\circ})F</th>
<th>Temp. Difference H-Btu/hr per sq.ft./ (^{\circ})F Room</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td>101(^{\circ})F</td>
<td>0.508</td>
<td>144(^{\circ})F</td>
</tr>
<tr>
<td>107</td>
<td>224</td>
<td>0.543</td>
<td>273</td>
</tr>
<tr>
<td>196</td>
<td>336</td>
<td>0.603</td>
<td>454</td>
</tr>
<tr>
<td>345</td>
<td>467</td>
<td>0.711</td>
<td>678</td>
</tr>
</tbody>
</table>

### 4 Layers

| 97          | 227\(^{\circ}\)F    | 0.473                                                    | 268\(^{\circ}\)F                                 |
| 203         | 357                 | 0.534                                                    | 497                                              |
| 342         | 490                 | 0.635                                                    | 719                                              |

### 5 Layers - to be discussed later

| 203         | 280\(^{\circ}\)F    | 0.530                                                    | 516\(^{\circ}\)F                                 |

### 6 Layers

| 106         | 272\(^{\circ}\)F    | 0.403                                                    | 320\(^{\circ}\)F                                 |
| 205         | 371                 | 0.468                                                    | 540                                              |
| 346         | 530                 | 0.556                                                    | 782                                              |

### 7 Layers

| 344         | 533\(^{\circ}\)F    | 0.545                                                    | 800\(^{\circ}\)F                                 |

### 8 Layers

| 331         | 538\(^{\circ}\)F    | 0.528                                                    | 800\(^{\circ}\)F                                 |
Results of tests on four inch pipe using smooth aluminium foil - 0".001 thick. - 5 Layers except where noted.

Using Hair Felt Strips As Separators

<table>
<thead>
<tr>
<th>Watts Input of Insul.</th>
<th>Mean Temp.</th>
<th>Kf-Btu/hr. per sq.ft./Pipe Surface in/°F</th>
<th>Temp.Diff. to Room</th>
<th>H-Btu/hr. per sq.ft./°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>123°F</td>
<td>0.259</td>
<td>95°F</td>
<td>0.162</td>
</tr>
<tr>
<td>38.5</td>
<td>157</td>
<td>0.281</td>
<td>155</td>
<td>0.177</td>
</tr>
</tbody>
</table>

With top layer of foil removed and 4 top hair felt strips.

<table>
<thead>
<tr>
<th>Watts Input of Insul.</th>
<th>Mean Temp.</th>
<th>Kf-Btu/hr. per sq.ft./Pipe Surface in/°F</th>
<th>Temp.Diff. to Room</th>
<th>H-Btu/hr. per sq.ft./°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.7</td>
<td>117°F</td>
<td>0.249</td>
<td>95°F</td>
<td>0.155</td>
</tr>
</tbody>
</table>

Using asbestos belting as separators

<table>
<thead>
<tr>
<th>Watts Input of Insul.</th>
<th>Mean Temp.</th>
<th>Kf-Btu/hr. per sq.ft./Pipe Surface in/°F</th>
<th>Temp.Diff. to Room</th>
<th>H-Btu/hr. per sq.ft./°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>49.7</td>
<td>173°F</td>
<td>0.322</td>
<td>181°F</td>
<td>0.201</td>
</tr>
<tr>
<td>107</td>
<td>266</td>
<td>0.347</td>
<td>356</td>
<td>0.214</td>
</tr>
<tr>
<td>148</td>
<td>342</td>
<td>0.371</td>
<td>473</td>
<td>0.219</td>
</tr>
<tr>
<td>202</td>
<td>410</td>
<td>0.391</td>
<td>601</td>
<td>0.235</td>
</tr>
<tr>
<td>203</td>
<td>400</td>
<td>0.395</td>
<td>596</td>
<td>0.239</td>
</tr>
<tr>
<td>338</td>
<td>567</td>
<td>0.457</td>
<td>885</td>
<td>0.271</td>
</tr>
</tbody>
</table>
PLATE TEST

The next step taken in this investigation of aluminium foil was to determine the value of thermal conductivity by the standard plate method. This method as approved by the Bureau of Standards consists essentially of a hot plate surrounded by a guard ring which is maintained at the same temperature as the central hot plate. All the heat from the hot plate then passes vertically upward and downward to the cold plates which cover the whole. Cold water circulates through the cold plate keeping it at a constant temperature. Thermocouples at the edge of the hot plate and in guard ring indicate when these are at the same temperature and hence balanced. Thermocouples in the center measure the hot surface temperature and thermocouples at outside of insulation measure the temperature of the cold side of insulation. A better idea of the location of the couples and general setup can be seen from accompanying drawing.

Since a great deal more tests on the pipes were made with crumpled foil rather than smooth foil, it was felt that the plate test should be run with crumpled the aluminium foil. However, what was learned by/plate method applied equally well to the pipe runs with smooth foil as with crumpled foil. Two inches of crumpled foil 0".00028 thick were used, six layers in the two inches on both sides of the hot plate. The cold plate through which the cold water circulated was held separated the two inches from the hot plate by two
inch blocks Carey alumino Hi Temp. about two inch square. There were six used, three on each side of hot plate and spaced about 120° apart on the guard ring.

The outside of the plate tester was flanked all around by asbestos board and hair felt on the extreme outside.

As was anticipated it took considerable time to get the guard ring and heater balanced and kept balanced for at least two hours. Several days, nearly a week, was necessary before reliable results were obtainable.

Whereas with solid insulating materials a difference of ± 0.02 millivolt between the guard ring and the heater would be sufficiently accurate balance, it was found with the more or less "airy" crumpled aluminium foil that an exact balance was necessary before any results at all reliable were obtained. For example, with the variation in balance of ± 0.02 M.V. as mentioned above, values varying from \( K_f = 0.47 \) to \( K_f = 0.18 \) were obtained – the former figure when the guard ring was from 0.02 - 0.03 M.V. "colder" than plate heater and the latter when the guard ring was that much "hotter" than the plate heater.

The value for \( K_f \) for six layers of crumpled aluminium foil in a two inch space by the plate method is given on the next page.
Test on six layers of crumpled aluminium foil 0.00028 thick by Plate Method.

<table>
<thead>
<tr>
<th>Watts Input</th>
<th>Mean Temp.</th>
<th>$K_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.6</td>
<td>120°F</td>
<td>0.298</td>
</tr>
</tbody>
</table>

**BARE PIPE LOSS**

After the plate test was concluded, a bare pipe loss determination on the four inch pipe was run. This was accomplished by removing the outside sheeting, outside couples, and crumpled foil insulation. The pipe couples were left as before and the end block was left intact. Three runs were made, the results of which are given below:

<table>
<thead>
<tr>
<th>Input Watts</th>
<th>Temp.Diff. to Room</th>
<th>Value of $H$ Btu/hr/sq.ft/°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>92</td>
<td>44°</td>
<td>2.07</td>
</tr>
<tr>
<td>198</td>
<td>83°</td>
<td>2.36</td>
</tr>
<tr>
<td>354</td>
<td>131°</td>
<td>2.68</td>
</tr>
</tbody>
</table>

A curve showing these results is given on a subsequent page.

Curves giving a comparison between aluminium foil and some other commercial insulators are also given.
DISCUSSION

The tests on the six inch pipe as compared to the four inch pipe reveal some variations between the two. From a comparison of the curves, it will be found that the thermal conductivities ($K_f$) of two layers per inch and four layers in 2"1/16 at 470°F mean temperature are about 0.56 and 0.60 respectively. It is likewise the same on the lower end of the scale for at 150°F mean temperature $K_f$ for the six inch pipe = 0.39 and for the four inch pipe $K_f = .43$. A difference of .04 units in both cases. The fact that there are less than two layers per inch on the four inch pipe (due to the 2"1/16 for the four layers) will lower 0.60 to 0.58 for exactly two layers per inch. The comparison of 0.56 to 0.58 is then a very good check. Likewise for the lower temperature (150°F) 0.39 and 0.41 there is a good check.

In comparing the other layers the results are in substantial agreement. The difference between eight layers in 2"1/16 and eight layers in two inch would, of course, be less significant. In all cases, therefore, the two pipes agree within the experimental error. This fact brings out a rather interesting feature of the crumpled foil. The fact that results can be duplicated with an entirely new setup. This indicates that the method of applying the foil is not of paramount importance. A much neater job was done in insulating the four inch pipe than
the six inch pipe due, as intimated before, to experience gained on the six inch pipe.

The variation shown is not more than is met with in commercial samples of solid insulating materials, although uniformity is certainly more to be expected from solid materials than the hand crumpled and hand applied aluminium foil.

In comparing the single plate test on six layers of crumpled foil in two inches, to the corresponding test on the pipe a discrepancy will be noted. The value of substantially 0.30 at 120°F mean temperature is lower than the value 0.33 obtained on both the six inch pipe and the four inch pipe. This makes a variation of 10%. Whether this indicates that the values obtained by the pipe test are too high by that amount, it is a little difficult to say.

It appears doubtful, however, that such an error exists. The plate method is indeed a more accurate way of determining thermal conductivity, but the pipe cover method is certainly not by comparison inaccurate. The explanation appears to lie in the nature of the surface in both cases in relation to convection loss. It is fairly well known that for pipes in Dia. less than eight inches the heat loss per unit area decreases as the diameter increases and that for pipes of 8" - 12" in diameter the heat loss per unit area appears the same for cylinders and plates. The convection loss in either case
must be small but it is probably sufficient to account for the discrepancy.

The difficulty found in balancing the guard ring and heater in the plate test was undoubtedly due to lateral transmission.

When we come to investigate the difference between crumpled aluminium foil 0".00028 thick and smooth 0".001 aluminium foil, an interesting variation is noted. Of course, it is relatively impossible to crumple 0".001 aluminium foil by hand, and it was not tried in this thesis. We will compare the five layers of smooth foil in 2"1/16 separated by asbestos belting with crumpled foil in the same space. It will be noted that the curve for the smooth foil is flatter than the curves for the crumpled foil. Hence, although the smooth foil has nearly the same $K_f$ value at 100°F mean temperature as eight layers of crumpled foil in 2"1/16, the variation is more marked at mean temperatures in the neighborhood of 500°F. At 500°F mean temperature $K_f$ for smooth foil is 0.435 while for eight layers of crumpled foil in 2"1/16 it is 0.51.

With regard to smooth foil with half inch hair felt strips as separators, rather remarkable results were obtained. The value $K_f = .26$ at 123°F mean temperature with five layers in 2"1/16 was by far the best.
value obtained in the whole thesis. At the same mean temperature, \( K_f = 0.3 \) for eight layers of crumpled foil in 2\( 1/16 \) or five layers in 2\( 1/16 \) of smooth foil with asbestos belting separators.

The difference between the values obtained in using hair felt as compared to asbestos belting is probably due to the higher coefficient of conductivity of the latter.

The five layers to the inch was omitted from the plot on the six inch pipe because it would tend to confuse matters. It lies between the two layers to the inch curve and the three layers to the inch curve.

The five layers in 2\( 1/16 \) values are omitted from the plot of the four inch pipe since it is obviously too high. The pipe was reinsulated for the sixth layer because of this. The foil was highly crumpled in the three and four layer runs in order to fill up the 2\( 1/16 \) space as much as possible. Hence, when the fifth layer was introduced, considerable jamming had to be resorted to in order to make room for it. The difficulty was eliminated for the sixth layer by reinsulating the pipe.

The bare pipe loss is of value when the efficiency of the insulation is to be determined. It is a value, however, that has wide variations since the nature
of the pipe surface is of extreme significance. In general, smooth pipe surfaces will radiate much less heat than rusty rough surfaced pipes. The pipes used in this thesis were rather rusty and rough surfaced.

As far as a discussion of the possible commercial application of the excellent insulating qualities of aluminium foil is concerned, it is not within the province of this investigation. The experience gained by handling it in the laboratory is, of course, of some value in estimating the applicability of the foil in industry. As far as insulating small pipes below four inches in diameter is concerned, it is probably much more expensive, as far as labor is concerned, than most standard solid pipe insulating materials. In large pipes, the lower cost of aluminium foil would probably offset the higher labor cost.

The situation with respect to insulating flat surfaces is entirely different on the other hand. For example, in insulating large refrigerating rooms, uptakes aboard ship, etc., it is believed that the labor costs would be of the same order of magnitude as with solid insulating materials. Hence, the total cost except for low temperature installations would probably be less. Low temperature insulators like hair felt and cork have low coefficients \( K_f = 0.27 \) and \( 0.32 \) respectively of conductivity and are likewise relatively inexpensive.
The only way aluminium foil could compete with such low temperature insulators would be in the field of refrigerating cars or any other place where weight is a factor. Aluminium foil, as far as weight is concerned, is almost negligible. For example, for four layers only 52.5 grams - 0.1155 pounds of aluminium foil were used to insulate the six inch pipe. This corresponds to 0.041 pounds per linear foot. For 80% magnesia this would be 3.12 pounds per linear foot.

The foil is much used in Europe as stated before and finds application both in low temperature and moderate temperature work. The application in Europe can be better appreciated by glancing at the photographs at the back of the thesis which were taken from an extract by Hans Nieman in "Die Kaelte Industrie" May 27, 1930 in his article on "Metallic Insulation for Refrigeration."

Schmidt has found the following values for crumpled aluminium foil 0".00028 in thickness.

Mean Temperature 32°F 212°F 392°F 572°F
Kf 0.331 0.376 0.51 0.598

These values were obtained from a two inch pipe with an outside casing of sheet iron. Four air layers were used in a space of 0.83 inches. This corresponds to between three and four layers of crumpled foil in a one inch space.

In comparing these values with those ob-
tained in this thesis, it will be found that they correspond to between two and three layers of crumpled foil per inch as determined on either the four or six inch pipe.

The values obtained by Schmidt would necessarily be lower than the corresponding values obtained in this thesis since he had used for an outside casing ordinary sheet iron, whereas a bright aluminium casing was used in this thesis. Also he used supports of asbestos cord only $2\frac{1}{2}''$ apart on a pipe $6\frac{1}{2}$ feet long. This material has a relatively high coefficient of thermal conductivity and the combination of close spacing and high coefficient would have a material bearing on the value for the combination.

Comparison of Densities of Insulating Material

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (pounds per cubic foot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium foil</td>
<td>0.224</td>
</tr>
<tr>
<td>Balsam Wool</td>
<td>2.2</td>
</tr>
<tr>
<td>Cork</td>
<td>10</td>
</tr>
<tr>
<td>85% Magnesia</td>
<td>17</td>
</tr>
</tbody>
</table>

With regard to the diamond embossed pattern on the 0".00028 foil, the effect of the embossing has a decided significance in the crumpling process. The embossing has the effect of facilitating the crumpling, since the diamond shaped pattern serves to break up the "crumple"s more uniformly and the contour of the individual crumple appears to follow the diamond shaped pattern in a rather rough way.
CONCLUSIONS

1. The tests made with aluminium foil indicate that it is an insulator of no mean merit. As far as fairly high temperature work is concerned, such as is met with in steam pipes it is remarkably good. The curves making a comparison of heat losses with the same thickness of insulation of 85% magnesia show convincingly the superior insulating properties of aluminium foil.

2. With regard to the use of aluminium foil for fairly low temperatures — below 212°F — aluminium foil compares very favorably with cork.

3. Both cork and 85% magnesia are favorite insulators in their respective fields. Cork, however, is limited to mean temperatures below 212°F and 85% magnesia cannot be used successfully without calcination above 500°F hot surface. Aluminium foil, on the otherhand, can be used up to the melting point of aluminium — 1200°F.

4. The behavior of crumpled aluminium foil at temperatures above its melting point is rather remarkable. Four layers of crumpled foil 14" x 6" wide were laid on top of two pieces of fire brick standing upright. A Bunsen burner with an oxidizing flame was placed under the foil. The hottest part of flame — the tip of inner cone —
was in contact with the bottom layer. The foil immediately in contact with flame oxidized almost instantaneously to the white aluminium oxide. The insulating qualities of this bottom layer were still so good that the three layers above it were not oxidized though the temperature of the burner must have been in the neighborhood of 2700°F. The burner was kept going five minutes with no further change in either the bottom or upper three layers. The structure of the foil was not affected except for the bottom layer, which however, did not lose its crumpled shape.

5. The foil is not affected adversely by moderate handling, that is, it does not lose its crumpled state very easily. It can stand shocks very well, due no doubt to its small mass. A test on this particular phase was carried out in Germany and the crumpled foil was found to be virtually unaffected after a fifty hour vibration test. Small tears in the foil also have no particular bearing on the insulating properties. They probably would have some affect in the case of smooth sheets of foil separated from each other by about an inch, but since this condition was not met with in this thesis the question cannot be answered definitely.
RECOMMENDATIONS

These tests show that this relatively new idea of insulating with metals represents a field which would be very fruitful for additional research. Aluminium, at the present time, appears to be the best metal suited for this type of work. Therefore, it is recommended that additional research be conducted with both plain and crumpled foil not only in the manner in which it was used in this thesis, but also with prepared forms such as half cylindrical forms as is used for solid pipe insulation and block forms such as is used for house insulation.

In any case results would be of material benefit in order to obtain a better understanding of the principles in back of insulation with metallic foil.
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                                Davis
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Metallic Insulation for Refrigeration..Nieman
Refrigerator Car. Arrangement of Floor Insulation.

Edge view of Crumpled Foil.
Refrigerator Car. Insulation of the Roof.

Showing arrangement of layers of Crumpled Foil.
Abb. 4. Gefachstruktur nach 50 Std. Versuchsdauer.

Structure of Crumpled Foil after Fifty Hour Vibration Test.

Front view of Crumpled Foil.
WIRING DIAGRAM - Showing Connections of one Couple - Other Couples Connected Similarly
Arrangement of separating insulation on a pipe using smooth foil-on-layer

- Pipe surface
- Hairfelt or Asbestos belting
- Smooth foil wrapped around strips of insulation

Arrangement tried with Celotex cubes as separators - found unsatisfactory

- Iron wire holding cubes in place

Plate tester showing location of thermocouples

- Water-cooled plates
- Guard ring
- 6 layers of crumpled foil on either side
Degrees Centigrade

Copper-Constantan Couple

Standardization Points

<table>
<thead>
<tr>
<th>°Centigrade</th>
<th>Millivolts</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>100-26</td>
<td>4.47</td>
</tr>
<tr>
<td>231.8</td>
<td>11.18</td>
</tr>
</tbody>
</table>

Millivolts
Centigrade - Hot Surface

Values of f of void blocks of various temperatures.
$K_f$ vs Mean Temp - 6" pipe

2 & 4 layers of crumpled foil per inch

Mean Temperature of Insulation °F
Value of $H$ - Btu/hr/sqft/°F

Temperature Difference °F

Pipe Surface Temp.

Layers of

Compressed Soil in one inch space

Marl

Clay

Tappan 6" rock

Temp. Off.
Kf vs Mean Temp. 4" Pipe
3-8 Layers of Crumpled Foil in 21/2
Value of $H = \frac{Btu}{hr/1594^\circ F}$

Temperature difference °F

Pipe Surface + Room

Heating or Cooling 5.5

20% 50% 80%
Bare pipe loss
4" pipe
H vs Temp. Diff.

Temperature Difference °F
Pipe Surface to Room
Kₚ vs No. Layers on 4" pipe

Number of Layers per inch
Comparison of Cork with Crumpled Aluminum foil - 3-4 layers per in

(Cork D=0.1 and D=0.2 taken from International Critical Tables)
Value of thermal conductivity of air at various temperatures - Air absolutely still - No convection loss from International Critical Tables