

(Paper No. 2740.)

“On the Determination of the Thermal Conductivities of Heat-Insulators.”

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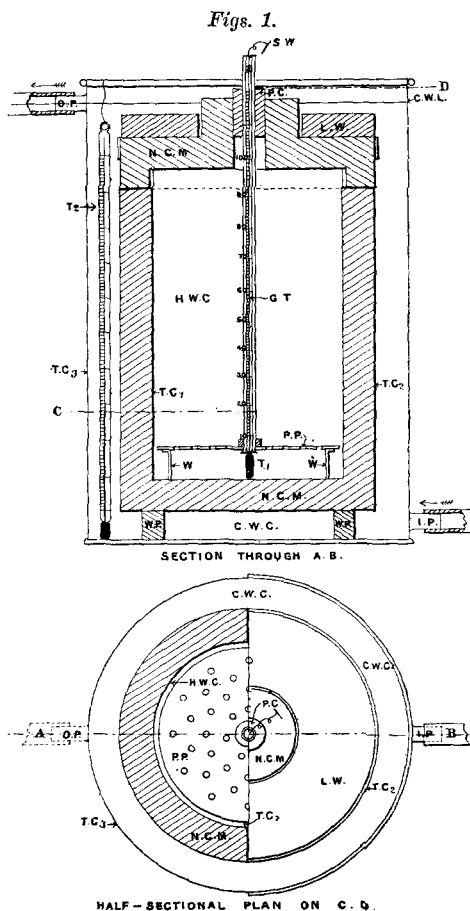
THE investigation described in this Paper was undertaken for the purpose of determining the relative and absolute thermal conductivities of substances used as lagging for steam-boilers, for parts of steam-engines and for refrigerating-machines.

The method adopted was to observe the fall of temperature in a known weight of hot water contained in a vessel coated on all sides with a certain thickness of the material under examination, the outer surface of which was maintained at a constant temperature by the continuous flow of cold water through a water-jacket.

Description of the Apparatus.—The apparatus used in the tests consisted of three cylindrical tin cases, indicated in *Fig. 1* by $T C_1$, $T C_2$, $T C_3$. The first or innermost of the three, $T C_1$, was $9\frac{3}{4}$ inches high by 6 inches in diameter, and, when filled, held exactly 10 lbs. of fresh hot water. It was fitted with a watertight lid, having a central funnel, through which the hot water was supplied. The second vessel, $T C_2$, which contained the first, measured $11\frac{3}{4}$ inches in height by 8 inches in diameter. The non-conducting material, N C M, under test filled the space, of 1 inch in thickness, between the outside of the first and the inside of the second case. The third or outer vessel, $T C_3$, was $14\frac{1}{2}$ inches high by 10 inches in diameter. It formed the water-jacket for the first and second cylinders and the material under test between them.

A perforated piston, P P, fixed to a central glass tube, G T, which contained a tightly-fitted thermometer, T_1 , was provided for stirring the water in the innermost vessel. Stops, W W, were attached to its under side to prevent the thermometer-bulb striking the bottom of this vessel. In order to permit of the introduction of the perforated piston into the inner tin case $T C_1$,

the latter was provided with a lid which was coated to a thickness of 1 inch with the same non-conducting material as the sides and bottom. The glass tube, G T, passed tightly through the centre of a paraffined wooden plug, P C, fitted into the neck of the lid. It was used as a handle to move the perforated piston whilst



stirring the water in the hot-water chamber, H W C. The thermometer was raised and lowered in the tube by the string with wire check, S W. The cold-water chamber, C W C, or space between the second and outer vessels, also contained a thermometer, T_2 , and was provided with inlet and outlet water-pipes, I P and O P. The water in this vessel was maintained at the level C W L. The second and inner vessels with their contents were supported in their position inside the outer vessel by four wooden pegs, W P. The circular lead weight, L W, was placed on the lid of the second vessel in order to prevent it and its contents from floating, and to keep the non-conducting material dry during a test. The lids of the

inner and second vessels were cemented to their respective cases by means of Chatterton's compound.

In the appended list of the non-conducting materials tested, the index letters refer to those upon the curves, *Fig. 2*, and in the Table of results, p. 297.

B. Composition of fossil meal, roasted and mixed in Glasgow, consisting of 60 per cent. of washed white German kieselguhr and 40 per cent. of binding matter. It is applied in a wet state to steam-pipes or boilers, steam being kept up to dry the material quickly. It adheres well to the surfaces, making a neat covering.

C. Silicate cotton, or slag-wool, produced by blowing steam into melted blast-furnace slag.

D. Composition of kieselguhr¹ from mines in Germany, with 10 per cent. of binding material, viz., fibre and mucilaginous extract of several vegetable matters.

E. Cement consisting of fine blue clay mixed with flax, jute and woollen waste or cow-hair in equal proportions, surrounded by a layer of hair-felt and canvas.

F. Fibrous composition of fine blue clay from the Glasgow district, mixed with flax, hemp, rope, jute, cow-hair and woollen waste.

G. Papier maché composition consisting of paper-pulp mixed with clay and carbon, together with hair and fragments of hemp-rope.

H. A lighter modification of G.

Method of making the Tests.—A separate inner case was provided for each specimen of non-conducting material, with which it was covered to a uniform thickness of 1 inch in the manner in which it would be employed in practice. The non-conducting composition was applied in layers, carefully dried in succession, to ensure that the dryness necessary to the accuracy of the tests was obtained. Each covered tin case was tested as follows: Ten pounds of boiling water were poured through the funnel into the hot-water chamber. Cold water was then allowed to flow uniformly from the main water-pipe, and to circulate freely through the cold-water chamber. During no test

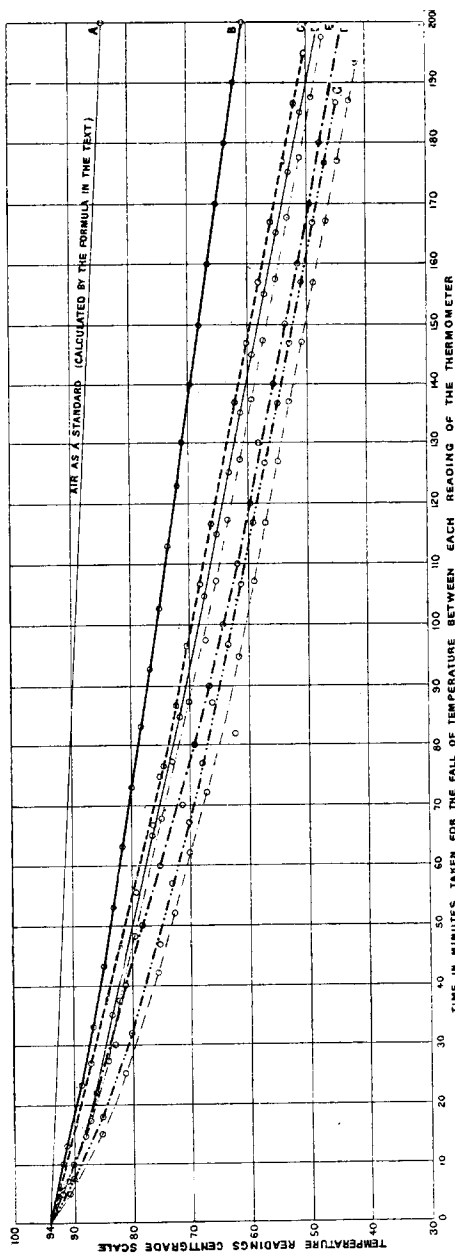
¹ AVERAGE ANALYSIS OF THE KIESELGUHR USED IN PREPARING
SAMPLE D.

	Per cent.
Silica	83·8
Magnesia	0·7
Lime	0·8
Alumina	1·0
Peroxide of iron	2·1
Organic matter	4·5
Moisture and loss	7·1
	<hr/> 100·0 <hr/>

was the temperature in this chamber observed to rise as much as 1° C. The outer surface of the non-conductor was, therefore, kept at a constant temperature throughout each test. In order to prevent the temperature of the hot water from falling too quickly at first, and to bring the non-conductor and the whole apparatus to a condition of constant temperature or heat-equilibrium, steam at atmospheric pressure, generated in a florence-flask, was first passed into the inner vessel by means of a glass tube led into it through the funnel. The steam-pipe was then removed, and the paraffined cork fitted tightly into its position. The first reading was always taken when the temperature of the hot water had just fallen to 94° C. The water was stirred by the perforated piston prior to the readings of the thermometers in the two chambers, which were taken simultaneously, being noted. Successive readings of both thermometers were then taken in the same way, and recorded every ten minutes. These readings have been plotted as ordinates, with the time between each reading in minutes as abscissæ, *Fig. 2*. The curves show the gradual fall of temperature of the water in the inner chamber during the tests of each of the several substances experimented upon. Each experiment lasted about three hours, during which a fall in temperature through a good range was obtained. The loss of heat at the end of any fixed time therefore constitutes a measure of the conductivity of each substance. The results are given in Table I, which shows in each case the total fall of temperature in degrees Centigrade after an interval of two hours from the commencement of the test.

The higher the specific gravity of the composition under test the greater will be the quantity of heat which it draws from the boiling water in the hot-water chamber, at the beginning of the test, to bring it and the apparatus to a condition of heat-equilibrium. The curves fall very quickly at first, thus indicating the rapid abstraction of heat at the start; but as soon as the compositions and the apparatus became heated throughout their mass, the fall of temperature was more regular, and the curves, therefore, fall away more gradually. While, therefore, the beginning of a curve may show for one material a greater conductivity than that of a material of a smaller density, the subsequent portions of the curves may show the reverse. The readings from which the absolute thermal conductivities of the different substances are calculated were chosen from the uniform portions of the curves, and, consequently, the rapid fall near the starting-point has no effect on the results.

Fig. 2.
CURVES SHOWING FALL OF TEMPERATURE DURING THE TESTS.



REFERENCE LETTERS TO CURVES. (See also list of materials, p. 293.)

- | | | |
|---------------------------------|----------------------------|----------------------------------|
| A. Dry air. | D. Kieselguhr composition. | G. Papier maché composition (a). |
| B. Fossil meal composition. | E. Cement with hair-felt. | H. " " (b). |
| C. Silicate cotton composition. | F. Fibrous composition. | |

The thermal conductivities were calculated from the formula¹

$$K = \frac{m x}{A} \cdot \frac{\log_e \frac{\tau_1 - \tau_0}{\tau_2 - \tau_0}}{t_2 - t_1},$$

where,

m is the mass of the water together with the products of the masses and specific heats of all other bodies within the covering of the substance under test;

$\tau, \tau_1, \tau_2, \tau_3$, &c., the temperatures of the water in the inside case;

τ_0 the temperature of the water in the outside case (constant); and t_1, t_2, t_3 &c., the times of observation of the temperatures τ_1, τ_2, τ_3 , &c., A the mean area,

x the thickness, and

K the conductivity, of the substance under test.

The curve for air in *Fig. 2* is obtained directly from the above formula, in which the value 0.0000558 for its conductivity is substituted. The effects of the small uncovered area at the top of the hot-water chamber of the mass of the perforated piston or stirrer, with the thermometer, and of the corners, were neglected.

¹ This formula is obtained as follows:—

From the definition of quantity of heat—

$$Q = m (\tau - \tau_0);$$

$$\therefore dQ = -m d(\tau - \tau_0).$$

Again, from the formula for the flow of heat—

$$\frac{dQ}{dt} = \frac{KA}{x} (\tau - \tau_0);$$

$$\therefore dt = -\frac{mx}{KA} \cdot \frac{d(\tau - \tau_0)}{\tau - \tau_0};$$

and thus—

$$t_1 - t_2 = -\frac{mx}{KA} \int_{(\tau_1 - \tau_0)}^{(\tau_2 - \tau_0)} \frac{d(\tau - \tau_0)}{(\tau - \tau_0)};$$

$$\therefore t_2 - t_1 = \frac{mx}{KA} \log_e \frac{\tau_1 - \tau_0}{\tau_2 - \tau_0};$$

or—

$$K = \frac{mx}{A} \cdot \frac{\log_e \frac{\tau_1 - \tau_0}{\tau_2 - \tau_0}}{t_2 - t_1}.$$

TABLE I.—RESULTS OF THE TESTS.

Index Letter for Curves.	Name of Material.	Weight of Sample (including Tin)	Total Fall of Temperature in 120 Minutes.	Thermal Conductivity in Absolute Measure.	Conductivity as compared with Dry Still Air.
		Lbs. Oz.	° Cent.		
A	Dry air	6 0	6.0	0.0000558	1.00
B	Fossil meal composition . . .	7 2	21.5	0.0002689	4.82
E	Cement with hair-felt ¹ . . .	5 15	30.0	0.0003613	6.47
C	Silicate cotton, ² or slag wool . .	..	29.0	0.0003875	6.95
D	Kieselguhr composition . . .	7 13	29.0	0.0004336	7.77
G	Papier maché composition (a) . .	7 6	35.5	0.0004424	7.93
F	{ Fibrous composition (flax, hemp, cow-hair and clay). }	9 9	34.5	0.0004550	7.98
H	Papier maché composition (b) . .	8 12	37.5	0.0005019	8.99

Engineers when about to select non-conducting coverings for boilers, steam-pipes, or freezing-machines, must take many other things into consideration besides the value of the material as a non-conductor of heat. They must also take into account the first cost, appearance, and durability of the substance, as well as its weight, volume, and necessary thickness; the ease with which it can be removed for the repair of a leaky joint and replaced, its inodorousness when wet or dry, its incombustibility, non-liability to crack, and capability of resisting moisture. These, and such considerations, however, form no part of the present Paper, but the Author has pleasure in referring members to the other Papers enumerated in Appendix I, more especially to that by Professor Ordway, wherein these points are treated and discussed at length. In conclusion, the Author desires to thank Messrs. William J. Dale, George C. Laird, Andrew Gray, and David A. Ramsay for help with the experiments, drawings, and data for the Paper.

The Paper is accompanied by two drawings and a photographic print, from which the *Figs.* in the text have been prepared.

¹ The outside diameter of sample E was about $\frac{1}{4}$ inch smaller than the inside diameter of the middle tin case, TC₂. It had consequently a slight advantage over the other samples in having a thin layer of air between its outer surface and the tin case TC₂.

² The silicate cotton was pressed together tightly, and thus its conductivity appears greater than would have been the case had it been more loosely packed.

APPENDIXES.

APPENDIX I.

ACCOUNTS OF PREVIOUS EXPERIMENTS.

In 1879 Mr. W. J. Bird, in a Paper¹ on "Condensation in Steam Pipes," described experiments on five substances, viz., woollen-felt, sawdust, fir-wood, coal-ashes and plaster. The temperatures on the outside surface of these non-conductors, which covered a 4-inch pipe filled with steam at 212° F., were noted and compared with temperatures on the outside of a bare pipe. In a second Paper,² by the same Author, on "Non-conducting Coverings for Steam-Pipes," six materials, viz., silicate cotton applied in three different ways, Toope covering (composed of asbestos, compressed paper and hair-felt), a composition of a plastic fibrous nature, and hair-felt were compared. The temperatures were taken as before, and the heat-units lost per foot length of pipe per hour were calculated. The saving in fuel effected per annum by covering 1,000 feet of steam-piping with the several materials dealt with in the Paper was also computed. A third Paper³ by Mr. Bird, on "Non-conducting Coverings for Boilers and Steam-pipes," gives the results of tests of seven materials, viz., Dade silicate cotton, Dade silicate cotton composition, Toope covering, Burnett composition, Jones silicate cotton, and eagle cement and hair-felt. In a Paper⁴ on "Transmission of Power by Steam," Messrs. Liddell and Merivale describe a successful attempt at Broomhill Colliery to convey power by means of steam to a pumping-engine situated 1,294 yards from the boiler, the steam-pipes, traps, and engine being covered with the composition indicated by the letter G in the Paper. In a Paper⁵ on the same subject, Prof. J. H. Merivale deals with the extension and covering of the steam-piping at Broomhill Colliery, and demonstrates that power may be conveyed by steam in coal-pits for a distance of from 1,200 to 1,500 yards as economically as by ropes or by compressed air if the pipes are properly lagged with a good non-conducting material.

In 1881 Mr. Charles E. Emery, Ph.D., gave a Paper⁶ on "Experiments with Non-conductors of Heat," wherein the results of his tests on fourteen different substances, some of which have been entered in the Table, p. 299, are given. The apparatus consisted of a boiler, 4 feet in diameter and 12 feet long, constructed with three 10-inch tubes. Into these tubes were placed smaller tubes to receive steam, and around the inner tubes were placed the non-conducting substances; water being circulated through the larger shell outside of the outer tubes. The results were shown by the amount of steam condensed in the inner tubes, the water of condensation being conducted to small cylindrical vessels, each provided with a glass gauge.

¹ Transactions North of England Inst. of Mining and Mechanical Engineers, vol. xxix., 1879-80, p. 7.

² *Ibid.*, vol. xxxi., 1881-82, p. 77.

³ *Ibid.*, vol. xxxii., 1882-83, p. 35.

⁴ *Ibid.*, vol. xxxv., 1885-86, p. 159.

⁵ *Ibid.*, vol. xxxvii., 1886-87, p. 13.

⁶ Transactions American Society of Mechanical Engineers, vol. ii., 1881, p. 34.

In 1884 Prof. John M. Ordway, of Boston, Mass., described, in a Paper¹ on "Experiments upon Non-conducting Coverings for Steam-Pipes," tests of a great variety of substances by three methods; (1) by measuring the temperatures on the outside of the coverings; (2) by measuring the weight of steam condensed in a certain time over a certain length of covered pipe; and (3) by a calorimeter. His results are stated in such a way that the Author was unable to include them in the appended Table.

In 1884 Mr. J. J. Coleman gave² the results of a series of experiments (see Table below) on nine substances tested by means of a modification of Lavoisier ice calorimeter. The object of the experiments was to find the substance which would make the best covering for the "Bell-Coleman Freezing-Machines," now so much used in the transport of meat from the United States and the Colonies.

In 1884 Mr. D. K. Clark, M. Inst. C.E., reported³ to the National Smoke Abatement Institution the results of tests carried out at the works of Messrs. Samuel Hodge and Sons, Millwall, of seven substances as compared with a bare pipe. The results are not stated, however, in such a form that they can be included in the Table below.

In 1891 Mr. Hepworth Collins, read a Paper on "The Comparative Value of various Substances used as Non-conducting Coverings for Steam-Boilers and Pipes,"⁴ giving results of experiments in which a mass of each material to be experimented upon, 1 inch thick, was carefully prepared and placed on a perfectly flat iron plate or tray, which was then maintained at a constant temperature of 310° F. The heat transmitted through each non-conducting mass was calculated in lbs. of water heated 10° F. per hour.

RESULTS OF DIFFERENT EXPERIMENTS ON THE HEAT CONDUCTIVITIES OF
VARIOUS SUBSTANCES.

(Silicate cotton being taken as 100.)

Substance.	C. E. Emery, 1881.	J. J. Coleman, 1884.	W. H. Collins, 1891.	Prof. Jamieson, 1894.
Fossil meal composition . . . . .	..	..	..	70
Cement with hair-felt	83	..	..	93
Silicate cotton, or slag wool	100	100	100	100
Hair-felt or fibrous composition . . . . .	..	117	114	112
Papier maché . . . . .	..	..	147	111
Kieselguhr composition . . . . .	..	136	..	112
Sawdust	122	163	142	..
Charcoal	132	140	..	..
Cotton wool . . . . .	..	122	..	..
Sheep's wool . . . . .	..	136	..	..
Pine wood (across the grain)	150	..	..	..
Loam . . . . .	..	..	..	..
Gasworks breeze or coal ashes	240	230	299	..
Asbestos	229	..	179	..

¹ Transactions American Society of Mechanical Engineers, vol. v., 1883-84, p. 73.

² Proceedings Philosophical Society of Glasgow, vol. 15, 1883-84, p. 90.

³ *The Engineer*, vol. lvii., 1884, p. 65.

⁴ Report of the British Association for the Advancement of Science, Cardiff, 1891, p. 780.

APPENDIX II.

TESTS OF LAGGING FOR STEAM-PIPES.

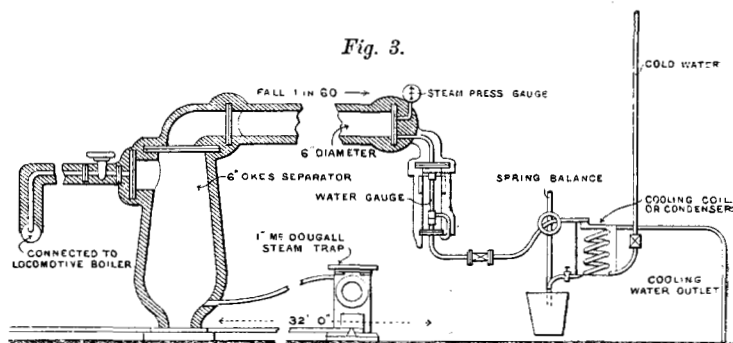
The Author has received permission to publish for the first time the following account of tests which have recently been made at an important works, the name of which, however, he has been requested to withhold. The results form an interesting comparison with those of the specimens D and G in the Paper.

Steam from a locomotive boiler (which was doing no other work), was passed through a separator to ensure its being delivered perfectly dry, into a 32-foot length of wrought-iron steam-pipe of 6 inches internal diameter and $\frac{1}{4}$ inch thickness, *Fig. 3*. This pipe for the whole of its length was covered with the non-conducting material to be tested. The condensed steam accumulated in a water-gauge placed at its lower end, from which it could be drawn off through a stop-cock into a receiver freely hanging on a spring-balance. The water-level in the gauge-glass was maintained as constant as possible, and the water

RESULTS OF TESTS.

Substances.	Pressure of Steam— Lbs. per Square Inch.	Lbs. of Steam Condensed per Square Foot of Internal Surface of Pipe per Hour.	Thermal Units radiated from Pipe per Hour.		Amount of Steam Condensed in Lbs. per Hour.	Percentage of Increase of High Pressure Steam Condensed.	Remarks.
			Per Square Foot of Internal Surface.	Per Square Foot of External Surface.			
Naked pipe . . .	{ 150 60	1·169 0·937	1,129 905	815 653	....	....	.. ..
Pipe covered with 2 inches of the material (G) in the Author's tests . . .	150	0·294	284	156	..	..	{ Tough, hard, and dark brown in colour, and makes a neat cover.
Pipe covered with 2 inches of the material (G) and $\frac{3}{4}$ inch of hair-felt . . .	150	0·216	212	98	11·1	..	
Pipe covered with 2 inches of the material (D) in the Author's tests . . .	{ 150 60	0·226 0·166	218 160	119 89	11·6 8·6	34·8	{ Very friable and difficult to apply without numerous cracks. Light yellow in colour. Does not last long.
Pipe covered with 2 inches of the material (D) and $\frac{3}{4}$ inch of hair-felt . . .	{ 150 60	0·188 0·125	182 121	86 56	9·7 6·5	49·0	
Pipe covered with $\frac{3}{4}$ inch of cork strips and two layers of canvas	{ 150 60	0·198 0·152	191 146	132 102	10·2 7·7	32·4	{ The felt improves its appearance and possibly also its lasting qualities. Easily applied, making neat cover. Joints easily accessible, but may possibly perish with the heat.

was cooled to atmospheric temperature in a condenser before being weighed. Readings of the spring-balance were taken every quarter of an hour, and



APPARATUS FOR TESTING LAGGINGS OF STEAM-PIPES.

Scale, $\frac{1}{4}$ inch to 1 foot.

were plotted upon curves. The trials were made at steam-pressures of 60 lbs. and 150 lbs. per square inch. The results are given in the Table on p. 300.

APPENDIX III.

TESTS OF ASBESTOS AND KIESELGUHR COMPOSITIONS.

The conductivities of asbestos and kieselguhr composition are indicated by the following account of experiments, which is taken from a letter received by the managing agents of the British India Steam Navigation Company from their Superintending Engineer at Calcutta, Mr. John G. Dobbie, and published by their permission:—

The experiments were made with two boiler-tubes— $3\frac{1}{2}$ inches in outside diameter and 7 feet long, closed at both ends, and covered with a thickness of 2 inches of asbestos and kieselguhr composition respectively. The tubes were suspended side by side, and steam was admitted at the top, a gauge-glass being fitted at the bottom of each by which the amount of condensation inside the tubes could be accurately observed. Steam at a pressure of 30 lbs. per square inch was used in the tubes. In the first trial, which lasted one hour, 12·375 inches of water were condensed in the tube covered with asbestos, and 8·375 inches in that covered with kieselguhr composition, showing 33 per cent. less water condensed with kieselguhr composition. In the second trial, of one hour also, the condensation was noted every fifteen minutes, and gave the results shown in Table on p. 302.

From these, and from several other tests which the Author has investigated since conducting his experiments, he has come to the conclusion that hard-pressed asbestos paper or cloth conducts heat much better than silicate cotton, felt, hair, wool, or some of the kieselguhr compositions. Fibrous porous matter acts well as a non-conductor mainly in virtue of the occluded and entrapped air, and hence, the looser the asbestos and other fibrous materials are laid on, the better will they prevent radiation of heat. Asbestos paper applied

between a high-pressure steam-pipe and hair-felt fails to prevent the hair from being scorched. Its incombustibility is evidently frequently assumed to include the distinct and separate property of non-conductivity.

RESULTS OF TESTS.

	Asbestos.	Kieselguhr Composition.
	Water Condensed in Inches.	Water Condensed in Inches.
After 15 minutes . . .	$4\frac{1}{4}$	$2\frac{1}{2}$
„ 30 „ . . .	$3\frac{3}{8}$	$2\frac{3}{8}$
„ 45 „ . . .	$3\frac{3}{8}$	$2\frac{1}{4}$
„ 60 „ . . .	$3\frac{3}{8}$	$2\frac{1}{8}$
Totals in one hour . .	$14\frac{3}{4}$	$9\frac{1}{4}$

This experiment shows a saving of 36 per cent. in favour of kieselguhr composition.