TRANSACTIONS.

I.—*An Account of some Experiments on Radiant Heat, involving an extension of Prevost's Theory of Exchanges.* By BALFOUR STEWART, Esq. Communicated by Professor FORBES.

(Read 15th March 1858.)

Division of Subject.

1. This paper consists of two parts, the first of which is confined to describing the experiments performed; while in the second it is attempted to connect these with certain theoretical views regarding Radiant Heat.

2. The experiments were made with a fourfold object; at least, for the sake of clearness, it is well to class them into four distinct groups:—

Group I. Contains those experiments in which the *quantities* of heat radiated from polished plates of different substances, at a given temperature, are compared with the quantity radiated from a similar surface of lamp-black, at the same temperature.

II. Those in which the *quantities* of heat radiated at the same temperature, from polished plates of the same substance, but of different thicknesses, are compared with one another.

III. Those in which the radiations, from polished plates of different substances at any temperature, are compared with that from lamp-black at the same temperature, with regard to the *quality* or *nature* of the heat radiated.

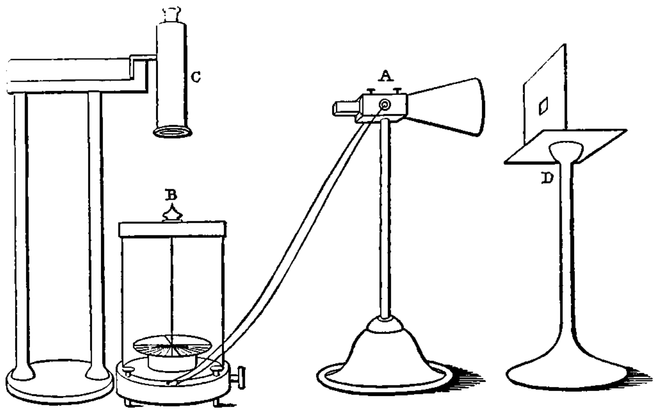
IV. Those in which the same comparison is made between the radiations from polished plates of the same substance, but of different thicknesses.

Instruments used, and Method of using them.

3. I am indebted to the kindness of Professor FORBES for the use of a delicate thermo-multiplier, consisting of the sentient pile, and its attached galvanometer and telescope; as well as for much valuable information with regard to the proper method of using the apparatus.

The following arrangement was adopted for the great mass of the experiments:—

A. Is the sentient pile, with a polished brass cone attached to it, for collecting the rays of heat.
B. Is the galvanometer, the position of its needle being read to $\frac{1}{10}$th of a degree by the telescope C.
D. Is a screen placed before the mouth of the cone in which there is a small hole or diaphragm ·65 inch square. The screen is covered with gilt paper, in order that, should it get slightly heated, it might radiate as little as possible.



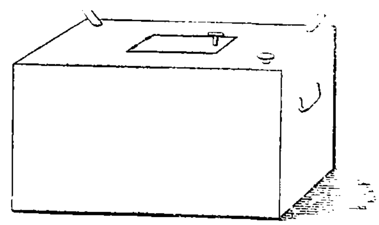
The heated body is placed behind the diaphragm, filling up the field of view from the cone; so that every ray reaching the cone from behind the diaphragm comes from the heated body.

In the following experiments, unless the contrary is mentioned, the distance of the diaphragm from the mouth of the cone is 2 inches.

The dimensions of the cone itself are as follows:—

Length of axis, or distance between centre of mouth and pile, . .	5 inches.
Diameter of mouth or opening, ...	2·6 inches.

The temperature to which the heated body was raised was generally 212°, and the apparatus used for heating it was of the following construction:—



It consisted of a tin vessel, having its top, bottom, and sides double (or a box within a box), and furnished on the top with a lid, also double, by means of which the body to be heated was introduced into the interior. Water was poured into the chamber between the outer and inner boxes, and allowed to boil; and, when the lid was shut, the temperature of the interior was found to rise very nearly to the boiling point; a thermometer placed in the air of the chamber showing a temperature of 200°, and when lying on the bottom, a temperature of 210°. When an observation was to be made, the hot body was taken out, and that surface which lay on the bottom of the inner chamber placed behind the diaphragm, so as to radiate into the cone. In the following experiments, unless the contrary is mentioned, the body has been heated in this manner.

The first swing of the galvanometer needle was taken as representing the intensity of the heating effect; and Professor FORBES has shown, in a paper read before this Society, 2d May 1836, that this will hold up to angles of about 20°, which is the maximum deviation used in these experiments.

Observations were always made with as little sunlight as possible; and under these circumstances, it was ascertained that the stray heat reaching the cone was inappreciable. The needle, it was calculated, reached the limits of its swing about 12 seconds after the heated body had been taken out of the boiling-water apparatus.

Experiments were made to ascertain if the body cooled sensibly during this short period of time, and it was found that its cooling was so trifling as not to interfere in any degree with the results of these observations. In the following experiments, it is therefore assumed that the body remains at its original temperature of 210° while the observation is being made.

Four observations were generally made, and three if they agreed together exceedingly well, but never fewer. Very often the agreement was exact.

First Group of Experiments described.

4. With these remarks, I proceed to describe the experiments belonging to the first group, or those made with the view of comparing the heat radiated from polished plates of different substances with that radiated from a surface of lamp-black at the same temperature.

The reason why lamp-black was chosen as the standard is obvious; for, it is known from LESLIE's observations, that the radiating power of a surface is proportional to its absorbing power. Lamp-black, which absorbs all the rays that fall upon it, and therefore possesses the greatest possible absorbing power, will possess also the greatest possible radiating power. The first substance compared with it was glass.

A. *Glass.*—A piece of plate-glass, ·3 inch thick, having paper coated with lamp-black pasted on its surface next the pile, gave a deviation of 18·1. This may be taken as the radiation from lamp-black.

Three plates of crown-glass, each ·05 inch thick, placed one behind the other, gave	17·7
A single piece of crown-glass of the same thickness gave . .	16·5

This difference is probably owing to the single plate cooling faster than the three plates. It may be argued that the radiation from glass is very nearly equal to that from lamp-black; and indeed this is already well known.*

B. *Alum.*—Here the boiling-water apparatus could not be used, since alum becomes calcined at a temperature much below 212°; but a self-regulating apparatus, invented by the late Mr KEMP, was employed instead, giving a steady temperature of 98°.

A piece of plate-glass ·18 inch in thickness gave	5·0
A piece of alum of the same thickness gave	5·0

The radiation from alum may therefore be reckoned equal to that from glass.

* See LESLIE's "Inquiry into the Nature and Propagation of Heat."

C. *Selenite.*—At the temperature of 98°—

A piece of selenite ·125 inch in thickness gave	5·1
Under the same circumstances, glass ·18 inch thick gave	5·0

In the boiling-water apparatus,

The same piece of selenite gave	18·0
While blackened glass gave	18·5

The radiation from selenite may therefore be reckoned equal to that from alum or glass.

D. *Mica.*—A small box was constructed, having two windows of mica, the thickness of the mica in the one being ·0009 inch, and of that in the other ·02 inch. This box was filled with mercury (Professor FORBES having suggested the use of that metal, to keep up the temperature, while interfering very little with the radiation). The whole was then set on a glass dish in the boiling-water apparatus.

The radiation from the thin window was,	11·2
While that from the thick window was,	12·7

As it would have been manifestly erroneous to compare these with the radiation from blackened glass lying in contact with the bottom of the apparatus, the thin window was removed, and blackened paper substituted in place of it.

While the thick mica window gave	12·7
The blackened paper gave	13·8

In comparing the radiations from the two windows, they were observed alternately. We see, therefore, that the radiation from mica, especially thin mica, is less than that from lamp-black in the proportion of 11·2 to 13·8, or the heat from thin mica is 80 per cent. of that from lamp-black.

E. *Rock-Salt.*—As in the experiments with rock-salt, it was desirable to obtain results of the greatest possible accuracy, the radiation from the rock-salt was not compared with that from blackened glass; for it was found that glass cooled more rapidly than rock-salt. The following plan was adopted:—

A piece of rock-salt ·18 inch thick (the temperature as in all the previous examples being about 210°), gave	3·2
A canister with water kept boiling, coated with lamp-black,	22·0

In order to estimate how much the rock-salt had cooled during the observation, the following experiment was made, without any diaphragm:—

Rock-salt ·18 inch thick taken to the cone at once, gave	5·1
After cooling for 15 seconds, it gave	4·9

It will be seen from this, that were the rock-salt, instead of cooling during the 12 seconds necessary for the observation, kept at the temperature of 212°, it would not have given more than 3·3, while the hot-water canister gave 22·0.

5. From these experiments, it appears that glass, alum, and selenite, at low temperatures, have an intensity of radiation very nearly equal to that from lamp-black; while mica radiates somewhat less, and rock-salt greatly less. This is shown by the following table:—

TABLE I.

Radiating Substance.	Temperature.	
	212°	98°
Lamp-black,	100	
Glass,	98	27
Alum,		27
Selenite,	98	27
Thick mica,	92	
Thin mica,	81	
Rock-salt,	15	

Second Group of Experiments described.

6. I now proceed to the second group of experiments, or those designed to compare together the quantities of heat radiated at the same temperature from polished plates of the same substance, but of different thicknesses.

A. *Glass.*—No direct experiment of this kind was made on glass; for although a thick plate gave a somewhat greater radiation than a thin plate, it was imagined that this was due to the unequal cooling of the two plates. Indirectly, however, we may gather that thick glass radiates somewhat more than thin glass, from the following experiment, which belongs more properly to the fourth group:—

A plate of crown-glass ·05 inch thick, being placed before the cone as a screen, and a similar plate ·05 inch thick, and 3·75 inches square, being used as the source of heat at a distance of 6 inches, and no diaphragm used, the deviation was	0·95*
But when the source of heat was a similar plate ·10 inch thick, the deviation became	1·45

Such a difference cannot be accounted for by the unequal cooling of the plates; and it would seem to indicate that a small quantity of heat from the interior of the thick plate reached the surface; which heat, having already been sifted by its passage through glass, was easily able to pierce the screen.

In another similar experiment,

One plate of crown-glass ·05 inch thick, gave a deviation of	1·1
Two plates ·05 inch thick, the one behind the other,	1·55
Three such plates,	1·9

B. and C.—No experiments of this kind were attempted with alum or selenite.

* Without any screen, it was calculated that the intensity of effect would have been equal to about 150°.

D. *Mica.*—Experiments similar to those already described, only at a distance of $2\frac{1}{2}$ inches from the cone, gave—

For mica, ·0009 inch thick (average of two sets of experiments),	8·2
For mica, ·02 inch thick (average of two sets of experiments),	9·3

The experiments already quoted, which were made at a shorter distance from the pile, gave—

For mica, ·0009 inch thick,	11·2
For mica, ·02 inch thick,	12·7

E. *Rock-Salt.*—Three pieces of rock-salt were used. Their dimensions were—

	1st Piece.	2d Piece.	3d Piece.
Length,	1·15 inch	2·15 inch	2·5 inch
Breadth,	1·15 ...	1·4 ...	1·4 ...
Thickness,	0·18 ...	0·36 ...	0·77 ...

For these pieces, as well as for the other substances, I am indebted to the kindness of Professor FORBES. When placed behind the diaphragm, the farthest off surface was large enough to fill up the field of view,—that is to say, all rays from the cone striking the nearest surface, struck also the surface farthest off; the distance between the two surfaces being the thickness of the piece.

The following are the means of four sets of experiments:—

Radiation from 1st or thinnest piece,	3·4
... 2d or middle piece,	4·3
... 3d or thickest piece,	5·3

This proves that more heat is radiated by a thick than by a thin piece of rock-salt.

The following experiments were devised by Professor FORBES, to confirm the above results.

(*a.*) The second piece of rock-salt was placed obliquely behind the diaphragm, making an angle of 20° with the prolongation of the axis of the cone. A piece of fir-wood of the same dimensions was placed in the same way. The two substances being compared in this position, and also in the usual position behind the diaphragm (viz., perpendicular to the direction of the cone's axis), the following was the result:—

	Oblique.	Usual position.
Rock-salt ·36 inch thick,	4·0	4·0
Wood, same size as rock-salt,	9·1	14.1

In order that this experiment may be understood, it may be well to mention. that, when the plate was placed obliquely behind the diaphragm, it did not quite fill up the field of view. Hence the wood gave out less heat to the cone in this than in its ordinary position.

It appears, therefore, that the radiation from rock-salt, in a direction making a small angle with the surface, bears a greater proportion to the corresponding radiation from wood than when both radiations are taken perpendicular to the surface. The reason undoubtedly is, that in the former case the rays come from a greater thickness of the substance, so that their intensity is increased.

(β.) The middle-sized piece of rock-salt was bound tightly to the thickest piece, with a slip of tin-foil between, so that the whole might cool as one piece, and thus obviate any objection that might be brought against the results, founded on the unequal cooling of the plates, owing to their thicknesses being different.

The surface of the middle-sized piece facing the pile, gave	6·3
That of the thickest piece, gave	8·1

The plates, therefore, still retained their inequality of radiation; but the amount from each was increased, owing, no doubt, to reflection and radiation from the tin-foil. The radiation from the tin-foil may be estimated at 1·0, deducting which, we have 5·3 and 7·1; the increase now being due to reflection from the tin-foil.

7. It thus appears, that while the difference between the radiating power of thick and thin glass is so small as not to be capable of being directly observed, there is a perceptible difference between the radiation from thick and thin mica, and a still more marked difference between the radiation from plates of rock-salt of unequal thickness.

But (at least with the thicknesses used) the greatest radiations from mica and rock-salt were still below that from lamp-black, and the radiation from rock-salt greatly so.

The following table exhibits the results of the second group of experiments:—

TABLE II.

Substance.	Radiation from thick plate.	Radiation from thin plate.
Glass, ...	100	100
Mica, . . .	100	89
Rock-salt, ...	100	Middle 81 thin 64

Third Group of Experiments described.

8. I now proceed to consider the third group of experiments, or those made with the view of comparing the radiations from various polished surfaces with that from lamp-black, as regards the *quality* of the heat; its quality being tested by its capability of transmission through a screen of the same material as the radiating plate.

A. *Glass.*—In an experiment already described, where a plate of crown-glass ·05 inch thick was used as a screen, and a similar plate of crown-glass as the source of heat—

We had, ...	0·95
A similar plate ·1 inch thick as the source of heat, gave	1·45
Blackened paper attached to a similar surface of plate-glass, ·3 inch thick, the blackened side being next the pile, ...	1·95

Therefore heat from a thin plate of glass is less transmissible through glass than heat from blackened paper.

B. and C.—No experiment of this nature was made with alum or selenite.

D. *Mica.*—The apparatus already described gave—

	Without screen.	With mica screen, ·0025 inch thick.
For window (the window, it will be borne in mind, is the radiating surface), ·0009 inch thick, ...	11·2	2·5
Window ·02 inch thick, ...	12·7	3·2
Blackened paper attached to glass lying on the bottom of the boiling-water apparatus, gave	21·0	6·3

We have therefore the proportion of heat passed by mica screen—

For heat from thin mica window, ...	·223
... thick	·260
... blackened paper, ...	·300

E. *Rock-Salt.*—The thickest piece of rock-salt (thickness ·77 inch) being used as a screen, and the diaphragm withdrawn, in order to give greater results; the middle-sized piece of rock-salt gave—

With screen.	Without screen.
6·1	19·6

The same screen stopped 3 rays out of 12 for *ordinary* lamp-black heat.

This experiment is sufficient to show that rock-salt is much less diathermanous for heat from rock-salt than for ordinary heat. The common opinion, that rock-salt is equally diathermanous for all descriptions of heat, is therefore untenable.

9. From the third group of experiments it appears, therefore, that heat emitted by glass, mica, or rock-salt, is less transmissible through a screen of the same material as the heated plate, than heat from lamp-black; this difference being very marked in the case of rock-salt.

Fourth Group of Experiments described.

10. I now proceed to the fourth group of experiments, or those made with the view of comparing the radiations of plates of the same substance, but of different thicknesses, with regard to the quality of the heat radiated.

A. *Glass.*—It has been already shown (Art. 8), that heat from crown-glass ·05 inch thick is less transmissible through glass, than that from crown-glass ·10 inch thick.

B. and C.—No experiments of the kind were made on alum or selenite.

D. *Mica.*—It has been already shown (Art. 8), that heat from thin mica is less transmissible through a mica screen than heat from thick mica.[1]

E. *Rock-Salt.*—With a screen of rock-salt ·18 inch thick, the following result was obtained:—

Thickest piece of rock-salt, heated to 210°	(thickness ·77 inch), gave	2·5
Middle sized	(thickness ·36 inch), gave .	1·7
Thinnest piece	(thickness ·18 inch), gave .	1·1

Without any screen, the same pieces gave—

Thickest,	4·9
Middle-sized,	4·1
Thinnest,	3·3
Proportion of heat from thickest piece passed,	·51
... ... middle-sized ...	·41
... ... thinnest ...	·33

A similar experiment, with a screen ·29 inch thick, gave—

	With screen.	Without screen.	Proportion passed.
Thickest piece,	2·6	5·4	·48
Middle-sized,	1·8	4·5	·40
Thinnest,	1·2	3·5	·33

It follows from this, that a screen of rock-salt passes heat from thick, more easily than heat from thin rock-salt.

11. From this fourth group of experiments, we learn that heat from thick plates of glass, mica, or rock-salt, is more easily transmitted by screens of the same nature as the heated plate than heat from thin plates of these materials.

The following table exhibits the results of the third and fourth group of experiments:—

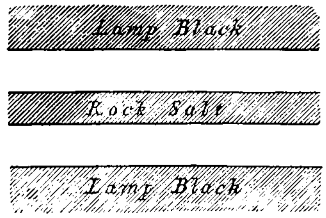
TABLE III.

Source of Heat.	No. of Rays out of every 100 that pass through a screen of the same material as the source of Heat in 1st column, the screen being of only one thickness for each material.	No. of Rays of Lamp-black Heat, out of every 100 that pass through the same screen.
Glass (crown $\frac{1}{20}$th inch thick),	0·66	1·33
Glass (crown $\frac{1}{10}$th inch thick),	1·0	
Mica (thickness ·0009 inch),	22	30
Mica (thickness ·02 inch),	26	
Rock-salt (thickness ·18 inch),	33	82 (Art. 12)
Rock-salt (thickness ·36 inch),	41	
Rock-salt (thickness ·77 inch),	50	

Results deducible from the foregoing Experiments.

12. These experiments, as well as others yet to be described, may be explained by PREVOST's theory of exchanges, somewhat modified.

In the first place, it would seem to be a consequence of this theory, that radiation must take place from the interior as well as from the surfaces of bodies. For suppose that we have two indefinitely extended surfaces of lamp-black, as in the figure, and between them a plate of rock-salt of a certain thickness, also indefinitely extended; and let the whole be kept at the same temperature. Then, since the temperature of the rock-salt remains the same, it must radiate as much as it absorbs. But a thicker plate of rock-salt, placed under the same circumstances, would absorb more of the heat radiated from the lamp-black, because each ray would have to pass through a greater depth of the substance of the salt; hence a thick plate of rock-salt must radiate more than a thin plate. We see, likewise, the reason for the small radiative capacity of rock-salt to be its small absorptive capacity. In order to prove this deduction from PREVOST'S theory experimentally true, the following experiment was devised:—



A boiling-water canister, coated with lamp-black, was put behind the diaphragm, filling up the field of view, and the three pieces of rock-salt heretofore used as sources of heat, were now separately used as screens, being put before the diaphragm, so that the heat from the canister had to pass through their subtance before reaching the cone. The following was the result:—

	Without any Screen.	Screen of Rock-salt, ·18 inch thick.	Screen of Rock-salt, ·36 inch thick.	Screen of Rock-salt, ·77 inch thick.
Radiation from Canister, .	21·3	17·6	16·8	15·8

The difference between heat absorbed by plate, thickness = ·18 inch,
And that absorbed by plate, . . thickness = ·36 inch, Is 1·2 } Mean 1·1
Another similar experiment gives . . . 0·9

The difference between heat absorbed by plate, thickness = ·36 inch,
And that absorbed by plate, . . thickness = ·77 inch, Is 1·0 } Mean 1·1
Another similar experiment gives . . . 1·3

These should nearly correspond with the differences between the radiations from the same plates, under their ordinary circumstances of position (if the theory be true which asserts that the absorption of such a plate equals its radiation); accordingly we find that

The difference between heat radiated by plate, thickness = ·18 inch,
And that radiated by plate, . thickness = ·36 inch, Is 0·9

While the difference between radiation of plate, thickness = ·36 inch,
And that ... ... of plate, ... = ·77 inch, Is 1·0
(Art. 6, mean of four sets of experiments).

We see, therefore, that there is an agreement between the two sets of differences, as near as can be reasonably expected.

13. If we now suppose a plate of glass, and not a plate of rock-salt, placed between surfaces of lamp-black, the plate, whether thin or thick, will allow scarcely any heat to pass through it; and, consequently, plates of different thicknesses will all absorb very nearly the same amount,—that is, nearly all that enters them. In this case, therefore, the radiation (which is equal to the absorption) will be very slightly increased by an increase of thickness of the plate. Also the amount

of heat radiated, being equal to the heat absorbed, will be very nearly as great as that from lamp-black.

14. There are, therefore, two peculiarities of the radiation from plates of diathermanous substances, and which are most marked for those substances which are most diathermanous.

1*st*, That the amount of radiation from such plates is less than that from lamp-black.

2*d*, That the amount of radiation from such plates increases with the thickness of the plate.

The correlation between these different properties of bodies is seen from the following table:—

TABLE IV.

Bodies ranked according to their Radiating Capacity (least radiating first).	Bodies ranked according to their Diathermancy (most diathermanous first).	Bodies ranked according to the proportion by which their Radiation is increased by increasing the thickness.
A stratum of heated gas (from Melloni's Experiments),	A stratum of gas.	...
Rock-salt.	Rock-salt.	Rock-salt.
Mica.	Mica.	Mica.
Glass. }	Glass. }	Glass.
Selenite. }	Selenite. }	...
Alum. }	Alum. }	...

15. The reason why radiation has hitherto been supposed to be confined to the surface, or to an exceedingly small distance below the surface of a body now becomes obvious. The effect of coating a surface of polished metal with gum, for instance, is to increase the radiation; but, after a very small thickness of film, an additional coating is powerless to increase the radiation; the reason being, not that radiation is incapable, in all cases, of taking place, except at the surface; but because, such films being exceedingly impervious to heat of low temperatures, the radiation from them is very little increased by increasing their thickness.

Since, therefore, it appears that radiation takes place from the interior as well as from the surface of bodies, the question arises, are we to suppose each particle of each substance to have, at a given temperature, an independent radiation of its own, equal, of course, in all directions? *A priori*, this is the most probable supposition, and it seems likewise to be conformable to experiment.

In an experiment already described,

A plate of crown-glass ·05 inch in thickness being used as a screen, the quantity of heat radiated from crown-glass ·05 inch thick that passed, was . .	0·95
While of that radiated from crown-glass, ·10 inch thick, there passed . .	1·45

Another experiment gave—

Quantity of heat from crown-glass ·05 that passed, ...	1·1
Quantity radiated from two plates of crown-glass, each ·05 inch thick, the one placed loosely behind the other, ...	1·55

From this we may infer, that the radiation from two plates of glass placed loosely behind each other, is the same as the radiation from a plate of double the thickness, and, consequently, that the radiation from a particle of a substance does not diminish, owing to its being placed in the interior.*

17. Let us now refer to the radiations from rock-salt:—

The radiation from a piece ·18 inch thick, was . . .	3·4
That from a piece ·36 inch thick, was . . .	4·3
That from a piece ·77 inch thick, was . . .	5·3

Now, if we suppose the radiation of a particle in the interior to be as intense as that of a particle at the surface, why, it may be asked (since rock-salt is extremely diathermanous), does not a piece of double the thickness give nearly a double radiation, and so on, the radiation increasing very nearly as the thickness?

If we still hold the doctrine of an equal and independent radiation from every particle, we are shut up to the conclusion that rock-salt must be comparatively opaque to heat radiated by itself,—a result which is abundantly confirmed by experiment.

Thus, while the radiation from rock-salt ·18 inch thick, without any screen, is 3·4, with a screen of rock-salt ·18 inch thick it becomes 1·1.

If, therefore, we have a piece of rock-salt of double this thickness, or ·36 inch thick, we should expect that the radiation from it would be $=3{\cdot}4+1{\cdot}1=4{\cdot}5$. It is, in fact, 4·3. The difference (0·2) being within the limit of error of observation.

In rock-salt, therefore, we may suppose each particle to have an independent radiation of its own, unaffected by its distance from the surface.

18. We see, therefore, that the opacity of rock-salt with regard to heat radiated by itself, is a consequence of the admission, that the radiation from rock-salt does not increase so rapidly as the thickness increases; and this again results from the fact, that the absorption of heat by a plate of rock-salt does not increase so rapidly as the thickness increases. This, again, is due to the fact, that the first part of the plate of rock-salt sifts the heat so that it is more easily transmitted by the second part; and this confirms the results arrived at by Professor FORBES, who, finding that rock-salt stopped heat of low temperature rather more

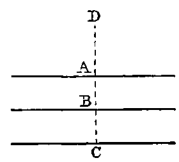
* The idea of this experiment was derived from a remark of Professor FORBES, who suggested that several plates of rock-salt, the one behind the other, might be advantageously substituted for a thick plate of the same material, as giving the very same result.

readily than heat of high temperature, concluded that there are a few rays for which rock-salt is opaque.*

We conclude, therefore, that every body which sifts heat in its passage through its substance, is more opaque with regard to heat radiated by a thin slice of its own substance, than it is with regard to ordinary heat.

19. This conclusion may be also stated thus: We have before proved (Art. 12.) that the radiation of a thin slice of any substance equals its absorption; we now add, that the heat radiated is the same as that absorbed, with regard to quality as well as quantity.

For this expresses the fact, that substances which sift heat are likewise opaque with respect to heat radiated by themselves. For, since the heat which they absorb is manifestly that kind of heat for which they are opaque, if the description of heat radiated is the same as that absorbed, then they will also be opaque with respect to heat radiated by themselves. Considering, therefore, the heat of any temperature to consist of heterogeneous rays, we may state the law thus: "*The absorption of a plate equals its radiation, and that for every description of heat.*"



20. A more rigid demonstration may be given thus:—Let AB, BC be two contiguous, equal, and similar plates in the interior of a substance of indefinite extent, kept at a uniform temperature. The accumulated radiation from the interior impinges on the upper surface of the upper plate; let us take that portion of it which falls on the particle A, in the direction DA. This ray, in passing from A to B will have been partly absorbed by the substance between A and B; but the radiation of the upper plate being equal to its absorption (since its temperature remains the same), the ray will have been just as much recruited by the united radiation of the particles between A and B, as it was diminished in intensity by their absorption. It will therefore reach B with the same *intensity* it had at A. But the *quality* of tne ray at B will also be the same as its *quality* at A. For, if it were different, then either a greater or a less proportion would be absorbed in its passage from B to C, than was absorbed of the equally intense ray at A, in its passage between A and B. The amount of heat absorbed by the par-

* To take a numerical example, let us suppose the heat from a single plate of rock-salt to be $=1$, then the heat from a plate four times the thickness, or (which is the same thing) the heat from four single plates, one behind another, should be nearly four times as much, or $=4$ (if we suppose the heat from each of these four plates to be readily passed by the plates between it and the pile), but the heat from the fourfold plate, instead of being four times as much, is not double of the heat from the single plate; hence, the heat from any of the interior plates of the compound plate is passed with great loss, by the plates between it and the pile. Now, since the absorption of a plate equals its radiation, the reason why the fourfold plate scarcely radiates twice so much as the single one is, that it scarcely absorbs twice as much; and this again is due to the fact, that the heat after it has passed the first plate of the fourfold plate has become sifted, and passes with little diminution of intensity through the other three plates.

ticles between B and C would therefore be different from that absorbed by the particles between A and B. But this cannot be; for, on the hypothesis of an equal and independent radiation of each particle, the radiation of the particles between B and C is equal to that of the particles between A and B, and their absorption equals their radiation. Hence the radiation impinging on B, in the direction of DB, must be equal in quality as well as quantity to that impinging upon A; and, consequently, the radiation of the particles between A and B must be equal to their absorption, as regards quality as well as quantity; that is, this equality between the radiation and absorption must hold for every individual description of heat.

21. The following experiment illustrates this law:—

The quantity of heat radiated from crown-glass ·05 inch thick, which passes through a crown-glass screen, ·05 inch thick, ... =0·95

While that from plate-glass ·3 inch thick, covered with blackened paper (the blackened paper being next the pile), which passes through the same screen, =1·95

But, if the surface of crown-glass ·05 inch thick, farthest from the pile be coated with paper, the polished surface being next the pile, then the amount of radiation which passes the screen, ... =1·85

And if three plates, the one behind the other, of crown-glass, each ·05 inch thick, be used as the source of heat, the surface farthest from the pile of the farthest off plate only being covered with paper, the amount of radiation which passes the screen, ... =1·95

Such a plate of glass, or series of plates, therefore, by having the farthest off surface coated with paper, gives out heat similar to that from paper or lamp-black; the reason being, that the heat from the paper on the farthest off surface is as much recruited as it is absorbed by its passage through the glass, both as regards quantity and quality; so that the radiation which falls upon the cone is virtually that from paper or lamp-black.

22. There is little difficulty in explaining why heat from a thick plate of any substance should pass more readily through a screen of the same substance than that from a thin plate. The reason is, that the heat from the interior of the thick substance, having been sifted in its passage, is, therefore, now more easily able to pass through a screen of the same substance.

23. We see also why, generally speaking, bodies at the same temperature radiate the same quality of heat; let us, for instance, take a tolerably thick plate of glass, and a surface of lamp-black, and compare them together. Since the plate of glass absorbs nearly all the rays that fall upon it, it will radiate nearly as much as lamp-black; and since the quality of the radiated is the same as the quality of the absorbed heat, its radiated heat will very nearly have the same quality as that which is radiated by lamp-black.

The Influence of the Reflective and Refractive Powers of Bodies on their Radiation considered.

24. Hitherto, in these investigations, no account has been taken of reflection at the surfaces of the plates, because—1*st*, those rays only were considered which

passed perpendicularly, or nearly so, through such plates; and, 2*d*, because the indexes of refraction for the substances experimented on were not very high.

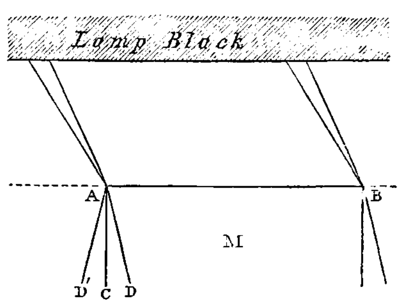
But for rays passing obliquely through such media, or for rays passing in any direction into substances, such as metals, we must take account of reflection from the surface, which will influence materially our results.

Thus, no substance is so opaque for heat as metals, but yet only a small portion of the heat falling on them is absorbed, the rest being reflected back; consequently for such bodies the radiation (which must be equal to the absorption) is very small.

It is also desirable, for another reason, to investigate the laws according to which the reflective nature of the surface of a body influences its radiation. For the question arises, Is the law of an equal and independent radiation of each particle of a body theoretically consistent with equilibrium of temperature? That is, suppose we have any irregularly-shaped inclosure walled round with a variety of substances, and each particle of each substance radiating into the inclosure, from the sides of which it is reflected many times backwards and forwards before it is finally absorbed,—this being the case, will the law of equal and independent radiation, and those of reflection and refraction, so fit with one another, that every particle of the walls of the inclosure shall absorb precisely as much heat as it radiates? It will be endeavoured to show that these laws are so adapted to each other; and I shall select for the proof a definite form and description of inclosure, the conclusions arrived at rendering it highly probable (if not rigidly demonstrating) that the same adaptation will hold good for every inclosure, however irregular or varied.

For those reasons, I shall now endeavour to investigate what connection the radiation of a substance has with the reflective power of its surface; and in doing so (in order to abstract entirely from the effects produced by the variable thickness of the radiating plate), I shall suppose it to be of indefinite thickness; so that all the heat which enters it is absorbed. Our consideration is, therefore, limited to the effects of *one* surface.

25. Let AB be a portion of the line of section of an indefinitely extended surface with the plane of the paper supposed perpendicular to the surface, and let this surface belong to a body (M) of indefinite thickness downwards; also let there be an indefinitely extended surface of lamp-black parallel to this lower surface, as in the figure. Lastly, let the whole be kept at a uniform temperature. In order that the body (M) may be maintained at this temperature, it is necessary that the heat which has left the surface AB, having come from the interior of (M), in the directions contained in any very small angle CAD, shall be replaced by an equal quantity of



heat entering the surface AB, to diverge into the interior through the same small angle CAD. For, by this arrangement, it is clear the particles in CAD get back as much heat as they give out.

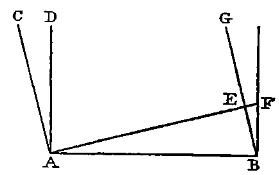
Part of the heat, no doubt, which fell on A in any direction DA, would be reflected back in the direction AD′, making the same angle with the surface as AD; but this loss would be made up for by part of the heat falling on A, in the direction D′A, being also reflected back in the direction AD.

The internal reflection at A being thus compensated for, if the heat that really leaves the medium be also compensated for, then as much heat will be passing at A in the direction AD as will be passing in the direction DA. It will be the same, therefore, as if the body, instead of having a surface at A, were indefinitely extended upwards from A, as well as downwards; in which case, as has been already shown (Art. 20), there will be equilibrium of temperature, provided that the radiation of a particle is equal to its absorption, and that for every description of heat.

Before proceeding further with this investigation, it will be necessary to establish some preliminary propositions.

26. 1*st Preliminary Proposition.*

The heat which falls on the line AB in the directions contained in the very small angle CAD, is the same which falls on AE, perpendicular to EB, through the same very small angle. For every ray which fell on AB passed through AE, with the exception of a small quantity which passed through EF; but the angle EBF being very small, EF is very small compared with AE, and consequently the heat falling on EF may be neglected in comparison with that falling on AE.



It is clear also, that the heat falling on AB is proportional to AB, and to the size of the very small angle CAD.

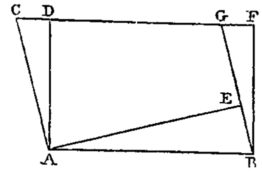
The above will still hold, if, instead of the substance of which AB is the surface being supposed below AB, and the rays falling on it through a vacuum, we suppose the substance to be indefinitely extended upwards, and the rays to originate in the substance itself, and fall on its surface AB.

For, although any ray GE, which falls on E, will be partly absorbed between E and B, it will be as much recruited by the united radiation of the particles between E and B as it was absorbed; so far, indeed, as regards quality and intensity (from what has been already proved, Art. 20), we may consider such a ray to be traversing a vacuum, it being recruited just in proportion as it is absorbed.

It is evident, also, that in this case the quantity of heat falling on AB will be proportional to the size of the very small angle CAD.

27. *2d Proposition.*

1st Case.—If AB represent a surface (the substance being below AB), and CF a surface of lamp-black indefinitely extended (as in Art. 25), from which rays fall on AB through a small angle CAD; then, if AE be drawn perpendicular to GB, the heat that falls on AB will = a constant × AE, whatever be the value of the angle CAB.



For, since the angle CAD is exceedingly small, CD may be considered very small in comparison with CF or CG; therefore the heat which impinges on AB through the angle CAD may be taken to be that which radiates from CG in directions between CA and DA; but, since the radiative power of lamp-black in any direction varies as the sine of the angle which that direction makes with the surface, this will = const. × AE. Hence, if R × CAD be the quantity of heat which falls on AB, when AB is perpendicular to GB, that which falls on it when GB makes any angle GBA with AB, will be R × CAD sin GBA.

If i denote the angle which GB makes with the perpendicular to AB, then the heat impinging on AB will be R cos. i × CAD.

2d Case.—If the substance be above AB, and the rays falling on AB originate in the substance, the same formula will hold; for it has been shown, in Prop. 1st, that in this case, the heat falling on AB through the small angle CAD = that which falls on AE through the same small angle; but, since the radiation from the interior of the substance is the same in all directions (each particle radiating independently and equally in all directions), the amount falling on AE will not be affected by the angle which AE makes with the surface; hence the heat falling on AB = const. × AE = const. × sin GBA.

If R′ × CAD = quantity which falls on AB when AB is perpendicular to GB, that which falls on it when GB makes any angle GBA with AB, will be R′ × CAD sin GBA; also the expression corresponding to R cos i × CAD will be R′ cos i' × CAD.

28. *3d Proposition.*

Let a ray strike the surface of a medium, at an angle of incidence $= i$; and another ray at an angle of incidence $i + \delta i$, it is required to find the difference between the two angles of refraction.

Let μ be the index of refraction, then,

$$\sin i = \mu \sin i'$$

Hence,

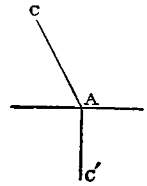
$$\delta (\sin i) = \mu \delta (\sin i')$$

$$\cos i \, \delta i = \mu \cos i' \delta i'$$

Hence,

$$\delta i' = \frac{\cos i}{\mu \cos i'} \delta i$$

29. I shall also make the following supposition with regard to the laws of reflection and refraction.



1*st*, That if Q represent the quantity of heat falling on the surface of a medium in any direction CA, and aQ be the quantity of heat reflected, then $(1-a)$ Q is the quantity of heat refracted into the medium in the direction AC′. This follows from the law of the conservation of *vis viva*.

2*d*, That if the same heat Q originate in the medium, and strike A in the direction C′A, the quantity reflected back into the medium will be aQ, and the quantity refracted out in the direction AC will be $(1-a)$ Q.

30. These preliminary propositions being established, and suppositions made, let us suppose that heat from the surface of lamp-black strikes the surface AB of the indefinitely thick medium (Fig. Art. 25) through a small angle δi (i being the angle of incidence), by Proposition 2d, the quantity of this heat will be $R \cos i\delta i$; while the part of it which enters the substance we shall call $(1-a) R \cos i\delta i$. These rays will diverge in the substance through an angle $\delta i' = \frac{\cos i}{\mu \cos i'} \delta i$ (Prop. 3).

But the quantity of heat that falls on AB from the interior through this angle will be

$$R' \cos i'\delta i' = R' \cos i' \frac{\cos i}{\mu \cos i'} \delta i = \frac{R'}{\mu} \cos i\delta i,$$

and the portion of this which leaves the medium will be $\frac{(1-a) R' \cos i\delta i}{\mu}$.

Equating this with $(1-a) R \cos i\delta i$, which enters the medium, we have $\frac{R'}{\mu} = R$ or $R' = \mu R$. With this supposition, therefore, the law of an equal and independent radiation of each particle will give us equilibrium of temperature in the particular case under consideration. Had R′ been a function of i', it would have shown that the law of an equal and independent radiation was inconsistent with equilibrium of temperature.

31. Only part, however, of the heat from the lamp-black falling on AB entered into the medium, a portion of it $= aR \cos i\delta i$ being reflected back to the lamp-black, hence the total quantity of heat radiated and reflected which leaves the surface AB through the small angle δi will be $= R \cos i\delta i$, the same as if the substance had been lamp-black, the only difference being, that, in the case of lamp-black, *all this heat is radiated*, whereas in other substances *only part is radiated, the remainder being reflected heat*.

32. Although we have considered only one particular case, yet this is quite sufficient to make the general principle plain. Let us suppose we have an inclosure whose walls are of any shape, or any variety of substances (all at a uniform temperature), the normal or statical condition will be, that the heat, radiated and reflected together, which leaves any portion of the surface, shall be equal to the radiated heat which would have left that same portion of the surface, if it had been composed of lamp-black. And, indeed, we may see, from what has been

already proved, that, should such a state of things only once take place, it would always remain, there being no disposition to alter it.

Let us suppose, for instance, that the walls of this inclosure were of polished metal, then only a very small quantity of heat would be radiated; but this heat would be bandied backwards and forwards between the surfaces, until the total amount of radiated and reflected heat together became equal to the radiation of lamp-black.*

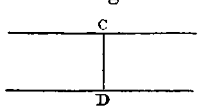
33. The equation $R' = \mu R$ must necessarily hold for every individual description of heat. We have, therefore, two laws necessary to the equilibrium of temperature,—1*st*, That the absorption of a particle is equal to its radiation, and that for every description of heat; 2*d*, That the flow of heat from the interior upon the surface of a substance of indefinite thickness, is proportional *cæteris paribus* to its index of refraction, and that for every description of heat. It will, however, be borne in mind, that the former of these laws has been verified by experiment, while the latter is only deduced from a theoretical investigation. It will also be seen, that by increasing the thickness of the radiating plate indefinitely, the radiation becomes ultimately independent of the diathermancy of the plate and is regulated only by its refractive index.

34. The connection which we have attempted to trace between the refractive and radiative power of a substance, presumes that those rays which we have been considering, have the power of forming wave lengths within the medium under consideration; that is, of being capable of proper reflection and refraction.

It may be, however, that glass and other similar substances are so opaque, with respect to most of the rays of heat of low temperature, as to stop them almost entirely at the surface.

As such rays may, therefore, be conceived to be absorbed within the limit of the physical surface of the medium, the corresponding radiation may be conceived to proceed from this physical surface. To such a case we may perhaps suppose reasoning similar to that of FOURIER (as given by Professor FORBES in the

* This will be clearly seen if we consider only those rays that are radiated perpendicular to the surface in the case of two parallel plates of polished metal of the same description radiating to one another. For let r be the common radiation of the point C in direction CD, and of the point D in the direction DC, then since these radiations are bandied backwards and forwards in the directions CD, DC, until they are extinguished, we have the total quantity of heat falling on D in the direction CD (if ar denote the proportion of r reflected after one single reflection) expressed as follows:—



$$\text{Total heat radiated and reflected, falling on D} = \left\{ \begin{array}{c} r + a^2r + a^4r + \text{, \&c.} \\ + ar + a^3r + a^5r + \text{, \&c.} \end{array} \right\} \begin{array}{l} = r(1 + a + a^2 + a^3) \\ = \dfrac{r}{1-a} \text{ (since } a<1) \end{array}$$

But $1-a$ denotes the absorptive power of the metallic surface (all the heat not reflected being absorbed). Hence, since the radiative powers of bodies are proportional to their absorptive powers (LESLIE'S Inquiry), 1 being the absorptive power of lamp-black, the perpendicular radiation of a lamp-black point will be $= \frac{r}{1-a}$ which is the very same expression we have obtained for the total heat radiated and reflected together, falling on D, in the same perpendicular direction from the metallic point C.

Philosophical Magazine for Feb. 1833) to be applicable; the intensity of radiation being therefore proportional to the sine of the angle which the direction makes with the surface.

35. Let us now see, in conclusion, whether these investigations seem to point out any connection between internal radiation and conduction.

Now, without in the least affirming that these are identical, there seem to be two points of similarity between them.

1*st*, Since the heat which enters metals is all absorbed at a very small depth, it follows that the flux of radiant heat from within upon the interior of a metallic surface is derived from a very small depth.

Also, if we allow (what it has been endeavoured to prove, Art. 30) that the flux of heat upon the interior of a surface is proportional to the index of refraction, this flux will be greatest in the case of metals, which may be supposed to have a very high refractive power; besides which, it will, as we have seen, be derived from a very small depth. The radiation of a metallic particle is therefore very great.

Now, if internal radiation be in any way connected with conduction, we might expect that good conducting substances should also be good internal radiators of heat, and we see they are so.

2*d*, The second bond of similarity is this. It seems to be a law that substances are almost invariably more diathermanous for heat of high temperature than for heat of low; consequently, at high temperatures, the radiation of a thin plate or particle of a substance will bear a smaller proportion to the total lamp-black radiation of that temperature than at low temperatures. The internal radiations of particles of bodies would therefore diminish at high temperatures (not absolutely, but with respect to the proportion which they would bear to the total radiation of these temperatures). If the same rule holds for metals, and conduction be connected with internal radiation, we should expect that at high temperatures the conducting power of metals would be less than at low temperatures. Now this has been proved to be the case by Professor FORBES.

9th March 1858.