December 22, 1887.

Admiral Sir GEORGE HENRY RICHARDS, K.C.B., Vice-President, in the Chair.

The Presents received were laid on the table, and thanks ordered for them.

The following Papers were read :—

I. "On the Heating Effects of Electric Currents. No. II." By WILLIAM HENRY PREECE, F.R.S. Received November 24, 1887.

On March 19th, 1884, I submitted to the Royal Society a paper on the heating effects of electric currents,* showing the strength of current necessary to fuse the fine platinum wire employed for protecting submarine cables from the ill effects of atmospheric electricity. The paper proved that the law that regulates the production of heat is one which can be expressed by the formula $C = ad^{3/2}$, "a" being a constant dependent on the metal used, and "d" the diameter of the wire. The current observed was that which heated the wire up to the point of self-luminosity (525° C.).

Since "cut-outs" of the same character as the cable lightning protector have become an essential feature of all electric lighting installations, to act as safety fuses when from accident or design an excess of current is allowed to pass through the conductor, it became most desirable to determine the current that would fuse wires of different diameters, and of different materials, so as to determine the coefficient a for all metals. The best material to use and the proper dimensions of the fusible wire to be employed for the protection of the electric light conductors would thus be easily deduced.

My source of electricity was a large secondary battery of 52 cells. I could regulate the current flowing at will by a rheostat of thick iron wire, and by varying the number of cells. The current strength was calculated by measuring the potential difference at the ends of a thick flat platinoid bar, whose resistance was $0{\cdot}1822^{\omega}$, inserted in the circuit, and so large that it would not perceptibly warm up nor have its resistance appreciably increased with any current used. The sizes of wire experimented upon were limited by the current. It is not safe

* 'Roy. Soc. Proc.,' 1884, No. 231.

to draw upon secondary cells for more than 10 ampères per negative plate of the dimensions at present followed. The packed plates disintegrate and become damaged with too great an output of current. Hence all my experiments were made with currents well within the range of the battery. I obtained samples of wire of various metals and of various diameters from 0·004 inch up to 0·040 inch. It is convenient to take these measurements in thousandths of an inch (*mils*), for all our manufacturers and electric light engineers in the United States and the United Kingdom work to this gauge. The conversion of the values thus obtained into the metrical and more scientific system is very simple. The wire to be experimented upon was clamped between two small brass binding screws fixed upon a dry wooden stand.

I pointed out in my previous paper how the cooling effects of the terminals or binding screws might vitiate the results, and how necessary it was to experiment on wires of sufficient length to prevent any error occurring from this cause. I used lengths of 6 inches to determine the constants for wires free from the cooling effect, but lengths of $1\frac{1}{4}$ inch with massive terminals to determine the constants for wires used in practice as "cut-outs."

The cooling effect of the terminals very seriously affects the efficiency of the cut-outs used in actual practice, and the larger the fusing wire and the terminals the more serious is the error introduced. On the other hand, the greater the lengths of wire used as a fuse the greater the resistance inserted, and the efficiency of the system itself may be reduced. Cut-outs, therefore, should be employed sparingly and with judgment, and the fusing wire should not be so short as to impair the fusing point.

In the following tables I have tabulated the results of the numerous experiments made.

When we consider the irregularities in drawing these fine wires to true cylinders, the difficulty in determining the current at the exact moment of fusion, and the variation in the specific resistance of the metals, I think the results must be considered very satisfactory in support of the law.

Three points of observation were taken :—

1. The melting point of a small flake of shellac placed on the wire, which may be taken at 77° C.

2. The point of self-luminosity, 525° C. This was only determined roughly in air without the dark chamber I employed previously.

3. The fusing current.

Series I. "Cut-outs."

Copper.

Diameter of wire.			Current in ampères.			Fusing current calculated from the formula $ad^{3/2}$. Ampères.	Constant "a" when d expressed in inches.
In inches.	In centi-metres.	Standard wire gauge No.	Flake of shellac melted.	Wire red hot. Visible in air.	Wire fused.		
0·004	0·010	42	2·41	3·057	3·299	3·48	13033
0·005	0·013	39	2·896	4·184	4·586	4·87	12964
0·007	0·018	37	5·631	7·000	7·724	8·07	13183
0·010	0·025	33	9·976	14·160	15·44	14·23	15433
0·012	0·030	30	11·22	16·29	19·35	18·71	14748
0·014	0·036	28	13·68	19·30	21·84	22·86	13162
0·018	0·046	26	21·71	31·43	36·40	34·37	15066
0·020	0·051	25	24·03	35·61	39·37	39·05	13699
0·026	0·066	22	30·69	44·59	54·43	57·88	12978
						Mean =	13807

Aluminium.

Diameter of wire.			Current in ampères.			Fusing current calculated from the formula $ad^{3/2}$. Ampères	Constant "a" when d expressed in inches.
In inches.	In centimetres.	Standard wire gauge No.	Flake of shellac melted.	Wire red hot. Visible in air.	Wire fused.		
0·004	0·010	42	1·427	(a) 2·243 (b) 1·876	2·536	2·536	9023·3
0·005	0·013	39	1·851	2·614	4·023	3·549	11372·0
0·007	0·018	37	3·138	3·861	5·712	5·874	9782·6
0·010	0·025	33	4·465	5·632	10·138	10·024	10132·0
0·012	0·030	30	6·115	8·610	13·840	13·178	10523·0
0·014	0·036	28	7·722	(a) 13·200 (b) 11·176	16·412	16·606	9902·4
0·018	0·046	26	8·810	(a) 18·823 (b) 14·602	22·688	24·206	9389·4
0·020	0·051	25	13·032	(a) 22·445 (b) 17·380	28·236	28·360	9977·3
0·026	0·066	22	20·122	(a) 35·400 (b) 33·783	44·256	42·040	10551·0
0·030	0·076	21		(a) 44·240 (b) 33·790	49·88	52·100	9597·2
						Mean =	10025·0

Note.—The wire becomes red, and then immediately much brighter (a dull white), owing probably to oxidation. To reproduce faint redness without breaking the circuit, the current can be considerably reduced. "*a*" is the current which caused the first visible rays of light, and so quickly changed the wire to a brighter state of incandescence, while "*b*" is the reduced current which reproduced the first redness. If the experiment be repeated, the same effects are obtained, although the molecular structure of the wire seems to be much changed by the first heating. After fusing the wire, a white powder, alumina, is found, and sometimes a white opaque bead. A wire 18 mils diameter and 10 inches long was raised to faint red with 11·22 ampères; it glowed (dull white) on one side of loop with 11·58 ampères, and when the heat had apparently spread over the whole length uniformly, redness reappeared, and the current was found to be again 11·22 ampères. The wire was next raised to a moderately white incandescent state with 15·93 ampères, and with this current broke in two minutes.

Platinum.

Diameter of wire.			Current in ampères.			Fusing current calculated from the formula $ad^{3/2}$. Ampères.	Constant "a" when d expressed in inches.
In inches.	In centimetres.	Standard wire gauge No.	Shellac flake melted.	Wire red hot. Visible in air.	Wire fused.		
0·010	0·025	33	2·365	3·915	6·281	6·008	6278·8
0·012	0·030	30	3·060	5·424	8·076	7·90	6141·3
0·014	0·036	28	3·916	6·688	9·625	9·95	5808·4
0·018	0·046	26	4·936	8·320	13·378	14·50	5537·1
0·020	0·051	25	5·926	11·430	17·780	17·00	6282·3
0·026	0·066	22	8·808	16·316	25·778	25·20	6145·8
0·030	0·076	21	9·618	20·32	30·47	31·20	5863·6
						Mean =	6008·2

Note.—The ratio of perceptible warmth : red heat : fusing point is (roughly) as 1 : 2 : 3 in platinum.

German Silver.

Diameter of wire.			Current in ampères.			Fusing current calculated from the formula $ad^{3/2}$. Ampères.	Constant "a" when d expressed in inches.
In inches.	In centimetres.	Standard wire gauge No.	Shellac flake melted.	Wire red hot. Visible in air.	Wire fused.		
0·005	0·013	39	0·910	1·530	2·150	2·062	6078·4
0·007	0·018	37	1·406	2·150	2·812	3·415	4799·3
0·009	0·023	34	1·905	3·492	5·000	4·978	5860·7
0·012	0·030	30	2·977	5·460	7·693	7·666	5849·8
0·014	0·036	28	3·639	6·619	9·926	9·660	5989·3
0·018	0·046	26	4·757	8·894	13·235	13·560	5478·1
0·020	0·051	25	5·790	11·167	15·717	15·880	5550·5
0·026	0·066	22	9·846	15·342	23·740	23·550	5060·0
0·030	0·076	21	15·055	23·740	30·690	30·300	5901·1
						Mean =	5618·6

Platinoid.

Diameter of wire.			Current in ampères.			Fusing current calculated from the formula $ad^{3/2}$. Ampères.	Constant "a" when d expressed in inches.
In inches.	In centi-metres.	Standard wire gauge, No.	Shellac flake melted.	Wire red hot. Visible in air.	Wire fused.		
0·007	0·018	37	1·609	2·092	3·218	3·223	5491·8
0·010	0·025	33	2·414	3·379	5·551	5·503	5195·1
0·012	0·030	30	2·655	4·666	6·998	6·820	5325·1
0·014	0·036	28	3·540	5·108	8·368	8·590	5045·9
0·018	0·046	26	4·626	8·042	12·230	12·530	5062·5
0·020	0·051	25	6·636	9·604	14·480	14·680	5116·6
0·027	0·069	22	9·253	13·275	23·332	23·020	5256·2
0·035	0·089	20	11·263	18·502	32·986	33·200	5035·3
						Mean =	5191·1

Iron.

Diameter of wire.			Current in ampères.			Fusing current calculated from the formula $ad^{3/2}$. Ampères.	Constant "a" when d expressed in inches.
In inches.	In centi-metres.	Standard wire gauge No.	Shellac flake melted.	Wire red hot. Visible in air.	Wire fused.		
0·007	0·018	37	1·101	1·713	1·998	1·930	3410·3
0·010	0·025	33	2·121	2·896	3·466	3·435	3460·7
0·012	0·030	30	2·406	3·425	3·996	4·320	3038·8
0·014	0·036	28	3·467	4·364	5·506	5·450	3326·5
0·018	0·046	26	3·915	6·200	7·750	7·950	3208·4
0·020	0·051	25	5·028	6·758	9·012	9·310	3180·9
0·026	0·066	22	6·362	11·500	13·212	13·800	3148·4
0·030	0·076	21	8·483	14·843	17·292	17·100	3326·1
0·036	0·091	20	13·702	22·510	24·145	22·500	3533·2
						Mean =	3292·6

I was anxious to see if the shellac flake had any influence on the fusing current:—

(*a*.) Shows the effect with shellac.

(*b*.) Without shellac.

Tin.

Diameter of wire.			Current in ampères.			Fusing current calculated from the formula $ad^{3/2}$. Ampères	Constant "*a*" when *d* expressed in inches.
In inches.	In centimetres.	Standard wire gauge No.	Shellac flake melted.	Wire red hot. Visible in air.	Wire fused.		
0·010	0·025	33	1·931	2·413	2·736	2·760	2730·7
0·014	0·036	28	3·181	(*b*) 4·282	(*a*) 3·630 5·058	4·570	3051·5
0·018	0·046	26	4·078	(*b*) 5·384	(*a*) 4·976 6·117	6·670	2884·8
0·020	0·051	25	4·485	(*b*) 6·812	(*a*) 6·281 7·667	7·810	2709·2
0·026	0·066	22	6·933	(*b*) 11·100	(*a*) 10·443 12·154	11·600	2897·5
0·030	0·076	21	9·300	(*b*) 13·703	(*a*) 12·725 13·950	14·350	2683·3
0·033	0·084	21	11·380	(*b*) 14·930	(*a*) 14·192 15·414	16·500	2570·1
0·036	0·091	20	11·745	(*b*) 17·620	(*a*) 15·908 17·860	18·800	2575·2
						Mean =	2762·8

Hence it appears that shellac acts as a flux and prevents oxidation. Thus tin fuses at a temperature less than that of luminosity.

Tin-Lead Alloy.

Diameter of wire.			Current in ampères.			Fusing current calculated from the formula $ad^{3/2}$. Ampères.	Constant "a" when d expressed in inches.
In inches.	In centimetres.	Standard wire gauge No.	Shellac flake melted.	Wire red hot. Visible in air.	Wire fused.		
0·010	0·025	33	..	*	2·132	2·491	2731·7
			..	2·494	2·735		
0·012	0·030	30	2·333	*	2·373	3·274	2354·7
				2·855	3·097		
0·014	0·036	28	..	*	3·298	4·127	2774·2
			..	3·942	4·586		
0·020	0·051	25	4·586	*	5·309	7·046	2420·1
			..	5·792	6·838		
0·026	0·066	22	7·566	*	8·206	10·220	2385·5
			..	9·331	9·978		
0·030	0·076	21	11·102	*	11·102	12·670	2321·5
			..	12·070	12·070†		
0·033	0·084	21	11·102	*	12·550	14·620	2333·9
			..	14·000	14·000†		
0·036	0·091	20	13·516	*	14·240	16·660	2189·7
			..	14·962	14·962†		
						Mean =	2438·9

* With shellac.

† Fused immediately after faint redness was visible.

Lead.

Diameter of wire.			Current in ampères.			Fusing current calculated from the formula $ad^{3/2}$. Ampères.	Constant "a" when d expressed in inches.
In inches.	In centimetres.	Standard wire gauge No.	Shellac flake melted with.	Wire red hot. Visible in air.	Wire fused.		
0·010	0·025	33	1·666 ..	* 1·984	1·984 2·341	1·990	2339·5
0·012	0·030	30	1·825 ..	* 2·461	2·659 2·777	2·616	2111·6
0·014	0·036	28	3·095 ..	* 3·016	3·095 3·821	3·296	2305·3
0·018	0·046	26	3·016 ..	* 3·889	4·023 4·383	4·640	1811·3
0·020	0·051	25	3·810 ..	* 4·827	4·907 4·927	5·430	1712·3
0·026	0·066	22	5·471 ..	* no redness	7·000 7·000	8·344	1668·5
0·030	0·076	21	6·838 ..	* no redness	8·366 8·850	8·980	1702·1
0·033	0·084	21	6·526	..	10·93	11·520	1828·2
0·036	0·091	20	7·831	..	12·40	13·120	1814·4
						Mean =	1921·5

* Lead wire fuses without previously emitting light when a small shellac flake touches the wire.

Series II.

The second series of experiments was made to determine the relative effect of the sudden application of powerful currents on wires of different materials such as would occur if in practice a short circuit suddenly took place. An electromotive force of 100 volts was used, and there being no appreciable resistance in the external circuit but the wire, the latter was subjected to the blow of a momentary current of immense and immeasurable strength.

Metal.	Gauge.	Remarks.
	inches.	
Tin	0·0185	Fused with a sharp report, and scattered molten particles quite 6 feet in all directions.
,, ...	0·136	Fuse produced little more than a large splay of metal.
,, ...	0·136 (repeated)	This wire was enclosed in a porcelain box covered by a glass plate. It fused with considerable flame. The glass was broken into fragments, and the porcelain box chipped. Some fiery particles were thrown about.
,, ...	0·064	One inch of wire was put into an earthenware box. When fused, the particles of metal were securely imprisoned by the box to which they adhered. All the lead was resolved into globules.
Platinum - silver alloy	0·061	Molten particles were shot a distance of 9 feet.
Platinum foil......	0·001 thick	Molten particles thrown about 4 feet.
,, ...	0·001 thick, 0·512 wide	,, ,, ,,
,, ...	0·00025 thick, $\frac{1}{2}$ in. wide	This strip of foil was $1\frac{1}{4}$ in. long. Sparks thrown a few inches only.
Aluminium foil	0·001 thick	Molten particles scattered about 9 feet.
,, ...	0·004 thick, $\frac{1}{2}$ in. wide	Incandescing particles thrown upwards and around, but not more than 3 feet distant.
,,	0·001 thick, $\frac{1}{2}$ in. wide	Profuse particles, and some thrown 6 feet distant in a white hot state.
Silver foil	0·001 thick, $\frac{21}{32}$ in. wide.	Not so much splaying as in last experiment.
Pure silver wire....	0·017	No incandescent particles reached the ground. The wire was destroyed with a sharp report.
Zinc foil	0·003 thick, $\frac{1}{2}$ in. wide	Better than silver foil, no particles being scattered.
,, ...	0·003 thick, $\frac{1}{2}$ in. wide 2 strips	A few particles were shot about 4 feet; one was of considerable size.
Copper wire.......	No. 20 B.W.G.	Large incandescent globules scattered around for a distance of 4 or 5 feet.
Brass wire	No. 18 B.W.G.	This went off with a flash, and threw to a short distance a splay of metal which remained incandescent for some moments, and burnt a hole in the table.
Hard-drawn bright steel wire	No. 18 B.W.G.	Scintillating particles flew in all directions to a great distance. This was the most dangerous break of all the experiments.
Mercury	.. ..	Considerable flame produced, and particles widely scattered.

The conclusions derived from these experiments were that the best metal to use for small diameters was platinum, and for large wires tin. Platinum fuses in a wax-like kind of way without explosion or scattering of molten particles. Platinum has great advantages over other materials ; it neither tarnishes nor deteriorates. It is easily soldered.

Tin behaves very much in the same way when its dimensions are large. But it is very questionable whether large wires should ever be used for fusible cut-outs. Owing to radiation the surface keeps cool and solid, while the centre is molten and liquid. It bursts with an explosion, and the incandescent particles are forced away radially in all directions with considerable energy.

Fusible cut-outs are effective but somewhat barbarous, and from the absence of any scientific enquiry into their character and judgment in their use, they have in the majority of instances become rather a source of danger than of safety.

Series III.

The third series of experiments was made to determine the constant "*a*" when each wire was 6 inches long and therefore free from any cooling effect of the terminals.

Copper.

Diameter in inches.	Actual fusing current in ampères.	Fusing current calculated. $ad^{3/2}$.	Constant "*a*."
0·004	3·253	2·956	12888
0·005	4·444	4·130	12569
0·007	7·618	6·842	13007
0·010	13·33	11·684	13330
0·013	15·55	17·32	10491
0·014	17·14	19·35	13835
0·018	25·55	28·22	10580
0·020	27·77	33·04	9818
0·023	35·55	40·75	10192
0·030	52·69	60·71	10140
		Mean =	11684

Aluminium.

Diameter in inches.	Actual fusing current in ampères.	Fusing current calculated. $ad^{3/2}$.	Constant "a."
0·004	3·322	2·011	13130
0·007	5·253	4·654	8970
0·010	10·20	7·948	10200
0·012	10·51	10·45	7996
0·014	16·19	13·17	9757·3
0·018	21·01	19·20	8700
0·020	23·48	22·48	8302
0·026	28·93	33·33	6900
0·030	37·08	41·30	7133
0·033	38·93	47·65	6493
0·036	43·80	54·30	6413
0·040	52·53	63·57	6568
		Mean =	7948·4

Platinum.

Diameter in inches.	Actual fusing current in ampères.	Fusing current calculated. $ad^{3/2}$.	Constant "a."
0·004	1·723	..	6826·5
0·005	2·192	1·859	6200
0·007	3·211	3·080	5482·7
0·010	5·285	5·258	5285
0·012	6·734	6·910	5122·8
0·014	8·104	8·710	4884
0·018	11·28	12·700	4671
0·020	13·78	14·872	4872
0·027	22·55	23·330	5082·8
0·030	28·12	27·320	5411·8
0·033	32·75	31·520	5463·2
0·037	37·08	37·420	5209·9
0·040	43·26	42·063	5407·4
		Mean =	5258

German Silver.

Diameter in inches.	Actual fusing current in ampères.	Fusing current calculated. $ad^{3/2}$.	Constant "a."
0·004	1·825	1·317	7230·7
0·005	2·143	1·840	6061·3
0·010	5·554	5·204	5554
0·012	6·824	6·840	5191·2
0·014	9·125	8·620	5499·4
0·018	12·78	12·57	5292·2
0·020	14·40	14·72	5091·2
0·026	20·16	21·82	4808·8
0·030	27·14	27·04	5223·1
0·033	30·90	31·20	5150
0·037	36·15	37·03	5079
0·040	43·26	41·63	5407
		Mean =	5203·7

Platinoid.

Diameter in inches.	Actual fusing current in ampères.	Fusing current calculated. $ad^{3/2}$.	Constant "a."
0·007	3·675	2·846	6275
0·010	5·285	4·860	5285
0·012	6·532	6·389	4969·1
0·014	8·036	8·050	4843·1
0·018	11·670	11·74	4832·6
0·020	14·21	13·75	5024
0·016	21·38	22·77	4563·2
0·028	28·436	29·13	4744
0·035	28·82	31·82	4401·3
0·040	40·67	38·88	5084
		Mean =	4860·7

Iron.

Diameter in inches.	Actual fusing current in ampères.	Fusing current calculated. $ad^{3/2}$.	Constant "a."
0·007	2·10	1·869	3585·6
0·012	3·88	4·194	2951·7
0·014	5·277	5·285	3180·3
0·018	7·142	7·706	2957·4
0·020	8·888	9·026	3142·3
0·026	13·02	13·38	3105·7
0·030	15·71	16·58	3023·4
0·033	19·00	19·13	3169·0
0·036	21·90	21·80	3206·2
0·040	28·74	25·53	3592·5
		Mean =	3190·9

Tin.

Diameter in inches.	Actual fusing current in ampères.	Fusing current calculated. $ad^{3/2}$.	Constant "a."
0·010	2·55	1·800	2550
0·014	3·244	2·983	1959
0·018	4·095	4·348	1696
0·020	4·675	5·093	1653
0·026	6·570	7·548	1567
0·030	8·656	9·356	1666
0·033	9·430	10·800	1573
0·036	11·60	12·30	1699
0·040	13·14	14·41	1643
		Mean =	1800·6

Tin-Lead Alloy (2 parts of Lead to 1 part of Tin).

Diameter in inches.	Actual fusing current in ampères.	Fusing current calculated. $ad^{3/2}$.	Constant "*a*."
0·010	2·124	1·455	2124
0·0125	2·395	2·034	1714
0·014	2·472	2·411	1493
0·018	3·283	3·515	1359·5
0·020	3·515	4·117	1243
0·026	5·794	6·101	1382
0·030	6·990	7·562	1345
0·033	7·722	8·725	1289
0·036	8·961	9·941	1312
0·040	10·35	11·64	1294
		Mean =	1455·5

Lead.

Diameter in inches.	Actual fusing current in ampères.	Fusing current calculated. $ad^{3/2}$.	Constant "*a*."
0·010	1·893	1·512	1893
0·012	2·202	1·988	1675
0·014	2·588	2·504	1565
0·018	3·824	3·652	1584
0·020	4·171	4·277	1475
0·026	6·025	6·339	1437
0·030	7·182	7·858	1382
0·036	8·600	10·33	1259
0·040	10·74	12·10	1342·5
		Mean =	1512·27

The value of the constant "a" for the different metals is therefore :—

	Inches.	Centimetres.
Copper	11684·0	2886·0
Aluminium	7948·4	1964·0
Platinum	5258·0	1299·0
German silver	5203·7	1285·0
Platinoid	4860·7	1201·0
Iron	3190·9	788·0
Tin	1800·6	445·0
Alloys (lead and tin, 2 to 1)	1455·5	359·5
Lead	1512·27	373·5

The values in the second column are obtained from those in the first by multiplying the latter by $\frac{1}{(2{\cdot}54)^{3/2}} = 0{\cdot}247$.

Since $C = ad^{3/2}$ gives the fusing current of any wire of a given diameter d, inversely—

$$d = \left(\frac{C}{a}\right)^{2/3}$$

will give the diameter of the wire which will fuse with a given current C. Very useful tables can thus be calculated which would be of service to the electric light engineer.

[Jan. 5, 1888.—In all these experiments the results obtained on wires finer than those recorded, viz., those below 10 mils, were excluded, because it was found that they did not follow the law of the 3/2 power. In the discussion which followed the reading of the paper, Professor Ayrton pointed out that this must be so, and that it followed from Mr. Box's researches of 1868* that the current required to maintain a fine wire of a given material at a given definite excess of temperature is approximately directly proportional simply to the thickness of the wire. This has been fully developed in a paper read before the Society of Telegraph-Engineers and Electricians, November 24, 1887 ('Journal,' vol. 16, p. 539).]

* 'A Practical Treatise on Heat,' 1868.