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(With One Plate)

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(WITH ONE PLATE)

In 1927, V. M. Shulgin[1] suggested an improvement of the water-flow standard pyrheliometer.[2] He pointed out, and our experience abundantly confirms it, that fluctuations of the rate of flow and of the temperature of the water lead to irregular drift and wiggle of the galvanometer record in the use of such an instrument, for instance, as water-flow pyrheliometer No. 3. These irregularities make up a principal part of the total error in using the instrument as described by us in Volumes 3 and 4 of the Annals of the Astrophysical Observatory. Shulgin's improvement consists in duplicating the instrument so as to have two chambers instead of one. He divides the current of water nearly equally between them. Solar radiation is introduced in one chamber, and compensating electrical energy in the other. Thus a null method is substituted for the deflection method, and the irregularities of the water current are eliminated as a source of error because they affect both chambers equally and simultaneously.

We wholly approved of Shulgin's principle but felt that a more favorable mechanical and electrical expression than his could be given to it. Accordingly, by the skill of A. Kramer, mechanician, we duplicated last winter the water-flow pyrheliometer No. 3, described at page 52 of Volume 3 of the Annals. We combined the two chambers thus made available to form a new standard water-flow pyrheliometer No. 5. In combining the two instruments, in order to control surrounding conditions, we added a common enclosing metallic case whose hollow walls were bathed by a separate current of tap water. We also arranged a common entrance pipe for the distilled water used in the measurements. This entering water stream was protected by a closely surrounding Dewar vacuum enclosure and was well stirred by a baffle circulatory system. To determine the equality of temperatures of the

[1] Monthly Weather Rev., August, 1927.

[2] See description of this instrument, Ann. Astrophys. Obs., Smithsonian Inst., vol. 3, p. 52, 1913.

water streams outflowing from the two chambers we employed eight thermoelectric junctions of nickel-platinum connected in series with their elements passing alternately from one stream to the other. Short glass outflow tubes pierced to admit these thermoelectric elements were skilfully made by L. B. Clark of this Institution. These delicate parts of the apparatus were enclosed completely by an air-tight box made of cellophane and wax. Thus air currents could not directly affect the thermoelectric system. Plate 1, Figures 1, 2, 3, show the instrument in various stages of completion as thus constructed and used. The electric heating coils are wound on the rear surfaces of the receiving cones at the extreme rear of the absorption chambers. In water-flow pyrheliometer No. 3 we wound heating coils not only in that position, but also on the front edges of the cone. We found in our use of that instrument that coils in these two positions give equal results; hence we felt justified in omitting the edge coils in water-flow pyrheliometer No. 5.

With the cooperation of Doctor Süring, Messrs. Abbot and Martens compared at Potsdam in October, 1931, silver-disk pyrheliometers S.I.5_{bis} and S.I.12. The latter instrument has been for about 20 years in the possession of the Meteorological Observatory at Potsdam. The constant of S.I.5_{bis}, 0.3715, as used last October, was determined by Messrs. Abbot and Hoover in August, 1931, by 24 comparisons with A.P.O.$8_{bis\ bis}$. We have used the latter instrument since 1912 solely for standardizations at Washington. Using this constant, 0.3715, readings of pyrheliometer S.I.12 were found to satisfy within 0.3 per cent the identical constant found for it in 1912. In order to carry through a direct comparison with S.I.12 in use at Potsdam, we employed at Mount Wilson in June, 1932, silver-disk pyrheliometer S.I.5_{bis} as the comparison instrument, together with our improved water-flow pyrheliometer No. 5. For convenience of observing, the latter was supported in a fork carried by an equatorial telescope mounting, and pyrheliometer S.I.5_{bis} was so attached that its tube for admission of solar rays was exactly parallel to the two tubes of No. 5. In this way the observer of S.I.5_{bis} kept No. 5 as well as S.I.5_{bis} continually pointing at the sun during comparisons. Times of reading of the silver disk pyrheliometer were governed by a sounder beating seconds. Observers C. G. Abbot and L. B. Aldrich interchanged duties in reading the pyrheliometers. No difference in result was noted.

Water currents of approximately 45 cubic centimeters per minute in each branch of pyrheliometer No. 5 were found to give good results, but different rates of flow were tried at various times without affecting the results of the comparisons of pyrheliometers. There was a deflection of about 9 centimeters on the scale of the moving coil galvanometer when sun rays were allowed to enter one chamber of pyrheliometer No. 5 without electric compensation. No wiggle as great at 0.01 centimeter was ever detected during observations. Accidental fluctuations were therefore less than 1/1000 part of the deflections. Slow drift of a millimeter or two during a run of half an hour sometimes occurred, but was eliminated by alternating the chambers exposed to solar and electric heating. In short, water-flow pyrheliometer No. 5 behaved far better than we had expected and indeed so perfectly that we can not conceive of its improvement.

In the use of it, we at first regarded as the zero of the galvanometer that position on the scale which was assumed when no outside energy of sun or electricity was entering either chamber. There was then considerable inequality in the results from the two chambers. Later we perceived the advantage of using as galvanometer zero the position assumed when solar rays were shining fully into both chambers simultaneously. Using this zero, the results from the two chambers were then very nearly equal, usually within 1 per cent. But no difference in the mean result of the comparisons with S.I.5_{bis} was discerned, whichever zero was employed.

In using the water-flow pyrheliometer No. 5, we found that an exposure of two minutes before interchanging chambers was ample. It is clear that a certain time must be allowed to elapse before interchanging, for the electric heating is applied where the water current is about to issue from the chambers. A small part of the solar heating, on the other hand, is absorbed near the front orifices of the chambers. From that location the current of water must flow several meters through its spiral channel within the hollow walls of the chambers before emergence. Hence the full effect of electric heating reaches the thermoelectric junctions quicker than can the full effect of solar heating. It is therefore necessary to wait until both sources of heating can exert their full effects before making a balance. We assured ourselves that two minutes was ample time for this by trying much longer exposures and finding thus no change of the results of comparisons of pyrheliometers.

The accuracy of the results with water-flow pyrheliometer No. 5 does not depend on any measurements of the rate of flow or of the temperature of the water.[3] It depends on the measurement of the

[3] The question of temperature concerns us only in reducing the electric energy in joules to its equivalent in calories. We use the factor 4.185 to reduce to 15° calories.

areas of the solar apertures, on the adjustment of the heating current to reproduce exactly the observed zero reading of the galvanometer, and on an exact determination of the electric heating current required. The solar apertures were turned truly circular and equal, and a plug exactly fitting them was made. This plug was inserted from time to time during observations to surely clear the aperture of dust particles. It was measured at numerous diameters with two different Browne & Sharpe micrometers. The mean value was 2.312 centimeters. The computed area of the aperture was thus found to be 4.198 square centimeters. Two milliammeters in series were used to measure the currents. One of them was a more satisfactory instrument than the other, and its results were used exclusively in the final computations. The others differed from them only very slightly. These electric instruments were calibrated several times during the measurements against new Weston standard cells. It is believed that the errors of individual current measurements did not exceed 0.1 per cent, so that the errors of individual energy measurements, due to inaccuracy in reading the current values, did not exceed 0.2 per cent. In the mean of many observations given below this error would be sensibly eliminated.

We computed the loss of solar radiation by reflection through the entrance of the receiving chamber and made a plus correction of 0.1 per cent for the imperfect "blackness" due to it.

In our earlier days of observing in June, 1932, the sky was very exceptionally clear at Mount Wilson. Observed values of radiation reached 1.53 calories according to silver-disk pyrheliometer S.I.5_{bis} notwithstanding that the earth was then in aphelion, and besides, the temperature being high, the atmospheric humidity was considerable. At that time we used the water-flow pyrheliometer No. 5 with exactly the same sky exposure as that described for No. 3 in Volume 3 of the Annals, which had an angular aperture as viewed from the limiting diaphragm of about 16°. The silver-disk pyrheliometer S.I.5_{bis}, on the other hand, was of our modern improved type, exposing only 5° 48′ angular diameter as viewed from the silver disk, or 0.0013 hemispheres. Fearing that the June measurements of the two instruments would not be quite comparable, despite the exceptional clearness of the sky, we subsequently erected a double highly reflecting screen in front of pyrheliometer No. 5 designed so as to give it exactly the same sky exposure as S.I.5_{bis}. We repeated the comparison on July 8 with these arrangements but obtained almost exactly the same results as before.

The following table includes all the comparative observations of pyrheliometer S.I.5_{bis} and water-flow pyrheliometer No. 5, except a

SUMMARY

Date 1932	Time	Calories by water-flow No. 5	Corrected reading of S.I.5_{bis}	Constant of S.I.5_{bis}	Deviation from mean
June 26	10h 11m	1.461	3.950	0.3699	+74
	17	1.460	4.007	.3644	+19
	23	1.467	4.031	.3639	+14
	29.5	1.465	4.008	.3655	+30
	38	1.469	4.049	.3628	+ 3
	42	1.472	4.059	.3626	+ 1
	48	1.464	4.084	.3586	−39
	11 22	1.470	4.033	.3645	+20
	26	1.485	4.064	.3654	+29
	30	1.473	4.058	.3630	+ 5
	35	1.485	4.058	.3659	+34
	40	1.488	4.117 (?)	.3614 (?)	−11
	1 44	1.460	4.021	.3631	+ 6
	47	1.450	4.046	.3584	−39
	53	1.453	4.023	.3612	−13
	57	1.452	4.053	.3583	−42
	2 11	1.451	4.021	.3609	−16
	22	1.447	3.965	.3649	+24
	25	1.455	3.961	.3673	+48
	31	1.438	3.986	.3608	−17
	34	1.438	4.035	.3564	−61
			Mean, 21 values	.3628	
June 27	9 50	1.495	4.101	.3645	+20
	54	1.507	4.133	.3646	+21
	10 05	1.497	4.168	.3592	−33
	10	1.498	4.178	.3585	−40
	52	1.502	4.140	.3628	+ 3
	57	1.508	4.148	.3635	+10
	11 04	1.502	4.164	.3607	−18
	08	1.505	4.164	.3614	−11
	32	1.523	4.190	.3635	+10
	37	1.520	4.211	.3610	−15
	43	1.530	4.216	.3629	+ 4
	48	1.530	4.215	.3630	+ 5
			Mean, 12 values	.3621	
July 8	10 14	1.411	3.866	.3650	+25
	23	1.402	3.890	.3604	−21
	36	1.390	3.852	.3609	−16
	44	1.406	3.885	.3619	− 6
			Mean, 4 values	.3621	

Mean of 37 observations (3 days) 0.3625
Average deviation, 0.00217
Probable error, 0.00030, or 0.08 per cent

few preliminary ones of June 24, at which time the silver-disk pyrheliometer measurements were affected by a timing error. From these comparisons the constant of pyrheliometer S.I.5_{bis} results as 0.3625.

Many comparisons were made at Washington in August, 1931, and in September, 1932, between silver-disk pyrheliometers S.I.5_{bis} and A.P.O.$8_{bis\ bis}$. The latter instrument has been used for many years to standardize silver-disk instruments sent abroad. The former was furnished with 12-1/2 inch vestibule and the other changes made upon it in August, 1931. The comparisons just referred to resulted as follows:

Date	Number of comparisons	Ratio $\frac{\text{S.I.}5_{bis}}{\text{A.P.O.}8_{bis\ bis}}$
Aug. 8, 1931	8	1.0206
Aug. 17, 1931	18	1.0177
Sept., 1932	8	1.0170
	Weighted mean	1.0182

According to these results and to the observations made with Standard No. 5, the constant of A.P.O.$8_{bis\ bis}$ could now be taken as 0.3691. We have hitherto adopted 0.3786. A change of − 2.5 per cent is indicated.

Is this difference to be regarded as due to error in the experiments with our water-flow and water-stir pyrheliometers No. 3 and No. 4 with which we established the Smithsonian scale of 1913? First of all we recall that in the use of these instruments at Washington and Mount Wilson their sky exposure, reaching an angular diameter of about 16°, is to be contrasted with the sky exposure to only 10° 38′ in the original silver-disk instruments. More than twice as much sky area was observed by the standard instruments as by the silver-disk pyrheliometers in 1913. This may have made several tenths of a per cent too high a scale value in the work of 1913.

In the second place, the calibration of the platinum resistance thermometers used in standard pyrheliometers No. 3 and No. 4 involved the whole technique of exact mercury thermometry. Those who have had occasion to use mercury thermometers for exact work will know what was involved in the determinations of temperatures, as given in Tables 10 and 19 of Volume 3 of the Annals, and that appreciable inaccuracy there may have been possible. Indeed, the irregularity of run of the numbers in the latter part of Table 10 seems to throw some doubt on the sufficient accuracy of the coefficients of temperature change determined.

In the third place, we pointed out, as Shulgin has done also, that irregularities of flow of the water current in the use of standard pyrheliometer No. 3 caused galvanometer drift and wiggle, and difficulty in deciding as to the true deflections due to solar heating. Personal equation might well enter in such a case, and there may have been a tendency to read the deflections too large.

As compared with all these complex and numerous sources of error in the older standard pyrheliometer, the extreme simplicity and perfect operation of standard pyrheliometer No. 5 must strongly incline us to attribute very much greater weight to its results.

In the fourth place, we have altered the silver-disk pyrheliometer vestibules in recent years to expose only to an angular diameter of 5° 48′. In making this change of vestibules of A.P.O.8_{bis} on December 1, 1927, it is possible that some slight structural modification of the pyrheliometer occurred. We did, indeed, make careful comparisons of A.P.O.8_{bis} with silver-disk instrument S.I.5 before and after the change. These comparisons resulted as follows:

Date	Number of comparisons	Ratio $\frac{\text{S.I.5}}{\text{A.P.O.8}_{bis}}$	Ratio $\frac{\text{S.I.5}}{\text{A.P.O.8}_{bis\ bis}}$
Apr. 15, 1911	7	1.0389	......
Dec. 20, 1912	18	1.0281	......
Oct. 14, 1921	12	1.0339	......
Mar. 6, 1922	20	1.0291	......
Oct. 10, 1927	8	1.0457	......
Oct. 22, 1927	20	1.0305	......
Nov. 1, 1927	20	1.0395	......
Dec. 1, 1927	8	......	1.0328
Dec. 27, 1927	8	......	1.0311
Feb. 27, 1928	8	......	1.0422

Allowing for the almost unavoidable irregularities of such comparisons over so long a time, due to sky conditions, personal equation, and watch eccentricity, there is nothing here to indicate any change of constant of A.P.O.8_{bis} with respect to S.I.5. The latter instrument had not been changed at all during all this time. The weighted mean values are as follows:

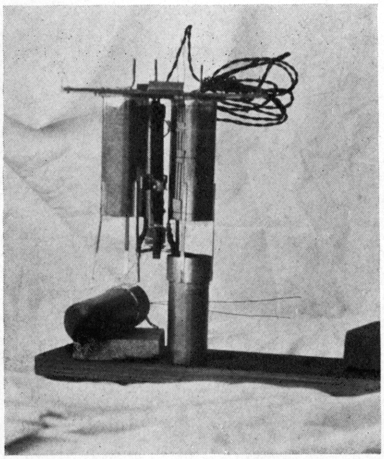
Date	No. of values	Weighted mean ratio
1911-1922	57	1.0310
Mar.-Nov., 1927	48	1.0368
Dec., 1927-Feb., 1928	24	1.0354

Pyrheliometer S.I.5 after these experiments was altered early in August, 1931, as explained on a preceding page and called S.I.5_{bis}. Other comparisons support the view that pyrheliometer A.P.O. $8_{bis\ bis}$ still gives fairly the standard scale of 1913. Thus the comparisons referred to on a preceding page made in Potsdam in October 1931 on exceptionally clear days indicate through S.I.5_{bis} and A.P.O. $8_{bis\ bis}$ for S.I.12 the constant 0.3624. The original calibration made in September 1912 resulted 0.3631. Again a long series of comparisons between A.P.O.8_{bis} and S.I.1 from 1911 to 1920 indicate even greater constancy than the set of comparisons with S.I.5 just quoted.

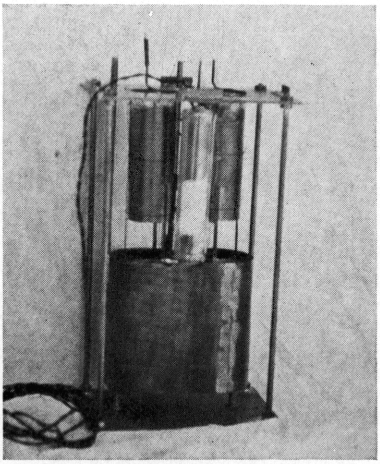
On the whole, therefore, we are forced to conclude that the standard scale of radiation as indicated by water-flow pyrheliometer No. 5 lies 2.5 per cent below the Smithsonian scale of 1913. The great simplicity and freedom from accidental error in the measurements of standard No. 5 warrants very high weight for its results compared to those obtained from pyrheliometers No. 3 and No. 4. In confirmation it may be added that a long series of unpublished measurements made by Messrs. Abbot and Aldrich with No. 3 at Mount Wilson in the year 1920 also tended to give results below the scale of 1913. We hope, however, to make additional experiments on this question next summer.

In our solar-constant values hereafter to be published, we regard comparability with preceding ones as more important than absolute scale. Hence we shall not introduce our new scale into such future publications. We may remark, however, that if applied to our mean value, 1.940 calories per square centimeter per minute, for the solar constant of radiation, it would become as corrected 1.893. We have admitted, however, our belief that a contrary small correction of undetermined magnitude should be applied to allow for extreme ultraviolet rays not observed, some of which cannot enter the atmosphere through the ozone layer.

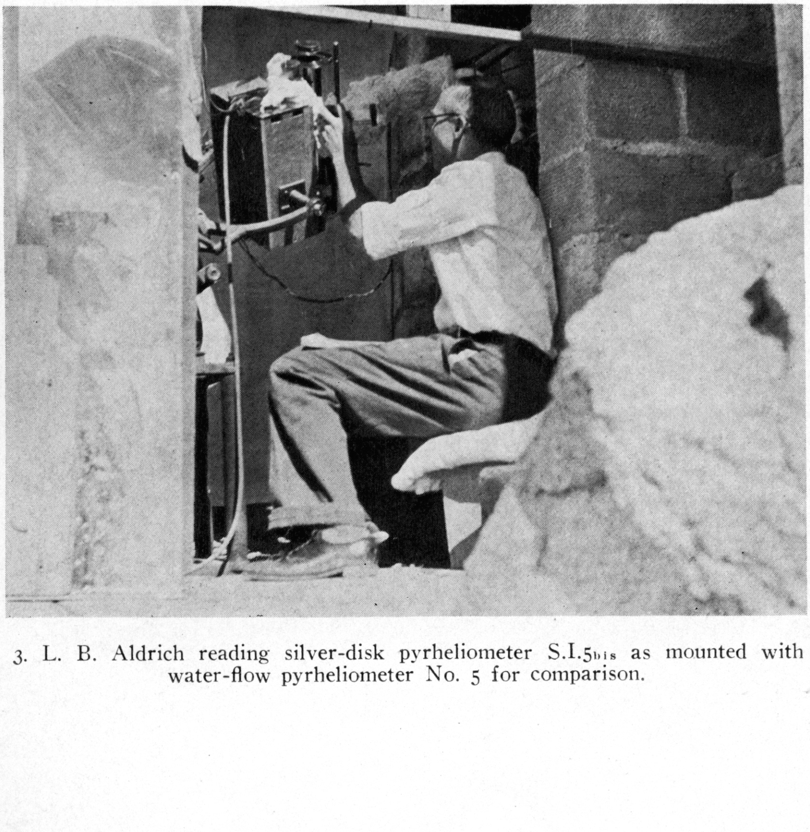
In his publication "Ein neues Pyrheliometer für Absolutmessungen," C. Tingwaldt gives a preliminary result obtained by experiments at Davos. This indicates a plus correction of 1.9 per cent to the Ångström scale, and according to Tingwaldt indicates a minus correction of 1.8 per cent to the Smithsonian scale of 1913. Our own correction is in that direction, but of greater magnitude. We hope that further experiments on very clear days may be made by Tingwaldt and his colleagues, in which silver-disk pyrheliometer S.I.12 will be the comparison instrument. We shall then be in a position to evaluate very closely the difference, if any, between our new water-flow pyrheliometer No. 5 and the absolute pyrheliometer used by Tingwaldt.



1. Water-flow pyrheliometer No. 5 disassembled.



2. Water-flow pyrheliometer No. 5 assembled.



3. L. B. Aldrich reading silver-disk pyrheliometer S.I.5_{bis} as mounted with water-flow pyrheliometer No. 5 for comparison.