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NAVY DEPARTMENT
BUREAU OF ENGINEERING

Report on

The Specific Gravity-Temperature Relationships
of the NRL and "A" Series of
Fuel Oils.

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A B S T R A C T

The coefficient of expansion has been determined on two series of fuel oils using the Westphal balance.

The first series tested was the NRL group consisting of eight cracked residuums, three blends made from cracked residuums, eleven straight run residuums, seven blends of unknown base, and two shale oils. The second series is known as the "A" series and is made up of cracked residuums and fuels blended from such residuums.

The average coefficient of expansion for the "A" series is 0.000369 per degree F and the NRL series is 0.000361 per degree F.

The results of the study of the "A" series show that the average variation of gravity determinations is 0.23^o A.P.I. as determined by eleven cooperative laboratories.

The results in this report show that the present fuel oil tables used by the Navy are satisfactory for the fuels studied when considering the variations that may be obtained by different observers.

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INTRODUCTION

(a) Authorization

1. This problem was authorized by Bureau of Engineering Project Order No. 86/31 of 2 June 1931.

(b) Statement of Problem

2. The original problem given in the above reference dealt with the characteristics and supply of fuel oil for the Navy. During the years of 1931 to 1933, this Laboratory studied a series of fuels known as the NRL series. This group consisted of straight run residues, cracked residuums, and blends made from these basic stocks. During the fiscal year of 1933 to 1934, the Engineering Experiment Station, the Naval Boiler Laboratory, and this Laboratory studied 18 cracked fuels with the purpose of finding why certain fuels cause trouble and others do not. This series of fuel oils is known as the "A" series to differentiate it from the "NRL" series studied previously at this Laboratory. In this report will be found the specific gravity of these fuel oils at various temperatures and from these data the change in specific gravity per degree is calculated.

(c) Facts Bearing on the Problem

3. Specific gravity is ordinarily determined by the use of a hydrometer. This hydrometer may be calibrated either in terms of specific gravity or °A.P.I. As the temperatures at which the determinations are made very rarely are the same as the reference standard temperature of 60° F, tables are used for the correction of the gravity to 60° F.

4. Fuel oils usually are not made from one single source and they never contain one single type of organic compound. In the past few years, cracked residues have been blended to the necessary viscosity and gravity requirements established by the contracts and sold as fuel oils. The Navy Department is cognizant of this fact and therefore the "A" series, made from cracked residuums, was studied.

5. The standard tables used for the correction of the gravity due to temperature are made by the study of the expansion of certain carefully prepared oils. The expansion of these reference oils will vary, depending upon the gravity, source, and whether the oil is a straight run, cracked residuum, or a blend. Therefore the standard tables vary.

6. In this report, the change in gravity with temperature will be discussed and the results found will be compared with the tables now in use by the Navy.

(d) Original Work at this Laboratory

7. The change in gravity with temperature for the "A" series will be found in NRL Reports P-1012 of 28 December 1933, P-1031 of 28 February

1934, and P-1049 of 27 April 1934. No report has been filed on the NRL series. No report has been filed discussing the change in gravity with temperatures such as will be described in this report.

METHOD OF TEST

8. The density of any fuel or organic liquid can be determined by any one of three methods:

- (a) By the use of a pycnometer, or a vessel of known volume.
- (b) By the use of a Westphal balance, or
- (c) By the use of a hydrometer.

In organic research the first method is largely used. In commercial practice the third practice is favored. The Westphal balance is used mainly with materials where greater accuracy is wanted than can be determined with hydrometer and where the pycnometer cannot be readily used, such as with heavy fuels.

9. Specific gravity measurements in this report were taken with the well known Mohr-Westphal balance. This apparatus was chosen because of its easy manipulation and because it gives results accurate to the fourth decimal place. Since the glass plummet used in this apparatus is subject to change in volume with change in temperature, it was necessary to first calibrate the instrument against distilled water. This was done between the temperature range of 25°C to 95°C and so provided the necessary correction factors to apply on the fuel oils.

10. A 0-110°C thermometer, graduated in degrees, was standardized against a certified Bureau of Standards calibrated thermometer and was used throughout the entire experimental work. Estimation of the temperature in tenths of degrees was then necessary and the temperature readings are probably accurate within two tenths of a degree.

11. The fuel oils whose specific gravity measurements were to be taken were first heated to about 100°C in an atmosphere of CO₂ and the oil then transferred to the Dewar flask as in the diagram of Plate I. In the diagram is also seen the following:

- A - Dewar flask.
- B - The calibrated thermometer inserted in the cork stopper.
- C - A test tube, with side arm, fitted into cork stopper. A suction pump is attached on the side arm for the purpose of limiting condensation of the oil on the platinum wire. Test tube C is just large enough to permit passage of glass plummet.

D - Platinum wire suspension.

E - Glass plummet.

F - 3/16" copper tubing. This served as a stirrer and also to cool the oil to the desired temperature where a specific gravity reading was to be taken. The coil was free to move through the cork stopper.

12. After the oil was transferred to the Dewar flask, the cork stopper carrying the thermometer copper cooling coil, and test tube was fitted to the Dewar flask and the suction pump started. The glass plummet was then lowered into the oil, through the test tube, and attached to the Westphal balance. After the oil had been thoroughly stirred and the apparatus and the oil had come to a temperature equilibrium a specific gravity reading was taken on the Westphal balance. The temperature of the oil and apparatus was then lowered by passing water through the copper coil and the operation repeated until all the necessary measurements were made.

DATA OBTAINED

13. The readings on each oil are given in Appendix A in detail. In examination of this data, it will be noted that measurements have been taken on some oils over a greater temperature range than others. The reason for this is that some of the oils were so viscous that a measurement at a relatively lower temperature makes for uncertain readings and therefore was not attempted. It can be said that measurements were taken at as low a temperature as the fluidity of the oil would permit to allow a sufficient sensitivity to the Westphal balance for accuracy.

TABLE I

Specific Gravity and Coefficient of Expansion
at 60° F for the NRL Series.

1 No.	2 Gravity 60° F	3 Change in sp. gr. °C	4 °F	6 ° A.P.I.		7 Sp.gr.hydro- meter 1931
				5 From gravity col. 2	A.P.I. hydrometer	
3	0.9608	.000661	.000367	15.8	15.4	15.7
4	0.9525	.000673	.000374	17.1	17.1	17.1
5	0.9034	.000716	.000398	25.1	25.3	24.8
6	0.9304	.000692	.000384	20.6	20.5	19.7
8	0.9858	.000653	.000363	12.0	11.9	12.0
9	1.0001	.000660	.000367	10.0	10.1	10.9
12	0.9278	.000643	.000357	21.0	20.8	19.3
13	0.9550	.000629	.000349	16.7	16.3	16.5
14	0.9971	.000672	.000373	10.4	10.4	10.0
15	0.9405	.000650	.000361	18.9	18.8	20.3
16	0.9832	.000641	.000356	12.4	12.2	12.9
17	0.9693	.000651	.000362	14.5	14.2	14.5
21	0.9600	.000631	.000350	15.9	15.5	15.7
22	0.9529	.000640	.000356	17.0	16.5	17.1
24	1.0275	.000643	.000357	6.2	5.9	6.2
25	1.0039	.000650	.000361	9.4	9.3	10.1
26	0.9450	.000641	.000356	18.2	17.8	18.2
27	1.0746	.000659	.000366	0.2	0.0	0.3
27-A	0.9827	.000643	.000357	12.5	12.2	12.7
28	0.9720	.000660	.000367	14.1	13.9	14.5
30	0.9598	.000647	.000359	15.9	15.7	15.4
31	0.9884	.000647	.000359	11.7	11.6	11.4
32	0.9471	.000655	.000364	17.9	17.6	17.6
33	1.0080	.000667	.000370	8.9	8.8	8.9
36	0.8854	.000633	.000351	28.3	28.2	28.2
37	0.9378	.000637	.000354	19.4	19.2	19.0
38	1.0559	.000660	.000367	2.5	2.3	2.0
39	1.0572	.000650	.000366	2.3	2.1	2.0
41	0.9612	.000656	.000365	15.7	15.6	15.1
44	0.9510	.000641	.000356	17.3	17.1	16.8
45	0.9447	.000650	.000366	18.3	18.0	17.8
Avg.	0.9716	.000654	.000363	14.39	14.20	14.28
Omitting 5 & 6		.000650	.000361			

TABLE II

Density and Coefficient of Expansion of
"A" Series.

No.	Gravity at 60° F	Change in sp.gr.		° A.P.I. From gravity col. 2
		°F	°C	
1	1.0123	0.000381	0.000686	8.3
2	0.9853	0.000358	0.000644	12.1
3	1.0241	0.000405	0.000729	6.7
4	1.0165	0.000381	0.000686	7.7
5	0.9978	0.000394	0.000709	10.3
6	0.9843	0.000371	0.000668	12.3
7	0.9895	0.000363	0.000653	11.5
8	0.9643	0.000361	0.000650	15.25
9	1.0087	0.000364	0.000655	8.77
10	0.9867	0.000364	0.000655	11.89
11	0.9646	0.000359	0.000646	15.2
12	1.0225	0.000368	0.000662	6.9
13	1.0070	0.000365	0.000657	9.01
14	0.9914	0.000371	0.000668	11.23
15	0.9923	0.000349	0.000628	11.1
16	0.9766	0.000366	0.000659	13.41
17	0.9895	0.000350	0.000631	11.5
18	0.9872	0.000365	0.000657	11.83

14. The data were plotted and the density at 60° F, or 15.5° C, was determined. This determination was based upon the assumption that the same change in specific gravity held from the lowest experimental determination to 15.5° C, or 60° F, the reference standard. This is open to question as some oils have a pour point of 65° F and others are so viscous at 70° F that readings cannot be made with any satisfaction. The value at 60° F then was determined by extrapolation of the experimental data and is given in column 2 of Table I for the NRL series and in Table II for the "A" series. In columns 3 and 4 of Table I is given the change in specific gravity for the same oils calculated from these data.

15. As most specific gravity determinations are made by use of hydrometers, the gravity was determined by the use of (1) hydrometers calibrated in specific gravity and then converted into degrees A.P.I. by use of tables and (2) hydrometers graduated in degrees A.P.I. The gravities by means of specific gravity hydrometers were determined in 1931 or about two years earlier than the determinations with the API hydrometers. This may account for the variations between the two sets of determinations. Column 5 of Table I gives the degrees A.P.I. corresponding to the gravity at 60° F as determined by the Westphal balance. Certain oils due to their heavy specific gravity could not be converted to degrees A.P.I. with the tables available. These were converted to degrees A.P.I. by using the following equation:

$$^{\circ}\text{API} = \frac{141.5}{\text{sp. grav. at } \frac{60^{\circ}}{60^{\circ}}} - 131.5$$

The range between 0° A.P.I. and 10° A.P.I. in terms of specific gravity was calculated by the above formula and is given on the following sheet.

Conversion of degrees A.P.I. between 0° and 1.0° to
specific gravity

	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
0.0	1.0760	1.0752	1.0744	1.0736	1.0728	1.0720	1.0712	1.0704	1.0696	1.0688
1	1.0679	1.0671	1.0663	1.0655	1.0647	1.0639	1.0631	1.0623	1.0615	1.0607
2	1.0599	1.0591	1.0583	1.0575	1.0568	1.0560	1.0552	1.0544	1.0536	1.0528
3	1.0520	1.0512	1.0505	1.0497	1.0490	1.0482	1.0474	1.0466	1.0459	1.0451
4	1.0443	1.0435	1.0427	1.0420	1.0412	1.0404	1.0396	1.0399	1.0381	1.0374
5	1.0366	1.0358	1.0351	1.0343	1.0336	1.0328	1.0321	1.0313	1.0306	1.0298
6	1.0291	1.0284	1.0276	1.0269	1.0261	1.0254	1.0247	1.0239	1.0232	1.0224
7	1.0217	1.0210	1.0202	1.0195	1.0187	1.0180	1.0173	1.0165	1.0158	1.0150
8	1.0143	1.0136	1.0129	1.0121	1.0114	1.0107	1.0100	1.0093	1.0085	1.0078
9	1.0071	1.0064	1.0057	1.0049	1.0042	1.0035	1.0028	1.0021	1.0014	1.0007
10	1.0000	0.9997	0.9989	0.9982	0.9974	0.9965				

TABLE III
 Specific Gravities of the A Series in Degrees A.P.I. as Reported by this
 Laboratory and the Cooperating Laboratories Reporting.

	NRL	1	2	3	4	5	6	7	8	9	10	11	Average
A-1	8.30 -.18	8.59 +.11	8.87 +.39	8.20 -.28	8.30 -.18	8.40 -.08	8.80 +.32	8.50 +.02	8.60 +.12	8.40 -.08	8.30 -.18	8.30 -.18	8.48 ±.17
A-2	12.10 +.15	12.01 +.06	11.60 -.35	12.10 +.15	12.00 +.05	12.10 +.15	12.10 +.15	11.80 -.15	12.20 +.25	12.00 +.05	11.60 -.35	11.60 -.35	11.95 ±.17
A-3	6.70 -.70	7.20 -.20	8.46 +1.06	7.40 +.30	7.40 +.30	7.40 +.30	7.70 +.30	6.60 -.80	7.70 +.30	7.40 +.30	7.40 +.30	7.20 -.20	7.40 ±0.35
A-4	7.70 -.29	7.60 -.39	8.32 +.33	8.00 +.01	8.00 +.01	8.20 +.21	8.30 +.31	8.00 +.01	8.10 +.11	7.90 -.09	7.90 -.09	7.90 -.09	7.99 ±0.16
A-5	10.30 -.73	11.43 +.40	12.00 +.97	11.40 +.37	11.10 +.07	10.80 -.23	10.90 -.13	10.90 -.13	11.20 +.17	10.80 -.23	10.60 -.43	10.60 -.43	11.03 ±0.35
A-6	12.30 -.25	12.74 +.19	12.50 -.05	12.50 -.05	12.60 +.05	12.40 -.15	12.40 -.15	12.30 -.25	12.80 +.25	13.40 +.85	12.20 -.35	12.20 -.35	12.55 ±0.23
A-7	11.50 -.07	11.86 +.29	11.57 +.03	11.60 +.03	11.50 -.07	11.50 -.07	11.60 +.03	11.50 -.07	11.70 +.13	11.60 +.03	11.40 -.17	11.40 -.17	11.57 ±0.09
A-8	15.25 +.42	15.13 +.30	14.20 -.63	15.30 +.47	13.20 -1.63	15.20 +.37	14.70 -.13	14.50 -.33	15.00 +.17	15.70 +.87	15.20 +.37	14.60 -.23	14.83 ±0.49
A-9	8.77 -.07	8.87 +.03	8.70 -.14	8.90 +.06	9.00 +.16	8.80 -.04	9.10 +.26	8.80 -.04	8.90 +.06	8.80 -.04	8.70 -.14	8.70 -.14	8.84 ±0.09
A-10	11.89 +.02	12.30 +.43	11.30 -.57	12.00 +.13	12.00 +.13	11.90 +.03	12.00 +.13	11.80 -.07	12.10 +.23	11.80 -.07	11.50 -.37	11.50 -.37	11.87 ±0.19
A-11	15.20 +.30	15.44 +.54	13.50 -1.40	15.10 +.20	15.00 +.10	14.80 -.10	14.90 -.20	14.70 +.10	15.00 +.10	15.40 +.50	14.90 +.10	14.90 +.10	14.90 ±0.28

TABLE III (cont'd.)

	NRL	1	2	3	4	5	6	7	8	9	10	11	Average
A-12	6.90 -0.13	7.37 +0.33	7.20 +0.17	6.90 -0.13	7.20 +0.17	6.70 -0.33	7.20 +0.17	7.40 +0.37	6.70 -0.33	7.10 +0.07	6.90 -0.13	6.80 -0.23	7.03 <u>+0.21</u>
A-13	9.01 -0.16	9.57 +0.40	9.00 -0.17	9.20 +0.03	9.10 -0.07	8.90 -0.27	9.20 +0.03	9.60 +0.43	10.00 +0.83	9.00 -0.17	8.80 -0.37	8.70 -0.47	9.17 <u>+0.30</u>
A-14	11.23 -0.13	11.43 +0.07	10.90 -0.46	11.40 +0.04	11.30 -0.06	11.20 -0.16	11.40 +0.04	11.40 +0.04	11.20 -0.16	11.50 +0.14	12.30 +0.94	11.20 -0.16	11.36 <u>+0.21</u>
A-15	11.10 -0.13	11.43 +0.20	11.90 +0.67	11.20 -0.03	11.20 -0.03	11.10 -0.13	11.20 -0.03	11.10 -0.13	11.20 -0.03	11.70 +0.47	10.80 -0.43	10.90 -0.33	11.23 <u>+0.23</u>
A-16	13.41 -0.07	13.93 +0.45	13.20 -0.28	13.50 +0.02	13.50 +0.02	13.50 +0.02	13.50 +0.02	13.50 +0.02	13.40 -0.08	13.80 +0.32	13.40 +0.08	13.20 -0.28	13.48 <u>+0.15</u>
A-17	11.50 +0.28	11.43 +0.22	10.40 -0.82	11.40 +0.18	11.60 +0.38	11.60 +0.38	11.10 -0.12	10.70 -0.52	11.10 -0.12	11.70 +0.48	11.40 +0.18	10.70 -0.52	11.22 <u>+0.35</u>
A-18	11.83 -0.11	12.15 +0.21	11.90 -0.04	11.90 -0.04	12.00 +0.06	12.00 +0.06	12.00 +0.06	12.00 +0.06	12.00 +0.06	12.20 +0.26	11.70 -0.24	11.70 -0.24	11.94 <u>+0.12</u>
A.D.	+0.23	+0.26	+0.47	+0.12	+0.20	+0.14	+0.12	+0.21	+0.18	+0.27	+0.23	+0.26	+0.23

16. In examining the data for the NRL series in Table I, it is seen that the values in columns 5 and 6 have much closer agreement than the data in columns 5 and 7 or 6 and 7. This may be due to the change in specific gravity of the oil during storage as the values given in columns 5 and 6 were taken two years or more after those in column 7. The distribution of the differences in the readings is given below:

Difference in Degrees A.P.I.	: Column 5 from 6		: Column 5 from 7		: Column 6 from 7		
	: +	-	: +	-	: +	-	
0		2		6		3	
0.1	8		1	2	2	1	
0.2	9		1	2	1	3	
0.3	5			4		3	
0.4	4			2	1	1	
0.5	1			4	1	2	
over 0.5	0			4	2	2	
Total	27	2	2	18	6	7	
							12
							3
							16
Avg. deviation °A.P.I.....		0.22		0.39		0.42	
Specific gravity (15° API basis).....		0.0014		0.0026		0.0028	

It should be noted that the readings taken with the Westphal balance, when converted to degrees A.P.I., give a higher value than those taken with either an A.P.I. hydrometer or a hydrometer calibrated in specific gravity. This means that the specific gravity is less, determined by the Westphal balance and using the change in specific gravity with temperature, than the values determined with the A.P.I. hydrometers and the tables used for correction of temperature such as U.S. Bureau of Standards Circular #154.

17. The values for the "A" series show the opposite findings. Table III gives the specific gravity in °A.P.I. for the "A" series as found by this and the cooperating laboratories. The determinations made by these laboratories are probably made with hydrometers. The values at this Laboratory gave thirteen gravities that were lower than the average and five higher. This means that the results at this Laboratory will report a fuel as denser than the other laboratories. But the findings are such that the average error for all the gravities reported is $\pm 0.23^\circ$ A.P.I. or about 0.0015 specific gravity units based upon a 15° A.P.I.

18. In any determination with a hydrometer, if the oil is not heated to a temperature sufficient to make the hydrometer float freely there is very apt to be a resistance to the slow drop of the hydrometer in the fluid and as a result the readings will be low; that is, the fuel oil will show a gravity of an oil heavier than it really is. This error may be as great as 0.2° A.P.I. and may account for the differences found in columns 5 and 6 of Table I, and verifies the average variation found in Table III.

19. In comparing data of gravity of oils, it should be noted that degrees A.P.I. cannot be averaged. If the readings of degrees A.P.I. given in column 5 in Table I are averaged, the value is found to be 14.39. The value in specific gravity from column 2 is 0.9716, which in terms of degrees A.P.I. is 14.15 or 0.22° A.P.I. lower. To show what will happen if degrees A.P.I. are averaged, as well as the specific gravities, the following calculations were made:

Mix Equal Parts				Mix equal parts				Results			
° A.P.I.				specific gravity							
5	10	15	20	1.0366	1.000	.9659	0.9340	°API	°API	Spec. grav.	Dif-
								Av.	ference		
1	1			1	1			7.5	7.46	1.0183	0.04
	1	1			1	1		12.5	12.44	0.9830	0.06
		1	1			1	1	17.5	17.45	0.9500	0.05
			1			1	1	15.0	14.83	0.9670	0.17
1			1	1			1	10.0	9.81	1.0013	0.19
1				1	1		1	12.5	12.11	0.9853	0.39
1	1	1		1	1	1		10.0	9.89	1.0008	0.11
	1	1	1		1	1	1	15.0	14.89	0.9666	0.11
1	1	1	1	1	1	1	1	12.5	12.28	0.9841	0.22

This shows that the values found by averaging °A.P.I. are always higher than the true ones found by averaging specific gravities. Of course, in discussing the averaging of any gravity measurements it must be assumed that the resulting solution has no change in volume or abnormalities which will alter the resulting density.

DISCUSSION

20. The ordinary method of determination of specific gravity of any sample is by the use of a hydrometer. This hydrometer may be calibrated either in terms of specific gravity or degrees A.P.I. As the temperature is taken at the same time the specific gravity is determined, the corrected specific gravity can be obtained from the use of tables such as the Bureau of Standards Circular #154.

21. The corrected gravity, as determined by the use of these tables, is dependent upon the particular fuel oil chosen as standard and whose change of specific gravity per degree is used by those who prepare the tables. It is of interest to give the value used in various publications as follows:

BUREAU OF STANDARDS - Technical Paper #77 (Aug. 26, 1916)

Page 19 - Change in specific gravity for different specific gravities are shown in the following tables:

<u>Specific Gravity</u>	<u>Change in Specific Gravity</u>
$\frac{15.56^{\circ}\text{C}}{15.56^{\circ}\text{C}}$	$^{\circ}\text{C}$
0.890	0.00075
0.900	0.00074
0.910	0.00073
0.920	0.00072
0.930	0.00071
0.940	0.00070
0.950	0.00069
0.960	0.00069

Bureau of Standards Circular #154 - May 29, 1924.

Change in specific gravity calculated from data given in tables:

<u>Specific Gravity</u>	<u>Change in Specific Gravity 60° - 180°F</u>	
$\frac{15.5^{\circ}\text{C}}{15.5}$	$^{\circ}\text{F}$	$^{\circ}\text{C}$
0.999	0.000336	0.000605
0.980	0.000336	0.000605
0.960	0.000337	0.000607
0.940	0.000340	0.000612
0.920	0.000342	0.000616
0.900	0.000344	0.000620
0.880	0.000347	0.000625
0.860	0.000349	0.000629

Manual of Engineering Instruction - Chapter 39 - Tables (Revised Mar. 1929).

Using Table 30, the change in gravity per degree Fahrenheit from 60 to 100°F was calculated for the following densities:

<u>Density Observed</u>	<u>Change in Specific Gravity per degree F</u>
0.900	0.000352
0.920	0.000350
0.940	0.000350

Using Table 31 given in degrees A.P.I., the change in gravity per degree Fahrenheit was calculated for the following:

<u>$^{\circ}\text{A.P.I.}$</u>	<u>Density</u>	<u>Change in Specific Gravity per degree F</u>
10.0	1.0000	0.000356
14.0	0.9725	0.000358
19.0	0.9402	0.000348

Technical Data on Fuel by H.M. Spleys, British National Committee
World Power Conference, London, 1932.

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	From Mixed Base Crude		
	Diesel Oil Distilled (Gas oil)	Light Fuel Oil	Heavy Fuel Oil
Specific Gravity	0.870	0.895	0.949
$\frac{15.5^{\circ}\text{C}}{15.5^{\circ}\text{C}}$			
Correction to spec.grav.	0.000665	0.00066	0.00065

Fuel Testing - Lab.Methods in Fuel Technology, G.W. Himus, London, 1932.

Corrections per degree to be added or subtracted from the observed specific gravity as given on page 212 are as follows:

	$^{\circ}\text{F}$	$^{\circ}\text{C}$
Kerosene	0.00040	0.000720
Gas oils	0.00036	0.000648
Diesel Engine oils	0.00035	0.000630
Heavy Fuel Oils	0.00034	0.000612

22. The change in specific gravity per degree centigrade or per degree fahrenheit for the oils in storage at the Naval Research Laboratory will be found in columns three and four of Table I. The mean values for all the oils studied in this report as well as the data from the literature as given above are as follows:

	Change in Specific Gravity per degree	
	$^{\circ}\text{F}$	$^{\circ}\text{C}$
"A" series fuel oils.	0.000369	0.00066
NRL series fuel oils omitting shale oils #5, 6.	0.000361	0.00065
Manual of Engineering Instructions, Chapter 39.		
Specific gravity 0.900	0.000352	0.000634
Specific gravity 0.940	0.000350	0.00063
Bureau of Standards Tech. #77		
Specific gravity 0.900	0.000411	0.00074
Specific gravity 0.960	0.000380	0.00069

Bureau of Standards Cir. #154		
Specific Gravity 0.900	0.000344	0.00062
Specific Gravity 0.960	0.000337	0.00061
British Data - H.M. Spiers.		
Specific Gravity 0.895	0.000367	0.00066
Specific Gravity 0.949	0.000360	0.00065
Fuel Testing - G.W. Himus		
Heavy fuel oils	0.00034	0.000612

23. The above shows that data can be obtained giving a change in specific gravity per degree that will vary as much as thirteen percent. These differences will have a greater effect on determinations of gravity of oils as the temperature must be raised to obtain a reading with the hydrometer. To show this the following calculations were made using a change in specific gravity per degree Fahrenheit of 0.00034, 0.00036, and 0.00038 with temperatures of the observation of 77°F, 100°F, 120°F. The results are:

Temp. at which Sp. Gravity of 0.950 is observed :	Specific Gravity at 60°F or 15.56°C using change in specific gravity per degree F.					
:	0.00034	:	0.00036	:	0.00038	:
:	Sp.Gr. °API	:	Sp.Gr. °API	:	Sp.Gr. °API	:
77°F or 25.0°C	0.9557	16.56	0.9561	16.50	0.9565	16.43
100°F 37.8°C	0.9635	15.36	0.9644	15.23	0.9653	15.09
120°F 48.9°C	0.9703	14.33	0.9716	14.13	0.9730	13.93

These data are plotted in Plate 2. In terms of volume, such as gallons, it means that if the Navy purchased 1000 gallons with a density of 0.950 determined at 77°, 100°, or 120°F, and using the above change in density with temperature, the actual gallons calculated at 60°F would be:

Change in Density °C	Temperature		
	77	100	120
0.00034 (Circ.#154)	994.0	986.0	979.2
0.00035 (Navy)	993.8	985.5	978.5
0.00036 (NRL)	993.6	985.1	977.8
0.00038	993.2	984.2	976.4

24. The value now used in Circular #154 is 0.00034, the value in Manual of Engineering Instructions is 0.00035, and the average value as determined by this Laboratory is 0.00036. This shows that the Navy pays for more than it actually receives. It should be noted here that many of both the NRL and "A" series used in this study are not typical "Bunker Fuels" as delivered to the Navy but are the stocks from which the commercial deliveries are blended, and therefore this data should be used only as an indication for future trends. As the fuel oils become heavier or more viscous the temperature must be raised to be sure the hydrometer floats readily in the oil and in so doing this correction factor will give a greater deviation as shown above.

25. Lest the wrong impression is left, it should be noted from Table III that the average deviation in measuring the degrees A.P.I is ± 0.23 . From the calculated values given above, it is seen that the specific gravity A.P.I., when the reading is made at 77°F and corrected with the varying coefficient of expansions, varies only 0.13 of a degree A.P.I., which is about 60% of the average deviation in the observations. If the readings are taken at 100°F , the maximum difference is 0.27° A.P.I., or slightly more than the average deviation reported in Table III. If the readings are corrected by the Navy factor of 0.00035 and those for cracked fuels of the "A" series with a specific gravity of less than 1.000 are corrected by factor of 0.000364, then the difference will be about 0.1° A.P.I., when determined at 120°F or less when corrected to 60°F . Therefore, the Navy tables as now used are within the limits of error of the observations.

26. In the other reports the NRL and "A" oils have been compared as to types, specific gravity, viscosity at 122°F , molecular weight, etc. These oils will now be compared as to change in specific gravity per degree Fahrenheit as to gravity, etc.

27. The NRL fuel oils are grouped as to whether cracked, cracked blends, straight runs, blends of unknown source, or shale oils; and the change in gravity with temperature shows that the shale oils have the largest change in gravity with temperature, the blends of unknown source and cracked fuels are next, while the straight runs have the least change in specific gravity with change in temperature. This will be discussed further under molecular weights. The data are given in detail in appendices A and B, and are summarized as follows:

	No.	Change in Specific Gravity, $^{\circ}\text{F}$
"NRL" series - cracked	8	0.000364 \pm 0.000006
cracked blends	3	0.000362
straight run	11	0.000356 \pm 0.000004
blends	7	0.000364 \pm 0.000005
shale oils	2	0.000391 \pm 0.000007

"A" Series - cracked and blends 18 0.000369 ± 0.000010

28. The correlation between change in specific gravity per degree with the viscosity at 122°F is given below:

Viscosity	Average Change in Specific Gravity per °F			
	No.	NRL Series	No.	"A" Series
200 sec.F or greater	7	0.000359	6	0.000371
100-200 sec.F	8	0.000361		
50-100 sec.F	8	0.000362	8	0.000368
less than 50 sec.F	6	0.000362	4	0.000367

The above summarized data of these fuels grouped according to viscosity do not show any definite trend. With the "A" series the more viscous fuels have a slightly greater change in viscosity.

29. NRL Report P-25-7 gives on page 11 as one of the conclusions:

(4) That a cracked residuum has a smaller molecular weight than a straight run residuum. This correlates with the gravity of these residuums, i.e., the specific gravity increases as the molecular weight decreases.

The same conclusion can be drawn from the data in this report. The change in specific gravity per degree of a member of the aromatic series is greater than for those of the aliphatic series. The density as given in Report P-25-7 is greater for members of the aromatic series than for those of the aliphatic series. A few are given below:

	Molecular weight	Specific Gravity Temp.	Change in Spec. Gravity per °C
Hexadecane	226	18°C 0.7754	0.000688
N-Tetrakosan	338	51.1°C 0.7786	0.000638
Naphthalene	128	98.4°C 0.9621	0.000836
Diphenyl	154	82.0 0.9845	0.000819
1,4 dimethyl naphthalene	156	16.4 1.0180	0.000716
1,3,5 trimethyl 2-cetyl benzol	344	40. 0.8452	0.000654
Phenyl,o-tolyl sulfide	200	0 1.1131	0.000793

The above values show that an aliphatic hydrocarbon having a benzol nucleus fastened to the chain such as 1, 3, 5 trimethyl 2-cetyl benzol has a change in specific gravity similar to the fuel oils studied at this Laboratory while a straight chain hydrocarbon such as n-tetrakosane has a value equal to the smallest change in specific gravity found in this work.

30. The change in specific gravity per degree F is summarized as follows for the oils studied in this report:

Specific Gravity	<u>Average change in Specific Gravity - °F</u>			
	No.	NRL Series	No.	"A" Series
1.000 - 1.070	6	0.000366	6	0.000377
0.980 - 0.999	5	0.000361	9	0.000365
0.950 - 0.979	10	0.000361	3	0.000362
less than 0.950	7	0.000358		

The above summarized data show that the heavier fuels have the higher coefficients of expansion.

31. The change in specific gravity per degree F is summarized as follows for the oils studied in this report:

Molecular Weight	<u>Average change in Specific Gravity - °F</u>			
	No.	NRL Series	No.	"A" Series
Less than 350	5	0.000368	10	0.000372
350 - 375	7	0.000362	5	0.000368
375 - 400	9	0.000361		
Over 400	8	0.000356	3	0.000358

The above summarized data show that the smaller the average molecular weight is, especially with the cracked residues, the greater is the coefficient of expansion. This checks the literature and is expected.

32. The "A" series has been studied more in detail than the NRL series and in Appendix B will be found this series tabulated in order of the coefficient of expansion; given with this are the hydrogen-carbon ratio, NBL rating, and the average deviations of the observations given in Table III. No definite coordination can be made as to the cause of the high average deviation that some fuel oils show.

OPINIONS

33. It is the opinion of this Laboratory that the coefficient of expansion used by the Navy is satisfactory, especially so when the average variation of determinations is of the magnitude of 0.2° A.P.I. Therefore the present tables are considered satisfactory for fuel oils with a gravity of 12° A.P.I.

RECOMMENDATIONS

34. It is recommended that the Naval Boiler Laboratory in their study of fuel oils, check the coefficient of expansions of fuels delivered on Navy contracts at intermittent times.

SUMMARY

35. The present temperature conversion tables used by the Navy with fuel oils are satisfactory for the fuel oils studied in this report.

36. The coefficient of expansion calculated from the Navy tables is 0.000350 per degree F., while the "A" series which has a specific gravity of less than 1.000 (or 10° A.P.I.) is 0.000364 °F. This difference does not change the gravity at 60°F if the determination was at 120°F as much as the average deviation of the observations as made by various laboratories.

APPENDIX A

Data in this appendix give the specific gravity of the NRL series of fuel oils at different temperatures. The temperature range covered with each fuel is dependent upon the viscosity of the oil studied. The readings were taken at as low temperatures as possible, where the fluidity of the oil would permit accurate readings with the Westphal balance.

<u>Oil No.</u>	<u>Temp. °C</u>	<u>Sp.Grav.</u>	<u>Oil No.</u>	<u>Temp. °C</u>	<u>Sp.Grav.</u>
3	84.2	0.9153	13	90.5	0.9077
	76.1	0.9206		79.9	0.9145
	68.1	0.9259		68.2	0.9217
	60.9	0.9306		67.7	0.9222
		57.7		0.9284	
4	87.2	0.9042	14	83.7	0.9513
	78.4	0.9101		72.4	0.9589
	69.7	0.9160		63.5	0.9647
	60.8	0.9219		53.0	0.9718
	51.0	0.9282		43.9	0.9780
		30.9		0.9866	
5	81.8	0.8559	15	95.5	0.8885
	71.6	0.8632		82.0	0.8971
	71.1	0.8635		69.8	0.9051
	61.5	0.8702		59.6	0.9117
	52.2	0.8770		51.5	0.9170
	41.8	0.8844		41.9	0.9232
	28.9	0.8936			
6	83.3	0.8834	16	91.0	0.9347
	73.7	0.8901		82.5	0.9402
	62.0	0.8979		73.1	0.9462
	51.4	0.9054	17	91.5	0.9199
	42.6	0.9115		80.0	0.9281
	33.7	0.9176		69.8	0.9340
8	88.5	0.9378	60.5	0.9399	
	78.5	0.9445	49.2	0.9473	
	68.9	0.9509	37.9	0.9546	
	59.3	0.9569			
	59.0	0.9571	21	87.7	0.9142
	58.8	0.9575		78.7	0.9198
	51.4	0.9622		68.4	0.9263
				58.5	0.9326
9	92.3	0.9498	22	91.6	0.9042
	85.1	0.9546		82.4	0.9100
	76.1	0.9605		72.1	0.9168
	70.0	0.9645		62.9	0.9225
		54.5		0.9227	
12	80.2	0.8858			
	71.0	0.8917			
	61.9	0.8973			
	51.9	0.9041			

Oil No.	Temp. °C	Sp. Grav.	Oil No.	Temp. °C	Sp. Grav.
24	88.1	0.9804	32	88.1	0.9001
	79.2	0.9865		80.2	0.9048
	66.5	0.9947		71.1	0.9106
	58.2	1.0000		61.6	0.9168
		51.9		0.9232	
25	95.9	0.9516	33	90.2	0.9584
	83.0	0.9600		80.3	0.9650
	71.8	0.9673		71.7	0.9707
	61.1	0.9742		61.0	0.9777
26	88.1	0.8985	36	89.3	0.8383
	87.0	0.8992		81.1	0.8435
	78.2	0.9047		71.5	0.8495
	70.2	0.9099		61.2	0.8561
	69.7	0.9102		51.3	0.8625
	61.8	0.9152	37	87.5	0.8917
	61.1	0.9157		78.2	0.8976
	52.7	0.9210		69.1	0.9035
27	98.5	1.0199		58.4	0.9103
	90.0	1.0254		50.6	0.9152
	89.4	1.0258	38	85.8	1.0093
	79.7	1.0321		77.4	1.0147
	75.0	1.0352		76.4	1.0154
	71.0	1.0383		68.1	1.0210
	62.1	1.0436		61.0	1.0256
27-A	90.3	0.9341		54.1	1.0301
	80.4	0.9405	39	86.9	1.0105
	71.1	0.9465		79.9	1.0151
	70.7	0.9468		72.1	1.0202
	61.0	0.9531		65.7	1.0244
28	90.2	0.9240		41	80.5
	82.4	0.9290	70.0		0.9252
	74.6	0.9341	61.1		0.9308
	67.8	0.9385	52.5		0.9366
	67.1	0.9390	44		91.6
30	80.6	0.9174		81.2	0.9091
	71.2	0.9234		70.5	0.9156
	60.8	0.9302		60.0	0.9224
	52.0	0.9359		51.6	0.9280
31	98.1	0.9342	45	85.0	0.8996
	91.3	0.9389		75.1	0.9057
	83.1	0.9440		66.1	0.9115
	75.7	0.9488		57.3	0.9173
	67.3	0.9544		48.1	0.9233

The NRL series is tabulated as to type, whether cracked, straight runs or blends as follows:

<u>Cracked</u>	<u>Change in specific gravity of</u>
9	0.000367
14	0.000373
16	0.000356
24	0.000357
27	0.000366
27-A	0.000357
33	0.000370
38	0.000367
Ave.	0.000364 ± 0.000006
 <u>Cracked Blend</u>	
8	0.000363
17	0.000362
25	0.000361
Ave.	0.000362
 <u>Straight Run</u>	
12	0.000357
13	0.000349
15	0.000361
21	0.000350
22	0.000356
26	0.000356
30	0.000359
32	0.000364
36	0.000351
37	0.000354
45	0.000366
Ave.	0.000356 ± 0.000004
 <u>Blends</u>	
3	0.000367
4	0.000374
28	0.000367
31	0.000359
39	0.000366
41	0.000365
44	0.000356
Ave.	0.000364 ± .000005

<u>Shale oils</u>	<u>Change in specific gravity</u> <u>°F</u>
5	0.000398
6	0.000384
Ave.	0.000391 ± 0.000007

The coefficient of expansion of the NRL series is tabulated below according to the specific gravity of the fuel oil studied.

<u>Specific Gravity</u>	<u>No.</u>	<u>Change in Sp. Gravity /°F</u>	::	<u>Specific Gravity</u>	<u>No.</u>	<u>Change in Sp. Gravity /°F</u>
1.070	27	0.000366	::	0.969	17	0.000362
1.058	38	0.000367	::	0.969	28	0.000367
1.058	39	0.000366	::	0.965	41	0.000365
1.026	24	0.000357	::	0.963	30	0.000359
1.008	33	0.000370	::	0.961	3	0.000367
1.000	14	0.000373	::	0.961	21	0.000350
			::	0.956	13	0.000349
Ave.		0.000366 ±	::	0.954	44	0.000356
		0.000005	::	0.952	4	0.000374
			::	0.952	22	0.000356
0.999	25	0.000361	::	Ave.		0.000361 ±
0.994	9	0.000367	::			0.000006
0.986	8	0.000363	::			
0.981	27-A	0.000357	::	0.949	32	0.000364
0.980	16	0.000356	::	0.948	45	0.000366
Ave.		0.000361 ±	::	0.945	26	0.000356
		0.000003	::	0.940	37	0.000354
			::	0.938	12	0.000357
			::	0.932	15	0.000361
			::	0.886	36	0.000351
			::	Ave.		0.000358 ±
			::			0.000003

The coefficient of expansion of the NRL series is tabulated below according to the viscosity of the fuel oil studied at 122°F.

No.	Viscosity at 122°F Sec.	Change in Specific Gravity /°F
24	F 512.0	0.000357
27	F 396.1	0.000366
9	F 262.4	0.000367
25	F 225.3	0.000361
21	F 223.7	0.000350
16	F 215.4	0.000356
27-A	F 200.0	0.000357
33	F 191.2	0.000370
13	F 169.8	0.000349
28	F 153.3	0.000367
17	F 136.8	0.000362
22	F 124.4	0.000356
31	F 112.4	0.000359
39	F 105.8	0.000366
8	F 101.8	0.000363
44	F 85.6	0.000356
30	F 84.8	0.000359
41	F 80.0	0.000365
3	F 74.0	0.000367
32	F 73.7	0.000364
45	F 68.8	0.000366
26	F 65.0	0.000356
38	F 60.7	0.000367
15	F 49.3	0.000361
37	U 365	0.000354
12	U 240.1	0.000357
4	F 19.8	0.000374
36	U 151.2	0.000351
14	U 114.0	0.000373

The coefficient of expansion of the NRL series is tabulated below according to molecular weights of the fuel oils studied.

No.	Molecular Weight	Change in Specific Gravity /°F
14	273	0.000373
38	285	0.000367
4	306	0.000374
27	307	0.000366
39	314	0.000361
41	350	0.000364
3	364	0.000367
24	366	0.000357
33	366	0.000371
30	367	0.000359
8	370	0.000363
37	371	0.000354
26	377	0.000356
31	377	0.000359
12	381	0.000357
44	381	0.000356
15	382	0.000361
45	387	0.000366
32	391	0.000364
25	395	0.000361
28	397	0.000367
17	403	0.000362
9	404	0.000367
27-A	413	0.000357
16	417	0.000356
22	418	0.000356
36	419	0.000351
21	477	0.000350
13	510	0.000349

APPENDIX B

Data in this appendix give the calculated specific gravity of the fuel oils of the "A" series for different temperatures.

The "A" series is also separately tabulated as to specific gravity, increasing molecular weights, viscosity at 122°F, and coefficient of expansion.

		Sample Number					
		1	2	3	4	5	6
Gravity	40°F	1.0199	0.9925	1.0322	1.0241	1.0057	0.9917
	60°F	1.0123	0.9853	1.0241	1.0165	0.9978	0.9843
	80°F	1.0047	0.9781	1.0160	1.0089	0.9899	0.9769
	120°F	0.9894	0.9638	0.9998	0.9937	0.9741	0.9621
	160°F	0.9742	0.9495	0.9836	0.9784	0.9584	0.9472
	200°F	0.9589	0.9352	0.9674	0.9632	0.9426	0.9324
	240°F	0.9437	0.9209	0.9512	0.9480	0.9268	0.9176
Change in Gravity per °F		0.000381	0.000358	0.000405	0.000381	0.000394	0.000371
API at 60°F		8.3	12.1	6.7	7.7	10.3	12.3
		7	8	9	10	11	12
Gravity	40°F	0.9968	0.9715	1.0160	0.9940	0.9718	1.0299
	60°F	0.9895	0.9643	1.0087	0.9867	0.9646	1.0225
	80°F	0.9822	0.9571	1.0014	0.9794	0.9574	1.0151
	120°F	0.9677	0.9426	0.9869	0.9649	0.9431	1.0004
	160°F	0.9532	0.9282	0.9723	0.9503	0.9287	0.9857
	200°F	0.9387	0.9138	0.9577	0.9357	0.9143	0.9710
	240°F	0.9242	0.8993	0.9432	0.9212	0.9000	0.9563
Change in Gravity per °F		0.000363	0.000361	0.000364	0.000364	0.000359	0.000368
API at 60°F		11.50	15.25	8.77	11.89	15.20	6.90
		13	14	15	16	17	18
Gravity	40°F	1.0143	0.9988	0.9993	0.9839	0.9965	0.9945
	60°F	1.0070	0.9914	0.9923	0.9766	0.9895	0.9872
	80°F	0.9997	0.9840	0.9853	0.9693	0.9825	0.9799
	120°F	0.9851	0.9692	0.9713	0.9547	0.9685	0.9653
	160°F	0.9705	0.9543	0.9574	0.9400	0.9545	0.9507
	200°F	0.9559	0.9395	0.9434	0.9254	0.9405	0.9361
	240°F	0.9413	0.9246	0.9295	0.9107	0.9265	0.9215
Change in Gravity per °F		0.000365	0.000371	0.000349	0.000366	0.000350	0.000365
API at 60°F		9.01	11.23	11.10	13.41	11.50	11.83

Specific Gravity of "A" Series

Specific Gravity	No.	Change in Specific Gravity / °F
1.024	3	0.000405
1.023	12	0.000368
1.017	4	0.000381
1.012	1	0.000381
1.009	9	0.000364
1.007	13	0.000365
Ave.		0.000377 ± 0.000012
0.998	5	0.000394
0.992	15	0.000349
0.991	14	0.000371
0.990	7	0.000363
0.990	17	0.000350
0.987	10	0.000364
0.987	18	0.000365
0.985	2	0.000358
0.984	6	0.000371
Ave.		0.000365 ± 0.000009
0.977	16	0.000366
0.965	11	0.000359
0.964	8	0.000361
Ave.		0.000362 ± 0.000003

Molecular Weight of "A" Series

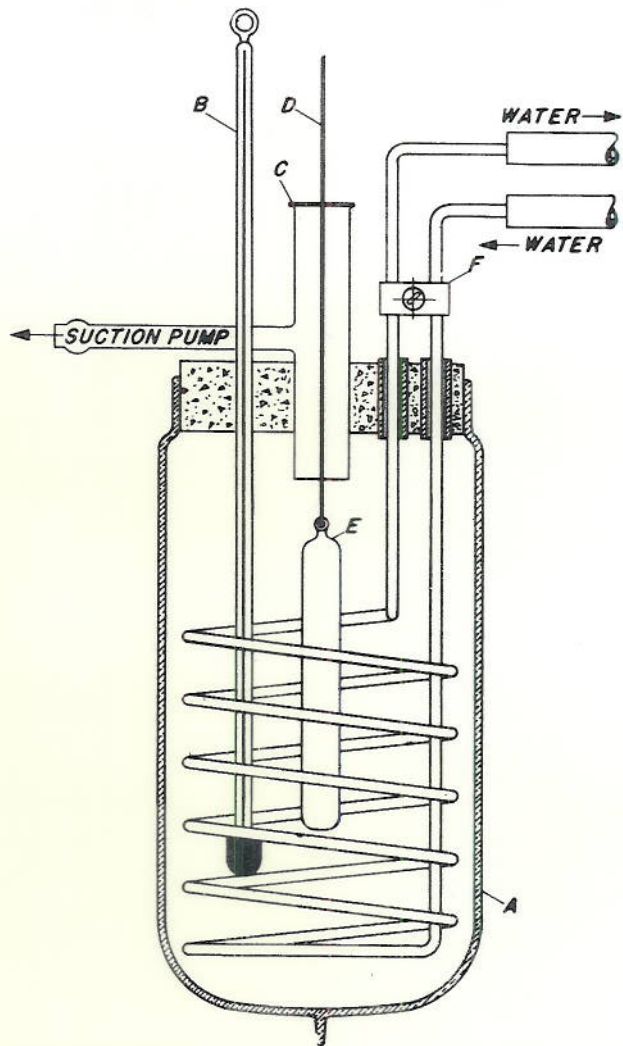
<u>No.</u>	<u>Molecular Weight</u>	<u>Coefficient of Expansion /°F</u>
1	261	0.000381
9	297	0.000364
12	306	0.000368
3	310	0.000405
4	320	0.000381
14	321	0.000371
11	332	0.000359
10	334	0.000364
7	341	0.000363
13	346	0.000365
16	355	0.000366
6	361	0.000371
2	365	0.000358
5	365	0.000394
17	374	0.000350
18	410	0.000365
15	415	0.000349
8	443	0.000361

Viscosity of "A" Series at 122°F

No.	Viscosity 122 °F	
	Sec. F	
A-15	233.0	0.000349
13	151.9	0.000365
18	148.9	0.000365
8	141.4	0.000361
4	136.1	0.000381
3	115.6	0.000405
17	86.5	0.000350
5	81.2	0.000394
6	80.8	0.000371
2	80.2	0.000358
12	77.2	0.000368
16	60.9	0.000366
14	56.2	0.000371
7	52.7	0.000363
10	48.7	0.000364
9	37.7	0.000364
11	28.2	0.000359
1	21.7	0.000381

Coefficient of Expansion	No.	Density	H/C Ratio	Molecular Weight	NBL Rating	Avg. Deviation from Table III
0.000349	15	11.10	1.437	415	51.2	0.23
0.000350	17	11.50	1.401	374	74.3	0.35
0.000358	2	12.10	1.404	365	53.0	0.17
0.000359	11	15.20	1.476	332	84.5	0.28
0.000361	8	15.25	1.518	443	45.2	0.49
0.000363	7	11.50	1.391	341	77.3	0.07
0.000364	9	8.77	1.292	297	78.6	0.09
0.000364	10	11.89	1.385	334	80.4	0.19
0.000365	13	9.01	1.351	346	66.6	0.30
0.000365	18	11.83	1.435	410	49.1	0.12
0.000366	16	13.41	1.477	355	77.6	0.15
0.000368	12	6.90	1.254	306	53.7	0.21
0.000371	6	12.3	1.418	361	70.4	0.23
0.000371	14	11.23	1.406	321	74.4	0.21
0.000381	1	8.3	1.253	261	90.9	0.17
0.000381	4	7.7	1.317	320	64.8	0.16
0.000394	5	10.3	1.398	365	76.1	0.35
0.000405	3	6.7	1.278	310	60.8	0.35

Average 0.000368⁶ ± 0.000010



APPARATUS USED FOR SPECIFIC GRAVITY MEASUREMENTS
PLATE I

