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THE FERA/CANMET PROJECT, PHASE II
PART I: EXPERIMENTAL DATA ON THE EFFECT OF ATOMIZATION VARIABLES ON HEAT TRANSFER FROM OIL FLAMES, USING A MODIFIED BARREL-MIX EMULSION BURNER

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by

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ABSTRACT

This report compiles the experimental data obtained in phase II of the FERA/CANMET project, performed at the Canadian Combustion Research Laboratory (CCRL) in December, 1980 and January, 1981. The objective of this project was to evaluate the effect of varying steam/oil ratios and fuel oil temperatures at higher burner emulsion pressures than were used in Phase I. No interpretation of the results is contained in this experimental data report.

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INTRODUCTION

This project was commissioned by the Combustion Sub-Committee of the Ferrous Energy Research Association (FERA) Technical committee. The work was performed at the Canadian Combustion Research Laboratory (CCRL) of the Energy Research Laboratories (ERL) during December, 1980 and January, 1981, under CANMET Project No. 332302-03 (Job No. 024384), using the CCRL research tunnel furnace. The work was a continuation of the Phase I project, performed for FERA in July, 1979 and the tunnel furnace was equipped with the same dual-fuel, barrel-mix, burner, provided by FERA. The objective of the Phase II project was to evaluate the effect of varying steam/oil ratio and fuel oil temperatures on the heating efficiency of the steam-atomized oil flame while maintaining a constant burner emulsion pressure. Burner emulsion pressures were maintained at approximately 50 or 70 psig by changing the burner tip size for each change in the steam/oil ratio. The burner tip sizes required to maintain these emulsion pressures were determined by the FERA Combustion Sub-Committee on-site personnel. Since Phase I of the FERA program, the CCRL tunnel furnace has been renovated by changing the furnace coolant, replacing the exterior furnace insulation and installing immersed thermocouples in the cooling circuits. These modifications were undertaken to give a more accurate and rapid response to changes in flame and heat transfer characteristics, but the changes will certainly make it difficult for a direct comparison between Phase I and Phase II flames.

DESCRIPTION OF COMBUSTION FACILITIES

A full description of the CCRL combustion facilities is given in Phase I, part II, FERA/CANMET project (Report ERP/ERL 80-7(CF). However, at the request of FERA, two changes were made to this equipment for Phase II: (1) the combustion air flowrates were measured by an orifice plate (supplied by FERA) installed in the primary air supply line, rather than a pitot tube and (2) a Milroyal reciprocating positive-displacement controlled-volume pump (supplied by FERA) replaced the CCRL variable positive-displacement pump to supply a constant flowrate of oil to the burner.

EXPERIMENTAL PROCEDURE

FERA analyses of the phase I data (CANMET Report ERP/ERL 80-6(CF) concluded that the two atomization variables that significantly affected cost performance and heat efficiency of the steam atomized oil flow were steam/oil ratio and burner tip nozzle diameter (or emulsion pressure). They then recommended that phase II be programmed to investigate the effect on the heating efficiency of steam/oil ratios at higher emulsion pressures and varying fuel oil temperatures as well as examining steam/oil ratios at a 50% turndown firing rate. This program was outlined in FERA document no. SCT-6-80, June, 1980 (see Table 1).

FERA stipulated that for all the tests in phase II, flame probing measurements would not be necessary and combustion air input will be maintained at a constant level, rather than controlled by a constant oxygen level in the flue gases (as was done in phase I). Preliminary trial runs indicated that a 50% turndown in the firing rate resulted in an unstable flame at steam/oil ratios greater than 0.3 and hence flames 40 to 44, as outlined in Table 1, could not be investigated.

The variables that were investigated during phase II of the FERA project were:

1. Varying the steam/oil ratio by maintaining a constant oil flow rate at a constant temperature and varying the steam flow rate at a constant temperature. The emulsion pressure in the mixing chamber was maintained at a constant pressure of 49 psig (corr.) by decreasing the diameter of the burner tip opening as the steam/oil ratio was decreased (flames 1-5, FERA No. 25-29).

2. Varying the steam/oil ratio by maintaining a constant oil flow rate at a constant temperature and varying the steam flow rate at a constant temperature. The emulsion pressure in the mixing chamber was maintained at a constant pressure of 69 psig (corr.) by decreasing the diameter of the burner tip opening as the steam/oil ratio was decreased (flames 6-10, FERA No. 30-34, 45).

3. Varying the fuel oil input temperature at a constant oil flow rate and a constant steam/oil ratio (flames 11-16, FERA No. 35-39, 48).

4. Two additional flames (flames 16-17, FERA No. 46-47) at a constant oil flow rate and a constant steam/oil ratio, but with burner tip openings larger and smaller than used in (3), were investigated.

The data accumulated in this test program represented a total of 18 test flames. Each flame was of approximately two hours duration. The data are listed in Tables 3 to 10, under input variables, output variables and heat transfer ratios for each of the flames investigated.

Table 1 - FERA recommended procedure to determine the effect of atomization variables on heat transfer from residual fuel oil flames

FERA FLAME NO.		25	26	27	28	29	30	31	32	33	34
Variable		The Effect of Steam/Oil Ratio at Two High Emulsion Pressures									
Fuel Condition											
MMBTU/h		← 1.5 →									
lb/h		← 82.7 →									
Temp	(°F)	← 190 →									
Air Condition											
SCFH		← 16500 →									
Temp.	(°F)	← 325 →									
Steam Condition											
lb/h		25	20	17	12	8	25	20	17	12	8
Steam/oil ratio		0.30	0.25	0.20	0.15	0.10	0.30	0.25	0.20	0.15	0.10
Emulsion Condition											
Pressure	(psig)	50	50	50	50	50	70	70	70	70	70
Burner Hardware											
Oil Orifice Dia.	(in.)	← 0.052 →									
Steam Orifice Dia	(in.)	← 0.113 →									
Burner Tip Dia.	(in.)	.0825	.0739	.0681	.0572	.0467	.0636	.0567	.0524	.0441	.0360

Table 1 - Cont'd

FERA FLAME NO.		35	36	37	38	39	40	41	42	43	44
Variable		The Effect of Oil Temperature					The effect of steam/oil ratio at 50% turndown firing rates				
Fuel Condition											
MMBTU/h				1.5			← 0.73 →				
lb/h				82.7			← 40 →				
Temp	(°F)	180	200	210	220	230	← choose best temperature →				
Air Condition											
SCFH		← 16,500 →					← 7,980 →				
Temp	(°F)	← 325 →					← 325 →				
Steam Condition											
lb/h		← Choose best flame →					16	24	32	40	48
Steam/oil ratio		from flames 25-34					0.4	0.6	0.8	1.0	1.2
Emulsion Condition											
Pressure	(psig)	← To be determined →									
Burner Hardware											
Oil Orifice Dia	(in.)	← 0.052 →									
Steam Orifice Dia.	(in.)	← 0.113 →									
Burner Tip Dia.	(in.)	← Choose best burner tip dia. from flames 25-34 →									

Table 2 - Analyses of No. 6 fuel oil

		Minimum	Maximum	Average
Specific gravity (60/60°F)		0.978	0.989	0.984
API at 60°F		11.6	13.2	12.3
Carbon	(%)	86.10	86.49	86.31
Hydrogen	(%)	10.36	10.93	10.61
Sulphur	(%)	1.62	1.77	1.72
Nitrogen	(%)	0.30	0.33	0.32
H_2O	(%)	nil	trace	nil
Ash	(%)	nil	0.037	0.018
Flash point	(°F)	200	230	211
Viscosity at 210°F	(cSt)	41.76	44.90	43.17
Pour point	(°F)	40	50	43
Heat of combustion (corrected for sulphur)	(Btu/lb)	18,412	18,479	18,447

Table 3 - Varying steam/oil ratio at 50 psig emulsion pressure

Input and output variables

FLAME		1	2	3	4	5
FERA NO.		25	26	27	28	29
DATE		80/12/09	80/12/10	80/12/11	80/12/12	80/12/13
		Input Variables				
OIL						
Flow	(kg/L)	37.5	37.7	37.8	37.7	(37.7)
Temperature	(°C)	87	90	88	88	-
Pressure (corr.)	(psig)	60	62	62	62	-
STEAM						
Flow	(lb/h)	24	21	17	13	(10)
Temperature	(°C)	182	182	182	183	-
Pressure (corr.)	(psig)	56	53	52	52	-
Ratio (steam/oil)	(kg/kg)	0.29	0.25	0.20	0.16	(0.12)
Mixing Chamber (emulsion)						
Temperature	(°C)	143	144	142	141	-
Pressure (corr.)	(psig)	49	49	49	49	(49)
Combustion Air						
Flow (calculated)	(scfh)	15,454	15,427	15,489	15,414	(15,450)
Metering temperature	(°C)	158	153	140	136	-
Temperature (at windbox)	(°C)	152	143	130	127	-
Pressure (at windbox)	(in. H_2O)	1.05	1.05	1.07	1.07	-
Barometric pressure	(in. Hg)	29.98	29.71	30.02	29.73	-
Burner Hardware						
Oil orifice no.		10	10	10	10	(10)
Steam orifice no.		10	10	10	10	(10)
Burner tip (drill size)		33	38	42	47	(52)
		Output Variables				
Flue Gas Analysis						
O_2	(%)	1.9	1.9	2.3	2.3	-
CO	(%)	.003	.003	.003	.004	-
Soot	(gr/scf)	.079	.064	.072	.098	-
Flame Temperature						
At no. 27 cooling plate	(°C)	940	935	917	823	-

Table 4 - Varying steam/oil ratio at 50 psig emulsion pressure

Heat Transfer Rates

FLAME			1	2	3	4	5
FERA NO.			25	26	27	28	29
DATE			80/12/09	80/12/10	80/12/11	80/12/12	80/12/13
Sink Temp. of Coolant	(°C)		110	110	107	108	-
Heat to Cooling Plates		1	16,326	17,537	18,064	17,643	-
(BTU/h)		2	23,489	24,911	25,543	24,647	-
		3	24,015	25,332	26,175	24,963	-
		4	25,174	26,175	26,807	25,490	-
		5	30,967	34,706	35,918	34,127	-
		6	30,493	32,600	32,652	31,072	-
		7	31,810	33,864	33,758	32,178	-
		8	31,336	32,810	33,495	31,968	-
		9	30,967	32,284	32,705	31,230	-
		10	32,652	33,811	34,127	33,390	-
		11	29,809	30,301	30,301	29,317	-
		12	28,776	29,564	29,022	28,432	-
		13	28,727	28,924	28,875	28,481	-
		14	26,267	26,907	26,809	26,858	-
		15	27,055	27,350	27,399	26,612	-
		16	24,890	24,890	24,743	24,644	-
		17	24,841	24,398	24,447	24,447	-
		18	21,348	21,201	21,103	20,758	-
		19	21,398	20,955	21,103	20,758	-
		20	19,135	18,889	18,741	18,791	-
		21	18,086	18,166	17,689	18,086	-
		22	16,973	16,457	16,178	16,695	-
		23	15,781	15,582	15,463	15,701	-
		24	15,185	14,946	14,628	15,026	-
		25	14,509	14,310	14,270	14,708	-
		26	13,714	13,555	13,078	13,555	-
		27	16,099	16,139	15,662	16,099	-
TOTAL			638,822	656,564	658,755	645,676	-
Visuals on Flame							
Stability			← Stable — pulsating — flame →				unstable
Flame length	(metres)		2.5 - 3.0	2.5 - 3.5	2.5 - 3.0	2.3 - 3.5	0 - >4.0
Flame diam.	(metres)		← 0.3 →				
Comments			Smokey tips on extended			Smokier tips	Would not
			← A few sparklers			more sparklers	stay ignited

Table 5 - Varying steam/oil ratio at 70 psig emulsion pressure
Input and output variables

FLAME		6	7	8	9	10
FERA NO.		45	30	31	32	34
DATE		80/12/15	80/12/10	80/12/11	80/12/12	80/12/13
		Input Variables				
OIL						
Flow	(kg/h)	37.8	37.4	37.8	37.6	37.8
Temperature	(°C)	88	88	88	89	88
Pressure (corr.)	(psig)	80	80	81	81	79
STEAM						
Flow	(lb/h)	32.5	27	23	22	10
Temperature	(°C)	182	183	183	182	183
Pressure (corr.)	(psig)	56	53	52	52	65±7
Ratio (steam/oil)	(kg/kg)	0.39	0.33	0.28	0.27	0.12
Mixing Chamber (emulsion)						
Temperature	(°C)	154	154	154	154	150
Pressure (corr.)	(psig)	68	69	69	69	69±3
Combustion Air						
Flow (calculated)	(scfh)	15,414	15,390	15,415	15,403	15,402
Metering temperature	(°C)	149	152	141	135	148
Temperature (at windbox)	(°C)	139	141	130	126	138
Pressure (at windbox)	(in. H_2O)	1.05	1.04	1.06	1.07	1.15±0.1
Barometric pressure	(in. Hg)	30.00	29.75	30.05	29.81	29.87
Burner Hardware						
Oil orifice no.		10	10	10	10	10
Steam orifice no.		10	10	10	10	10
Burner tip (drill size)		33	38	42	44	53
		Output Variables				
Flue Gas Analysis						
O_2	(%)	2.4	1.9	2.2	2.1	4.5
CO	(%)	0.003	0.002	0.002	0.002	0.003
Soot	(gr/scf)	0.057	0.058	0.070	0.067	0.137
Flame Temperature						
At no. 27 cooling plate	(°C)	842	932	924	805	869

Table 6 - Varying steam/oil ratio at 70 psig emulsion pressure

Heat Transfer Rates

FLAME		6	7	8	9	10
FERA NO.		45	30	31	32	34
DATE		80/12/15	80/12/10	80/12/11	80/12/12	80/12/13
Sink Temp. of Coolant	(°C)	107	109	106	104	102
Heat to Cooling Plates	1	15,220	16,221	17,169	16,537	11,797
(BTU/h)	2	21,909	23,383	24,226	23,278	17,643
	3	22,593	24,173	25,174	23,963	18,064
	4	25,648	24,963	25,496	24,805	18,169
	5	31,178	33,548	34,127	32,968	24,331
	6	27,439	31,020	31,072	29,861	22,119
	7	24,858	32,126	31,757	30,809	20,276
	8	27,755	32,020	31,862	30,704	22,593
	9	28,913	30,967	31,125	30,440	23,225
	10	30,546	33,337	33,337	32,442	25,279
	11	26,809	30,301	29,416	28,432	22,480
	12	26,366	29,317	28,776	27,694	21,939
	13	28,038	28,825	28,137	27,399	22,332
	14	26,317	27,202	26,071	25,382	21,349
	15	26,563	27,645	26,366	25,185	22,136
	16	25,382	25,382	24,497	23,365	21,349
	17	25,185	24,792	24,054	23,267	22,480
	18	21,988	21,594	21,152	19,873	19,479
	19	22,136	21,792	20,758	19,922	20,217
	20	19,873	19,233	18,938	17,708	18,397
	21	19,358	18,563	18,206	17,371	18,563
	22	18,285	17,530	16,655	15,821	17,689
	23	17,371	16,059	15,741	14,867	17,053
	24	16,218	15,423	14,867	14,111	16,496
	25	15,701	14,787	14,708	13,634	16,457
	26	14,708	13,754	13,475	13,078	15,463
	27	15,582	16,695	15,940	15,423	16,695
TOTAL		621,939	650,652	643,096	618,339	534,070
Visuals on Flame						
Stability		← Stable, pulsating flame →				
Flame length	(metres)	2.1 2.6	← 2.3 - 3.0 →			2.3 - >4.0
Flame diam.	(metres)	← 0.3 →				
Comments		← Smokey tips on extended flames → A few sparklers				Oil burning on walls- Heavy sparklers

Table 7 - Varying oil temperature at constant steam/oil ratio

Input and output variables

FLAME		11	12	13	14	15	16
FERA NO.		35	36	48	37	38	39
DATE		80/12/17	80/12/18	81/01/06	80/12/16	80/12/18	80/12/17
		Input Variables					
OIL							
Flow	(kg/h)	37.8	37.7	37.3	37.4	37.9	37.5
Temperature	(°C)	83	93	96	100	104	110
Pressure (corr.)	(psig)	60	64	60	60	65	63
STEAM							
Flow	(lb/h)	17	17	17	17	17	17
Temperature	(°C)	182	182	181	182	183	183
Pressure (corr.)	(psig)	48±2	54±3	51±2	51±2	56±3	54±3
Ratio (steam/oil)	(kg/kg)	0.20	0.20	0.21	0.21	0.20	0.21
Mixing Chamber (emulsion)							
Temperature	(°C)	141	144	143	143	146	146
Pressure (corr.)	(psig)	47±1	53±2	50±2	49±2	58±2	54±1
Combustion Air							
Flow (calculated)	(scfh)	15,478	15,445	15,427	15,458	15,472	15,427
Metering temperature	(°C)	145	155	139	164	154	141
Temperature (at windbox)	(°C)	135	145	130	153	143	131
Pressure (at windbox)	(in. H_2O)	1.10	1.16	1.15	1.09	1.16	1.10
Barometric pressure	(in. Hg)	29.95	29.75	29.78	29.95	29.76	29.91
Burner Hardware							
Oil orifice no.		10	10	10	10	10	10
Steam orifice no.		10	10	10	10	10	10
Burner tip (drill size)		42	42	42	42	42	42
		Output Variables					
Flue Gas Analysis							
O_2	(%)	1.9	2.0	1.5	2.0	1.9	1.9
CO	(%)	0.001	0.002	0.002	0.003	0.001	0.002
Soot	(gr/scf)	0.072	0.064	0.069	0.106	0.122	0.130
Flame Temperature							
At no. 27 cooling plate	(°C)	906	918	909	902	914	912

Table 8 - Varying oil temperature at constant steam/oil ratio

Heat Transfer Rates

FLAME		11	12	13	14	15	16
FERA NO.		35	36	48	37	38	39
DATE		80/12/17	80/12/18	81/01/06	80/12/16	80/12/18	80/12/17
Sink Temp. of Coolant	(°C)	106	109	111	109	111	112
Heat to Cooling Plates	1	19,539	17,169	17,485	19,697	17,327	17,643
(BTU/h)	2	26,122	23,910	24,331	26,069	24,068	24,911
	3	26,649	25,227	25,227	27,439	24,911	25,385
	4	28,966	26,807	26,175	30,282	27,175	27,070
	5	36,286	34,759	35,128	37,445	34,285	34,864
	6	31,810	31,599	31,230	33,653	31,599	31,388
	7	27,544	27,228	27,702	30,282	28,439	27,860
	8	30,282	30,177	30,967	32,968	30,651	29,966
	9	31,230	31,178	32,863	32,968	31,072	30,704
	10	33,179	33,495	34,390	34,970	33,284	33,021
	11	29,809	29,858	30,104	30,941	29,809	29,366
	12	28,629	28,727	29,317	30,006	28,825	28,678
	13	29,121	28,333	29,563	29,219	30,744	29,071
	14	27,202	26,612	27,546	27,301	27,055	26,907
	15	27,153	27,005	27,694	27,694	27,792	27,301
	16	25,087	25,038	25,579	25,530	25,726	25,235
	17	25,284	25,235	25,628	24,989	25,382	24,939
	18	21,594	21,398	21,496	21,053	22,677	21,152
	19	21,545	21,545	21,890	21,299	21,594	21,152
	20	19,332	19,135	19,430	19,086	19,037	18.840
	21	18,484	18,524	18,881	18,245	18,762	18,285
	22	17,053	17,212	17,212	16,814	17,093	17,093
	23	16,337	16,496	16,496	16,139	17,530	16,059
	24	15,304	15,582	15,542	14,867	15,701	15,105
	25	14,747	15,304	15,105	14,628	16,536	14,827
	26	13,436	13,873	13,674	13,356	13,833	13,475
	27	14,549	14,668	14,588	14,231	15,781	14,430
TOTAL		656,273	646,094	655,243	671,171	656,688	644,727
Visuals on Flame							
Stability		← Stable, pulsating flame →					
Flame length	(metres)	← 2.1 - 3.0 →	2.3 - 3.5	← 2.1 - 3.0 →			
Flame diam.	(metres)	← 0.3 →					
Comments		Smokey tips on extended flame with a few sparklers →					Smokier tips

Table 9 - Varying burner tip size at constant steam/oil ratio
Input and output variables

FLAME		17	18
FERA NO.		46	47
DATE		80/12/15	80/12/16
		Input Variables	
OIL			
Flow	(kg/L)	37.8	37.5
Temperature	(°C)	87	88
Pressure (corr.)	(psig)	65	50
STEAM			
Flow	(lb/h)	17	17
Temperature	(°C)	183	182
Pressure (corr.)	(psig)	53<3	38<2
Ratio (steam/oil)	(kg/kg)	0.20	0.21
Mixing Chamber (emulsion)			
Temperature	(°C)	143	134
Pressure (corr.)	(psig)	52<2	37<1
Combustion Air			
Flow (calculated)	(scfh)	15,517	15,563
Metering temperature	(°C)	151	170
Temperature (at windbox)	(°C)	141	158
Pressure (at windbox)	(in. H_2O)	1.06	1.09
Barometric pressure	(in. Hg)	30.00	29.95
Burner Hardware			
Oil orifice no.		10	10
Steam orifice no.		10	10
Burner tip (drill size)		44	37
		Output Variables	
Flue Gas Analysis			
O_2 . .	(%)	2.3	2.0
CO	(%)	0.002	0.001
Soot	(gr/scf)	0.074	0.061
Flame Temperature			
At no. 27 cooling plate	(°C)	825	827

Table 10 - Varying burner tip size at constant steam/oil ratio

Heat Transfer Rates

FLAME			17	18
FERA NO.			46	47
DATE			80/12/15	80/12/16
Sink Temp. of Coolant	(°C)		110	109
Heat to Cooling Plates		1	18,538	20,329
(BTU/h)		2	26,280	26,807
		3	26,805	28,492
		4	30,388	30,809
		5	37,287	38,288
		6	33,969	33,548
		7	29,914	30,124
		8	32,336	32,863
		9	32,547	33,390
		10	34,180	34,970
		11	29,612	30,498
		12	29,071	29,612
		13	28,727	28,776
		14	26,612	26,366
		15	26,910	26,612
		16	25,136	24,447
		17	24,152	24,005
		18	20,807	20,660
		19	21,103	20,512
		20	18,791	18,102
		21	18,007	17,490
		22	16,377	16,099
		23	15,860	15,582
		24	14,867	14,549
		25	14,469	14,270
		26	13,436	12,959
		27	14,032	13,913
TOTAL			660,213	664,072
Visuals on Flame				
Stability			Stable, pulsating flame →	
Flame length	(metres)		2.3 3.0	2.3 3.2
Flame diam.	(metres)		← 0.3 →	
Comments			Smokey tips on extended flame fewer sparklers	

APPENDIX A - Error analysis of measured parameters*

The calculated errors which may be incurred in the major measured parameters are as follows:

Steam/Oil Ratio

Steam Flow: ±2.6% (33 lb/h) to ±8.5% (10 lb/h)

Oil Flow: ±1.5%

Error: ±4.1% to ±10% (high : low)

Combustion Efficiency

Calorific value, measured to ±30 Btu in 18,000 Btu/lb: ±0.17%

Carbon loss, ±1% in 99.8% : ±1%

Error in efficiency: ±1.17%

Gas Temperatures

Low temperature: ±1° in 800°C : ±0.13%

High temperature: ±1° in 1500°C : ±0.07%

Oil and Steam Temperatures

Oil temperature: ±0.1° in 83°C (min): ±0.12%

±0.1° in 110°C (max): ±0.09%

Error: ±0.09% to 0.12%

Steam temperature: ±0.1° in 181°C (min): ±0.05%

±0.1° in 183°C (max): ±0.05%

Error: ±0.05%

Heat Transfer to Calormetric Sections

First Section: Flow ±0.5% in 10% : ±5.00%

(next to burner) DT ±0.1° in 30°C (min) : ±0.33%

±0.1° in 70°C (max) : ±0.14%

Error: ±5.14% to 5.33% in first section

Second Section: Flow ±0.5% in 30% : ±1.67%

DT ±0.1° in 35°C (min) : ±0.29%

±0.1° in 62°C (max) : ±0.16%

Error: ±1.83% to 1.96% in second section

Third Section: Flow ±0.5% in 40% : ±1.25%

DT ±0.1° in 33°C (min) : ±0.30%

±0.1° in 47°C (max) : ±0.21%

Error: ±1.46% to ±1.55% in third section

Overall error: ±1.46% to ±5.33%

*Based on precision of reading instruments.