Optimisation of Performance Parameters for High Precision Automated Mass Comparators

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Abstract

Modern day high precision mass comparators are high-tech measuring instruments that are capable of automated operations. The convenience of automation however introduces a number of 'time based' influencing parameters that affects the performance of the mass comparators to obtain accurate and repeatable readings.

This paper attempts to highlight a recent study carried out on the 'time based' performance parameters of the a5 and a100 Mettler-Toledo automated weighing comparators housed in SPRING Singapore. The parameters under investigation were namely the integration time, stabilisation time of the comparators, the number of pre-weighing, and the number of actual weighing where the calibration results were obtained. The length of the setting time for each parameter would affect the overall operating time. A set of experiments covering different settings were designed to investigate extensively the effects the setting combinations had on the repeatability performance of the mass comparators.

Typical experimental results have indicated that the number of weighing, stabilisation and integration times do affect the performance of the balance. However, there is a trade-off between the improvement in performance and operation time required. An optimal range of settings can be identified through experiments to maximise the mass comparator efficiency and ensure optimal repeatability in the shortest possible weighing time.

1. GENERAL

1.1. Introduction

Mass comparators, also commonly known as weighing balances, are high accuracy precision instruments used mainly for determining the mass values of reference grade mass (or weight) standards.

Two main types of mass comparators are generally used; manual or automated. Manual comparators require human operation and judgment to control the loading and unloading of the mass standard, and the recording of readings.

Modern day mass comparators are high-tech measuring instruments that are capable of automated operations. Automated comparators may be equipped with robotic arms or turntables that minimises the need for human intervention, but they generally require more planning and careful setting of the operating parameters. The convenience of automation however introduces a number of ‘time based’ influencing factors that affects the performance of the mass comparators to obtain accurate and repeatable readings. Together with data logging ability, the proper setting of the operating parameters becomes even more important for achieving optimal, repeatable and reliable measurement results.

1.2. Objective

This paper attempts to study the time-based performance parameters and determine a set of operating parameters that optimises the operation of the comparators to achieve optimal repeatability in the shortest time.

1.3. Scope

The time-based performance parameters of the Mettler-Toledo a5 and a100 automated mass comparators were investigated using a set of stainless reference masses through a series of weighings. The repeatability of the mass differences and operation times were monitored by varying the different time-based operating parameters.

2. DEFINITIONS

2.1. Stabilisation Time

Stabilisation time is the time taken for a balance to ‘settle’ to a stable reading. More commonly, it is the set time starting from the moment a load is placed on the weighing pan to the moment the result is released for display [1]. This time is also commonly known as the weighing speed [2]. The stabilisation time is primarily affected by the ‘vibration adapter’ setting function of the mass comparator. Longer stabilisation time setting allows the balance to have more time to come to ‘rest’ or to a state of lesser movement before the reading is taken. This usually results in a more stable and consistent measured value.

2.2. Integration Time

Integration time is the time required by a measuring instrument internally to compute and display a single measured value during a measurement process [1]. The process involves summing all current values or several values from individual measurements at the input of the measuring instrument over a certain time interval (integration time). The measuring instrument then outputs the mean value over this time period. Longer integration time setting allows more measurement data to be collected to give a better representation of the measured value.

2.3. Repeatability

Repeatability is the ability of an instrument to provide results that agree one with the other when the same load is placed several times in an identical way on the load receptor under reasonable constant test conditions [3]. For balance and mass comparators, this closeness of agreement of the indicated balance readings for successive weighing of the same load are usually carried out by the same observer using the same method under the same conditions in short intervals of time [4].

Repeatability is an important property in mass measurement as it is a measure of the balance's precision [4]. It is calculated as the standard deviation of a series of observations at the same load and is normally expressed together with the relative size of the maximum difference between successive readings [5]. The readings for the repeatability test should be obtained in a way similar to how the balance would be used in practise.

For a typical A-B-A weighing sequence (i.e. A_1-B_1-A_2; A_3-B_2-A_4; …. A_{n-1}-B_m-A_n), the mass difference (d_i) is usually given by:

$$d_i = B_m - \left(\frac{A_n + A_{n-1}}{2}\right)$$

where,

A_n : The 'known' mass reading recorded for the nth weighing
B_m : The 'unknown' mass reading recorded for the mth weighing

The average mass difference:

$$\bar{d} = \frac{1}{i}\sum_{u=1}^{i} d_u$$

The standard deviation for the mass difference for each design setting combination is:

$$S = \sqrt{\frac{\sum_{u=1}^{i}(d_u - \bar{d})^2}{i-1}}$$

Generally, the readings for the repeatability test should be obtained in a way similar to how the balance would be used practically. A control chart [6] can be created by periodically determining the repeatability of the balance and plotting the standard deviation obtained as a function of time (or date). When its standard deviation falls outside of the pattern of values or control limits, there may be a need to investigate the functionality of the instrument or the measurement techniques to determine if adjustment may be required [4]. The control chart is a useful tool as it is known that the long term repeatability of a balance is a major source of uncertainty in the weighing process [7].

The repeatability of a high resolution balance is dependant on many factors. Internal factors includes; the balance design and construction, settings parameters [8], surface finishing [9] size and shape of the object being weighed [10], etc. Externally, ambient conditions such as temperature [11], humidity [12], air drafts and pressure fluctuations [12], electrostatics [13], magnetism [12], vibration [14], and the way the balance is used [15], location of balance etc.

3. EXPERIMENTAL SETUP

In the planning and setting up of the experiment, the type of comparator to be used, the testing range, weighing cycles, operating parameters and evaluation criteria were considered carefully. Decisions made on the above factors are discussed as follows.

3.1. Mass Comparator Selection

Different mass comparators exhibit different characteristics due to their different internal constructions and circuitries. For the experiment, the Mettler-Toledo models ‘a5’ and ‘a100’, automated mass comparators (with resolution of 0.1 µg and 1 µg respectively, see Figure 1) were used because they were the most frequently used balances in the laboratory.

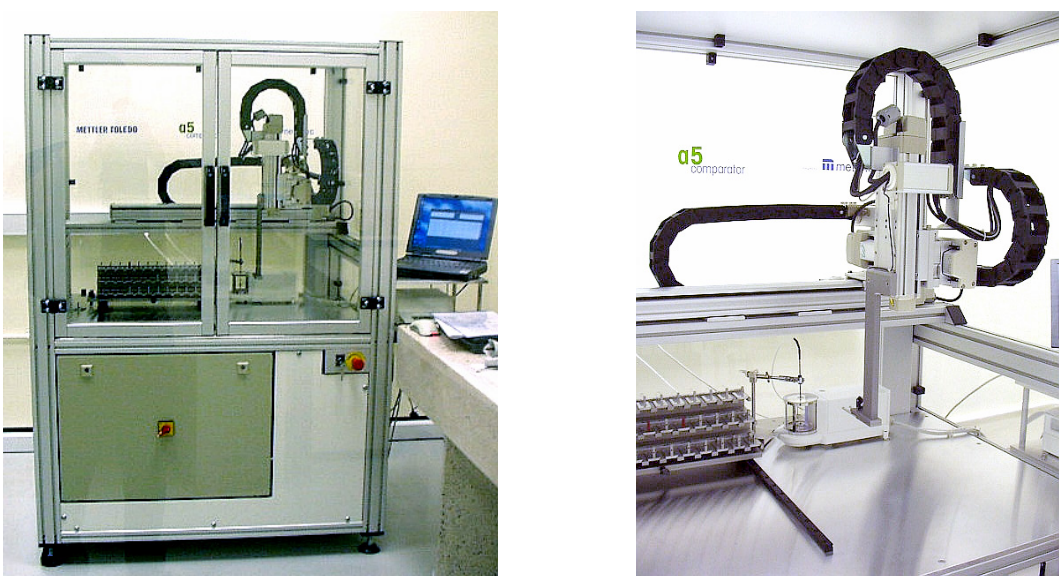

Figure 1 : a5 automatic mass comparator with robot arm

The a5 and a100 were integrated machines with precision mass comparators, weight magazine rack and robotic arms for automated weighing. The systems were controlled by laptop computers for automated weighing operation. Weighing results were automatically captured and fed into the computer for processing and reporting.

3.2. Reference Mass & Weighing Cycle Selection

Nominal masses of 5 g and 100 g were chosen for the experiment as the repeatability of the comparators at the maximum range of the balances were usually at their poorest [16]. This is because larger loads exert more stress on the comparators and environmental conditions changes in larger masses cause more turbulent influence on the weighing results than smaller masses. The A-B-A weighing cycle was chosen to closely resemble the normal calibration process.

3.3. Operating Parameters Selection

The a5 and a100 automatic mass comparator were controlled by Mettler-Toledo's proprietary control software. The software programme required various operating parameters to be set for optimal operation efficiency, namely; the 'Start Delay', 'No. of Pre-Weighing', 'No. of Weighing', 'No. of Series (group)', 'Stabilisation Time', 'Integration Time'.

No definite recommendations on the optimal settings were available, hence the most appropriate settings had to be determined. Figure 2 shows a typical setting menu of the software. Of all these parameters, three were selected for the study because of the following considerations.

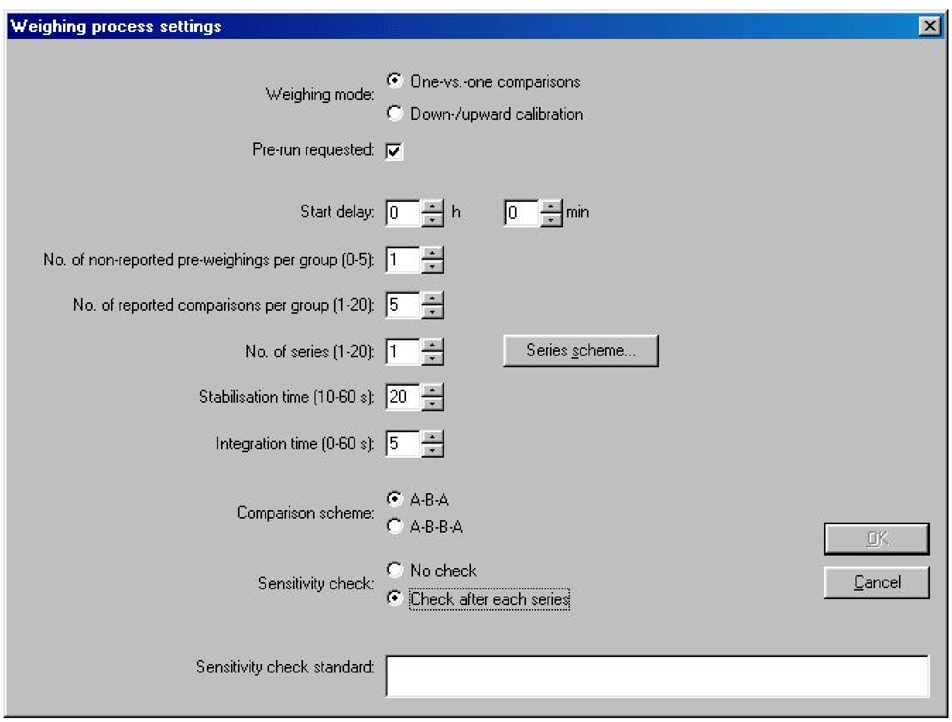

Figure 2 : a5 or a100 control software parameter setting menu

i. Start Delay

Start delay is the time delay before the start of the weighing operation to allow for environmental conditioning of the masses. The start delay was not examined as the time required to reach environmental stability could be carried out outside the bounds of the study, and also, no further conditioning time was required once the masses have reached their equilibrium with the surroundings.

ii. No of Pre-Weighings

The software programme allowed a maximum of 5 pre-weighings. Pre-weighing was not studied as the maximum number of pre-weighing was usually set to allow the mass comparator to have sufficient warm-up time to reach its stable operating temperature. Pre-weighing also helped to center the masses on the weighing pan.

iii. No of Weighing or Comparison

OIML R111 [17] recommends that the mass of different classes require different minimum number of weighings. Experiments were carried out to determine the effects of the number of weighing had on the performance of the balances. The software programme allowed a maximum of 20 weighings. For this experiment, 3, 5 and 10 repeated weighings were studied.

iv. No of Series of Group Weighing

One series of weighing is a complete weighing cycle. Additional weighings provided more measurement data for statistical study. The maximum setting for this parameter was 20 series. This parameter was not considered as it would take too much time to conduct the study.

v. Stabilisation Time

The manufacturer recommended a typical stabilisation time of 20 s. The processing setting allowed for a range from 0 to 60 s. A study was made to determine the effects on the performance of the balances.

vi. Integration Time

No recommendation was given in the manufacturer's technical data. The processing setting menu allowed for a range from 0 to 60 s. A study was done to determine the effects on the performance of the balances.

3.4. Experiment Design & Evaluation Criteria

The setting parameters were carefully chosen to test the performance of the time based parameters at their extremities. Combinations of different weighing cycles, stabilisation times, and integration times (see Table 1) were selected to reflect the wide ranges and variability of the parameters. The repeatability of the actual mass measurement at different design settings, and operation times were used as evaluation criterions.

Parameters	Stabilisation Time, S (s)	Integration Time, I (s)	No. of Pre-Weighing, P	No. of Weighing, W
Max. Setting	0 to 60	0 to 60	5	20
Proposed Design Settings	15, 30, 45, 60	10, 15, 20, 25, 30, 40, 60	5	3, 5, 10

Table 1 : List of mass comparator in SPRING Singapore

General conditioning of the reference standard masses and the comparators were carried out, and precautions were taken to prevent the measurement process from being influenced by the accumulation of dust particles, etc. To initiate the automatic operations, the setting parameters were first programmed in the Mettler-Toledo control software at the start of each weighing cycle.

4. RESULTS & ANALYSIS

4.1. Results

Using different setting parameters, a total of 168 combinations were tested. For different number of weighings (i.e. W = 3, 5, 10), the same set of stabilisation and integration times were repeatedly tested. The measurement results for a5 and a100 comparators are shown in Table 2 and 3. All the results are also shown graphically in Figure 3 to 8.

a5 Mass Comparator Performance									
S/n	Parameters			W = 3		W = 5		W = 10	
	S	I	P	Repeatability (mg)	Time (min)	Repeatability (mg)	Time (min)	Repeatability (mg)	Time (min)
1	15	10	5	0.00013	25	0.00023	32	0.00030	50
2	15	15	5	0.00009	27	0.00024	34	0.00019	53
3	15	20	5	0.00009	28	0.00024	36	0.00020	57
4	15	25	5	0.00014	30	0.00017	38	0.00014	60
5	15	30	5	0.00018	31	0.00016	40	0.00018	63
6	15	40	5	0.00020	34	0.00017	45	0.00019	70
7	15	60	5	0.00013	41	0.00016	53	0.00017	83
8	30	10	5	0.00027	30	0.00014	38	0.00015	60
9	30	15	5	0.00013	31	0.00007	40	0.00019	63
10	30	20	5	0.00013	33	0.00015	43	0.00019	67
11	30	25	5	0.00007	34	0.00011	45	0.00020	70
12	30	30	5	0.00006	36	0.00013	47	0.00012	73
13	30	40	5	0.00017	39	0.00006	51	0.00014	80
14	30	60	5	0.00018	46	0.00008	59	0.00016	93

a5 Mass Comparator Performance									
S/n	Parameters			W = 3		W = 5		W = 10	
	S	I	P	Repeatability (mg)	Time (min)	Repeatability (mg)	Time (min)	Repeatability (mg)	Time (min)
15	45	10	5	0.00021	35	0.00013	46	0.00031	71
16	45	15	5	0.00013	37	0.00017	48	0.00025	74
17	45	20	5	0.00004	39	0.00012	50	0.00014	78
18	45	25	5	0.00005	40	0.00015	52	0.00011	81
19	45	30	5	0.00006	42	0.00015	54	0.00016	84
20	45	40	5	0.00002	45	0.00011	58	0.00020	91
21	45	60	5	0.00002	51	0.00011	66	0.00014	104
22	60	10	5	0.00010	40	0.00016	52	0.00031	81
23	60	15	5	0.00018	42	0.00011	54	0.00013	84
24	60	20	5	0.00007	43	0.00014	56	0.00017	88
25	60	25	5	0.00013	45	0.00011	58	0.00019	91
26	60	30	5	0.00015	47	0.00016	60	0.00016	94
27	60	40	5	0.00010	50	0.00013	64	0.00017	101
28	60	60	5	0.00006	56	0.00009	73	0.00011	114

Table 2 : a5 Mass Comparator Performance

a100 Mass Comparator Performance									
S/n	Parameters			W = 3		W = 5		W = 10	
	S	I	P	Repeatability (mg)	Time (min)	Repeatability (mg)	Time (min)	Repeatability (mg)	Time (min)
1	15	10	5	0.0016	32	0.0011	41	0.0015	63
2	15	15	5	0.0015	34	0.0009	43	0.0011	67
3	15	20	5	0.0008	36	0.0006	45	0.0011	70
4	15	25	5	0.0013	37	0.0003	47	0.0012	73
5	15	30	5	0.0008	39	0.0006	50	0.0009	77
6	15	40	5	0.0001	42	0.0005	54	0.0006	83
7	15	60	5	0.0004	48	0.0005	62	0.0006	97
8	30	10	5	0.0008	37	0.0008	47	0.0012	73
9	30	15	5	0.0009	39	0.0006	50	0.0005	77
10	30	20	5	0.0003	40	0.0007	52	0.0006	80
11	30	25	5	0.0008	42	0.0005	54	0.0008	83
12	30	30	5	0.0001	43	0.0008	56	0.0008	87
13	30	40	5	0.0004	47	0.0006	60	0.0006	93
14	30	60	5	0.0001	53	0.0006	68	0.0004	107
15	45	10	5	0.0006	43	0.0006	55	0.0012	84
16	45	15	5	0.0004	44	0.0005	57	0.0007	88
17	45	20	5	0.0005	46	0.0006	59	0.0007	91
18	45	25	5	0.0002	48	0.0007	61	0.0005	94
19	45	30	5	0.0006	49	0.0005	63	0.0006	98
20	45	40	5	0.0001	52	0.0004	67	0.0008	104
21	45	60	5	0.0002	59	0.0008	76	0.0008	118
22	60	10	5	0.0007	48	0.0009	61	0.0006	94
23	60	15	5	0.0002	49	0.0005	63	0.0007	98
24	60	20	5	0.0003	51	0.0007	65	0.0004	101
25	60	25	5	0.0007	52	0.0006	67	0.0004	104

a100 Mass Comparator Performance									
S/n	Parameters			W = 3		W = 5		W = 10	
	S	I	P	Repeatability (mg)	Time (min)	Repeatability (mg)	Time (min)	Repeatability (mg)	Time (min)
26	60	30	5	0.0004	54	0.0008	69	0.0008	108
27	60	40	5	0.0004	57	0.0004	73	0.0007	114
28	60	60	5	0.0007	63	0.0004	82	0.0005	128

Table 3 : a100 Mass Comparator Performance

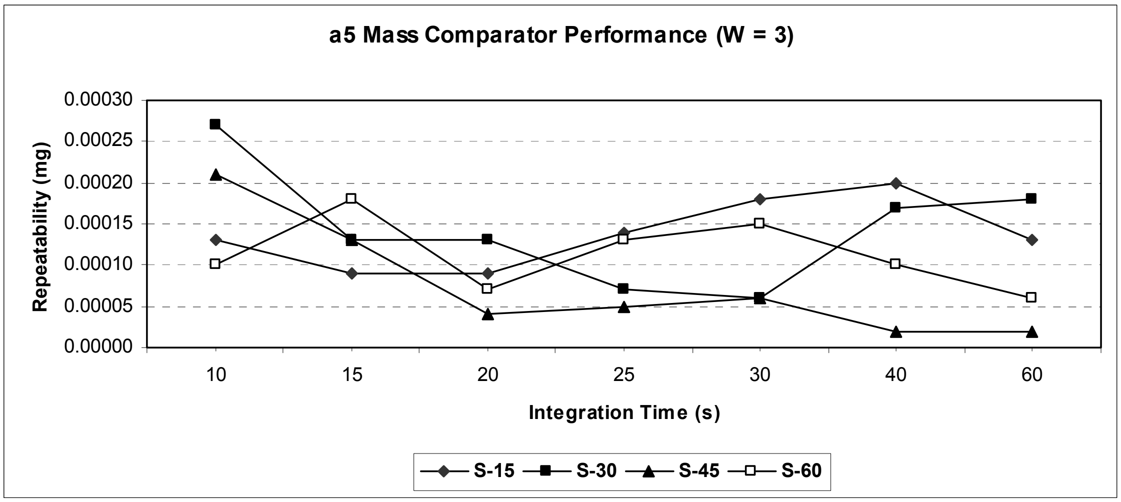

Figure 3 : a5 (W = 3) Results

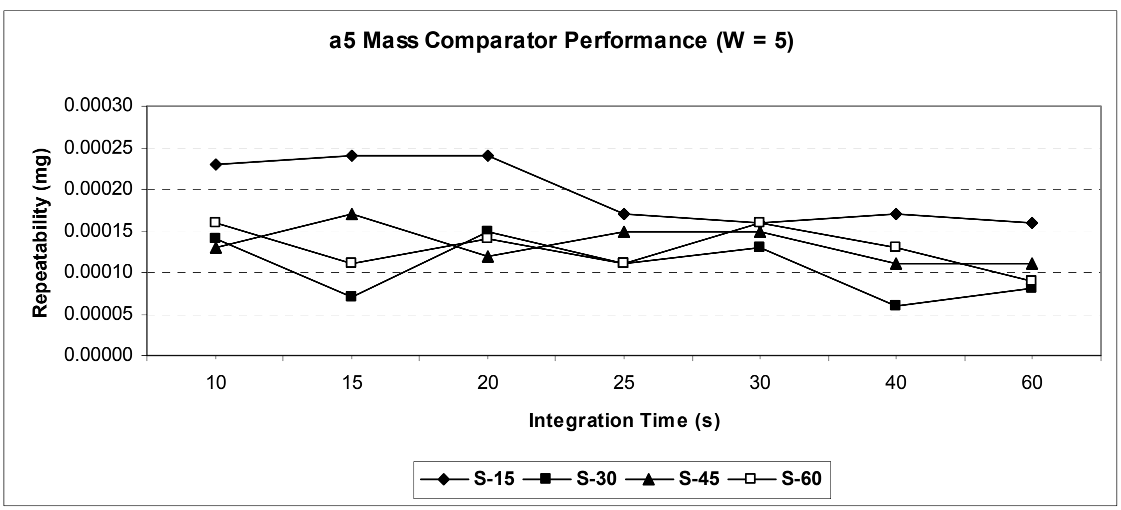

Figure 4 : a5 (W = 5) Results

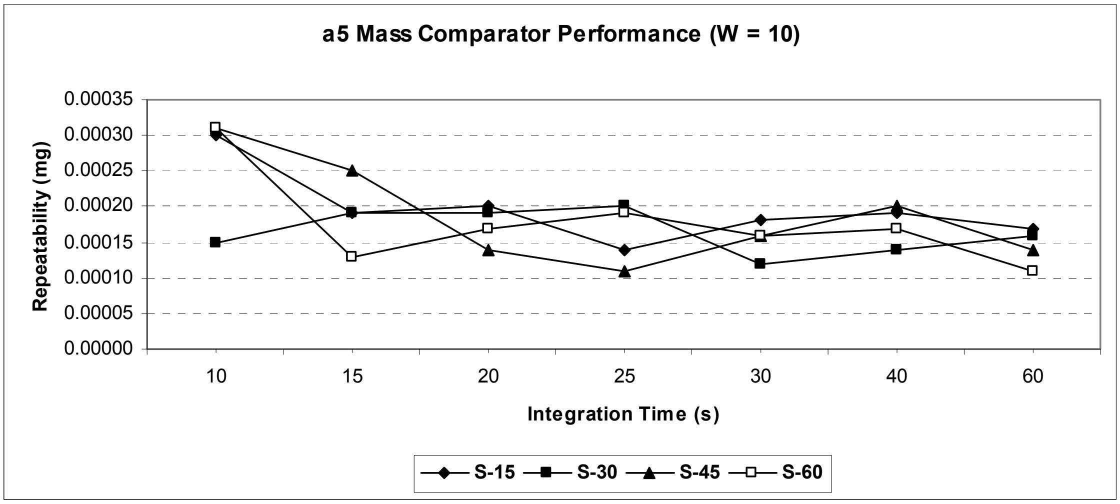

Figure 5 : a5 (W = 10) Results

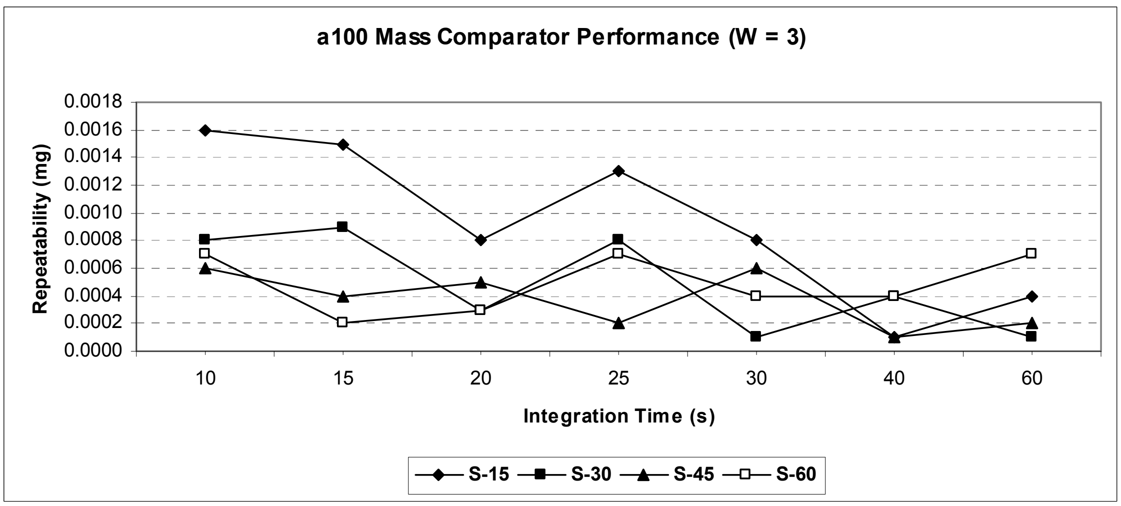

Figure 6 : a100 (W = 3) Results

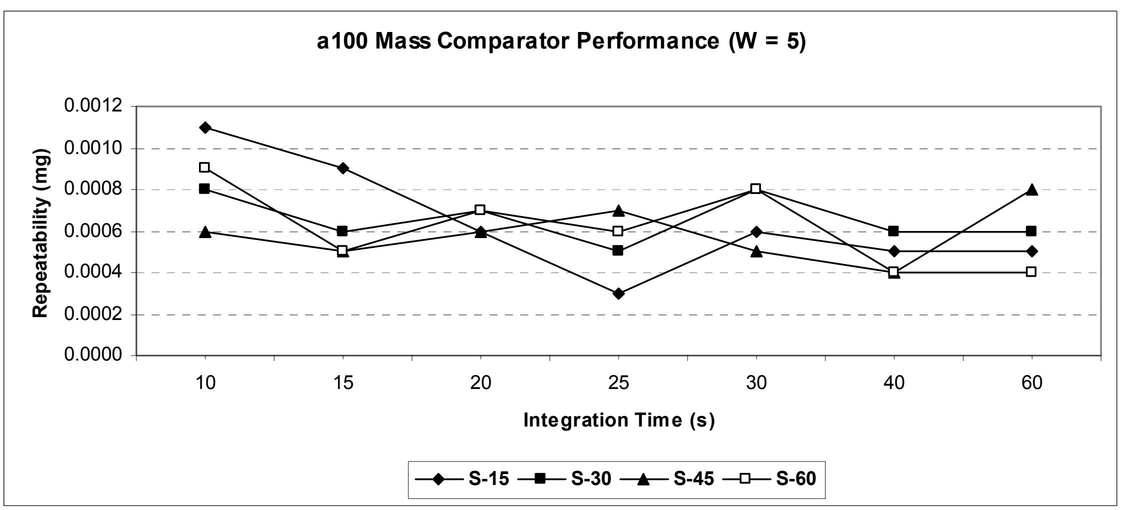

Figure 7 : a100 (W = 5) Results

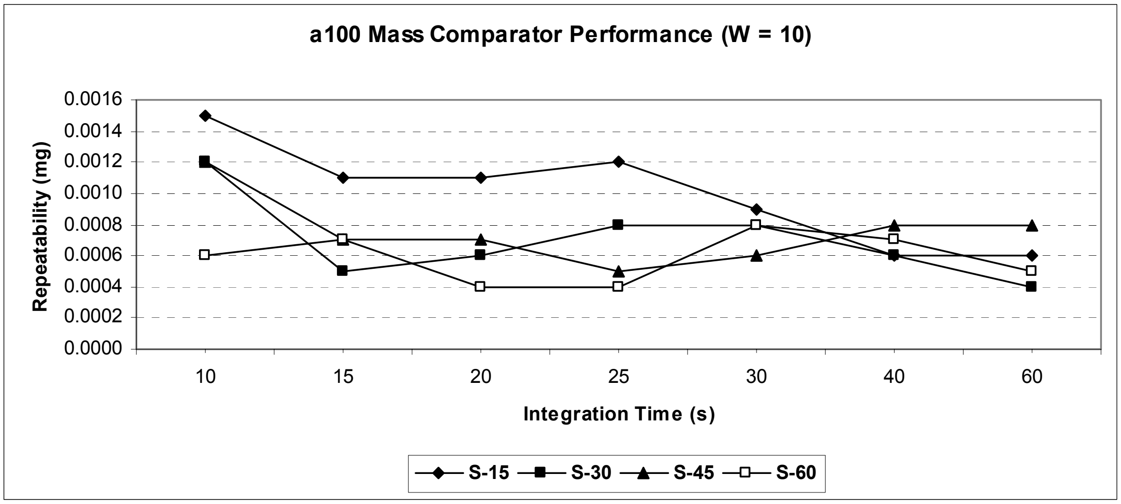

Figure 8 : a100 (W = 10) Results

4.2. Analysis & Discussions

i. General Observations

From the 168 measurements made, the following observations were noted:

- Similar trends were observed for both the a5 and a100 mass comparators.
- Balance performance generally improved with increasing integration and stabilisation time.
- Integration Time (I) greater than 15 or 20 s gave better repeatability.
- Stabilisation Time (S) greater than 30 s gave better repeatability.

To further evaluate and quantify the above observations, each of the parameters was segregated and individually evaluated with respect to the average repeatability measured and the average overall operation time.

ii. Number of Weighing (W)

Table 4 shows the effects of W on the average repeatability and average operation time.

W	a5 Mass Comparator				a100 Mass Comparator			
	Ave Time	Ave Repeatability	Change in Time	Change in Repeatability	Ave Time	Ave Repeatability	Change in Time	Change in Repeatability
	min	mg	%	%	min	mg	%	%
3	39	0.00012	0	0	46	0.00057	0	0
5	50	0.00014	29	21	59	0.00063	29	10
10	78	0.00018	101	55	92	0.00076	100	34

Table 4 : Effects of Number of Weighing (W)

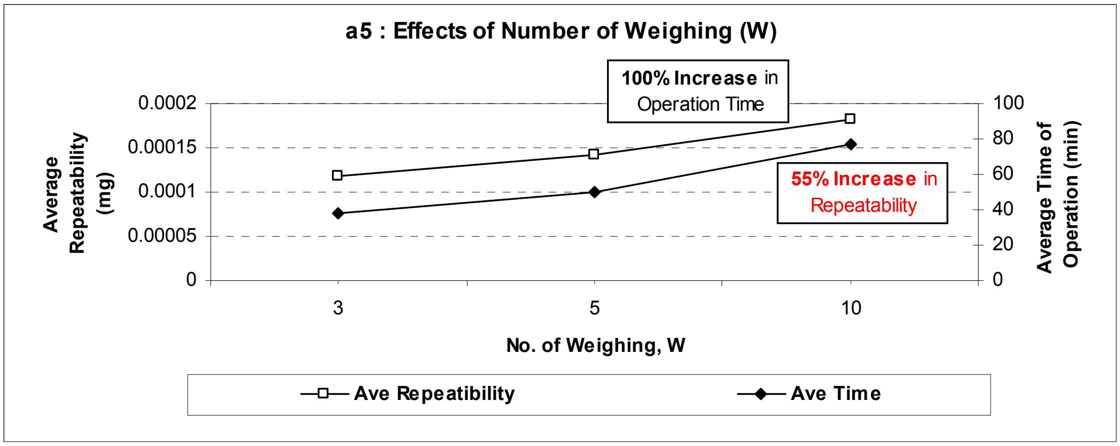

Figure 9 : a5 - Effects of Number of Weighing (W) on Repeatability & Average Operation Time

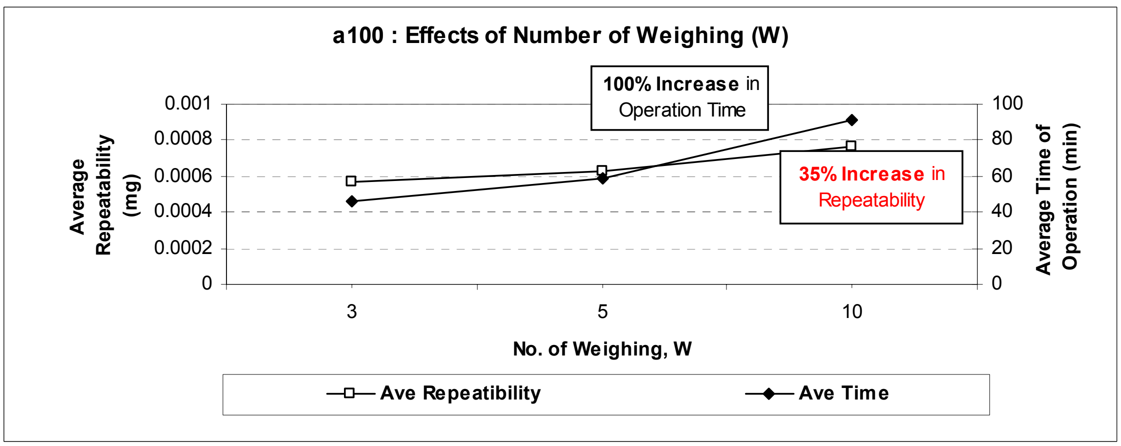

Figure 10 : a100 - Effects of Number of Weighing (W) on Repeatability & Average Operation Time

Excluding the effects of S and I, and averaging the repeatability measured for different W, the observed effects on the balance performance were as follows:

- W = 3 had the smallest average repeatability measurement (best balance performance), and required the shortest operation time.
- W = 10 had the highest average repeatability measurement, and required the longest operation time.
- Increase in W required longer operation time and resulted in larger repeatability (less desirable).

iii. Stabilisation Time (S)

Table 5 shows the effects of S on the average repeatability and average operation time.

S	a5 Mass Comparator				a100 Mass Comparator			
	Ave Time	Ave Repeatability	Change in Time	Change in Repeatability	Ave Time	Ave Repeatability	Change in Time	Change in Repeatability
s	min	mg	%	%	min	mg	%	%
15	44	0.00018	0	0	54	0.00086	0	0
30	51	0.00014	16	-24	61	0.00062	13	-28
45	59	0.00013	33	-26	70	0.00057	28	-33
60	66	0.00014	50	-22	76	0.00056	40	-34

Table 5 : Effects of Stabilisation Time (S)

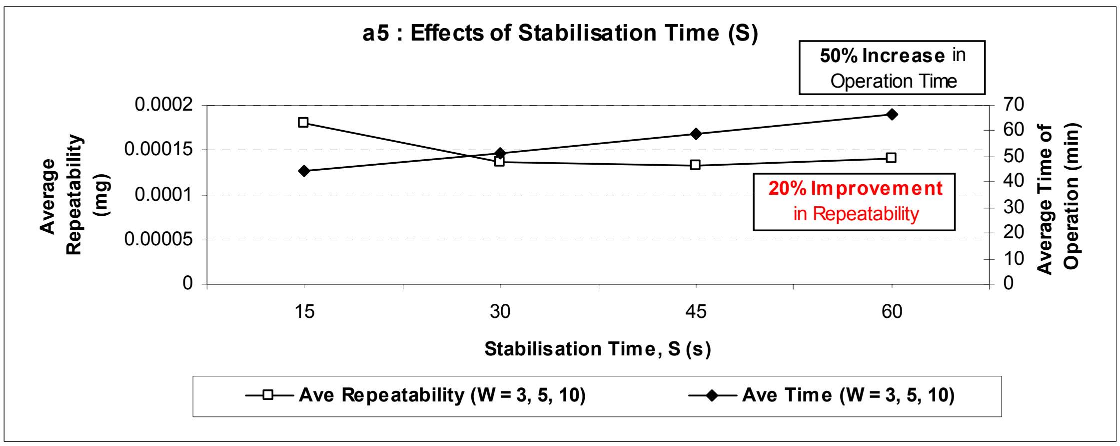

Figure 11 : a5 - Effects of Stabilisation Time (S) on Repeatability & Average Operation Time

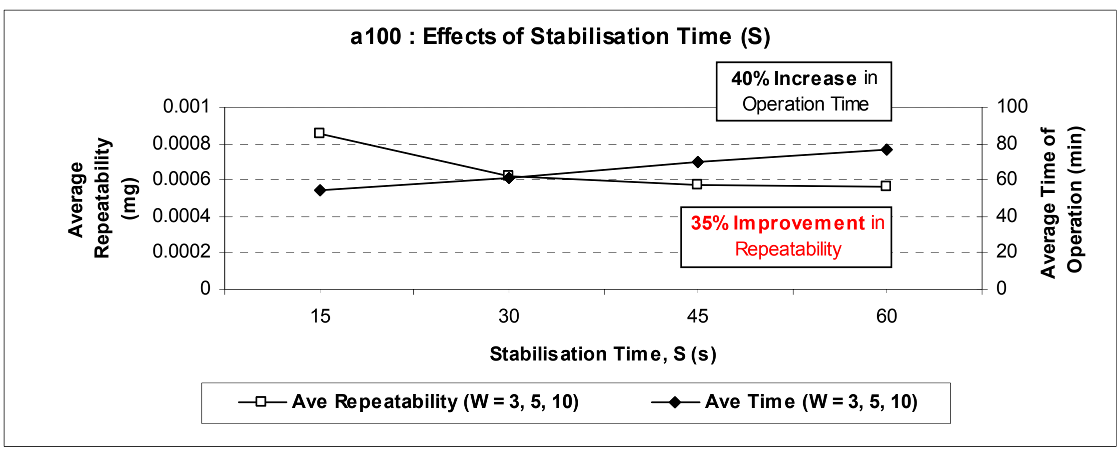

Figure 12 : a100 - Effects of Stabilisation Time (S) on Repeatability & Average Operation Time

Excluding the effects of W and I, and averaging the repeatability measured for different S, it was observed that an <u>increase in S</u> required a <u>longer operation time</u>, but resulted in a <u>smaller repeatability</u>, thus achieving better balance performance.

iv. Integration Time (I)

Table 6 shows the effects of I on the average repeatability and average operation time.

I	a5 Mass Comparator				a100 Mass Comparator			
	Ave Time	Ave Repeatability	Change in Time	Change in Repeatability	Ave Time	Ave Repeatability	Change in Time	Change in Repeatability
s	Min	mg	%	%	min	mg	%	%
10	47	0.00021	0	0	57	0.00097	0	0
15	49	0.00016	4	-24	59	0.00071	5	-27
20	52	0.00014	10	-32	61	0.00061	8	-37
25	54	0.00013	14	-35	64	0.00067	12	-31
30	56	0.00014	19	-32	66	0.00065	17	-33
40	61	0.00014	30	-32	71	0.00047	25	-52
60	70	0.00012	50	-42	80	0.00050	42	-48

Table 6 : Effects of Integration Time (I)

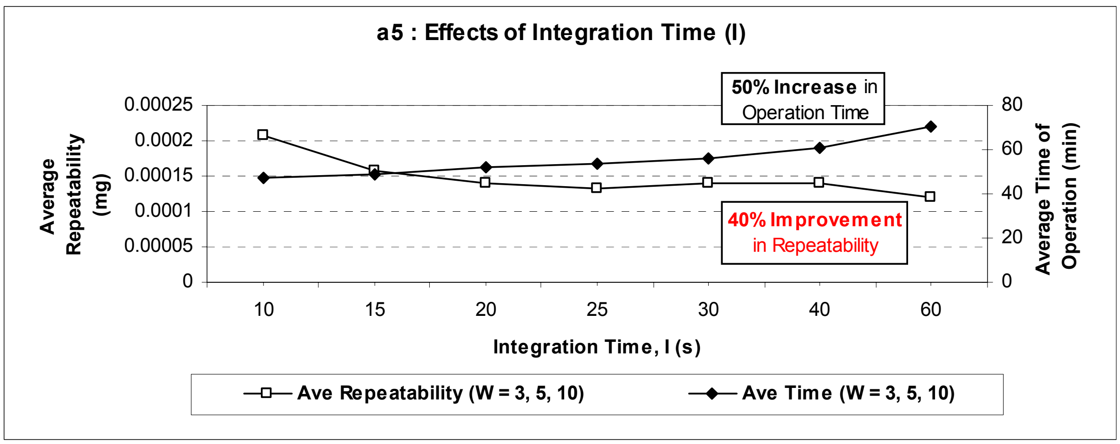

Figure 13 : a5 - Effects of Integration Time (I) on Repeatability & Average Operation Time

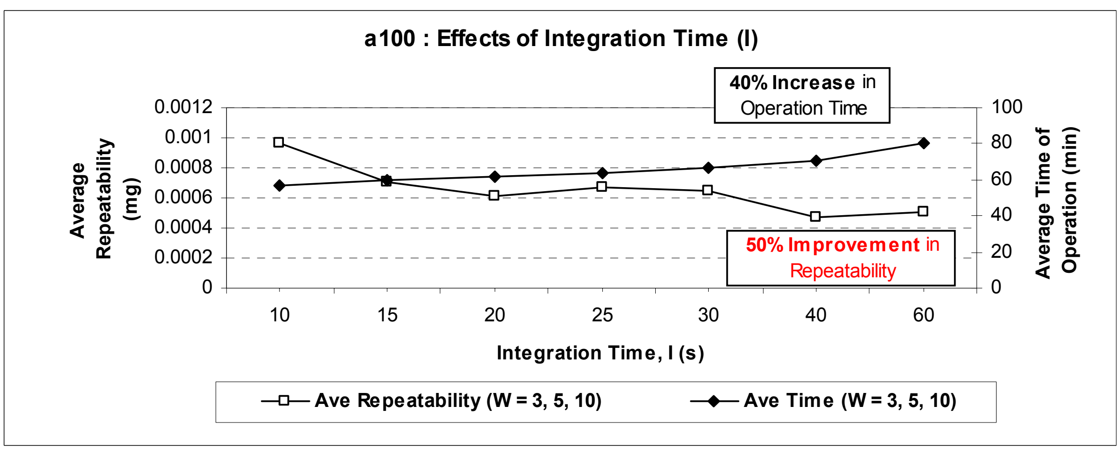

Figure 14 : a100 - Effects of Integration Time (I) on Repeatability & Average Operation Time

Excluding the effects of W and S, and averaging the repeatability measured for different I, it was observed that an increase in I required a longer operation time, but resulted in a smaller repeatability, thus achieving better balance performance.

v. Repeatability Range

Table 7 shows the range of the measured repeatability (maximum – minimum repeatability) for different parameters.

Parameters		a5 Mass Comparator			a100 Mass Comparator		
		Max	Min	Range	Max	Min	Range
		mg	mg	mg	mg	mg	mg
W	3	0.00027	0.00002	0.00025	0.00160	0.00010	0.00150
	5	0.00024	0.00007	0.00017	0.00110	0.00030	0.00080
	10	0.00031	0.00011	0.00020	0.00150	0.00040	0.00110
	15	0.00030	0.00009	0.00021	0.00160	0.00010	0.00150
S (s)	30	0.00027	0.00006	0.00021	0.00120	0.00010	0.00110
	45	0.00031	0.00002	0.00029	0.00120	0.00010	0.00110
	60	0.00031	0.00006	0.00025	0.00090	0.00020	0.00070
	10	0.00031	0.00010	0.00021	0.00160	0.00060	0.00100
	15	0.00025	0.00007	0.00018	0.00150	0.00020	0.00130
I (s)	20	0.00024	0.00004	0.00020	0.00110	0.00030	0.00080
	25	0.00020	0.00005	0.00015	0.00130	0.00020	0.00110
	30	0.00018	0.00006	0.00012	0.00090	0.00010	0.00080
	40	0.00020	0.00002	0.00018	0.00080	0.00010	0.00070
	60	0.00018	0.00002	0.00016	0.00080	0.00010	0.00070

Table 7 : Repeatability Range Comparison

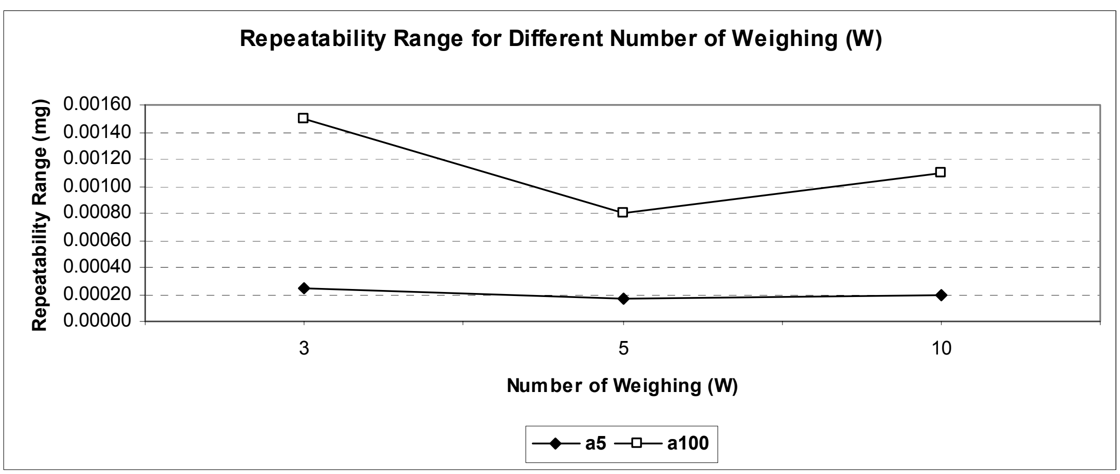

Figure 15 : Effects of Number of Weighing on Range of Repeatability

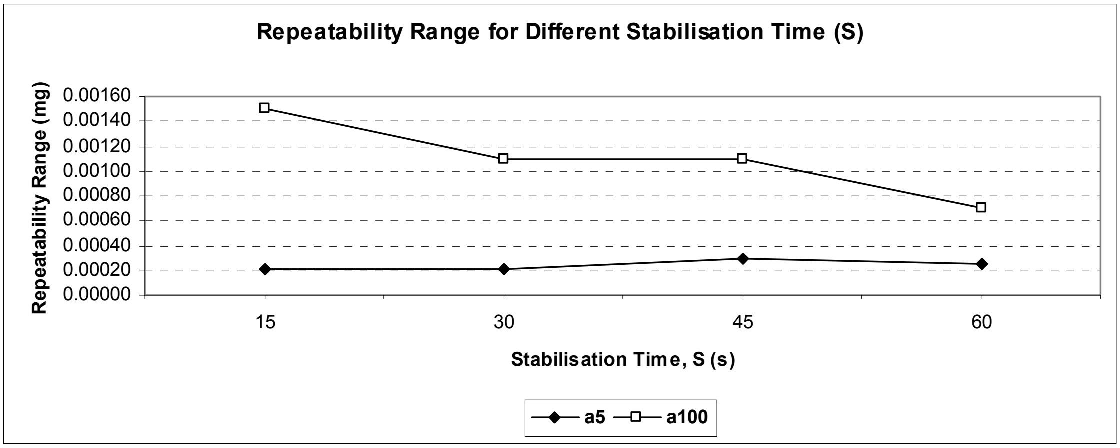

Figure 16 : Effects of Stabilisation Time (S) on Range of Repeatability

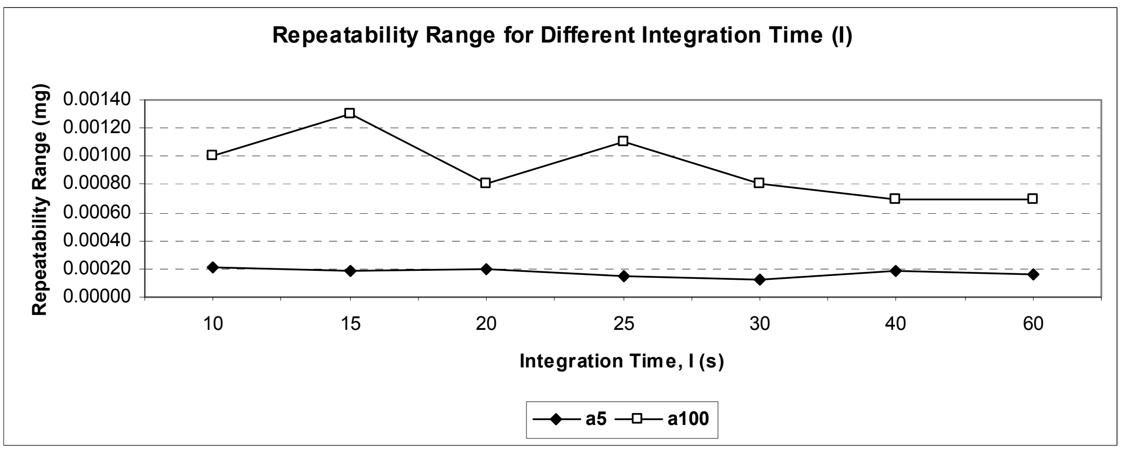

Figure 17 : Effects of Integration Time (I) on Range of Repeatability

From the repeatability range for both a5 and a100, the following observations were noted:

- The effects of different settings of S, I, W were more pronounced for the a100 comparator than the a5 comparator.
- For different W settings, W = 5 had the most stable measurement process as the repeatability range was the smallest. The repeatability range increased for both W = 3 and 10.
- For different S and I settings, the range generally decreased for larger S and I, and the measurement process generally became more stable (smaller range) with increasing S and I times.

4.3. Summary of Findings

All the experiments observations are summarised into Table 8 below.

Parameters	Observations / Remarks
General	▪ Similar trends were observed for both the a5 and a100 mass comparators. ▪ Balance performance generally improved with increasing I and S. ▪ The effects of different settings of S, I, W were more pronounced for the a100 comparator than the a5 comparator.
No. of Weighings (W)	▪ W = 3 had the smallest average repeatability measurement (best balance performance), required the shortest operation time, but had larger range of repeatability values (less stable process). ▪ W = 5 yielded moderate average repeatability, but had the smallest repeatability range (most stable measurement process). ▪ W = 10 had the largest average repeatability measurement, required the longest operation time, and had larger repeatability range (less stable process).
Stabilisation Time (S)	▪ S > 30 s usually yielded better repeatability. However, the improvement in repeatability for S greater than 30s was not significant. ▪ Longer S required longer operation time, yielded smaller repeatability (better balance performance), and smaller repeatability range (more stable process).
Integration Time (I)	▪ I > 15 s or 20 s usually yielded better repeatability. However, the improvement in repeatability for I greater than 15 s was not significant. ▪ Longer I required longer operation time, yielded smaller repeatability (better balance performance), and smaller repeatability range (more stable process).

Table 8 : Summary of Findings

5. CONCLUSIONS & RECOMMENDATIONS

From the summary of findings, the following conclusions and recommendations may be drawn:

- The optimal setting of the time based operating parameters of the Mettler-Toledo a5 and a100 automatic mass comparator are more appropriately defined by a range of values rather than a specific point.

- To obtain optimal repeatability performances, the recommended settings for both the a5 and a100 comparators are as listed in Table 9. The additional operation times required over the minimum settings are also shown.

Parameters	**Recommended Settings**	**Additional Average Operation Time Required (with respect to minimum setting)**	
	(for a5 & a100)	**a5**	**a100**
No. of Weighing (W)	5 weighings	29 % more	29 % more
Stabilisation Time (S)	30 s < S < 60 s	16 % more	13 % more
Integration Time (I)	20 s < I < 60 s	10 % to 50 % more	8 % to 42 % more

Table 9 : Recommended Settings & Corresponding Additional Operation Times

- S, I = 60 s seems to give the best balance performance for both a5 and a100 comparators. However, the corresponding increase in operation time is also very significant. Actual operation settings will be dependent on the compromise between achieving better repeatability and saving operation time.

- These recommended settings may vary between comparators of the same model, but general trends may be the same as components used in manufacturing are similar. Availability of further information from other users of the same comparators may be able to confirm this.

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