Evaluation of Safetherm® as a replacement for Mercury in Industrial Glass Thermometers

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Abstract: Mercury, a toxic poisonous liquid, has been the most reliable choice of liquids in liquid-in-glass thermometers because of its various physical and thermal properties. The aim of the study is to explore the use of the novel, environmentally friendly Safetherm® liquid in industrial glass thermometers and compare its performance with their mercury counterparts. It was found that Safetherm® thermometers can be used to replace mercury thermometers. The thermometers were compared for their accuracy, repeatability, and response time. The effect of temperature range, least count and total length on the accuracy of the thermometers was studied in a controlled manner. The study found that the average accuracy of both the Safetherm® and mercury thermometers was comparable and within the specifications. There was no significant effect of thermometer length or least count on the accuracy of these thermometers, whether Safetherm® or mercury. There is a slight correlation between accuracy and range of the thermometers, wherein the error is directly proportional to the range. However, this is true for both mercury and Safetherm®, and there is only a very small difference in accuracy between these liquids. The response time was longer, roughly double, for Safetherm® thermometers as compared to their mercury counterparts, and this was the only significant difference between the thermometers used in the study. Hence it was concluded that Safetherm® can be used to replace mercury thermometers, at least across the temperature ranges that were used in this study.

***Index Terms* - Thermometer, Mercury, ASTM, Error, Temperature measurement, Safetherm, non-toxic, Glass Thermometer.**

I. INTRODUCTION

For decades, mercury-in-glass thermometers [1] have been essential tools in meteorology, laboratory testing, and various industrial processes [2]. Their widespread use is attributed to their accuracy, responsiveness, reliability, and ease of maintenance. Mercury's unique properties [3] make it particularly suitable as a thermometric fluid: it expands and contracts uniformly with temperature changes, does not adhere to glass, and has a high coefficient of expansion. Additionally, mercury's broad liquid range—from its low freezing point of -39°C to its high boiling point of 356.7°C—enables accurate temperature measurement across a wide range [4].

Mercury thermometers have been utilized in several critical applications, as discussed below:

1.1 Temperature Measurement: The primary function of mercury thermometers is to provide precise temperature readings. As the temperature changes, the mercury column in the capillary tube rises or falls, allowing for accurate measurement.

1.2 Medical Applications: Historically, mercury thermometers were standard in medical settings for measuring body temperature. Their use has decreased due to mercury's toxicity, with many institutions transitioning to digital alternatives.

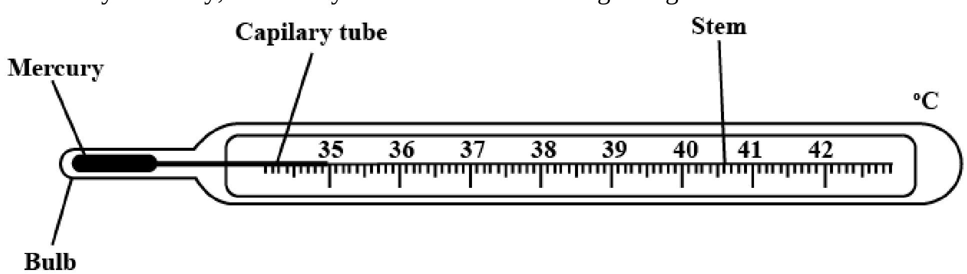


Figure 1: Mercury thermometer used for fever measurement.

1.3 Laboratory Use: In scientific laboratories, mercury thermometers are valued for their precision in various experiments and tests, particularly in chemistry and physics.

1.4 Industrial Applications: Certain industrial processes require the high accuracy and reliability that mercury thermometers offer, making them indispensable in these settings, for e.g., IP/ASTM thermometers for petroleum testing.

II. NEED OF THE STUDY

Despite the advantages stated above, the use of mercury is increasingly problematic due to its environmental hazards and the challenges associated with its disposal. Mercury is toxic [5], and the breakage of a thermometer can release harmful vapours. The regulatory landscape is also complex, with restrictions varying across regions. As a result, many countries have reduced or banned the use of mercury thermometers.

Alternatives to Mercury Thermometers and Their Limitations [6]

2.1 Teflon-Coated Mercury Thermometers: Teflon coatings can help minimize mercury release in case of breakage but do not resolve the issues related to the disposal and storage of toxic mercury.

2.2 Ethanol-Based Thermometers*:* Ethanol is a less toxic, more affordable alternative to mercury, and is easier to read when tinted red. With a freezing point of -114°C, it can measure lower temperatures than mercury (-38.8°C). However, ethanol's boiling point (78°C) limits its effectiveness at higher temperatures, necessitating the use of other liquids such as toluene (boiling point of 111°C), iso-amyl acetate (boiling point of 142°C), or kerosene (boiling point ~200°C), commonly used in spirit thermometers.
2.3 Digital Thermometers*:* Digital thermometers are versatile and generally superior to mercury-in-glass designs,[7] offering wider temperature ranges, faster response times, and features like LCD displays, memory functions, and alarms. However, while high-accuracy digital thermometers are costly, cheaper versions often lack the precision required for industrial applications. This highlights the need for an alternative that is both safe and affordable while maintaining the accuracy of mercury thermometers.
Standards organizations like ASTM and AASHTO have also recognized the challenges of mercury thermometers and are revising testing procedures to incorporate non-mercury alternatives. In response, JRM® Thermometers, based in Mumbai, has introduced Safetherm®. These thermometers use a proprietary non-toxic, biodegradable liquid with a highly visible dark blue colour against a white-backed stem for enhanced accuracy. Designed to replicate the performance characteristics of ASTM mercury-filled thermometers, Safetherm® thermometers comply with test method requirements and can be stored horizontally with a separation rate equal to or better than that of mercury thermometers.
This study evaluates Safetherm® as a potential alternative while addressing the safety and environmental concerns associated with mercury.

III. RESEARCH OBJECTIVE

This study aims to evaluate whether JRM Safetherm® glass thermometers can serve as a safe and effective replacement for mercury thermometers, while maintaining the stringent accuracy and repeatability standards essential in industrial and laboratory settings. The research evaluates their compliance with technical specifications and compares their performance to mercury thermometers in terms of accuracy, response time, range, and precision. Before we proceed, let us define these terms for better understanding of the objective:
3.1 Accuracy: The ability of an instrument (unit under test, UUT) to measure the accurate value is known as its accuracy. In other words, it is **the closeness of the measured value of the UUT to a standard or true value**. Accuracy can be expressed as an error, i.e., the difference between the standard reading and the unit under test (UUT) reading. This error can be expressed as an absolute error or a percentage of the std reading.
3.2 Response Time RT: It is a measure of how quickly a temperature sensor measures change in temperature. It is the time in which the UUT thermometer reading settles to the new value after a change in the actual temperature of the system.
3.3 Temperature Range TR: The minimum and maximum values that can be detected and displayed by the instrument.
3.4 Least Count LC: The smallest value or increment that a measuring instrument can accurately detect and differentiate. It is the minimum measurement interval that an instrument can discern, and it serves as a fundamental indicator of the instrument's precision.
3.5 Total Length TL: The total length of the thermometer from the bulb to the end of the capillary. As the length increases the number of lines that can be marked on the scale increases, therefore LC decreases or, for the same LC, the distance between the 2 consecutive lines increases.
3.6 Precision: The closeness of two or more measurements to each other is known as the precision of a measurement device. If one weighs a given substance five times and gets 3.2 kg each time, then the measurement is very precise but not necessarily accurate. Precision can be separated into:

3.6.1 Repeatability: The variation arising when the conditions are kept identical and repeated measurements are taken during a short time period.

3.6.2 Reproducibility: The variation arises using the same measurement process among different instruments (UUTs) and operators, and over longer time periods.

IV. RESEARCH METHODOLOGY

4.1 Accuracy Test

Safetherm® thermometers were compared with mercury thermometers for their accuracy as a function of the following variables: Temperature Range, Least Count and Total Length. To test the differences between the mercury and Safetherm® thermometers, duplicate sets of these units were manufactured at various ranges, lengths and least counts. The accuracy of the units was tested by the comparative method for calibration, wherein the thermometers under test (UUTs) were immersed, alongside a standard master thermometer, into a constant temperature bath set at a fixed temperature (as shown in Figure 2 below), and the settled steady state readings of both the UUT and Master were recorded. This was done for both the mercury and the Safetherm® UUTs. The thermometer error/accuracy at each temperature was calculated as the absolute value of the difference between standard reading and UUT reading. This process was repeated for all the thermometers at different temperature set points of 5, 50, 100, 150, 200 and 246°C as applicable. The average error for each thermometer was then calculated using the absolute of the error values at the various temperatures across the two replicate thermometers.

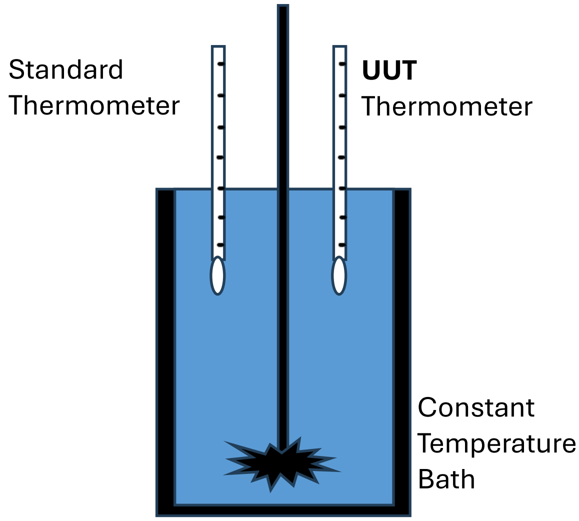


Figure 2: Comparative method for thermometer calibration using a liquid bath.

4.2 Precision study

The reproducibility and repeatability of the measurements was tested using thermometers with range -10/250℃ x 1℃ LC x 18-inch TL. Ten unique units each of Safetherm® and mercury thermometers were used for this test. The calibration bath was set at 100℃ and the steady state reading of each of the 10 Safetherm® thermometers was noted down one after another. The same exercise was repeated a total of three times for each of the ten thermometers. The above testing was then repeated for the set of 10 Mercury thermometers. All the testing was done by one operator only, to not introduce the variability associated with operator measurement. In this manner, repeatability (3 readings of the same unit) and reproducibility (10 different units of the same thermometer type) were tested for in the case of both mercury and Safetherm® thermometers.

4.3 Response Time Test

This was measured using a calibrated stopwatch along with three unique parts each of Safetherm® and mercury thermometers with -10/250℃ x 1℃ x 18-inch TL. The test was conducted at 6 different set point temperatures of 5, 50, 100, 150, 200 and 250℃. To perform this test, all UUTs were first set at room temperature. One UUT thermometer (at room temperature) was inserted into the constant temperature bath (set at a fixed set point) and the stopwatch was started. The column of liquid in the thermometer was observed closely as it rose or fell in the capillary and once it settled at the set temperature, the stopwatch was stopped, to measure the total time taken for the thermometer to reach this new temperature value. The same method was repeated for all three replicates of both Mercury and Safetherm® thermometers at each set point. The thermometers were brought back to room temperature before inserting into the next set temperature bath.

V. RESULTS AND DISCUSSION

5.1 Precision Study

The results of the precision study conducted with Safetherm® and mercury thermometers are shown in Table 1 below, which indicate that the average absolute error in both mercury and Safetherm® thermometers is the same i.e., 0.28℃, and both readings have similar standard deviations of ~0.3℃. This indicates that the manufacturing process and measurement process are both very consistent, and the variation between parts (reproducibility) and variability between each replicate (repeatability) is captured by this overall standard deviation. Also, both mercury and Safetherm® thermometers have almost identical values, again suggesting consistent manufacturing and measurement processes irrespective of liquid used. This data suggests that for further studies, 2 or 3 unique parts of the different type of thermometers under test can be used to get a good estimate of the error for that type of thermometer.

Table 1: Replicates & Part-to-Part Data at 100°C for Safetherm® and Mercury thermometers

Safetherm @ 100°C	**UUT Reading Trials**			**Error = Std-UUT**		
Part No	**Tr 1**	**Tr 2**	**Tr 3**	**Tr 1**	**Tr 2**	**Tr 3**
S 240805	99.5	99.5	99.5	0.5	0.5	0.5
S 240803	99.8	100	100	0.2	0	0
S 240809	99.8	100	100	0.2	0	0
S 240807	99.8	99.8	99.8	0.2	0.2	0.2
S 240801	100	100	100	0	0	0
S 240802	100.2	100.5	100.5	-0.2	-0.5	-0.5
S 240806	99.2	99.8	99.8	0.8	0.2	0.2
S 240810	99.2	99.5	99.5	0.8	0.5	0.5
S 240804	100	100	100	0	0	0
S 240808	99	99.8	99.5	1	0.2	0.5
Average Absolute Error: 0.28 °C						
Std Dev Absolute Error: 0.28°C						

Mercury @ 100°C	**UUT Reading Trials**			**Error - Std-UUT**		
Part No	**Tr 1**	**Tr 2**	**Tr 3**	**Tr 1**	**Tr 2**	**Tr 3**
S 240252	100	100	100	0	0	0
M 240730	100.5	100.5	100.5	-0.5	-0.5	-0.5
S 240235	100.8	100.8	100.8	-0.8	-0.8	-0.8
M 24028	99.8	99.8	99.8	0.2	0.2	0.2
S 240716	100.8	100.8	100.8	-0.8	-0.8	-0.8
M 240221	100	100	100	0	0	0
S 240253	100	100	100	0	0	0
M 240733	100.5	100.5	100.5	-0.5	-0.5	-0.5
M 23078	100	100	100	0	0	0
M 240135	100	100	100	0	0	0
Average Absolute Error: 0.28 °C						
Std Dev Absolute Error: 0.33 °C						

5.2 Response Time (RT)

The following table shows data for response time of each type of thermometer as a function of set temperature. In this study the thermometers used were:

Safetherm®: -10/250°C x 1°C LC x 18" TL – 3 pieces each

Mercury: -10/250°C x 1°C LC x 18" TL – 3 pieces each

Each thermometer was at room temperature at 25°C, before the test. The raw data is shown below in Table 2 and Figure 3.

Table 2: Response Time of Safetherm® and Mercury thermometers as a function of set temperature

Safetherm® Thermometers					
		Response Time (RT) in seconds			**Safetherm® Average RT**
Sr No.	**Set T**	**Part 1**	**Part 2**	**Part 3**	
1	5	17.6	18.34	16.9	17.6
2	50	29.61	31.15	25.6	28.8
3	100	35.9	37.37	32.7	35.3
4	150	72.3	63.33	76.96	70.9
5	200	79.24	84.5	90.77	84.8
6	250	65.57	65.37	73.14	68.0

Mercury Thermometers						**Ratio of Safetherm RT: Mercury RT**
		Response Time (RT) in seconds			**Mercury Average RT**	
Sr No.	**Set T**	**Part 1**	**Part 2**	**Part 3**		
1	5	6.49	7.49	9.1	7.7	2.3
2	50	8.05	8.37	8.03	8.2	3.5
3	100	17.12	18.91	18.67	18.2	1.9
4	150	39.78	39.21	39.72	39.6	1.8
5	200	53.15	53.66	54.87	53.9	1.6
6	250	36.72	36.83	41.93	38.5	1.8

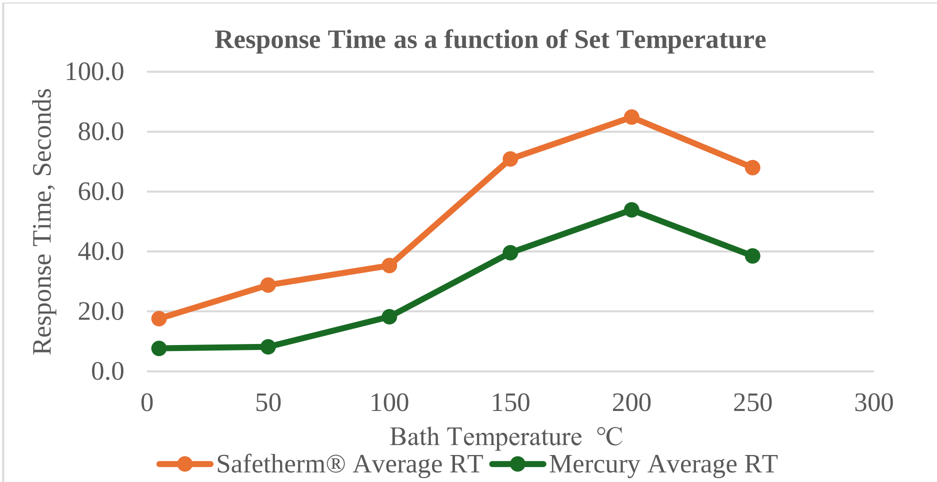


Figure 3: Response Time of Safetherm® and Mercury Thermometer as a function of Set Temperature

In the above graph both kinds of thermometers follow a similar trend with increasing set temperatures, wherein the response time increases more slowly between 5 to 100 °C, more rapidly from 100 to 200 °C and then drops from 200 to 250 °C. As the liquid in the column rises or falls (as the case may be), the time taken for this movement will depend on the ΔT, i.e., the difference between set bath temperature and initial temperature of the thermometer (i.e., room temperature). Accordingly, the next graph shows the response time as a function of ΔT.

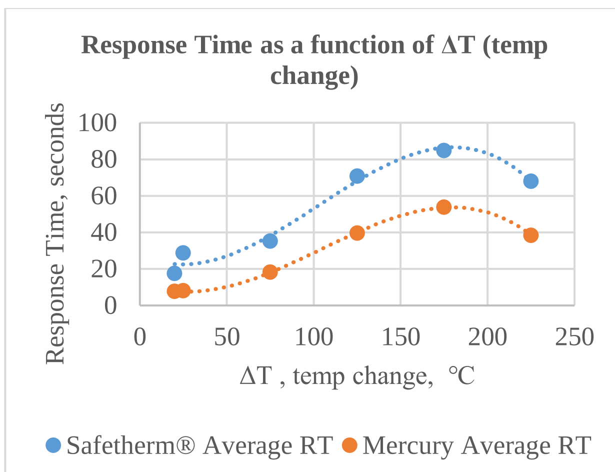


Figure 4: Response Time of Safetherm® and Mercury Thermometer as a function of ΔT

From room temperature to 5 °C and room temperature to 50 °C, the ΔT is very similar (between 20 and 25°C), and distance to be travelled in the liquid column, i.e., column length, is also similar, and hence the response time, RT is also similar at these two temperatures. However, as the temperature is increased till 200°C, the column length increases and so the response time also increases almost linearly. There is a decrease in response time seen at the highest temperature of 250 °C, which is counter intuitive as the column length is highest at this temperature. It is important to understand that apart from thermal expansion, the speed with which the liquid travels up the column also depends on the viscosity of the liquid. As the temperature increases, the viscosity keeps reducing [8], thus making it easier for the liquid to travel up the column. This explains why the response time of both types of thermometers reduces at 250 °C and can be attributed to the decreased viscosity of the liquids at this temperature.

When comparing Safetherm® to mercury it is observed that at all set points, the response time of Safetherm® is higher than that of mercury thermometers, and these ratios have been reported in the last column in Table 2 above. These numbers suggest that RT of Safetherm® is approximately double that of its mercury equivalent. This can prove to be a drawback for Safetherm® thermometers in certain applications such as flash point measurements etc., where response time needs to be very fast. These tests were done at steady state conditions of bath temperature, but more tests need to be done at unsteady state conditions to compare the response time of both when the bath temperature is dynamically increasing or decreasing to its steady state value.

5.3 Accuracy Tests

Safetherm® and mercury thermometers were compared under identical, controlled conditions and tested for their accuracy as a function of temperature range, total length and least count.

5.3.1 Temperature Range (TR)

The following table shows data for accuracy/error of each type of thermometer as a function of its temperature range. In this study, other variables such as total length and least count were kept constant at 18" and 1°C, respectively. The thermometers used for both Safetherm® and Mercury were:

Range x 1°C LC x 18" TL – 2pcs each where Range was varied as -10/50°C, -10/150°C and -10/250°C

The table below shows the effect of thermometer range on the average error of the thermometers (taken over its entire temperature range). The thermometer error at each temperature was calculated as the absolute value of the difference between standard reading and UUT reading. The average error was then calculated using these errors at various temperatures across the two replicate thermometers.

Table 3: Average thermometer error (over full range) Max error as a function of Range

Range, °C	Avg Error, °C		Range, °C	Max Error, °C	
	Mercury	Safetherm®		Mercury	Safetherm®
-10/50	0.21	0.25	-10/50	0.3	0.5
-10/150	0.19	0.40	-10/150	0.6775	0.8
-10/250	0.44	0.40	-10/250	0.906	1

Plotting these values graphically yields the following Figure 5

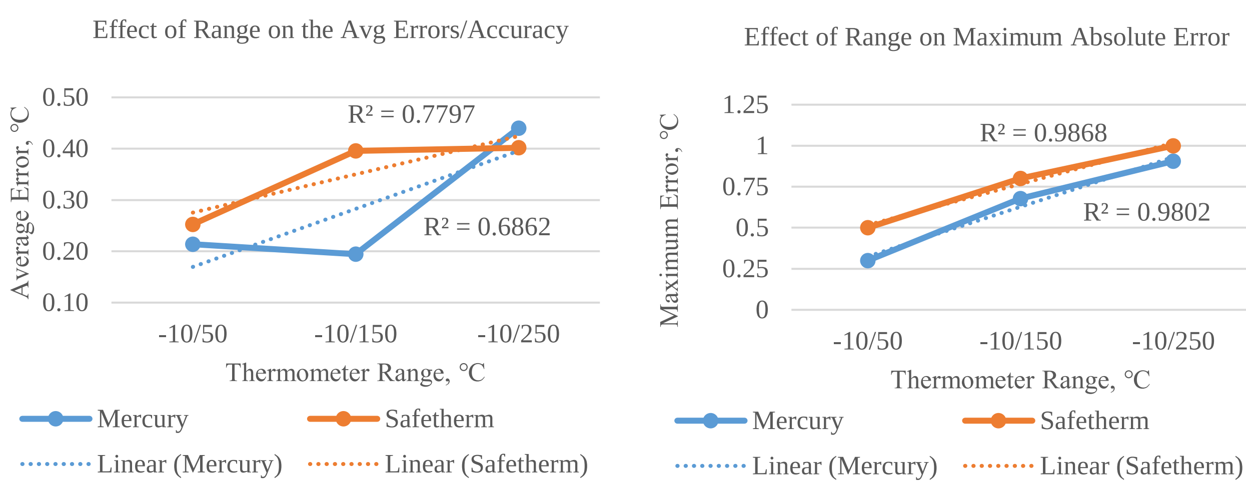


Figure 5: Accuracy/Error of Safetherm® and Mercury Thermometers as a function of Range

It can be seen from the above plot that the average error of the thermometers range between 0.2 to 0.45 °C across both mercury and Safetherm® thermometers for all the different ranges. Even though there is a slight correlation between error and temperature range as shown by the linear trend, it can be said that both Safetherm® and Mercury have similar accuracies, irrespective of the temperature range. All the errors are well within the manufacturing specification of 1 LC i.e., 1°C in this case. Also in Figure 5, we can see that the maximum error in the thermometers linearly increases with increasing range, and yet the maximum value of the error is less than or equal to the maximum allowable error of 1 LC, i.e., 1°C. Safetherm® thermometers have a slightly higher error than the corresponding mercury counterparts, but are considered similar for the applications they are used in, since they meet the manufacturing specification.

5.3.2 Total Length TL

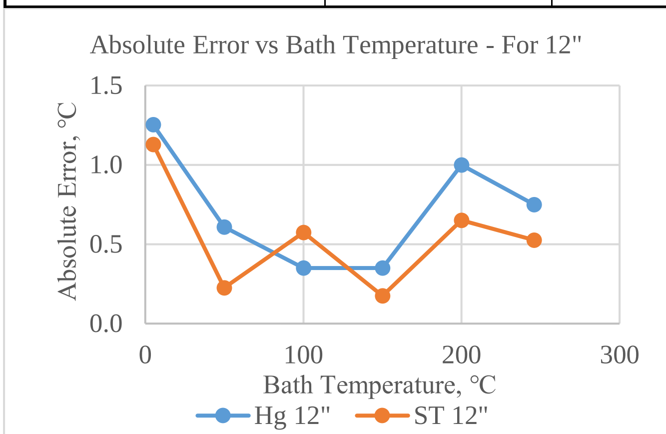
Table 4A shows data for the accuracy/error of each type of thermometer as a function of its total length. In this study, other variables such as range and least count were kept constant. The thermometers used for both Safetherm® and mercury were:

-10/250°C x 1°C LC x TL – 2pcs each where TL was varied as 12" and 18"

For each thermometer, error data was collected at 6 temperatures across the entire range i.e., 5, 50, 100, 150, 200, 246°C. The Table 4A and Figure 6 below show the error data for 12-inch and 18-inch-long thermometers at these six temperatures. Each error reported at a particular temperature is the average of the absolute error of the replicate thermometers at each temperature point.

Table 4A: Absolute error as a function of bath temperature

	Absolute Error (average of 2 to 3 replicates), °C			
Bath Temperature, °C	**Mercury 12"**	**Safetherm® 12"**	**Mercury 18"**	**Safetherm® 18"**
5	1.25	1.13	0.91	0.33
50	0.61	0.23	0.13	0.88
100	0.35	0.57	0.33	0.00
150	0.35	0.17	0.67	0.20
200	1.00	0.65	0.00	0.33
246	0.75	0.53	0.60	1.00



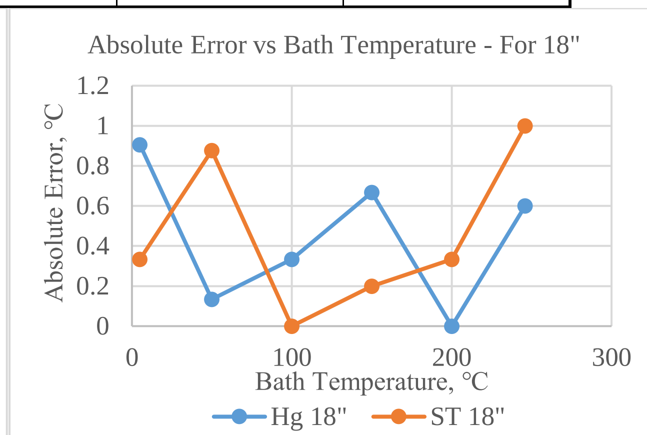


Figure 6: Absolute Error of 12-inch and 18-inch long Safetherm® and Mercury Thermometers

From Figure 6 above, we see that there is no significant effect of bath temperature on the absolute error of the thermometers for both mercury and Safetherm®. Even though for the 12-inch thermometers it may appear that the error is higher at the 5 °C and 200 °C points, overall, the error is scattered across the range for both liquids and at both lengths.

Subsequently, the average absolute error for each type of thermometer was calculated by taking an average of the errors at all the six temperature points across the range. This gives the following Table 4B:

Table 4B: Average Absolute error (over full range) as a function of total length

	Absolute Error (average of all Temp points), °C	
Total Length	**Mercury**	**Safetherm®**
12"	0.72	0.55
18"	0.44	0.46

The Figure 7 below shows this data on a plot which suggests there is no effect of total length on accuracy for both the liquids. Also, there is no significant difference between the average errors of Mercury and Safetherm® when compared at different lengths, keeping range and least count constant.

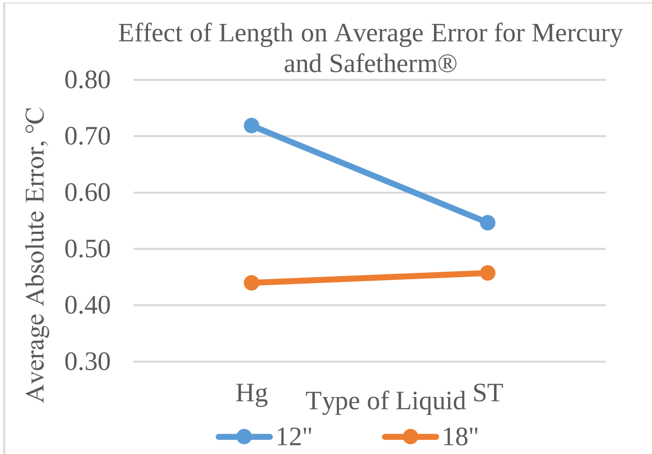


Figure 7: Average Error of 12-inch and 18-inch long Safetherm® and Mercury Thermometers

5.3.3 Least Count LC

In this study, the accuracy of Safetherm® and mercury thermometers were compared for various least counts. Since it is not possible to have the same range of thermometers for LC of 0.05°C all the way till 1°C, thermometers were chosen to maintain the range between -10/110°C.

Table 5: Absolute Error at 39 °C, as a function of least count

			Avg Absolute Error, °C	
LC, °C	**Range, °C**	**Length**	**Mercury**	**Safetherm®**
0.05	36.6/39.4 (IP31C)	12"	0.02	0.04
0.1	-10/50	18"	0.04	0.10
0.2	-20/102 (IP64C)	18"	0.09	0.10
0.25	-10/50	18"	0.09	0.08
0.5	-10/50	18"	0.19	0.05
1	-10/110	18"	0.13	0.08

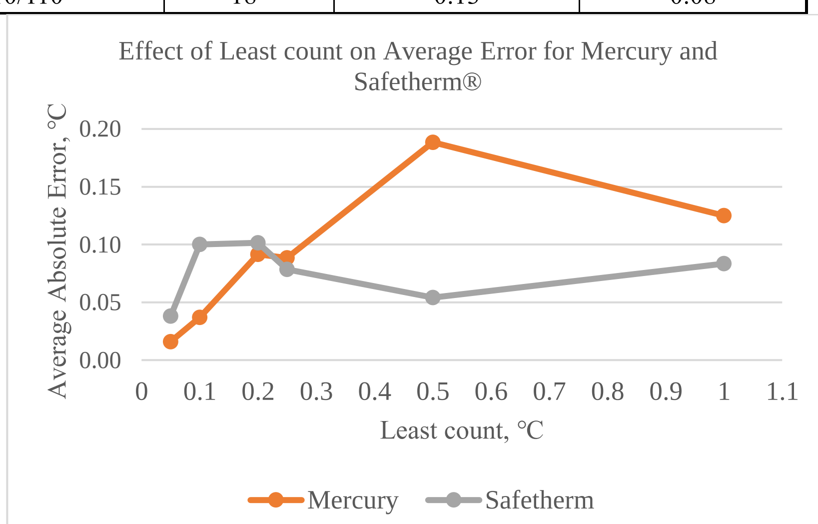


Figure 8: Average Error Safetherm® and Mercury Thermometers with varying least count.

The results presented above indicate that Safetherm® can be considered an effective and safe replacement for mercury in general-purpose industrial glass thermometers This study provides a foundation for further investigations of various IP/ASTM and Precision grade glass thermometers filled with Safetherm® and evaluated both at the laboratory and industrial scales. Also, this paper focussed mainly on partial immersion thermometers which can form the basis for future research work related to total immersion thermometers as well.

In this study all the measurements were done by only one operator, and hence operator to operator measurement variability was not factored in. Once these studies are conducted, the complete variability of the measurement process for both mercury and Safetherm® thermometers can be compared. Tests were done at steady state conditions, but more detailed tests need to be done at unsteady state conditions to compare the response time of both liquids when the temperature is dynamically increasing or decreasing to its steady state value.

VI. CONCLUSION

Safetherm® thermometers can be manufactured at temperature ranges equal to most mercury thermometers. An exception is on the high end of the temperature scale. Mercury thermometers can go up to 300°C, however Safetherm® thermometers were only manufactured up to 250°C for this study. Safetherm® thermometers have scale divisions equal to mercury thermometers. The least counts for which accuracy was tested ranged from 0.05°C to 1°C. Safetherm® thermometers were manufactured and compared with their mercury counterparts at 2 different total lengths of 12 inches and 18 inches. It was found that there is no effect of total length and LC on the accuracy of these thermometers, and no significant difference between the 2 liquids as well. It was found that the absolute error increases slightly with increasing thermometer range, however again no accuracy difference was seen between the two liquids even in this range study. The only notable and significant difference between Safetherm® and mercury thermometers was observed in response time, wherein it was found that Safetherm® has a response time of almost double as compared to the fast-responding mercury thermometers. This difference may not matter in most applications where steady state temperature is needed but might pose a problem during dynamic temperature measurements. All the testing in this study was done for steady state temperature measurements, however a detailed temperature study under dynamic increasing and decreasing temperature conditions needs to be conducted to further understand if there are any significant differences in response time between Safetherm® and Mercury thermometers under such dynamic conditions. Based on the results of this study, it can be concluded that Safetherm® can be a safe and promising replacement for the toxic mercury thermometers and can be evaluated in industry for various applications to gain large-scale feedback and data collection.

VII. ACKNOWLEDGEMENT

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