



## Measurement of HTHP Fluid-Loss Equipment and Test Fluids with Thermocouples

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### Abstract

The High-Temperature/High-Pressure (HTHP) fluid loss of a drilling fluid is very important in well construction because it has a direct correlation with the cost of maintaining the fluid and success of drilling the well. The HTHP filtrate value is set to minimize hole instability, filtrate invasion, and prevent differential sticking. The fluids engineer also uses the HTHP fluid loss to measure changes in the mud system and to design daily treatments. Operators and service companies emphasize controlling the HTHP fluid loss within a narrow range, which can be costly.

As part of API's continuing efforts to improve drilling fluid tests, a workgroup was established to determine whether modifications to current HTHP test methods could increase the accuracy of testing. Thermocouple devices were used to monitor the fluid temperature inside HTHP cells, using currently available HTHP equipment (internal volumes of 175 mL, 250 mL, and 500 mL).

Test results indicated the fluid's temperature met the targeted test temperature within the API-recommended 1-hour heat-up period for the 175-mL and 500-mL HTHP cells. However, the 250-mL HTHP cell significantly under-heated the fluid during testing while using API procedures. Thermocouple measurements found that the test fluid was as much as 30°F (16.7°C) lower than the test cell (wall) temperature.

This paper presents temperature data for commonly used HTHP filtration devices and suggests modifications to one style of equipment that does not currently meet API recommendations for heating. For thermally sensitive fluids, a thermocouple device may be required, especially with the 250-mL tester.

### Introduction

After density and viscosity, the filtration properties of drilling fluids are measured most frequently. Until the 1960s, the measurement of drilling-fluid filtration properties was conducted at ambient temperature and moderate pressure differential (100 psi, 690 kPa).

As wells became deeper and hotter, monitoring the filtration properties of drilling fluids at higher temperatures and differential pressures became necessary. This requirement led to the development of equipment and techniques for measuring drilling-fluid

filtration properties at elevated temperature and higher pressure differential.

### Principles of HTHP Filtrate Measurement

Measuring the HTHP fluid loss of a drilling fluid involves heating the fluid in a controlled environment to a temperature that is expected in the well. When test temperature is reached, filtrate volume and cake thickness is determined at a pressure differential to simulate downhole conditions. The equipment designed for this purpose includes a heating jacket (with a bi-metallic thermostat), a cell to contain the fluid, a means to pressurize the cell, and a means of collecting filtrate.

Historically, three different equipment designs have been used for measuring HTHP filtrate, each of which was evaluated. These 3.5-in.<sup>2</sup> (22.6-cm<sup>2</sup>) filtration area instruments have 175-mL, 250-mL, and 500-mL capacity test cells. Because the area of the standard API filter press is 7.1-in.<sup>2</sup> (45.8-cm<sup>2</sup>), the volume obtained from the HTHP test is doubled before reporting. Gauging the effect of temperature on the drilling fluid filtrate volume is the main purpose of the HTHP test and accurate temperature measurements are required.

### Bi-Metallic Stem Thermometers

Temperature accuracy is an important part of the HTHP filtrate test; therefore, commonly used bi-metallic stem thermometers were evaluated. API 13B-1 and 13B-2 specify using a 5-in. (12.7-cm) stem thermometer, capable of indicating to 350°F (175°C) for test temperatures up to 350°F (175°C).<sup>1,2</sup> An 8-in. (20.3-cm) stem thermometer capable of indicating to 500°F (260°C), is used for test temperatures greater than 350°F (175°C). API 13B-1 and 13B-2 do not specify a required accuracy for these thermometers, only that the test apparatus must maintain the temperature within ±5°F (±2.8°C) of the specified temperature throughout the test. Bi-metallic stem thermometers rarely provide accuracy better than 1% of the total scale range. For this reason, an evaluation of stem thermometer accuracy was devised and executed.

The evaluation was performed by measuring the highest indicated temperature of five new 5-in. (12.7-cm) 50°F to 350°F (10°C to 175°C) dial-stem thermometers placed in a temperature source providing a very

accurate temperature. These temperature sources are frequently used in calibrating many types of thermometers, thermocouples and instruments. The thermometers tested were randomly selected from recent purchases by a drilling-fluid equipment supplier. The temperature was increased in 50°F (27.8°C) increments, from 100°F (37.8°C) to 350°F (177.8°C). Table 1 summarizes the test results.

Based upon this testing, it can be reasonably concluded that commonly used bi-metallic stem thermometers exhibit accuracy sufficient to meet current API specifications for HTHP fluid-loss testing. Gross temperature errors with these devices are likely a result of damaged or misadjusted thermometers, which should be easily detected with a periodic quality assurance process.

Procedures for calibrating thermometers are given in the API Recommended Practices 13B-1 and 13B-2. These thermometers are provided with an external adjustment nut to facilitate recalibration. To recalibrate, adjust the thermometer by firmly holding the dial head, while immersing the stem at least 2-in. into a known temperature source (such as a water bath) and turn the hex nut with a wrench until the pointer indicates the correct temperature.

#### **Available HTHP Filter Press Models**

The three unique designs in common use are the 175-mL, 250-mL, and 500-mL HTHP filter presses. A description of each HTHP filter press is given in the following sections.

##### **175-mL Filter Press**

Figure 1 shows the 175-mL HTHP model. Typically, the pressurization source is carbon dioxide cartridges. This model is rated to 350°F.

##### **250-mL Filter Press**

Figure 2 shows the 250-mL HTHP model. As with the 175-mL model, the pressurization source is normally carbon dioxide cartridges. This model is also rated to 350°F. Early versions of this equipment had a back pressure receiver with a sight-glass, which was discontinued because of safety concerns.

##### **500-mL Filter Press**

Figure 3 shows the 500-mL HTHP model, which is rated to 450°F. It requires pressurized nitrogen. In most areas, this device is considered a laboratory instrument and is most widely used in drilling fluid laboratories rather than field locations.

#### **Test Instrumentation**

To properly evaluate the heating ability and internal temperature of the different HTHP filter presses, nitrogen was used for pressure, and a different temperature control system (than the usual bi-metallic heating jacket

thermostat) was used. Two devices were used to control and measure the temperature of drilling fluids during each HTHP filtration test. The first device is a HTHP heating jacket controller (Figure 4). The jacket temperature is set with an electronic controller that uses a thermocouple to measure the jacket temperature. This device provides for quickly heating the jacket to the set temperature, then cycling the jacket to within  $\pm 5^\circ\text{F}$  ( $\pm 2.8^\circ\text{C}$ ) of the set temperature. The second device is a multichannel data acquisition system (Figure 5).

The data acquisition unit measures three temperatures for each HTHP device. Using calibrated type K thermocouples, one channel records the temperature of the HTHP jacket, the second channel records the temperature of the HTHP test cell, and the third channel, using a type J thermocouple, measures the internal temperature of the drilling or test fluid (Figure 6). Instrument manufacturers supply calibrated type J thermocouple devices that are placed into the center of a HTHP filter cell to read the drilling fluid temperature approximately 1-in. above the filtration medium. Temperature measurements are recorded every ten seconds and saved to a spreadsheet by the data acquisition software. At the end of the test, a graph is prepared, showing the temperature profile of the jacket, test cell, and drilling fluid with respect to time (Figures 7 to 9). The accuracy of the type J and type K thermocouples used in this study was confirmed before testing.

#### **Test Procedure**

According to API procedures for HTHP testing (Recommended Practices 13B-1 and 13B-2), the jacket should be preheated to 10°F (5.6°C) above the test temperature. When the jacket reaches temperature, the test cell is placed in the jacket, the top and bottom pressure connections are made, and the pressurized test cell is allowed to heat. When the cell is within 5°F (2.8°C) of the test temperature, the top and bottom pressure is adjusted to the correct value, and the HTHP test begins. API recommendations are that the test cell and fluid should reach test temperature within one hour. In other words, the test should begin within one hour of placing the cell into the heating jacket.

For the tests presented, the following procedure is used:

1. The HTHP jacket is preheated to 10°F (5.6°C) above the test temperature. The temperature controller maintains the jacket temperature at the correct value.
2. The test fluid is mixed for 10 minutes, added to the test cell and prepared for testing. A thermocouple is placed into the top portion of the test cell, threaded through the top port, and sealed.
3. The test cell is placed in the preheated jacket and thermocouples are connected to the data-

acquisition system to measure the jacket, test cell, and internal fluid temperatures. Computer data acquisition begins.

4. Top and bottom pressure regulators are connected. Nitrogen gas is applied through the top valve at 100 psi (690 kPa).
5. The pressurized test cell and fluid is allowed to heat for 60 minutes.
6. At the end of 60 minutes, the pressure on the top regulator is increased to 600 psi (4,140 kPa) and the bottom receiver pressure is adjusted to 100 psi (690 kPa), resulting in a 500-psi differential pressure across the filter paper.
7. The bottom test cell valve is opened to start the test.
8. After 30 minutes, the bottom valve is closed to end the test.
9. Filtrate volume is measured and recorded.

Figures 7 through 9 illustrate the test data and temperature profiles of typical HTHP filtration tests using the instrumented cells.

More than one hundred thermocouple tests were conducted using the 175-mL, 250-mL, and 500-mL style HTHP filter presses. Many different types of fluids were tested, including fresh water, mineral oil, water-based mud, oil-based mud, and completion fluid. For most tests, only the heating characteristics of the cell were measured during the one-hour heating period. Other tests included measuring the HTHP filtrate (for 30 minutes) of fluids after the 60-minute heating period, resulting in temperature data collected for the 1½-hour time period. Differential temperature test data is obtained by subtracting the measured fluid temperature from the target test temperature. An example of data collected for analysis is seen in Table 2.

### Variations from Standard Procedure

To decrease the time required to run HTHP tests, a common practice is to set the temperature of the heating jacket 20°F to 30°F or more (11.1°C to 16.7°C) above the target test temperature. This variation to the recommended procedure was used on selected HTHP tests to evaluate the effect on the fluid temperature inside the cell.

### Test Results

#### 175-mL and 500-mL HTHP Equipment

Using the API-recommended heating procedure, thermocouple measurements indicated the 175-mL HTHP cell heated the test fluid to within an average of 3°F (1.6°C) of the target test temperature within the 60-minute heat-up time. When the heating jacket temperature was increased 20°F (11°C) above the test temperature, the internal fluid temperature was consistently 2°F (1.1°C) to 12°F (6.7°C) above the test temperature at 60 minutes (Figure 10).

Results with the 500-mL HTHP equipment were similar to the 175-mL equipment. The API procedure heated the test fluid to  $\pm 5^\circ\text{F}$  ( $\pm 2.8^\circ\text{C}$ ) of the test temperature within the one hour heat-up time. When the jacket temperature was set 20°F above the test temperature, the test fluid was consistently heated above the test temperature by 1°F to 18°F (0.6°C to 10.0°C) (Figure 11).

#### 250-mL HTHP Equipment

Using the API recommended heating procedure, thermocouple measurements indicate the 250-mL style equipment does not consistently heat the fluid to the test temperature. Test cell temperature readings from 25 tests averaged 8°F (4.4°C) below the test temperature after heating for 60 minutes. Test fluid temperature averaged 16°F (8.9°C) below the test temperature during these tests. When the jacket is set 20°F (11.1°C) above the target test temperature, the test cell reaches the proper temperature, averaging 1°F (0.6°C) over test temperature for ten tests. However, the average fluid temperature is 10°F (5.6°C) below the test temperature. Figure 12 shows the average temperature differences between the fluid and the test temperature. Figure 13 shows 250-mL HTHP equipment temperature differentials between:

- the heating jacket and test temperature
- the test cell and heating jacket
- the test fluid and heating jacket
- the test fluid and test cell
- the test fluid and target test temperature

This data indicates that the 250-mL HTHP equipment has a problem transferring heat from the jacket to the test cell and then to the test fluid.

Not all types of fluids or jacket temperatures were run in the data presented in Figures 10 through 13.

#### Heating Improvements to 250-mL HTHP Equipment

The size, configuration, and wall thickness of the 250-mL test cell prevents the fluid from being heated to the correct temperature when using the API procedure. Several modifications to improve heating performance were evaluated. Placing a metal heat sink (Figures 14 and 15) inside the test cell, as well as covering the top and bottom of the cell with high-temperature aluminum oxide insulation (Figure 16), dramatically improved the performance of this equipment. On tests with the heat sink and insulation, the fluid temperature increased by an average of 16°F (8.9°C). These modifications brought the 250-mL equipment within API recommendations. Differences in HTHP fluid-loss results were minor and could be attributed to the increased temperature of the fluid during the test. Two types of heat sinks, as well as an insulation jacket, are shown in Figure 4. Close-ups of the heat sinks are shown in Figures 14 and 15. Table 3 compares test

results with and without the heat sink and insulation. Table 4 shows changes in temperature and HTHP fluid-loss results with the modifications to the 250-mL test cell.

### HTHP Fluid Loss Test Comparisons

The API workgroup on thermocouple testing was not charged with conducting HTHP tests comparing the different types of test equipment. However, test results were obtained with several drilling fluids and are given as examples. Table 3 compares HTHP fluid-loss values between the different equipment and the temperature of the fluid when the test was started. These results show that the 250-mL test cell gives HTHP fluid-loss results that are mostly lower than the results obtained from the 175-mL and 500-mL test cells. The column marked with an asterisk shows HTHP fluid-loss test results when the 250-mL equipment was modified with a heat sink and insulation. Improvements in heating the 250-mL cell give similar test results to the other two cells.

### Field Problems

Recently, inconsistent HTHP fluid-loss values between field and laboratory tests were observed with an oil-based mud. The 400°F (204.4°C) HTHP fluid losses measured on location were in the 2.0-mL to 3.0-mL range, but laboratory test results were in the 7.0-mL to 8.0-mL range. An investigation into the test method used in the field and the lab identified a possible cause for the different fluid loss values of this drilling fluid.

Field testing used the following heating method:

1. Turn on the 500-mL heating jacket, and set the temperature to 450°F (232°C).
2. While the jacket heats, place the test cell in the jacket, connecting the top and bottom pressure regulators.
3. When the test cell reaches 375°F (190.5°C), reduce the jacket temperature to 400°F (204.4°C).
4. Start the HTHP filtrate test.

The 500-mL test cell was heated to 375°F (190°C) in 18 minutes and the HTHP fluid-loss test was run from start to finish in less than one hour. Using this test procedure, while measuring the jacket, test cell, and drilling fluid with thermocouples, very large test fluid temperature differences were recorded (Table 5).

The drilling fluid temperature was 275°F (135°C) or 125°F (69°C) below test temperature when the fluid-loss test began. The test fluid averaged 333°F (167°C), or 67°F (37.2°C) below the test temperature during the filtrate test period. At the end of the filtrate test, the fluid was 373°F (189.4°C), which was 27°F (15°C) below test temperature. Total test time was less than one hour.

Using the API-recommended heating procedure and the same equipment, the initial drilling fluid temperature after heating for one hour was 394°F (201.1°C), the final temperature was 403°F (206.1°C), and the average was

402°F (205.6°C). Total test time was two hours.

### Conclusions

Thermocouple devices proved to be very capable instruments for accurately monitoring fluid temperature inside HTHP filter press cells during filtration testing. The 175-mL and 500-mL HTHP equipment fluid temperature reached target test temperature when the test cell was heated for one hour with the heating jacket set 10°F (6°C) above the target temperature. The API recommends testing and maintaining the fluid temperature inside the cell within  $\pm 5^\circ\text{F}$  ( $\pm 3^\circ\text{C}$ ), and these two models performed within API guidelines. However, the 250-mL filter press did not reach the target test temperature within the one-hour heating time limit.

The 250-mL cell walls are noticeably thicker in this model (2.2 cm vs. 1.6 cm) than in the 175-mL and 500-mL test cells. This increased metal mass may be a primary reason for the lack of heat being transferred to the test fluid. Another possible reason for poor heat transfer is the relatively large surface area of the test cell's top and bottom, which increases heat loss.

Improvements in heating the 250-mL test cell (and test fluid) were obtained by using heat sinks inside the cell to improve heat transfer from the cell wall to the fluid. Additional heating improvements were made by insulating the top and bottom of the cell or by wrapping the heating jacket with an insulating cover. When these procedures were implemented, the 250-mL HTHP filter press performed within API guidelines for heating, as did the other models.

Although two of the three HTHP models performed within API guidelines for heating, thermocouples installed inside the test cell are the only way to accurately monitor fluid temperatures. This could be an important consideration for using thermocouples to accurately test temperature-dependent drilling fluids or products.

### Recommendations

Based on thermocouple work conducted to date, the following HTHP testing guidelines are suggested:

1. Follow API-recommended procedures for heating the test cell and fluid.
2. Increasing the heating jacket temperature greater than 10°F (6°C) is not recommended, nor is it necessary with the 175-mL and 500-mL test equipment.
3. Modify the 250-mL equipment with a heat sink and insulation to meet API recommendations.
4. For critical wells, thermal stability tests, or for measuring the performance of high-temperature drilling fluid products, the use of a thermocouple device to measure fluid temperature may be desired.

### Acknowledgments

Dr. Leon Robinson, PhD (retired) suggested the use of a heat sink in the 250-mL instrument. His help with this matter and other technical problems is greatly appreciated.

Willie Vasquez and Irina Goldenberg (Westport Technology Center International) spent many hours testing different fluids and measuring HTHP equipment heating characteristics. Their hard work increased our understanding of HTHP filtration equipment. Their work and suggestions are also greatly appreciated.

### References

1. Recommended Practice Standard Procedure for Field Testing Water-Based Drilling Fluids, API Recommended Practice 13B-1, Second Edition 1997.
2. Recommended Practice Standard Procedure for Field Testing Oil-Based Drilling Fluids, API Recommended Practice 13B-2, Third Edition 1998.

**Table 1 – Bi-Metallic Stem Thermometer Measurements**

Test Temp, °F	Minimum Temp, °F	Maximum Temp, °F	Average Temp, °F
100°F	102°F	104°F	104°F
150°F	150°F	152°F	151°F
200°F	200°F	203°F	202°F
250°F	251°F	256°F	253°F
300°F	300°F	306°F	303°F
350°F	352°F	356°F	354°F

**Table 2 – Examples of Thermocouple HTHP Heating Test Data**

<b>Test Cell</b>	<b>Target Test Temp (°F)</b>	<b>Jacket Setting (°F)</b>	<b>Jacket Over Test (°F)</b>	<b>Jacket at 60 min., (°F)</b>	<b>Cell at 60 min., (°F)</b>	<b>Fluid at 60 min., (°F)</b>	<b>Mud Type</b>	<b>Mud Weight (lb/gal)</b>
175	250	260	10	258	254	245	synthetic	10.5
250	250	260	10	257	239	221	synthetic	10.5
500	250	260	10	261	256	247	synthetic	10.5
175	300	310	10	310	308	301	diesel obm	17.7
250	300	310	10	310	294	282	diesel obm	17.7
500	300	310	10	310	306	306	diesel obm	17.7
175	300	320	20	320	316	308	diesel obm	17.7
250	300	320	20	318	300	285	diesel obm	17.7
500	300	320	20	319	318	317	diesel obm	17.7
175	350	370	20	367	360	348	diesel obm	17.7
250	350	370	20	367	340	327	diesel obm	17.7
500	350	370	20	368	357	355	diesel obm	17.7
175	250	260	10	260	252	250	water	8.3
250	250	260	10	261	247	245	water	8.3
500	250	260	10	259	252	250	water	8.3
175	300	310	10	302	297	295	water	8.3
250	300	310	10	302	284	282	water	8.3
500	300	310	10	310	302	300	water	8.3
175	250	270	20	267	252	250	water	8.3
250	250	270	20	270	250	250	water	8.3
500	250	270	20	270	263	262	water	8.3
175	300	320	20	320	308	306	water	8.3
250	300	320	20	319	299	295	water	8.3
500	300	320	20	319	311	310	water	8.3
175	320	340	20	339	336	320	Cs formate	17.0
250	350	370	20	366	335	320	Cs formate	17.0
500	320	340	20	337	337	324	Cs formate	17.0

**Table 3 – HTHP Fluid Loss Test Results of Drilling Fluids**

<b>10.5-lb/gal Synthetic, 250°F</b>	<b>175-mL</b>	<b>500-mL</b>	<b>250-mL</b>	<b>15.0-lb/gal Synthetic, 300°F</b>	<b>175-mL</b>	<b>500-mL</b>	<b>250-mL</b>
HTHP (mL/30 min)	3.8	3.4	3.2	HTHP (mL/30 min)	4.0	4.0	3.2
Fluid Start temp.(°F)	245	247	221	(water in filt., mL)	0.4	0.4	0.4
				Fluid Start temp.(°F)	298	299	281
<b>11.1-lb/gal Synthetic, 250°F</b>	<b>250-mL</b>	<b>250-mL*</b>		<b>15.9-lb/gal Diesel OBM</b>	<b>175-mL</b>	<b>500-mL</b>	<b>250-mL</b>
HTHP (mL/30 min)	3.6	5.6		HTHP (mL/30 min)	14.4	15.2	9.6
Fluid Start temp.(°F)	235	242		(water in filt., mL)	3.6	3.6	3.2
				Fluid Start temp.(°F)	297	299	283
<b>16.3-lb/gal Synthetic, 250°F</b>	<b>250-mL</b>	<b>250-mL*</b>		<b>16.8-lb/gal Diesel OBM, 375°F</b>	<b>500-mL</b>	<b>250-mL</b>	<b>250-mL*</b>
HTHP (mL/30 min)	1.2	1.6		HTHP (mL/30 min)	4.8	4.0	3.2
Fluid Start temp.(°F)	235	243		Fluid Start temp.(°F)	375	351	364

\* Indicates 250-mL cell modified with heat sink and insulation

**Table 4 – Effect of Modifying 250-mL HTHP Cell with Heat Sinks, Aluminum Oxide Insulation, or Insulation Jacket**

	<b>Start</b>		<b>Water</b>		<b>Start</b>	
<b>13.6-lb/gal Synthetic Mud, 300°F</b>	<b>Temp.</b>	<b>HTHP</b>	<b>In Filt.</b>	<b>11.0 lb/gal Lignite Mud, 300°F</b>	<b>Temp.</b>	<b>HTHP</b>
	<b>(°F)</b>	<b>Filt., (mL)</b>	<b>(mL)</b>		<b>(°F)</b>	<b>Filt., (mL)</b>
Heat Sink Type A	286	9.6	2.0	Base Mud	279	20.8
Heat Sink Type B	285	10.0	2.0	Heat Sink A	298	21.6
Insulation jacket	283	9.6	0.0	HS A, Top/Bottom Ins.	294	20.4
HS A, Insulation jacket	298	8.8	0.0			
HS A, Top/Bottom Ins.	298	12.4	4.0		<b>Start</b>	
HS B, Top/Bottom Ins.	288	12.4	4.4	<b>11.0 lb/gal Lignosulfonate, 300°F</b>	<b>Temp.</b>	<b>HTHP</b>
					<b>(°F)</b>	<b>Filt., (mL)</b>
	<b>Start</b>			Base Mud	278	19.2
<b>16.8-lb/gal Diesel OBM, 375°F</b>	<b>Temp.</b>	<b>HTHP</b>		HS A, Top/Bottom Ins.	299	18.8
	<b>(°F)</b>	<b>Filt., (mL)</b>				
Base Mud (500-mL cell)	375	4.8			<b>Start</b>	
Base Mud (250-mL cell)	351	4.0		<b>15.0 lb/gal Lignosulfonate, 300°F</b>	<b>Temp.</b>	<b>HTHP</b>
Base Mud (250-mL cell)*	361	6.0			<b>(°F)</b>	<b>Filt., (mL)</b>
Heat Sink A only	364	3.2		Base Mud	284	17.2
Top Insulation only	365	not run		HS A, Top/Bottom Ins.	292	17.2
Top/Bottom Ins. only	356	not run				
HS A, Top/Bottom Ins.	372	not run				

\* Jacket temperature set 30°F above target temperature

**Table 5 – Field Problem Test Data, Results of Overheating Jacket to Minimize HTHP Test Time**

	Jacket	Test Cell	Drilling Fluid	API Test Fluid*
Initial Temperature (°F)	450	75	75	75
Start Test Temp. (°F)	425	376	275	394
End Test Temp. (°F)	398	392	373	403
Average Temp. (°F)	405	391	333	402
Total Test Time, min.	-	-	48	120

\* API method (preheat jacket, heat cell for 60 minutes)



**Figure 1**  
175-mL HTHP filter press



**Figure 2**  
250-mL HTHP filter press





Figure 3 - 500-mL HTHP filter press



Figure 4 - Jacket insulation, heat sinks, and jacket heating controllers



Figure 5 - Thermocouple data-acquisition system



Figure 6 - 250-mL HTHP with thermocouples

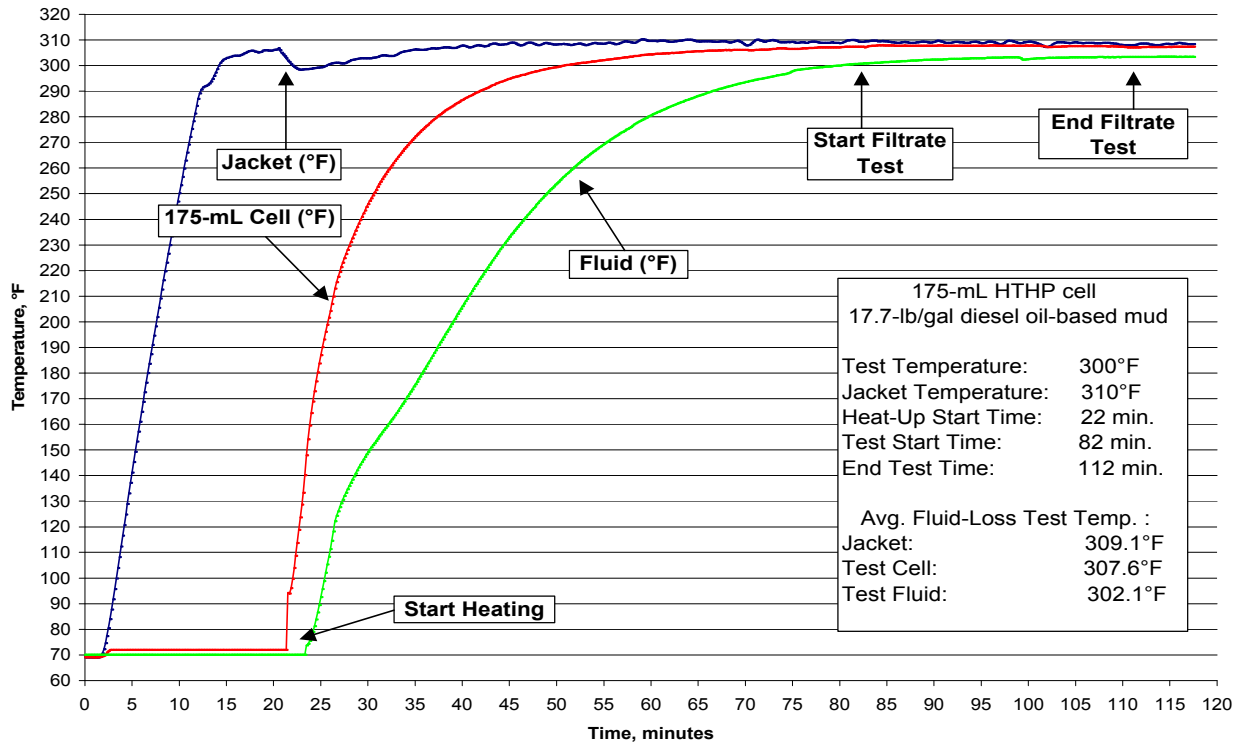


Figure 7 – Example test results for 175-mL cell

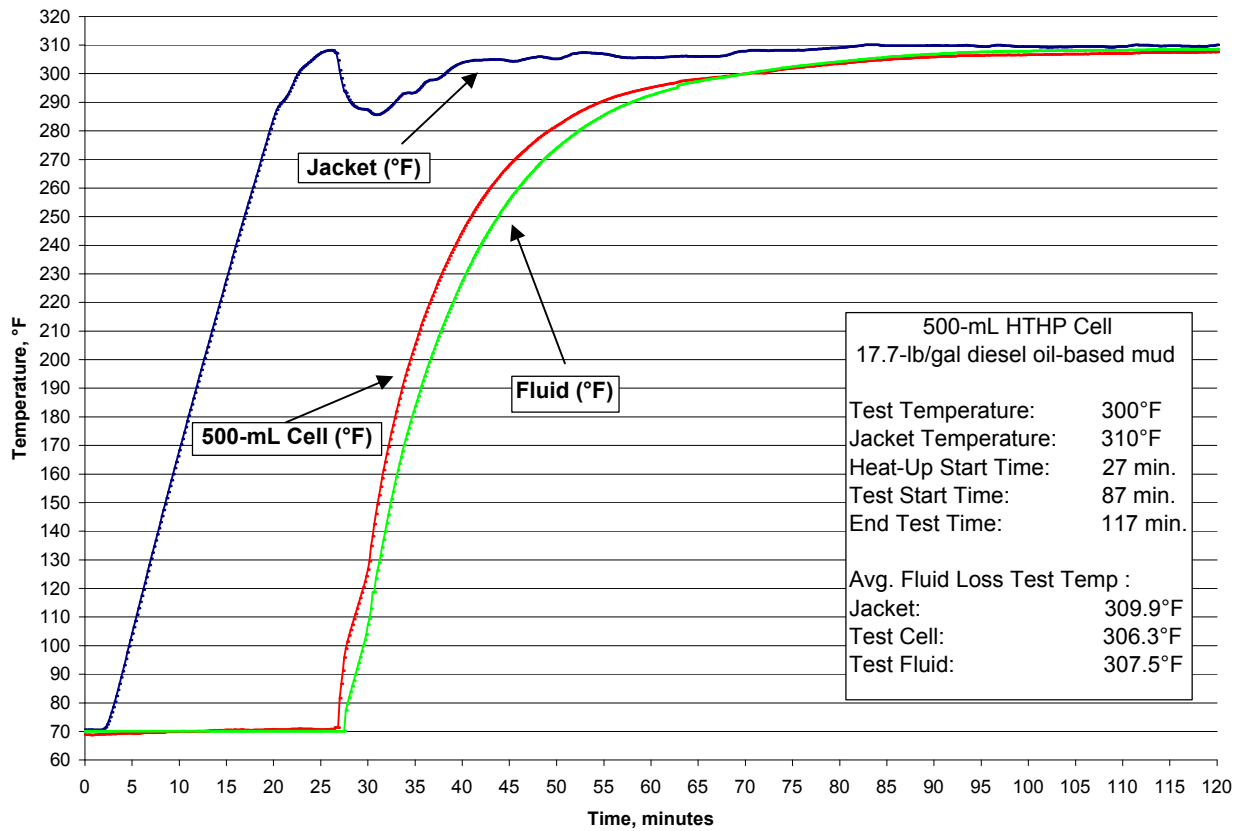


Figure 8 – Example test results for 500-mL cell

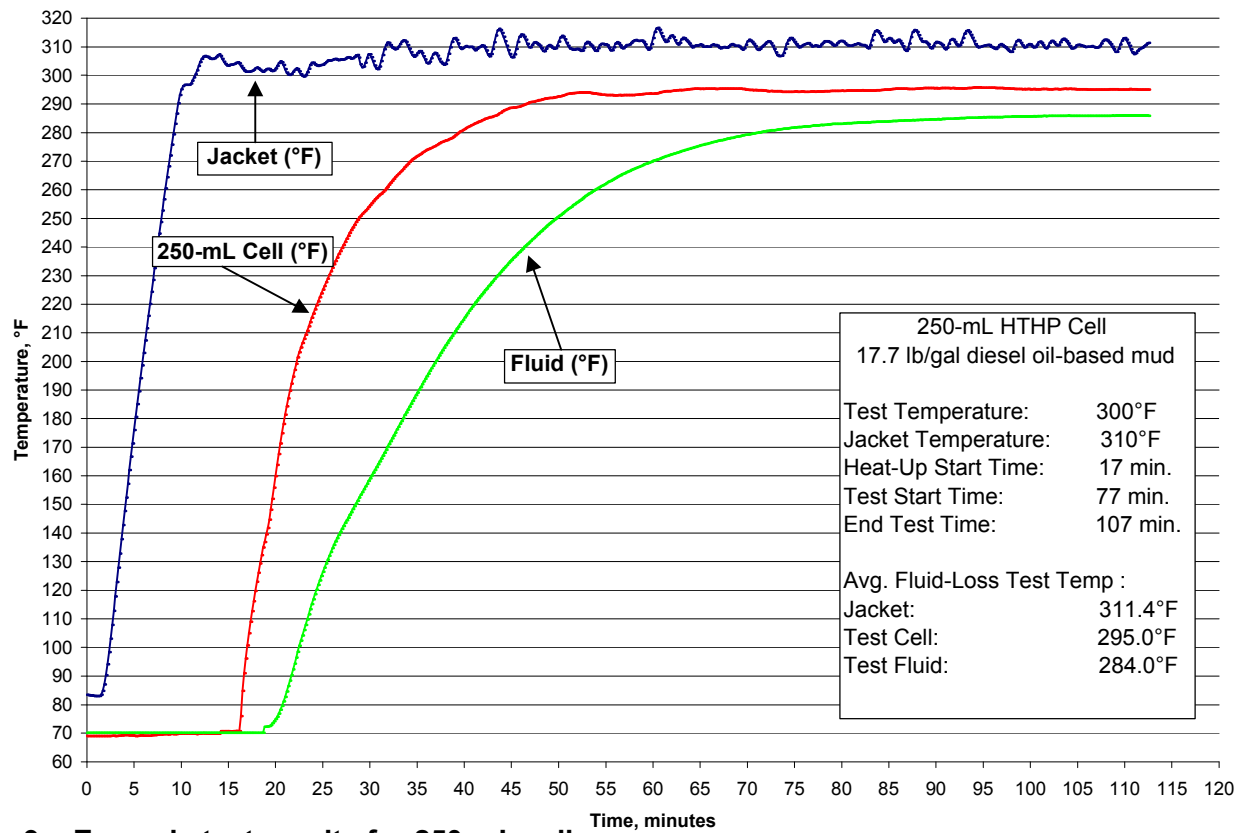


Figure 9 – Example test results for 250-mL cell

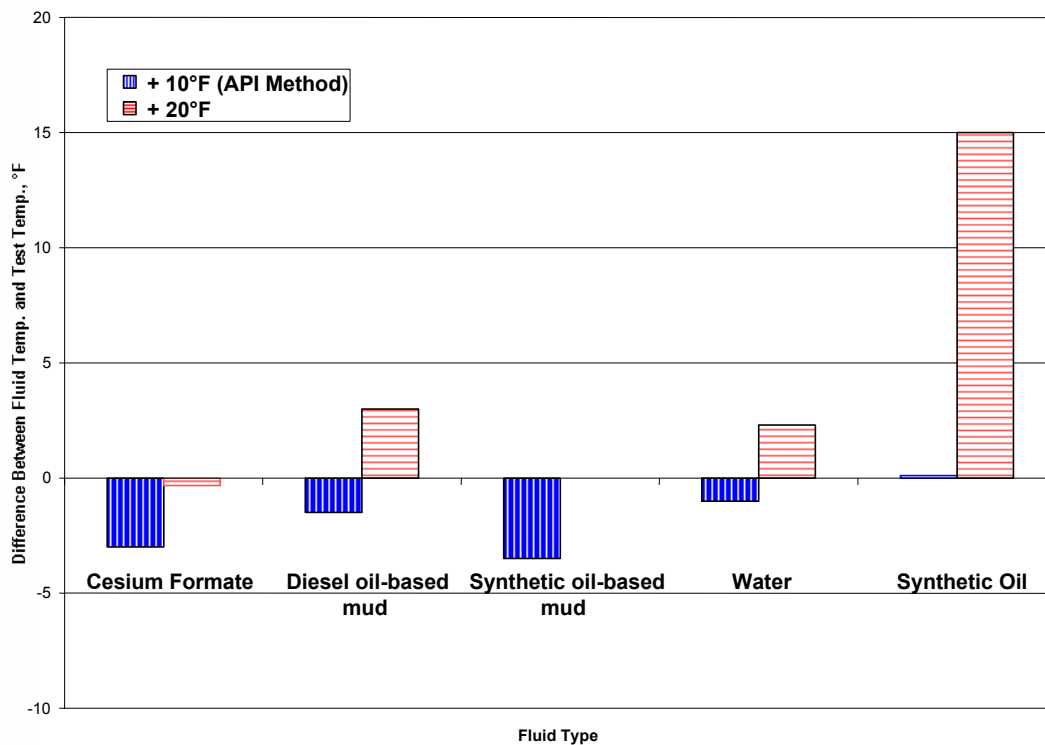
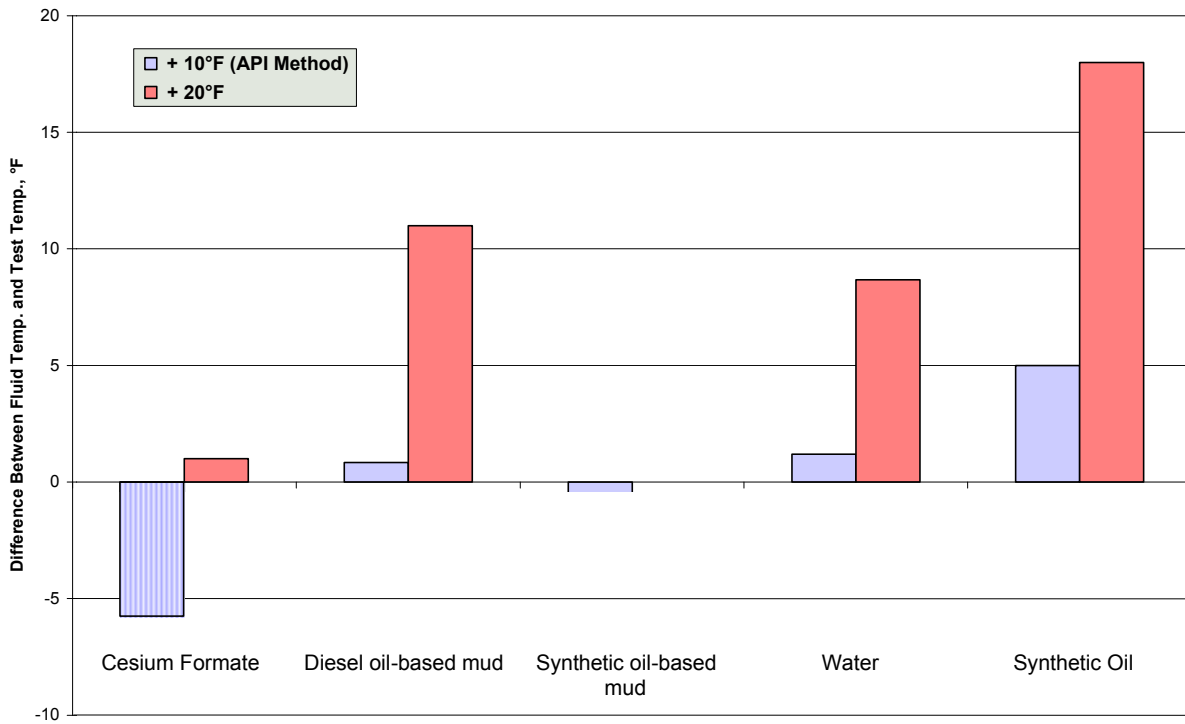
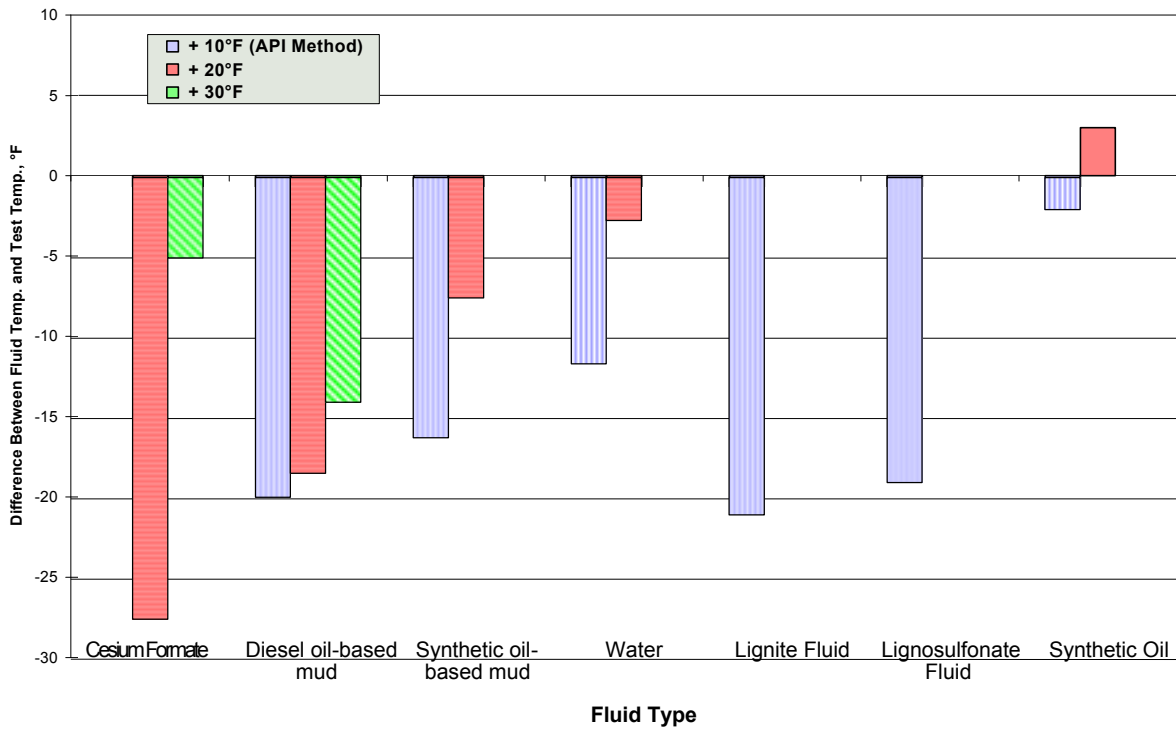


Figure 10 – Test temperature – fluid temperature average differences with 175-mL cell (jacket temperature set +10°F and +20°F above test temperature)



**Figure 11 – Test temperature – fluid temperature average differences with 500-mL cell (jacket temperature set +10°F and +20°F above test temperature)**



**Figure 12 – Test temperature – fluid temperature average differences with 250-mL cell (jacket temperature set +10°F, +20°F, and +30°F above test temperature)**

**Note: Diesel OBM was only fluid tested at all three temperatures**

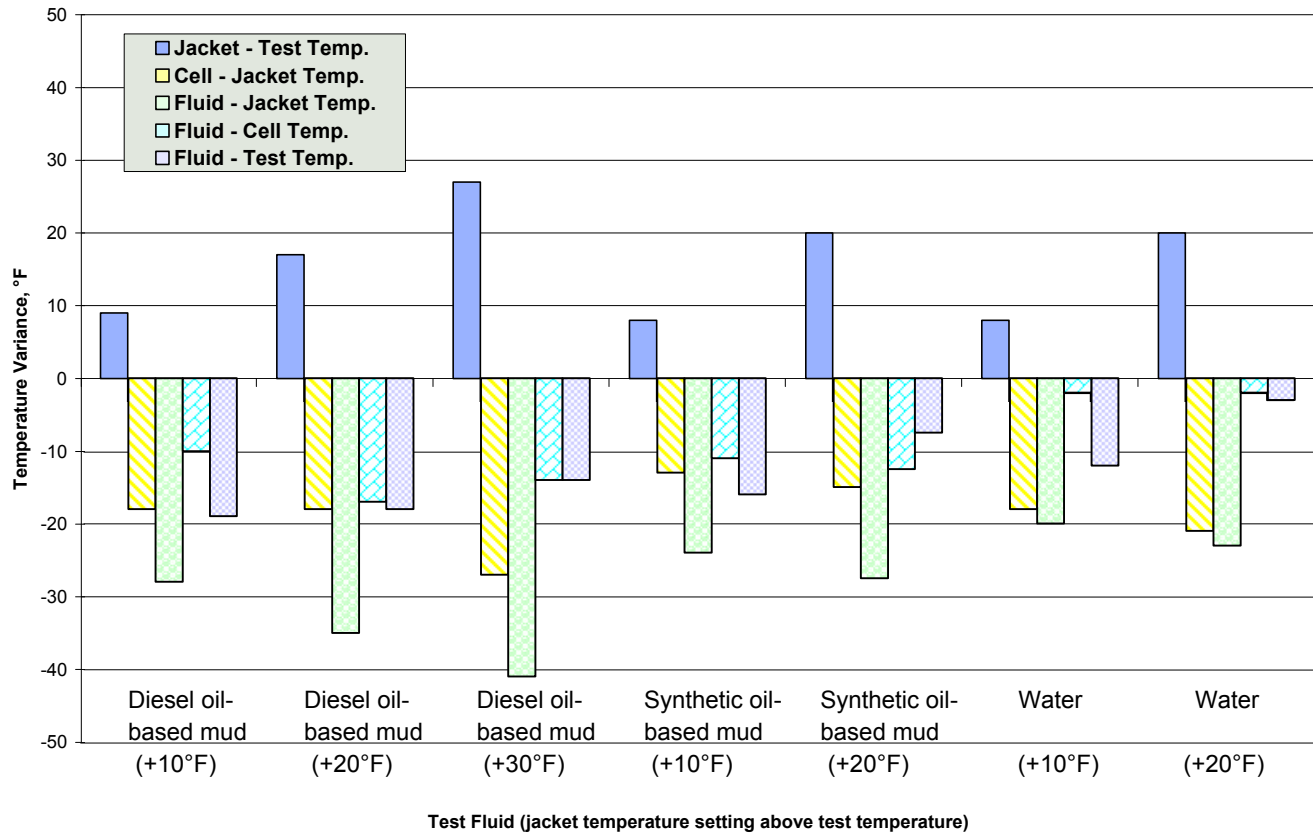


Figure 13 – 250-mL jacket, cell, and fluid average temperature differentials (jacket set +10°F, +20°F, and +30°F above test temperature)



Figure 14 – Heat sink A for 250-mL cell



Figure 15 – Heat sink B for 250-mL cell



**Figure 16 – Aluminum oxide top insulation for 250-mL cell**