



AEROSPACE RECOMMENDED PRACTICE

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Evaluation of Fouling Propensity of Aviation Lubricants Using the Mixed-Phase Flow Technique (High-Temperature Deposition Test)

RATIONALE

Aviation turbine lubricants are exposed to mixed-phase and dynamic temperature conditions during use. Many bench and laboratory tests used to characterize the oxidative stability or fouling properties of a lubricant are either static temperature tests or circulate the sample as a single, liquid phase. The high-temperature deposition test (HTDT) exposes the lubricant to mixed phase conditions, comingling humidified air and lubricant within the test loop.

1. SCOPE

The high-temperature deposition test (HTDT) method is designed to evaluate the deposition and degradation characteristics of turbine lubricants when stressed under mixed-phase flow conditions found in certain parts of aviation gas turbine engines. This method is applicable to lubricants that form deposits in the range of 0.1 to 100 mg during the course of a test.

2. APPLICABLE DOCUMENTS

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP5088 Test Method for the Determination of Total Acidity in Polyol Ester and Diester Gas Turbine Lubricants by Automatic Potentiometric Titration

2.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM D445 Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and the Calculation of Dynamic Viscosity)

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4. OUTLINE OF METHOD

A mixture of test oil and humidified air flow at a constant rate over a resistively heated test element for a predefined length of time, nominally 15 hours. The temperature of the test tube is monitored and used as a control input for the primary current transformer responsible for power input, and thus the heating of the test element. The temperature where the oil enters in contact with the test tube ("oil-in") is controlled using a water-jacketed heat exchanger. The heated test element is a 446-alloy stainless-steel tube that is precisely weighed before and after the test to determine the amount of deposition and/or coking that occurred. A 100-mesh stainless-steel filter is utilized to collect any sediment in the oil path or deposits that break free from the tube. This filter is also weighed before and after the test, with any added weight being reported. Physical and chemical analyses, such as total acid number and kinematic viscosity change, are performed on the oil before and after the test.

5. APPARATUS AND INSTRUMENTATION

The automated high temperature deposition tester (HTDT-auto) is comprised of a temperature-controlled cabinet containing a resistively heated tube-in-shell heat exchanger over which a mixture of oil and humidified air flow to simulate conditions within a turbine engine. The process is monitored and controlled by a programmable logic controller running a prewritten routine and monitored via a human machine interface. Currently, the only known manufacturer is Southern Petroleum Laboratories, Inc., in Houston, Texas.

5.1 Test Section

NOTE: Schematics of the test section, test tube, and other parts are shown in Section [A.1](#).

5.1.1 Heated Cabinet

A cabinet (99 cm tall × 38 cm wide × 38 cm deep) fitted with a 3000-W heater coil and a fan capable of baseline temperature regulation via convective airflow. Cabinet temperature must be held at $93\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$

5.1.2 Vent

A 304 stainless-steel tube, 9.25 mm in diameter and 61 cm in length, bent into a gooseneck shape. The unbent end is inserted through a hole in the top of the heated cabinet, down into the orifice at the top of the heat exchanger/oil sump. Oil that evaporates during the test will exit the test section through this vent and be collected in a beaker.

5.1.3 Heat Exchanger/Oil Sump

A water-jacketed oil sump constructed of stainless-steel with a total oil capacity of 240 mL. The water jacketing allows for cooling of the oil as it passes between the oil-out position and the oil pump inlet. On top of the sump are connections for the oil return, vent and extended oil reservoir line. A sight glass is affixed to the right-hand side to allow for assessment of the test oil level. The bottom of the sump terminates in a 6.35-mm diameter stainless-steel line that leads to the oil pump. This line is outfitted with a tee, to which a 3.18-mm diameter stainless line and vacuum gauge are connected.

5.1.4 Coolant (Water)

A controlled amount of water is injected into the jacket of the heat exchanger/oil sump which flashes to steam, allowing for thermal exchange between the test oil and metal surfaces of the heat exchanger. The amount of water injected is regulated to maintain an oil-in temperature of $163\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$.

5.1.5 Filter

A 100 mesh stainless-steel filter is placed in the oil path at the bottom of the oil sump/heat exchanger. This filter catches any particulate matter or coking that may have been dislodged from the tube during the test. This filter is precisely weighed before and after the test and the weight gain is reported to the nearest 0.1 mg. To ensure the reported weight does not include sludge or liquid oil, the filter is rinsed with heptane and dried in a 90 °C oven for 1 hour prior to measuring the “after-test” weight.

5.1.6 Pressure Monitoring

Water and air pressure are monitored using digital pressure gauges. Any pressure gauges and/or sensors capable of being calibrated to measure pressure with a precision of ± 0.5 psi between 0 psi and 100 psi will be sufficient. A vacuum sensor is used to detect a clogged filter in the bottom of the heat exchanger. This sensor is fit to the end of a line that tees off of the main heat exchanger exit line. Any vacuum sensor that can reliably measure a change of 1 psi between -5 psi and +15 psi will work for this task. Pressures referred to in the document may be assumed to be gauge pressure values.

5.1.7 Pump

A precision, constant displacement pump capable of flowing oil at 300 mL/min while also being regularly exposed to internal temperatures in excess of 160 °C for the duration of the test.

5.1.8 Drain Valve

A manual valve will suffice to terminate the drain line extending from the right side of the cabinet, used to recover the test oil after the test has been completed or during the pump flush phase. Ensure the drain valve is connected to the pump outlet at the lowest practical point in the system.

5.1.9 Humidified Air System

Filtered, oil-free shop air is passed through the humidifier vessel containing 110 mL of water, via a submerged porous aeration stone, before entering the test cell via a stainless-steel line connected to the mixing nozzle. This mixing nozzle is located in the oil path just downstream of the oil-in thermocouple location. The humidified air must be precisely calibrated to a flowrate of 1000 mL/min ± 15 mL/min. A humidifier vessel diagram can be found in [APPENDIX A](#).

5.1.10 Deposition Tube Housing

A three-part, stainless-steel housing, electrically isolated from the heated tube element and bus bar by fluoroelastomer O-rings on either end of the heated test tube. A schematic can be found in [APPENDIX A](#).

5.1.11 Test Tube

A seamless 446 stainless-steel tube with a 25.4 cm long, 63.5-mm diameter heated test section. The tube has been bored out to allow for the insertion of four temperature sensors, two from each end. A schematic can be found in [APPENDIX A](#).

5.1.12 Transformer

1500 kVA current transformer capable of producing current that is approximately 60-fold that of the voltage output. At full operating capacity, the load will be a current of 240 A at 4 V. A mechanism for safely and reliably controlling the transformer is also required, but not detailed here.

5.1.13 Thermocouples

Calibrated type K thermocouples are used in several points throughout the system to monitor and record temperature. In the case of the oil-in and cabinet thermocouples, the thermocouple readings also act as a control input. A list of thermocouple locations and associated control loops can be found in [APPENDIX B](#).

5.1.14 Temperature Sensors

Four calibrated 100-Ω platinum resistance temperature detectors (RTDs) are used to monitor the temperature along the length of the heated tube element. The top position is used as the control temperature for the 15-hour test. A schematic showing relative placement of the four RTDs to the heated tube element shown in [APPENDIX A](#).

5.1.15 Lines

The oil flow path is primarily composed of 6.35-mm diameter 316 stainless-steel tubing. The exceptions being the 3.1-mm diameter stainless-steel vacuum gauge line found at the exit of the heat exchanger and the 9.25-mm diameter, convoluted flexible stainless-steel oil return line that connects the oil-out thermocouple position to the oil sump, effectively closing the loop on an entire circuit for the oil path. Connections are made using off the shelf compression fittings where possible.

5.2 Instrument Control and Data Acquisition

The design and layout of the instrument control and data acquisition is exemplified in [APPENDIX B](#). The following control functions shall be met.

5.2.1 Heating Control

Cabinet air temperature and heater tube temperature are controlled using a closed-loop feedback method, such as a proportional-integral-derivative (PID) control loop running on a programmable logic controller. Though the temperature of the heater tube is measured at multiple locations along the inner bore of the heater tube, only the tube temperature measured at the control point is used in the control loop. The locations for the tube temperature probes are specified in Section [B.1](#). The tube temperature control point is shown as "Point 1", located 8.89 cm from the end of the heater tube.

5.2.2 Cooling System Control

An oil-in temperature of $163\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$ must be maintained throughout the duration of the test by injecting water into the jacket section of the heat exchanger. This is accomplished most effectively via a closed feedback system, such as a PID loop running on a programmable logic controller

5.2.3 Cabinet Temperature Control

Cabinet temperature must be maintained at $93\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$ throughout the duration of the test. This is accomplished most effectively via a closed feedback system such as a PID loop running on a programmable logic controller

5.2.4 Data Acquisition Device

A device capable of reading and recording control signals such as thermocouples, RTDs, as well as any required digital or analog signals produced by sensors throughout the system. Any method of monitoring and recording power input, oil flow rate, air flow rate, as well as the temperatures of interest (cabinet, oil-in, oil-out, and the four sensors along the length of the heater tube) will be adequate.

5.2.5 General Instrument Control and Monitoring

Some form of general instrument control such as a programmable logic controller is needed to handle the opening and closing of valves, relays, contacts, and solenoids throughout the system if automated control is desired. There are also some monitoring capabilities afforded by a digital logic controller that allow the test to run unattended for longer periods of time than would be possible otherwise. These capabilities include sounding alarms and/or automatically putting the machine into a safe state should some anomaly occur during the test that has the potential to threaten life, limb, or property.

5.3 Additional Apparatus Requirements

- A gravity convection oven capable of maintaining $90\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$ is required for drying test tubes and filters.
- An analytical balance, capable of measuring an object's mass to a precision of 0.1 mg, is required.
- An ultrasonic cleaner with a minimum 2 L capacity is required for cleaning parts after a test.

6. REAGENT AND MATERIALS

6.1 Solvents

Solvents used for cleaning should be technical grade or better. Choice of solvent is left to the user but the solvent selection should be sufficient to remove any traces of lubricant, test fluid, and cleaning fluids. Solvents should not leave a detectable residue on the wetted parts of the test instrument. The mention of specific solvents such as heptane, acetone and toluene in this method are optional and may be substituted with an acceptable alternative.

6.2 Cleaners

The cleaning process requires both a caustic cleaner and a laboratory glassware detergent. The choice of specific cleaner is left to the user.

6.3 Glassware

Testing requires the use of a 50-mL graduated cylinder, glass, Class A and a 250-mL beaker.

6.4 O-Rings

O-rings should be replaced after each test iteration. One each of the following dash number sizes is required: -233, -230, -229, -223, -202, and -012. In addition, the heater tube assembly requires the use of two -110 O-rings, one affixed at each end.

6.5 Brushes

It is recommended to keep an assortment of nylon-bristle brushes on hand to clean the vessels, tubing, and other parts.

6.6 Sandpaper

400 grit, silicon carbide "wet or dry" sandpaper is required for refinishing the heater tubes.

7. SYSTEM VERIFICATION

7.1 Thermocouples and RTD Calibration

Any appropriate calibration technique may be deployed by the test laboratory. The calibration procedure should be performed every 6 months or after any temperature sensor is replaced.

7.2 Pump Calibration

The oil pump shall be calibrated using a procedure whereby the pump is allowed to run at a constant speed for 30 seconds $\pm$ 0.5 second while collecting the effluent oil into a graduated cylinder. The pump flow rate is determined by dividing the volume of pumped fluid by the pump run time.

The calibration procedure should be performed every 6 months or if a part of the pump is repaired or replaced.

7.3 Air Flow Calibration

A calibrated rotameter is temporarily installed along the humidified airline at the connection between the humidifier and the oil/air mixing jet.

The calibration procedure should be performed every 6 months or if a component of the air delivery system is repaired or replaced.

8. PREPARATION OF APPARATUS

- a. Clean the test tube, filter, lines, pump, and other parts as described in [APPENDIX C](#).
- b. A clean and dry filter and test tube are weighed to nearest 0.1 mg and values recorded in a data sheet.
- c. Assemble the test section following the assembly instructions provided in [APPENDIX D](#). Use new O-rings when assembling the test section components.
- d. Connect the data acquisition device to the apparatus according to the manufacturer's instructions and recommendations.
- e. Add 110 mL $\pm$ 1 mL of distilled water to the humidifier.
- f. Load 100 mL $\pm$ 1 mL of test oil into the oil sump in preparation to flush the lines and pump out any residual oil or cleaning solvents that may have been left from previous tests. With a beaker in place below the drain, open the exit valve and run the oil pump manually until the oil flowing from the drain is flowing clear of visible contaminants. Take care to drain as much of the flush oil as possible before moving on to the next step. This requires running the pump until the constant stream of oil exiting the pump turns into an intermittent trickle. Be careful not to run the oil pump dry as this will damage the internal components. Discard all oil collected in this step.
- g. Load test oil to the oil sump, first adding approximately 200 mL, followed by manually running the pump for 10 seconds $\pm$ 1 second to charge the rest of the system with oil, freeing room in the sump. Add the remaining test oil required to bring the total oil charge to 285 mL $\pm$ 5 mL.
- h. Double check the lines for possible leaks.

9. PROCEDURE

Independent of using a manual or an automated control, such as a software or script, the test conditions applicable to this method are as shown in [Table 1](#).

Table 1 - High temperature deposition test conditions

Parameter	15-Hour Test
Test duration (hours)	15
Initial oil charge (mL)	285 $\pm$ 5
Oil refill during test	No
Oil-in temperature (°C)	163 $\pm$ 1
Tube temperature at Point 1 (°C)	357 $\pm$ 2
Cabinet temperature (°C)	93 $\pm$ 1
Air flow (mL/min)	1000 $\pm$ 15
Oil flow (mL/min)	300 $\pm$ 5

9.1 Sequence of Events

Using an automatic or manual control, the following sequence of events shall be followed.

- a. Turn on the convective air-flow within both the test cabinet and the instrument compartment.
- b. Turn on the cooling pump. Allow the water to flood the bus-bars, secondary transformer coil and cooling manifold. Keep the heat exchanger inlet valve closed for now so as to keep the jacket free of standing water.
- c. Turn on the oil pump and allow it to run at test speed (300 mL/min $\pm$ 5 mL/min) for 5 minutes $\pm$ 1 minute before opening the humidified air valve to avoid a vapor lock in the oil pump.

- d. Turn on the humidified air and maintain a flow-rate of 1000 mL $\pm$ 15 mL/min
- e. Turn on the cabinet heating and set the desired baseline temperature (93 °C $\pm$ 1 °C).

The remainder of the test can be divided into three phases: ramp, constant temperature mode, and constant power mode.

9.1.1 Ramp

Power is first applied to the heater tube element using a stepped sequence that lasts a total of 36 minutes from the point of first application. The ramp starts with the application of 200 W for 4 minutes, followed by a 100 W increase every 4 minutes, until the tube top (RTD1) temperature approaches 350 °C. Do not perform additional 100 W power increases if the additional power will cause the tube top (RTD1) temperature to exceed the target test temperature of 357 °C $\pm$ 2 °C.

NOTE: While this ramp is occurring, the oil-in temperature will increase as power is applied to the heater tube and the test oil is heated. Upon reaching an oil-in temperature of 135 °C, it is recommended to begin the automated cooling control system.

9.1.2 Constant Temperature Mode

The constant temperature mode starts as soon as the ramp ends. A PID loop calculates and applies the power required to maintain a control point (Point 1) temperature of 357 °C $\pm$ 2 °C. Once the control position has a five-minute running average temperature of 357 °C $\pm$ 2 °C, “test start” is declared. It is from this point that the fifteen-hour test duration is calculated. Constant temperature mode lasts for 90 minutes $\pm$ 1 minute. For the last thirty minutes of this mode, calculations are performed to determine the average power required to maintain the control point tube temperature at 357 °C $\pm$ 2 °C.

NOTE: The control point tube temperature may rapidly fluctuate by more than $\pm$ 2 °C due to the mixed-phase flow conditions. The average control point temperature, sampled over a period of at least 30 seconds, should be held at target test temperature.

9.1.3 Constant Power Mode

Constant power mode begins immediately after constant temperature mode finishes. The power level calculated in the previous step is applied to the tube for the remainder of the test duration.

9.2 Automated Control System

The operator or automatic control system needs to maintain conditions described in [Table 1](#) for the duration of the test (“constant temperature section” or “steady state period”). An automated control check at every 6 seconds, or more frequently, is recommended.

NOTE: During the “steady-state period,” all test parameters except tube temperature should remain within the ranges specified on [Table 1](#). Tube temperature may increase during the test as fouling deposits form on the heater tube. If the tube temperature reaches 435 °C, the test is terminated.

9.3 Test Data and Parameters

During the test, including the ramp up period, all parameters described in [Table 1](#) should be recorded at specific time intervals. For test instruments equipped with automatic data acquisition, it is recommended that data be recorded at a rate of once per minute. A representative power/temperature profile is shown below.

NOTE: The rate at which the instrument’s data acquisition system queries and collects data may be much more frequent than once per minute. This faster frequency of data collection may be required for effective control of test parameters but is not required to be saved as test data if the user wishes to reduce the size of data files associated with each test.

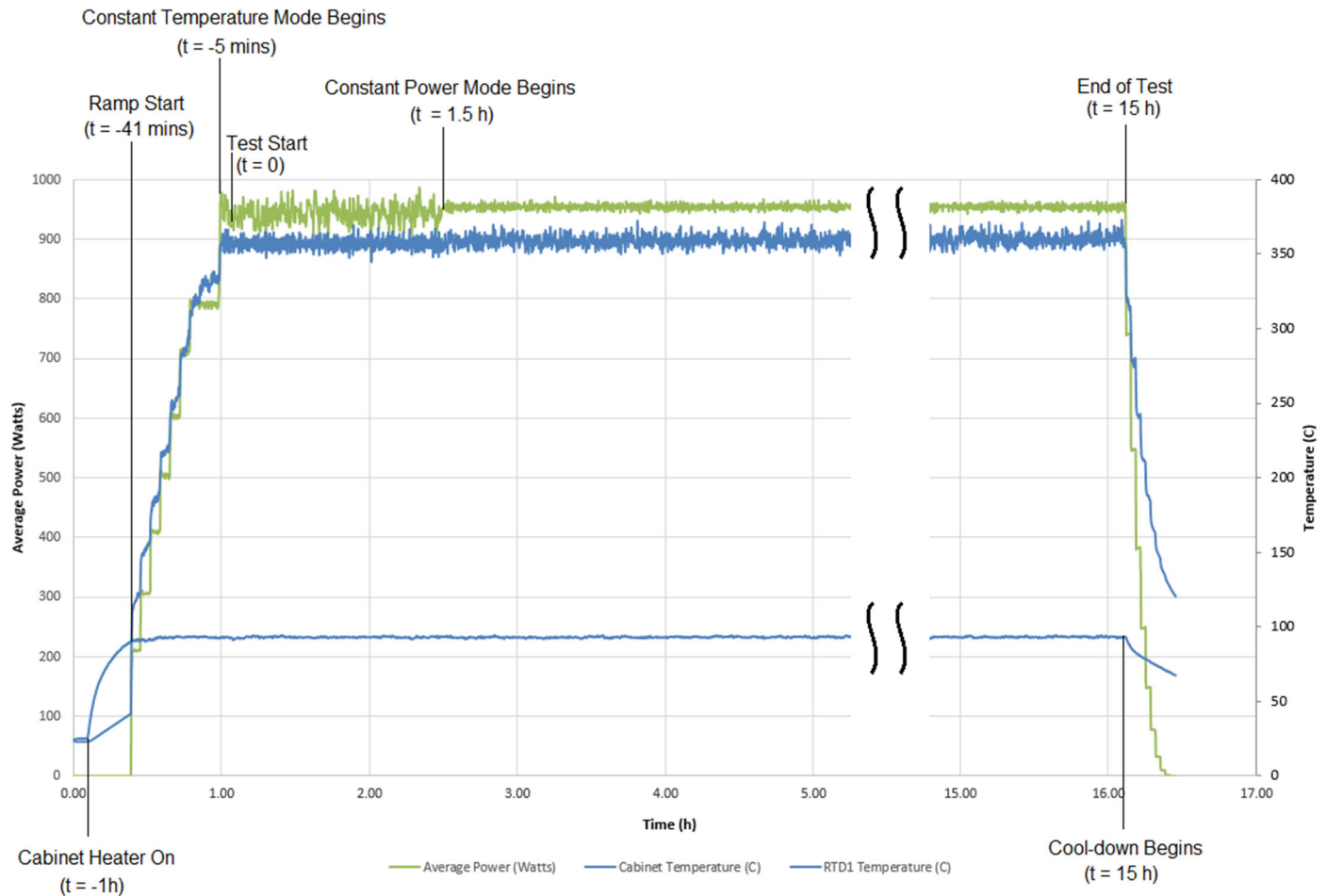


Figure 1 - Example test profile for power, cabinet temperature, and RTD1 temperature

9.4 System Cooling Procedure

After the soaking period of the test (15 hours), the system should be cooled by:

- Reducing the applied power by 5%. After 2 minutes, reduce the power applied to the heater tube by 5% of the instrument's full-scale power every 2 minutes, until the power is completely removed from the heater tube.
- Stopping the humidified air flow as soon as power is no longer being applied to the heater tube element.
- Turning off cabinet heaters and opening cabinet doors to allow test cell to continue to cool to a temperature at which it is safe to handle.

9.5 Disassembling Procedure

Allow the test oil and cabinet to cool to a safe temperature before recovering the oil sample and starting to disassemble the test components. The following disassembling procedure should be adhered to:

- Recover the oil using the drain valve. Use a graduated cylinder to measure the amount of oil recovered.
- Disassemble the test section and recover the test tube. Care must be taken to avoid losing deposits or adding undesirable contamination to the test tube.
- Disassemble the heat exchanger and recover the filter. Care must be taken to avoid losing deposits or add undesirable contamination to the filter.

9.6 End of Procedure

- a. Carefully immerse the tube in a graduated cylinder filled with heptane and allow it to soak for 3 minutes to remove any excess oil that may be clinging to the surface.
- b. Remove the tube from the graduated cylinder and carefully rinse with heptane, being careful to also rinse out the inner surface of the tube with a gentle stream of solvent. Rinse the excess oil and sludge from the stainless-steel filter using a gentle stream of heptane and air dry in the oven, alongside the test tube at $100\text{ }^{\circ}\text{C} \pm 5\text{ }^{\circ}\text{C}$ for 1 hour and cool in a desiccator for at least 30 minutes.
- c. Determine and record the mass of the reference tube, test tube, and filter to the nearest 0.1 mg. Weigh each tube and filter at least 5 times. If the reference tube weight has shifted by 2.0 mg over the course of the test, weights recorded cannot be considered valid.
- d. Calculate the total mass of deposits formed on the filter and on the test tube by calculating the mean of the five readings taken in the previous step (c).
- e. Photograph the filter and the test tube.
- f. Determine the viscosity of the sample oil using ASTM D445 at $40\text{ }^{\circ}\text{C}$.
- g. Determine the total acid number of both the new and used oil using ARP5088.
- h. Additional measurements (not mandatory), including any other suitable physical or chemical measurement of the filter, tube, or oil, may be performed to provide additional information regarding the test or material tested.

10. CALCULATIONS AND REPORT ITEMS

10.1 Deposit Weight on the Filter

Determine the deposit weight on the filter by subtracting the initial mean filter weight from the final mean filter weight. Report the weight change to the nearest 0.1 mg.

10.2 Deposit Weight on the Test Tube

Determine the deposit weight on the test tube by subtracting the initial mean tube weight from the final mean tube weight. Report the weight change to the nearest 0.1 mg.

10.3 Oil Consumption

Compute the oil consumption by subtracting the amount of oil recovered after a test from the total test volume of 285 mL.

10.4 Tube Deposition Visual Rating

Determine and report the tube deposition visual rating based on the procedure outlined in [APPENDIX E](#).

10.4.1 Rating Number

Rating number of each type of deposit = (Demerit rating number * Length of deposit).

10.4.2 Tube Rating

Sum of the rating numbers.

10.4.3 Demerit Rating Number

Demerit rating number = (Tube rating/Tube length). Report this value.