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REFUELING TANKER TRUCK TEMPERATURE MEASUREMENTS

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14. ABSTRACT
In support of efforts involving thermal management studies, an instrumentation package was assembled to monitor the temperature of refueling tank trucks (specifically for the Oshkosh Rl1 refueling truck).

As part of the program, two trucks were temporarily instrumented at two Air Force bases to log temperatures over a period of 1 to 4 weeks. The first instrumentation installation was performed at WPAFB and the data acquisition covered a 6-day period from June 6th to June 23rd. The second instrumentation package was installed at Nellis AFB and the data acquisition covered a 4-week period from July 13th to August 13th. The maximum measured temperatures occurred at Nellis AFB in late July (tanker skin; 168 °F, air space above the fuel; 136 °F, fuel; 112 °F). The data taken was also used to validate a two-dimensional computer model.

15. SUBJECT TERMS
Jet fuel, refueling truck, fuel temperature, tank temperature, intrinsically safe temperature logger, tank temperature model

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Summary

In support of efforts involving thermal management studies, an instrumentation package was assembled to monitor the temperature of refueling cargo tank trucks (specifically for the Oshkosh R11 refuelers). The 6,000-gallon tanker is designed to fuel and de-fuel government aircraft worldwide in all flying environments. The package consists of up to nine internal sensors and six external sensors. The internal sensors are attached to a cap-rod assembly that replaces a cap currently used for inspection at the top of the truck. The external sensors are placed under an aluminum holder that was designed to hold the sensor and provide flanges for taping the assembly to the outside of the truck with mil spec high-speed aluminum tape. The sensors are intrinsically safe and self-contained. The sensors / data loggers are programmable and can be set to start data collection at a specific time (day- hour- min) for a specific duration (reading interval selectable from 2 seconds to 12 hours). Once installed the sensors automatically store the information until they are retrieved.

As part of the program two refuelers were temporarily instrumented at two Air Force bases to log temperatures over a period of one to four weeks. The first instrumentation installation was performed at WPAFB and the data acquisition covered a six-day period from June 6th to June 23rd. The second instrumentation package was installed at Nellis AFB and the data acquisition covered a four-week period from July 13th to August 13th. The maximum measured temperatures occurred at Nellis AFB in late July (tanker skin; 168 °F, air space above the fuel; 136 °F, fuel; 112 °F).

The data taken was used to validate the two-dimensional simulations. This allows the model to be used in the future for predicting the efficiency of solar loading solutions (i.e. color changes, radiant shielding, etc.) on the fuel tank temperature.

Refueling Tanker Truck

The A/S32R-11 fuel servicing tank truck is a 6,000-gallon (usable) refueler designed to service any type of USAF aircraft with fuels conforming to: MIL-G-5572, MILT-5624, MIL-T-25524, MIL-T-38219 and MIL-T-83133. All equipment used for fuel servicing is self-contained within the Refueler. The Refueler is fully operational in temperatures ranging from –40 °F to +125 °F.

The types of fuel servicing include high-flow, low-flow refueling, and de-fueling. The tank trucks' fuel delivery system is capable of refueling at up to 600 gpm (at 150 psig) or de-fueling at up to 175 gpm. The tank barrel is constructed from 5454-H32 Aluminum, while the heads and baffles are made from 5454-0 Aluminum. (TO 00-25-172CL-4 and TO 36A12-13-17-82)

Figure 1: View of passenger side an Oshkosh R11 refueler truck.

Temperature Sensors

Two types of sensors were acquired for monitoring the temperature of the refueling truck.

The sensor selected to measure the fuel temperature inside the tank was the TEMP1000IS, a fuel proof, battery powered, stand-alone device, which can be used to automatically record temperatures between -40 °C and 80 °C (-40 F to 176 F). This device is able to measure and record up to 32,767 temperature measurements. The TEMP1000IS has been Factory Mutual certified as intrinsically safe for Class I, Division 1, groups A, B, C and D and non- incendiary for Class I, Division 2 groups A, B, C and D hazardous environments.

Internal Sensor Specifications:

Temperature Sensor Semiconductor	
Temperature Range	-40 °C to +80 °C
Temperature Resolution	0.1 °C
Calibrated Accuracy	±0.5 °C (0 to +50 °C)
Start Time programmable start time.	Up to six months in advance.
Reading Interval	1 reading every 2 seconds to one reading every 12 hours
Memory	32,767 readings
Power	3.6V lithium battery included
User Replaceable Battery	1 year typical at 25 ºC, 1 minute reading intervals
Time Accuracy	±1 minute/month (at 20 °C, RS232 port not in use)
Operating Environment	-40 °C to +80 °C, 0 to 100 %RH
Dimensions	4.3" x 1.0" Dia. (108mm x 26mm)
Weight	(Stainless) 8 oz (230 g)

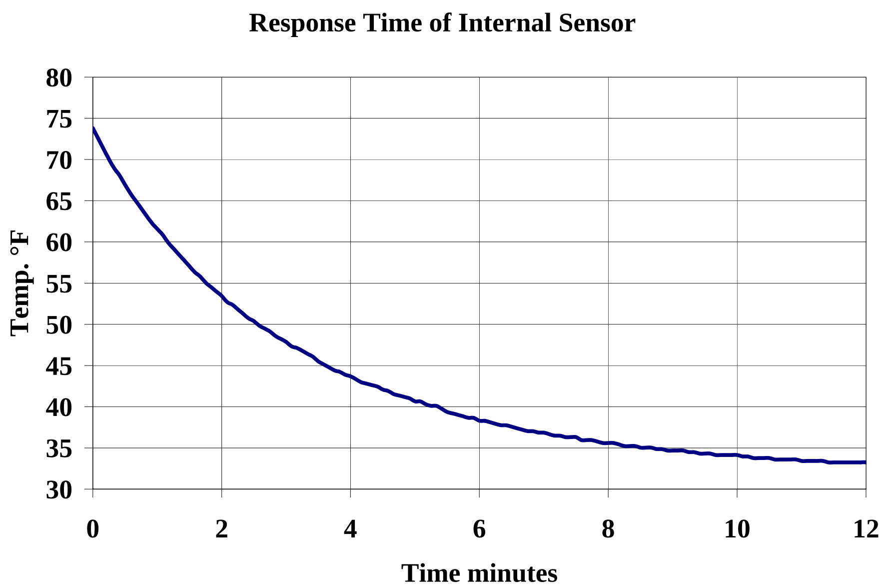


Figure 2: Internal sensor information and ice bath response curve.

The sensor selected to measure and record outside skin temperature of the tanker was the StowAway-IS. The StowAway-IS is rated intrinsically safe for recording temperatures in hazardous locations. The temperature sensor is a splash proof, battery powered, stand-alone device, which can be used to automatically record temperatures between -40 °C and 75 °C (-40 F to 167 F). The sensor is certified for deployment in harsh industrial environments, where explosives, propellants, combustible gases and other hazardous materials may be present. The device is rated Intrinsically Safe (by US standards): IS, Class I, II, Division 1, Groups A-G, Temperature Code T4 (<=135°C); NI, Class I, Division 2, Groups A-D, Temperature Code T4 (<=135°C); S, Class II, Division 2, Groups F and G; as specified in the US National Electric Code and approved by Factory Mutual.

External Sensor Specifications:

Operating Temperature Range	-40°F to +167°F (-40°C to +75°C)
User-selectable sampling	intervals of 0.5 seconds to 9 hours
Time Accuracy	±1 minute per week at +68°F (+20°C)
Capacity:	32,520 measurements total
Non-volatile memory	retains data even if battery fails
Size:	1.5" diameter x 0.8" thick (38 x 20mm), with 0.4" (10mm) mounting bail; hole diameter 3/16" (5mm)
Weight:	1.1oz (32g)
Battery:	1/10 D, 3.6 Volt Lithium, non-replaceable; Battery Life: 5 years continuous use with a logging interval >=10 minutes.

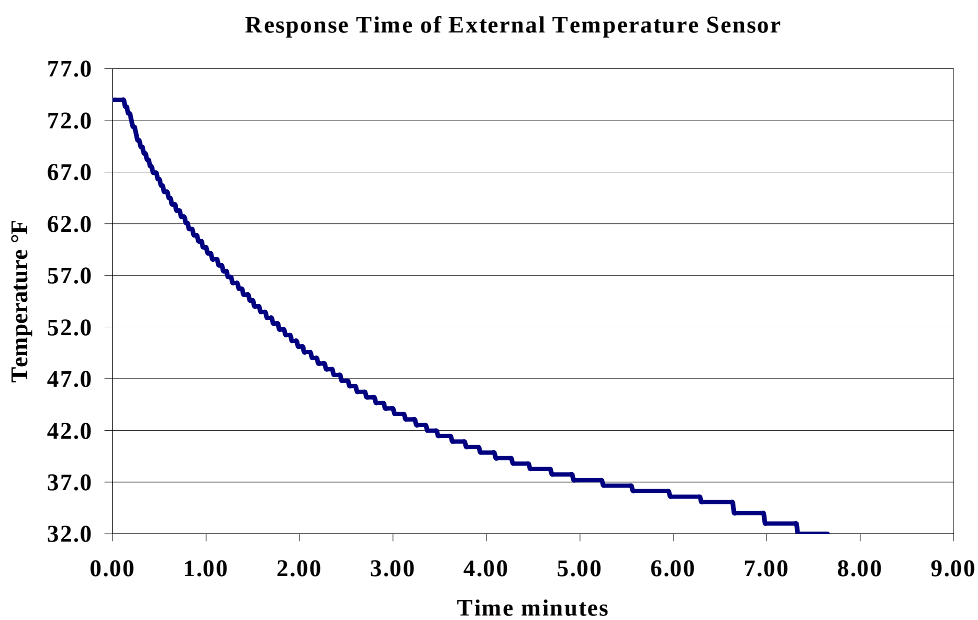
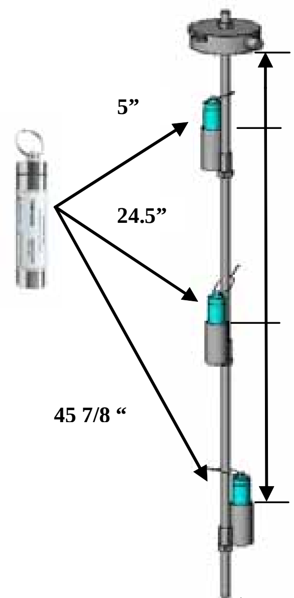


Figure 3: External sensor and ice bath response curve.

Sensor Assembly Installation and Designations

The internal data logging assembly consists of three sensors, set in 2 inch long open-end cups, attached to an extension rod. After setting the sensors into the cup holders they were safety wired to the extension rod. The extension rod is threaded through one of the inspection caps located in the top of the truck. The distance from the bottom of the cap to the top of the cup was set as show in Figure 4. The table shows the approximate volume from a completely full tank (i.e. 314 gallons pumped out would start to drop the fuel level below the top sensor).



From Top (in)	Volume (Gallons)
0	0
4	314
6	545
10	1042
25.5	3752
29.5	4284
47	5878

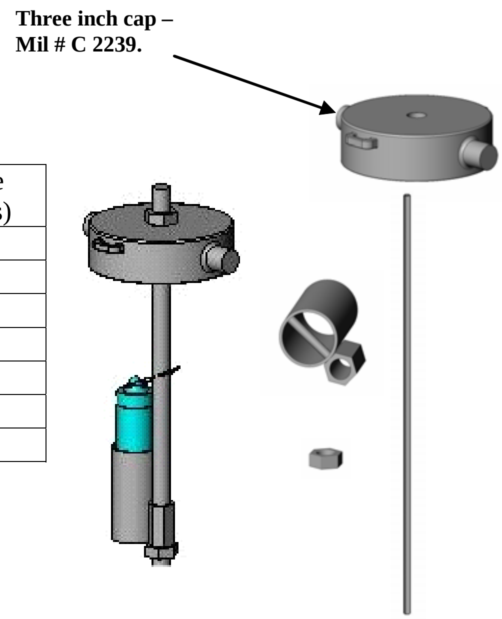


Figure 4: Internal sensor assembly and volume reference.

The external sensors are placed under an aluminum holder that was designed to hold the sensor and provide flanges for taping the assembly to the outside of the truck with mil spec high-speed aluminum tape. When taped down over the flanged area, the aluminum holder was designed to hold the sensor unit firmly to the truck. A thin insulation pad is placed between the aluminum holder and the top of the sensor, while a thin film of thermal conductivity paste was applied to the bottom of the sensors prior to affixing the assembly to the truck.

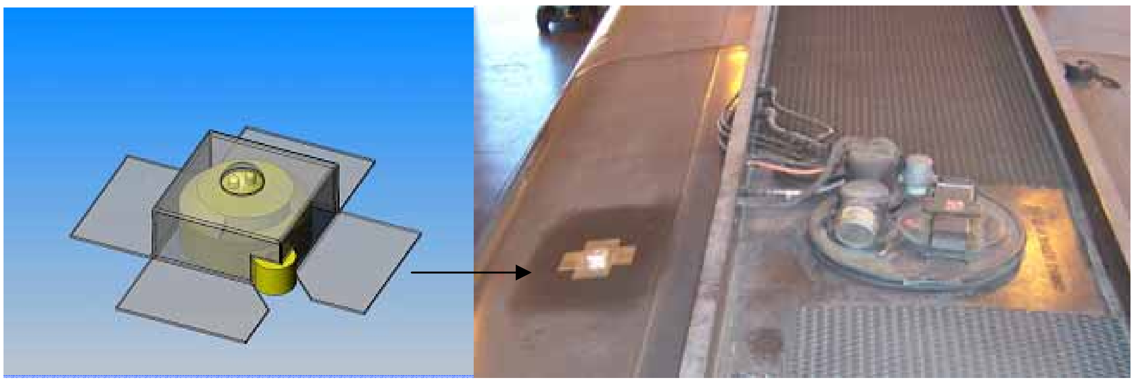


Figure 5: Drawing of the external sensor assembly and picture of the top external sensor placement.

The internal sensor assemblies are place as shown in Figure 6. The sensors are spaced to allow for measurement of temperature gradients along the length of the tank as well as from bottom to top. The sensor at “A3” is the closest to outlet and is considered the bulk fuel temperature that would actually be delivered to the aircraft. The top sensors “A1, B1 C1” will measure the maximum bulk temperature when covered with fuel (i.e. tank is full, and inactive, density variations will drive the warmer fuel to the top).

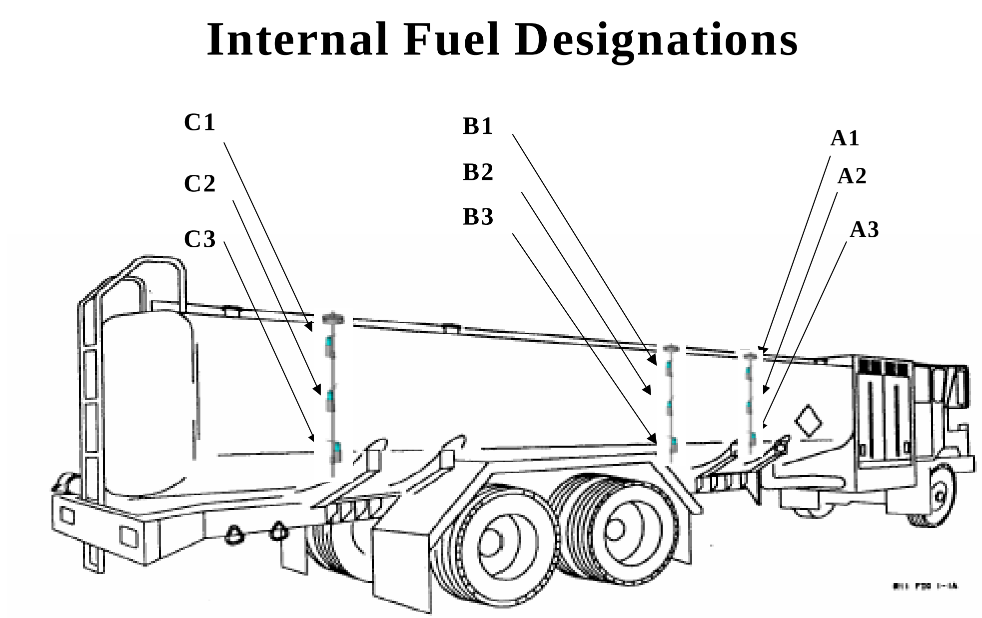


Figure 6: Fuel truck showing placement of internal data loggers.

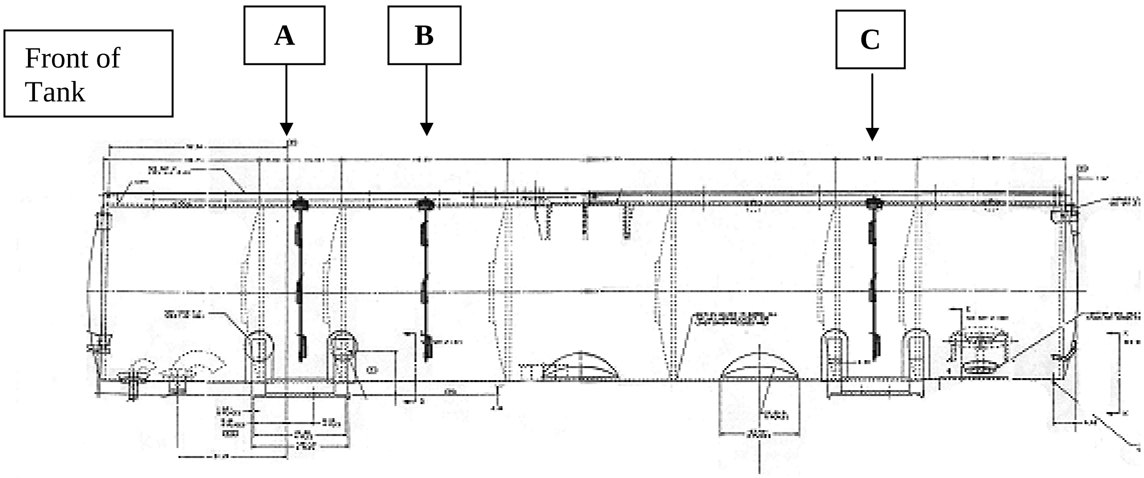


Figure 7: This figure shows a drawing of the side view of the fuel tank. The internal sensor placement is shown in reference to the internal baffle plates. Nine internal sensors (A, B & C) were used in WPAFB test, and six sensors were used during data collection at Nellis AFB (A& C).

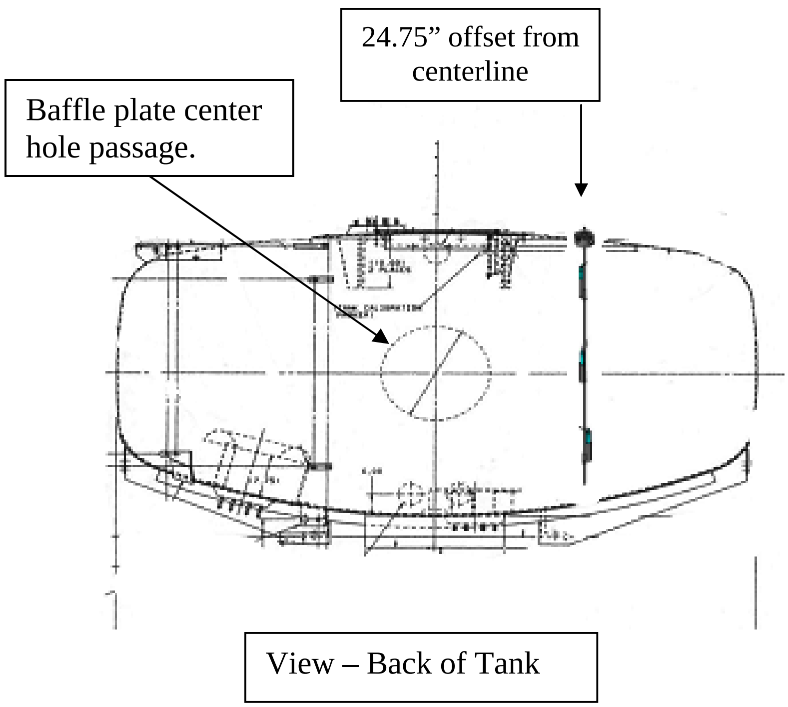


Figure 8: This figure shows a drawing of the back view of the fuel tank. The sensor arrays are offset from the center line of the truck by approximentlly 24.75 inches.

The external sensor assemblies are placed as shown in Figure 9. The sensors are spaced to allow for measurement of temperatures along the outside surface of the tank at the bottom, middle, and top. The sensor assembly on the top of the tanker is positioned so as to always be above the fuel level (i.e. the tanker is never filled to a point that the fuel reaches the top). The middle assembly may or may not have fuel adjacent to the wall depending on fuel level, while the bottom sensor will always have fuel adjacent to it (500 gallons is the lowest level available for pumping).

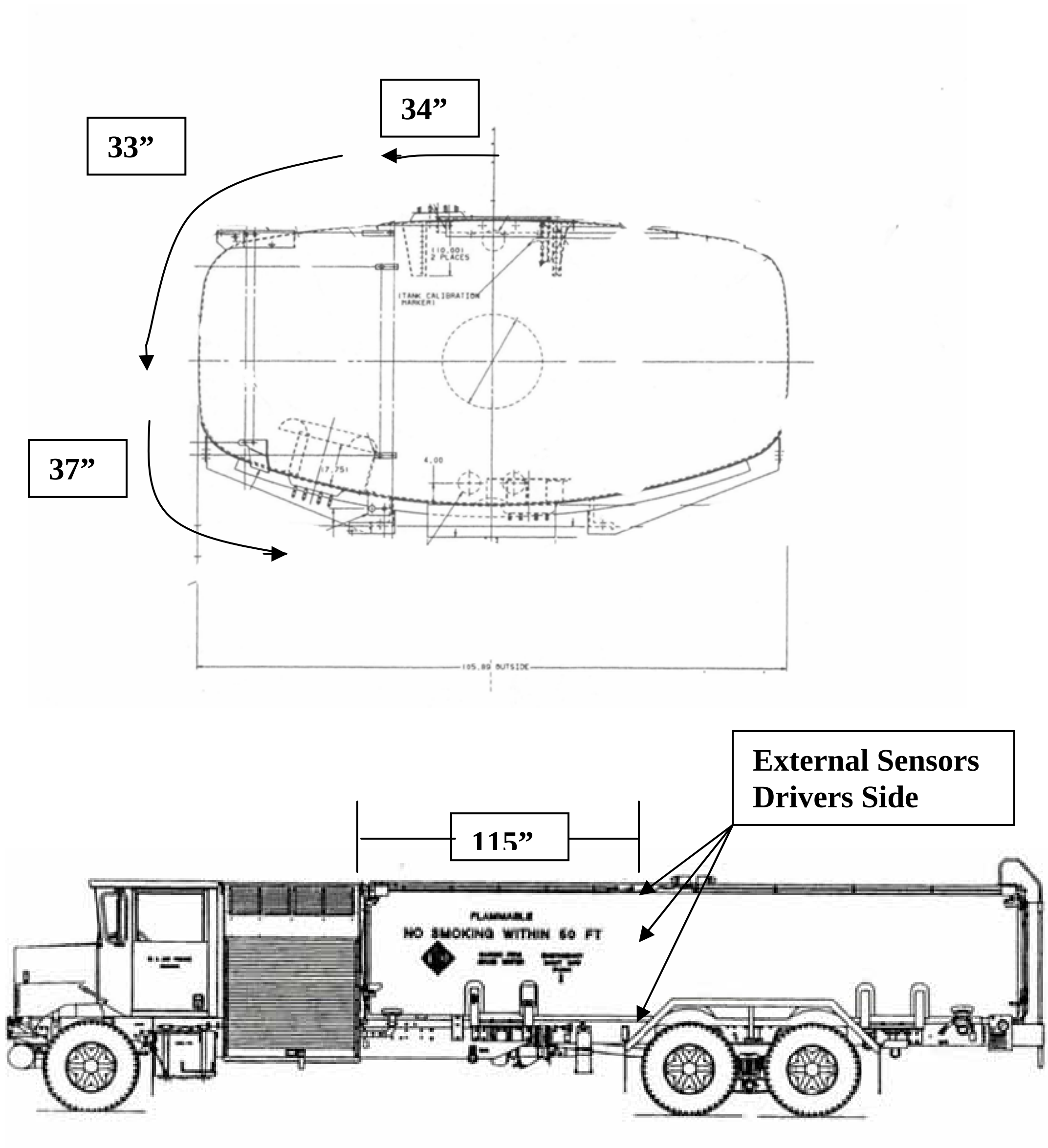


Figure 9: Three external sensors used for WPAFB test. The distance shown is measured in inches along the skin of the truck from top center.

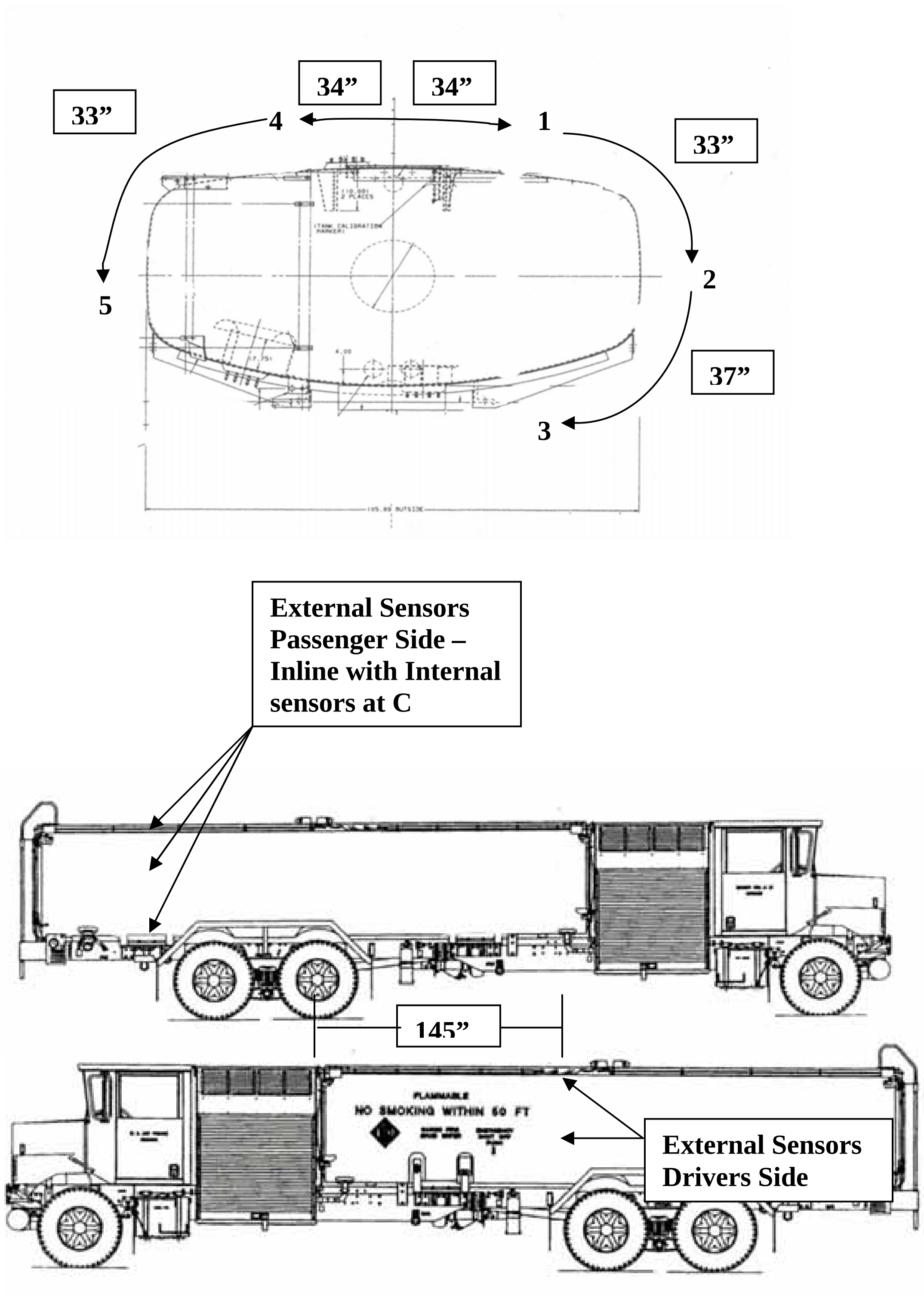


Figure 10: Five external sensors were used for the Nellis AFB test. Distance shown is measured in inches along the skin of the truck from top center.

WPAFB Tanker Data

Figure 11 show the temperature data from the front internal sensors and all of the external sensors installed on the refueler located at WPAFB, as well as, the ambient air temperature obtained from the airport database. The temperature plot shows the daily thermal cycle over a two-day time period. All of the sensors were programmed to record at five-minute intervals.

The internal sensors show no variation in the temperature at a specific level along the length of the truck. As shown in Figure 12 the measurements of A1, B1 and C1 are nearly the same. The same holds true for A2, B2, C2 and A3, B3, C3.

Interpretation of the temperature measurements requires a detailed reference to the refulers activity log sheet and the weather data sheet. For example the maximum temperature reading of 106 °F from the internal sensors occurred on 6/23/04 at 17:25. This temperature is not a fuel temperature measurement, but rather the internal ullage (air) temperature. As shown in Figure 13 the tanker was completely filled at 9:30, at approximately 15:08, 654 gallons of fuel was pumped out. This lowered the level of the fuel, uncovered the top sensors, and pulled in the lower temperature ambient air. This dropped the temperature of A1, B1, C1 and the top external skin temperature. At the same time, lowering the level brought a portion of the warmer fuel in contact with the lower sensors raising the temperature measurements of A2, A3, B2, B3, C2, and C3. The truck sat idle for approximately 2 ½ hours before 498 gallons was pumped out at 17:28. During that period the air in the tank above the fuel warmed up rapidly reaching the maximum 106 °F.

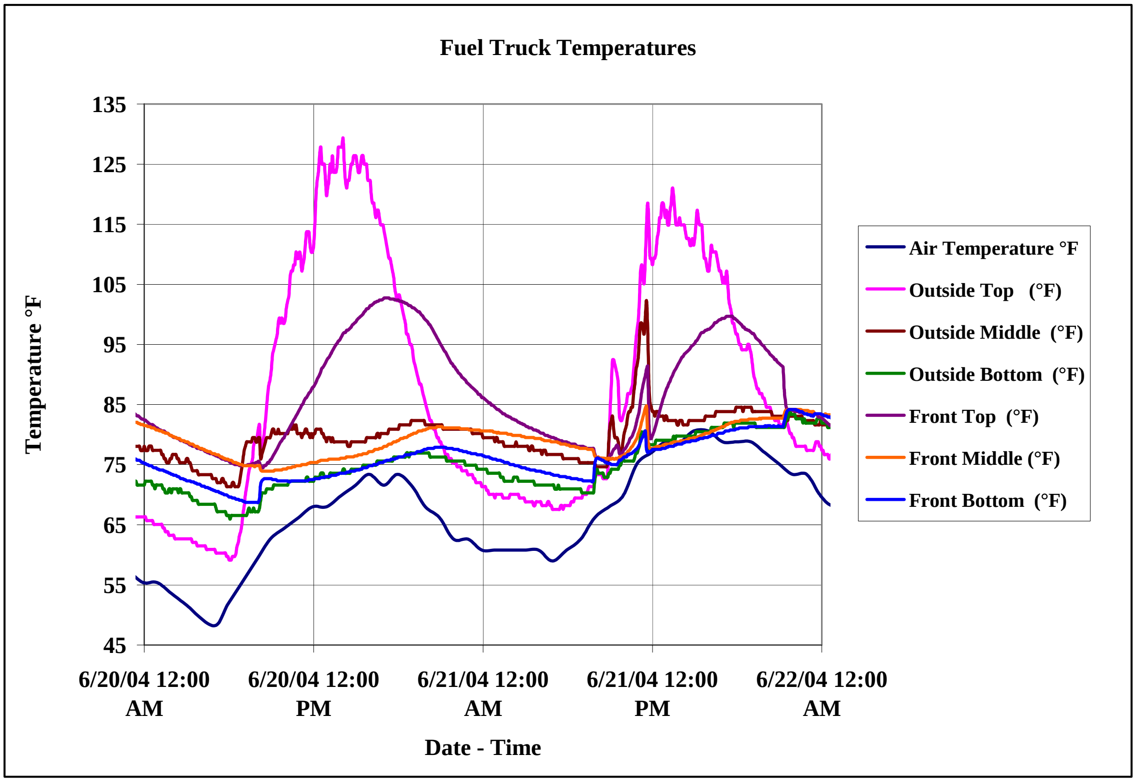


Figure 11: Temperature readings from sensors installed for WPAFB test from 6/20/04 to 6/22/04.

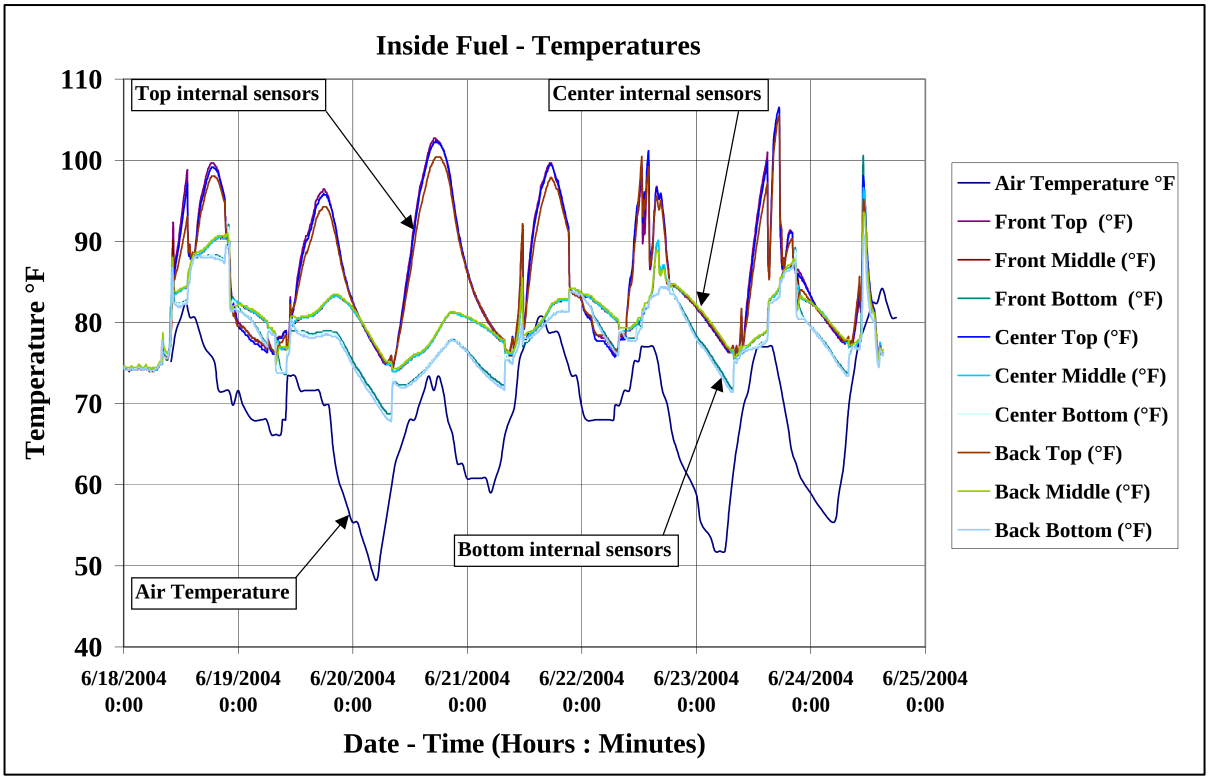


Figure 12: Internal temperature readings for WPAFB tests.

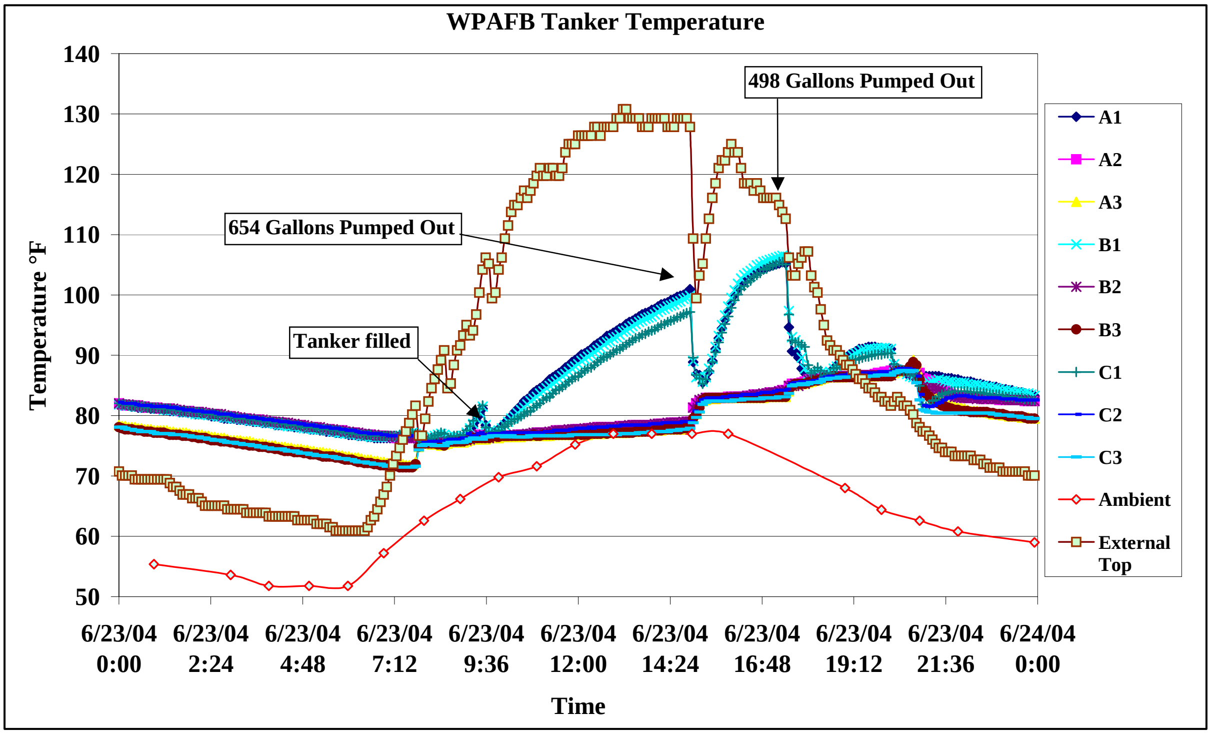


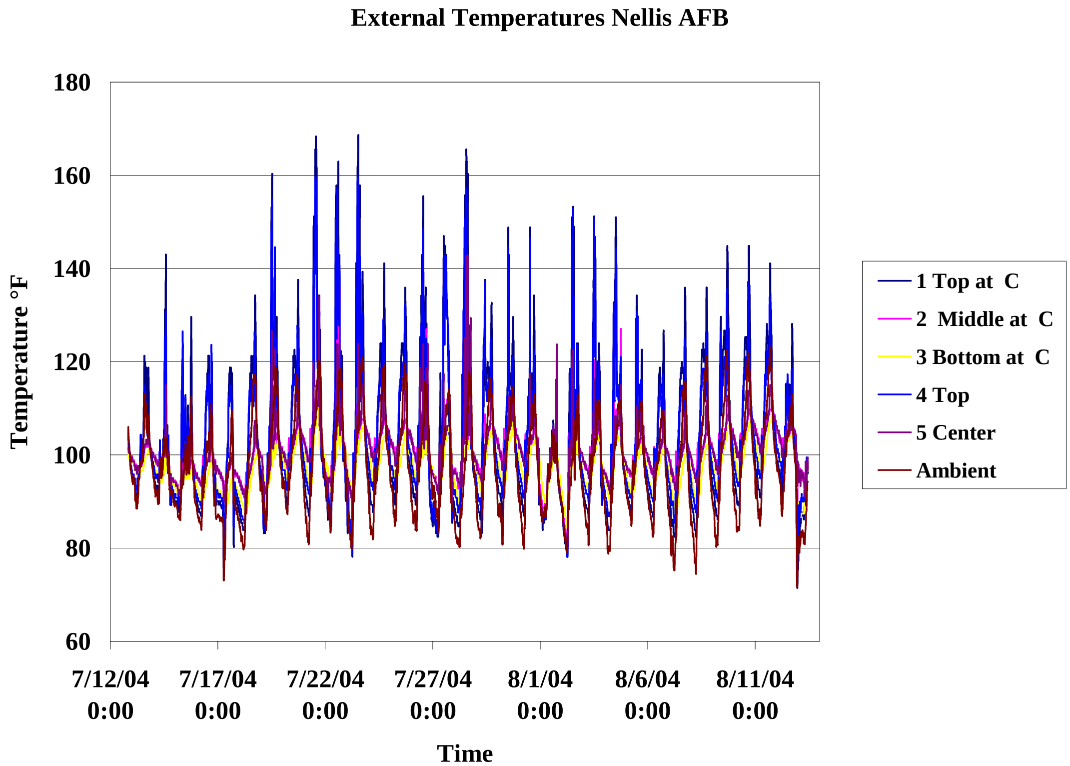
Figure 13: Temperature during activities on July 23[rd] WPAFB.

Nellis AFB Tanker Data

As shown in Figure 14 a TEMP1000IS temperature data logger was suspended from a support column in the shade park (overhead shade screened area) where the trucks are parked when not in use on the flight line. This sensor was programmed to take temperature measurements at the same rate and time as the internal data loggers, and is used as an ambient reference.

Figure14: Location of ambient temperature data logger.

Figure 15 shows, separately, the temperature data from all the internal & external sensors installed on the tanker truck located at Nellis AFB. The temperature plots show the daily thermal cycle over the one-month time period. All of the sensors were programmed to record at five-minute intervals. The charts are shown here to give an easy visual representation of the daily thermal cycles for the entire four-week period, <u>they are not meant to be used for detailed analysis</u>.



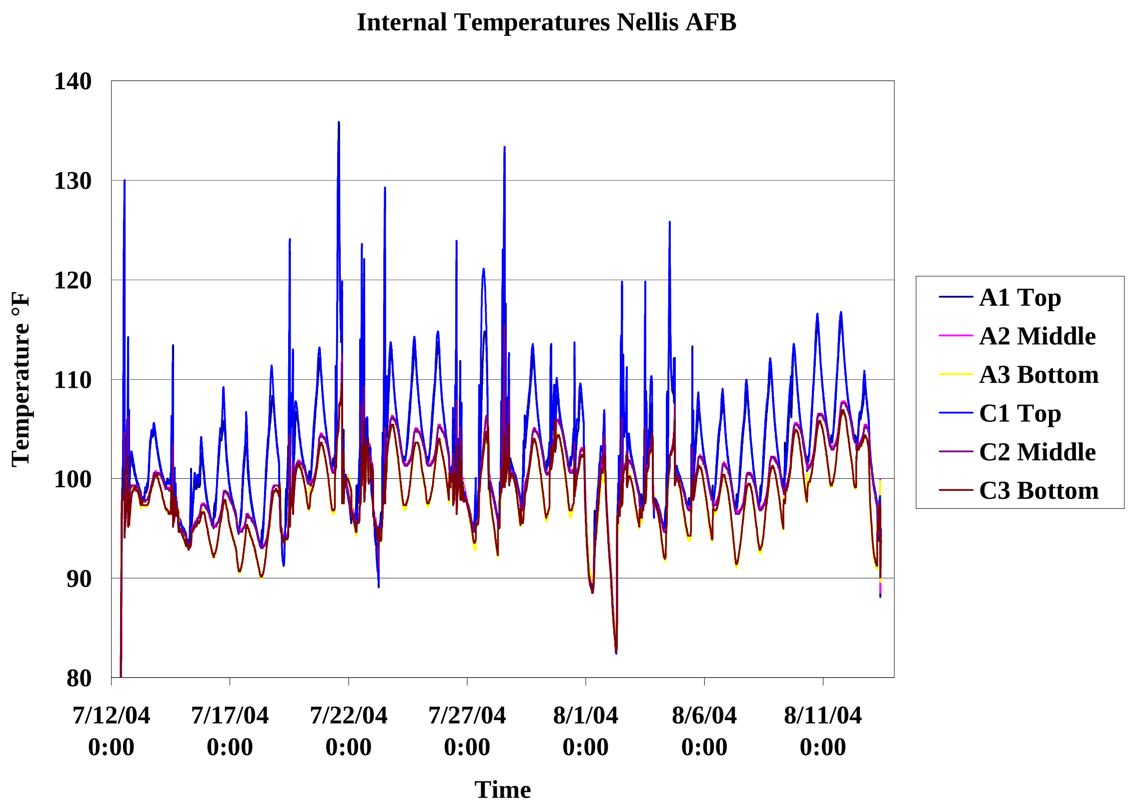


Figure 15: External and internal data from Nellis AFB testing.

The following is a narrative of the tanker activity on 7/21/04; on this day the sensors recorded the maximum external skin temperature (Top 4) and maximum internal temperature (A1).

At 10:45 the truck was filled, this covered the top internal sensor (A1) and brought all the internal sensors to approximately the same temperature approximately 102 °F. The large mass (3644 gallons) of cooler fuel reduced the overall temperature of the tanker reducing the external top temperature.

1. Between 11:27 and 12:05 the tanker delivered fuel to several aircraft. During this time (~11:50) fuel level was reduced to a point that exposed the upper internal sensor (A1) to air.
2. Between 12:05 and 13:25 the truck appears to have remained on the flight line. During that time, the temperature of the outside top sensor (Top 4) reached its maximum reading of 168 °F. The internal air temperature, as measured by A1, reached 136 °F. At about 13:30 the truck was returned to the shade park. Returning the truck to the shade park had a dramatic effect on the outside skin temperature, dropping the temperature from over 168 °F to 120 °F (Internal air temperature dropped from 136 °F down to 116 °F).
3. From 16:10 to 17:11 the truck returned to the flight line, servicing two more aircraft.
4. At ~17:15 the tank truck is refilled.

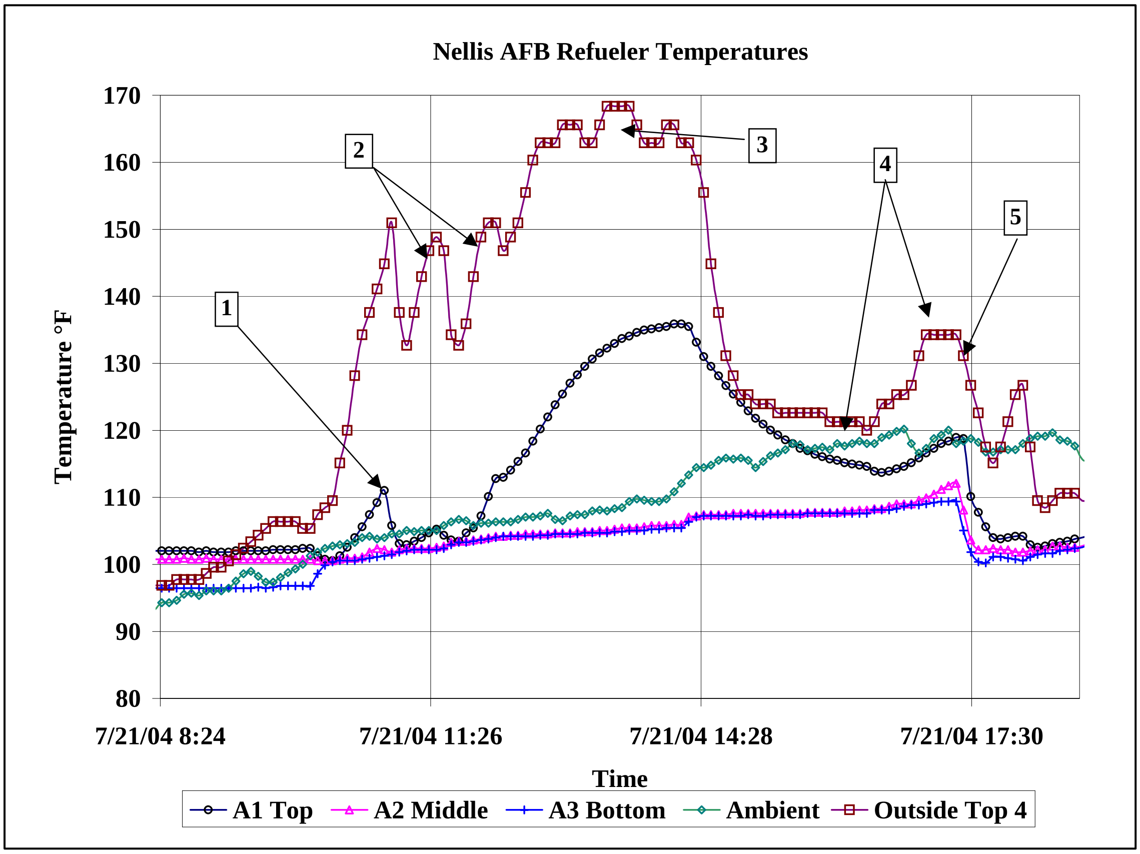


Figure 16: Temperature data for the day of 7/21/04.

During the weekend of July 24th the truck was parked after the tank was filled at 12:55, Friday afternoon. Figure 17 shows the temperature response of the full tanker truck to ambient air temperatures and solar heating in the partially shaded parking area (see Figure 14). The ambient temperature and the outside surface temperature start to increase at sunrise. At approximately 8:45 on both days the skin temperature begins to increase at a rate faster than the ambient temperature do to sunlight coming through the screen of the shaded area. At approximately 14:30 the angle of the sunlight relative to the screen starts to reduce the amount of sunlight on the tanker dropping the temperature reading of the top external sensor. By 16:30 the sun has moved to a position to allow sunlight directly on the tanker for a short period of time, increasing the top external reading by 25 °F. As the sun starts to set, the ambient temperature and the external skin temperature drop. By 18:45 they are reading the same temperature. Both the external top sensor and the ambient sensor continue to show a drop in temperature throughout the night. Beginning at sunrise the next morning the cycle is repeated. From sunset to sunrise (on the 24th- Sun Rise: 5:41 & Sun Set: 19:53, on the 25th- Sun Rise: 5:42 & Sun Set: 19:52) the fuel temperature is warmer than either the external top sensor reading or the ambient temperature. This same cycle can be seen occurring on the six days of inactivity from August 6th to the 12th (See Figure 18).

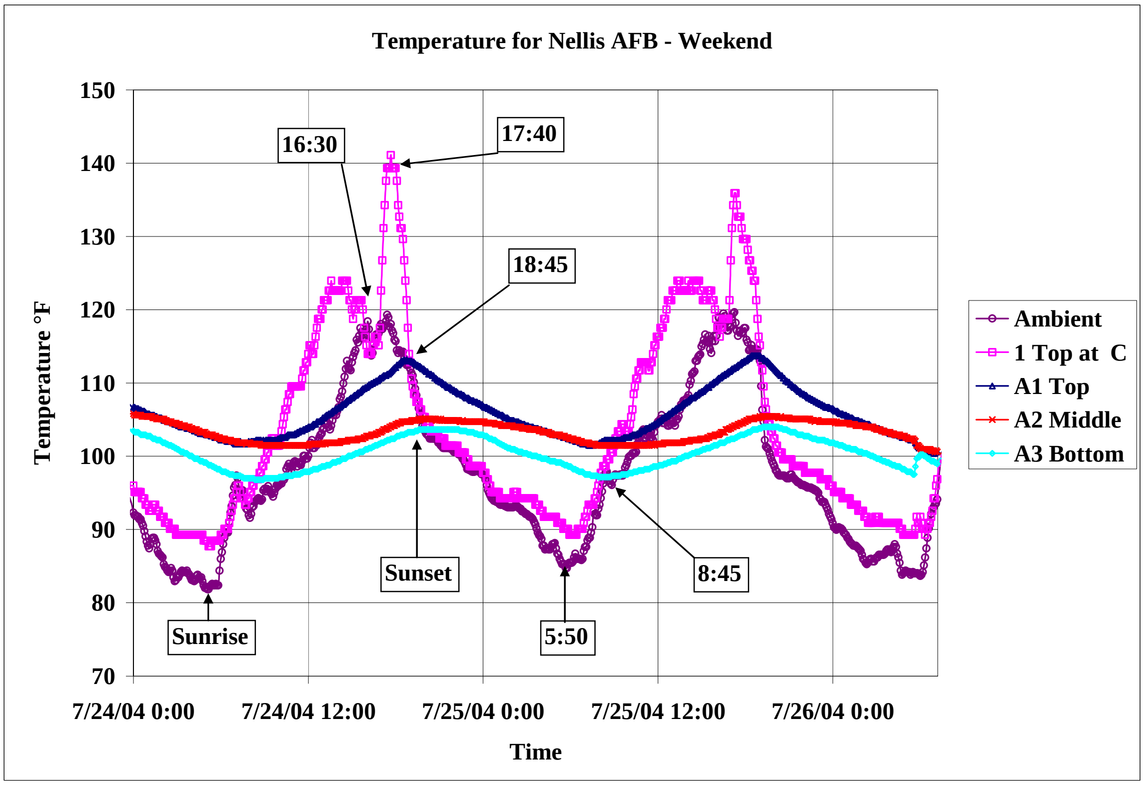


Figure 17: Temperature data for the weekend for July 24th.

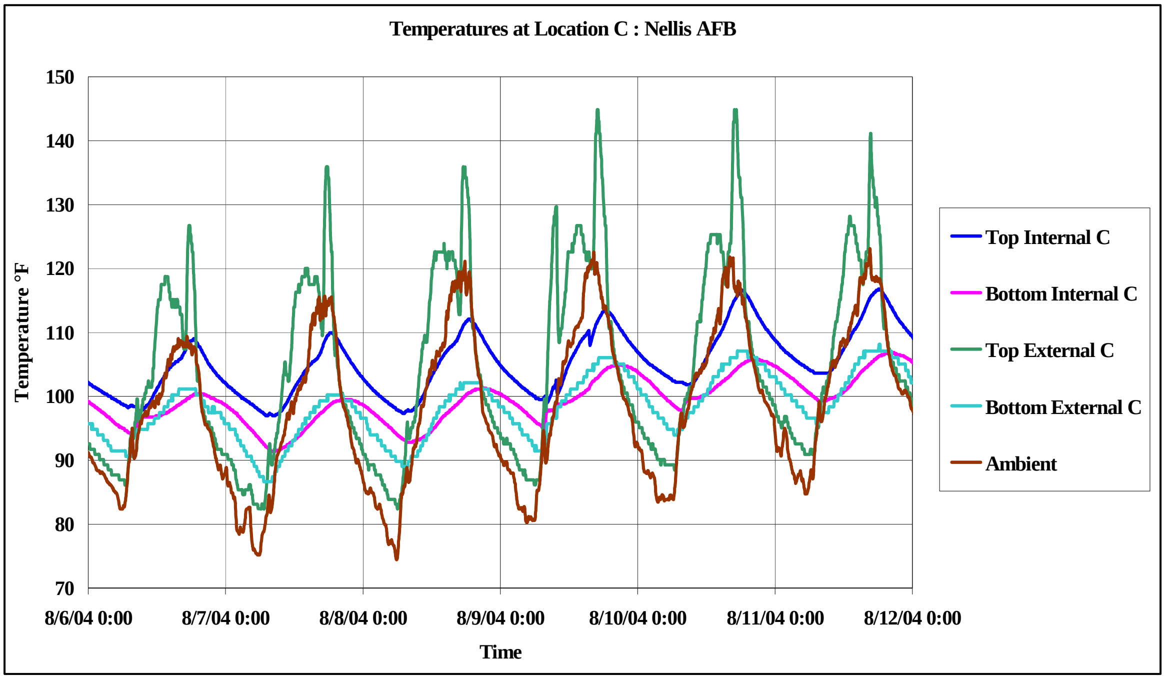


Figure 18: Temperature data for six days from 8/6/04 to 8/12/04, no activity for the truck was logged during this time period.

Simulations of Truck Tank Heat Transfer

For simulations of the heat transfer within the truck tank, it was assumed that the temperature varied little along the length of the tank. Thus, two-dimensional simulations of the laminar buoyancy-driven flow within the tank which neglected variations in the axial direction were performed. In addition, solar heating of the tank and, thus, the flow within the tank were both unsteady over the period of interest, 6:00 AM through roughly 6:00 PM. Beyond 6:00 PM, the temperature levels decrease as the tank is convectively cooled while solar radiation is simultaneously diminished as evening approaches. The Navier-Stokes and energy equations were solved here using a commercially available code (FLUENT Inc., 2002), an unstructured grid, and the QUICK differencing scheme.[1] The volume-of-fluid multiphase method was used at each iteration to locate the interface between the liquid fuel and air for reasonable calculation of the heat transfer and momentum exchange between the liquid and gas phases.[1] Here, evaporation of the fuel into the ullage space was neglected. On the exterior of the tank, solar irradiation was the dominant form of heat transfer, and the radiative flux levels impinging on the external surface were determined through the use of another commercially available code (MuSES IR Signature Prediction Software User Manual, ThermoAnalytics, 2003). At the beginning of the experiments, the fuel level within the truck was measured. From this fuel height, it was estimated that 80% of the truck volume was occupied by liquid fuel. For reference, Figure 19 shows the calculated position of the liquid-air interface within the tank. Figure 20 shows the measured and simulated temperatures mid-way along the tank length (center location) for a period beginning at 6:50 AM and ending at 4:35 PM (20 June 2004). For simplicity, the fuel and air were assumed to be at the same initial temperature of 20^{o}C. In the calculations performed, the absorptivity as well as other surface properties for the painted truck surface was unknown. The value of the absorptivity was adjusted until the measured fuel and air temperatures agreed with the simulated temperatures. This final value for the absorptivity was found to be approximately 0.12. Figure 20 shows that the air temperature rises much faster than the fuel temperature and that the simulations agree reasonably well with the measurements in both the air and fuel regions. In addition, Figure 20 shows that there is little difference between the measured fuel temperatures at the tank center and the tank bottom (2-3^{o}C). Thus, it is reasonable that the calculated temperatures at these locations are essentially the same.

Figure 21 shows color temperature contours for the fuel at 6:15 AM. The right side of the tank near the surface is warmer than the rest of the tank. As time progresses (Figure 22, 10:00 AM), the layer of warm fuel near the heated surface is now present at both the left and right surfaces, and the bottom of the tank remains relatively cooler than the left and right sides. Figure 23 shows that the temperature of the fuel is, everywhere at least, 2^{o}C higher than the initial fuel temperature. Like Figure 22, Figure 23 shows a layer of warmer liquid fuel adjacent to the heated left and right walls. Figure 24 shows calculated velocity vectors within the fuel. The vectors indicate the presence of two large counter rotating cells which arise from natural convection within the tank. In addition, the size of the vector is proportional to its magnitude, and the largest vectors represent velocities on the order of 0.4 cm/s.

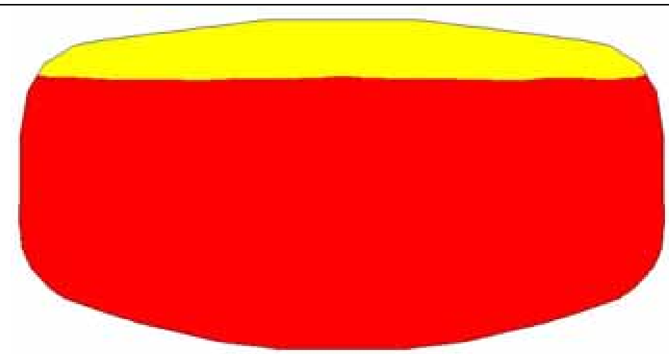


Figure 19: Locations of air and jet fuel within truck tank and accompanying liquid-gas interface.

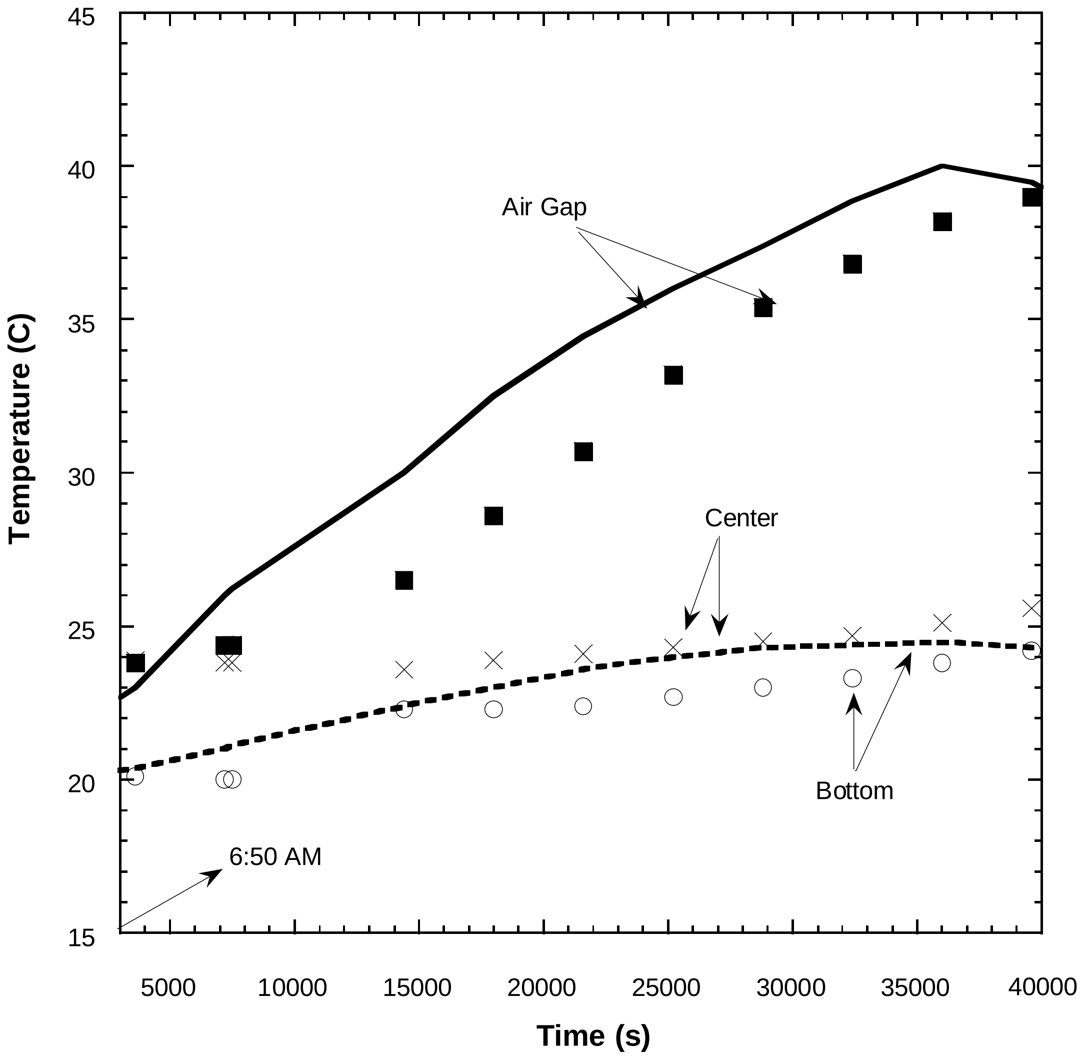


Figure 20: Measured and simulated truck tank temperatures at the axial center position from 6:00 AM to 9:45 PM on 20 June 2004.

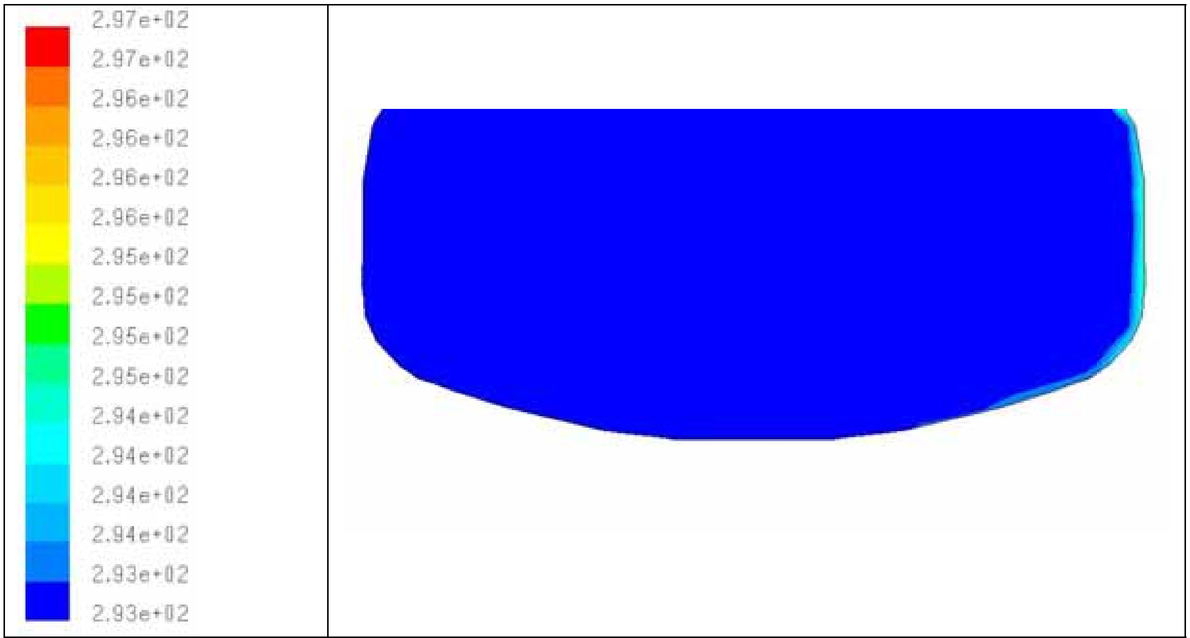


Figure 21. Temperature contours (degrees K) within the fuel at 6:15 AM.

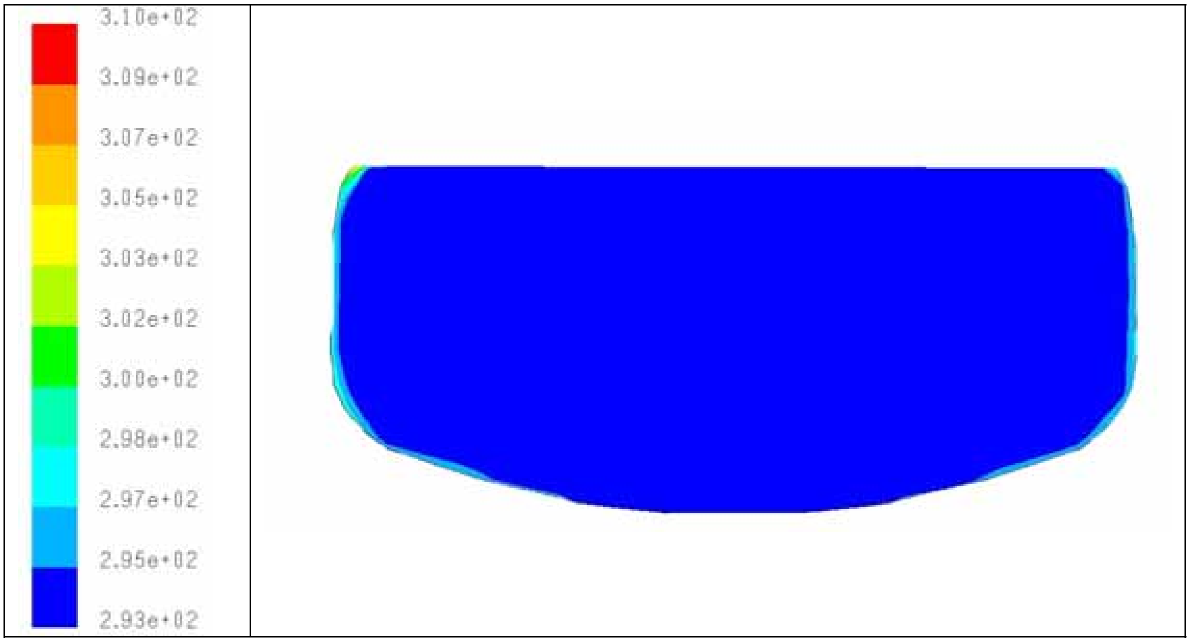


Figure 22. Temperature contours (degrees K) within the fuel at 10:00 AM.

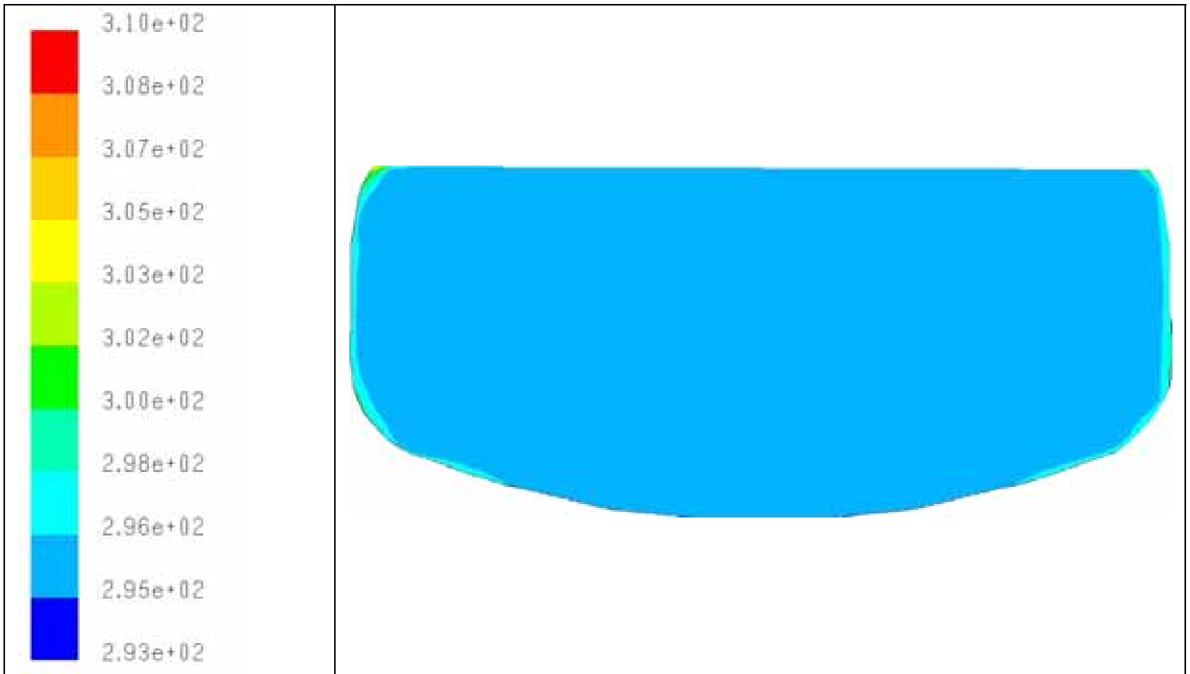


Figure 23. Temperature contours (degrees K) within the fuel at 6:30 PM.

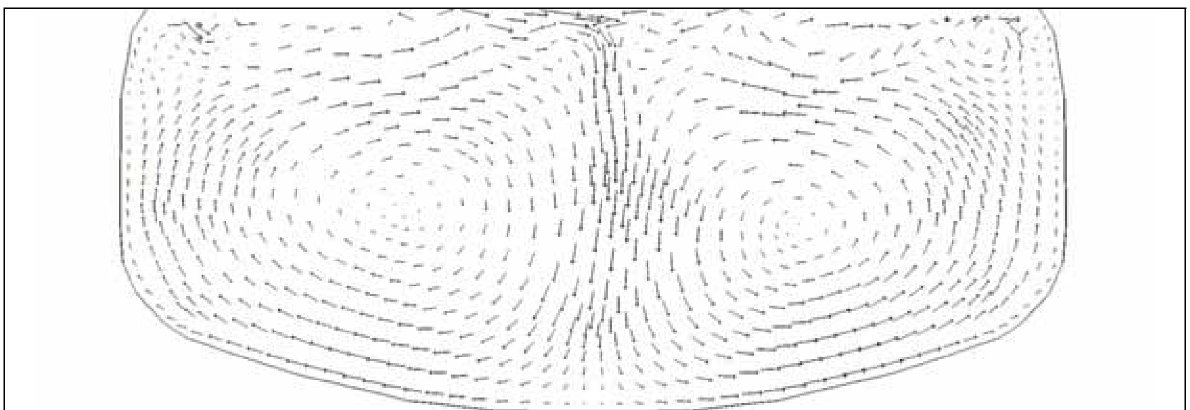


Figure 24. Velocity vectors showing circulation within the driven by natural convection (2:00 PM). Largest vectors represent velocities on the order of 0.4 cm/s.

Results

The scope of the report is limited to measuring, reporting and attempting to validate the temperatures that the refueling tanker trucks experience in flight line service.

While a detailed analysis of all of the temperature measurements can be useful, a more general interpretation of the data gives an overall view of the temperature conditions the fuel encounters while in the refueler. The bottom internal sensors read the temperature of the fuel closest to the point were the fuel is pumped out. This temperature will be very close or equal to the "aircraft fuel delivery temperature". The average measured temperature at WPAFB, shown in Figure 25, is derived from all of the temperatures measured at the same time of day during the week of June 17, 2004. Since we have used temperatures from the bottom internal tank sensor these temperatures represent the average temperature of dispensed fuel as a function of the time of day. The "Maximum Measured Temperature" and "Minimum Temperature Measured" indicate the highest and lowest temperature of fuel measured during the week. On average, the delivered fuel temperature ranged from 74 F to 82 °F. The highest measured temperatures occur when the tank is nearly empty.

Figure 26 was derived from measurements taken at Nellis AFB during the week of July 18, 2004. The chart shows the averaged values of the bottom internal sensors at the same time during each day of the week. Since fuel is withdrawn from the bottom of the tank we can say that on average, fuel was delivered to aircraft between the temperatures of 95 °F and 103 °F during the week. The lowest temperature present in the tank during the week was 90 F and the highest temperature available for delivery was about 112 °F. It is also apparent that fuel delivered to the truck was at least 90 °F since that was the lowest temperature recorded. From Figure 16 it is apparent that air and fuel vapors inside the tank can approach temperatures in excess of the flash point of JP-8, (120 °F) when the tank is exposed to direct sunlight for extended periods.

Figure 27 is a histogram showing the distribution of time spent at temperature during the entire month of testing. From the graph, the most common temperature of the top and middle internal sensors was between 105 and 110 °F. The higher temperatures experienced by the top internal sensors occurred when they were no longer covered by fuel and were exposed to the air beneath the sun-heated tank surface. The bottom sensors spent the most time between 100 and 105 °F. The bottom and middle sensors spent no time above 115 °F. The truck spent almost no time in the sun while the fuel level was below the middle sensors. Typically the middle sensors would be exposed to air while fueling an aircraft and while outside air was being pulled into the tank to take the place of fuel. After the fueling operation the truck would be driven to the fuel depot and refilled before being parked in the shade or driven to the ramp to fuel another aircraft.

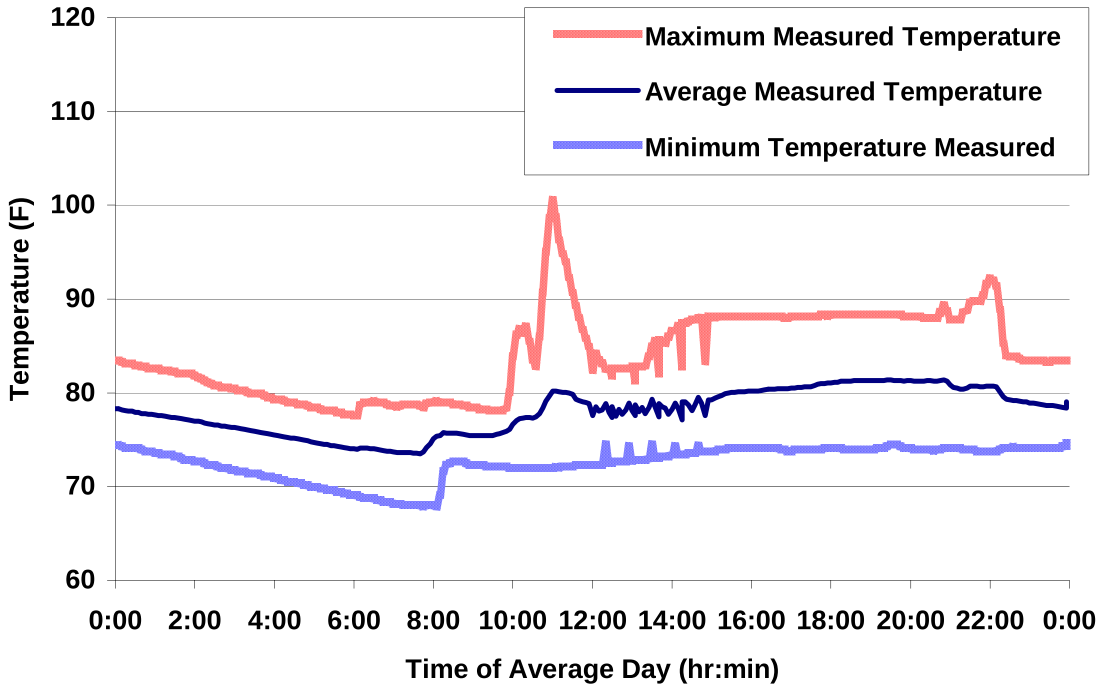


Figure25: The bottom internal sensor measures the temperature of the fuel that is near the tank drain and dispensed to the aircraft. Measured at WPAFB during the week of June 17, 2004 the Maximum and Minimum are individual extremes measured at that time of day while the Average Measured Temperature represents the average temperature at a particular time of day for the whole week of measurements.

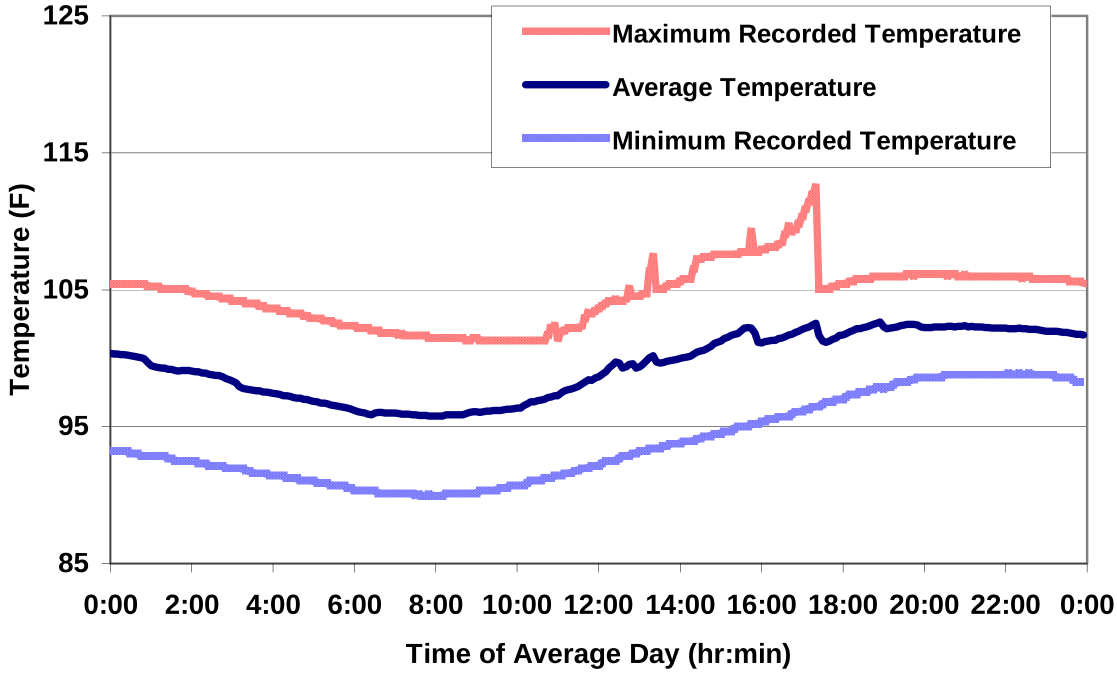


Figure26: The average temperature plot shows the tank bottom temperature as a function of time of day as found during the week of July 18 at Nellis AFB. The Maximum and Minimum Recorded Temperatures were the highest and lowest temperatures recorded during the week at that time of day. The Average Temperature was obtained by averaging all of the measurements taken at that time of day for the whole week.

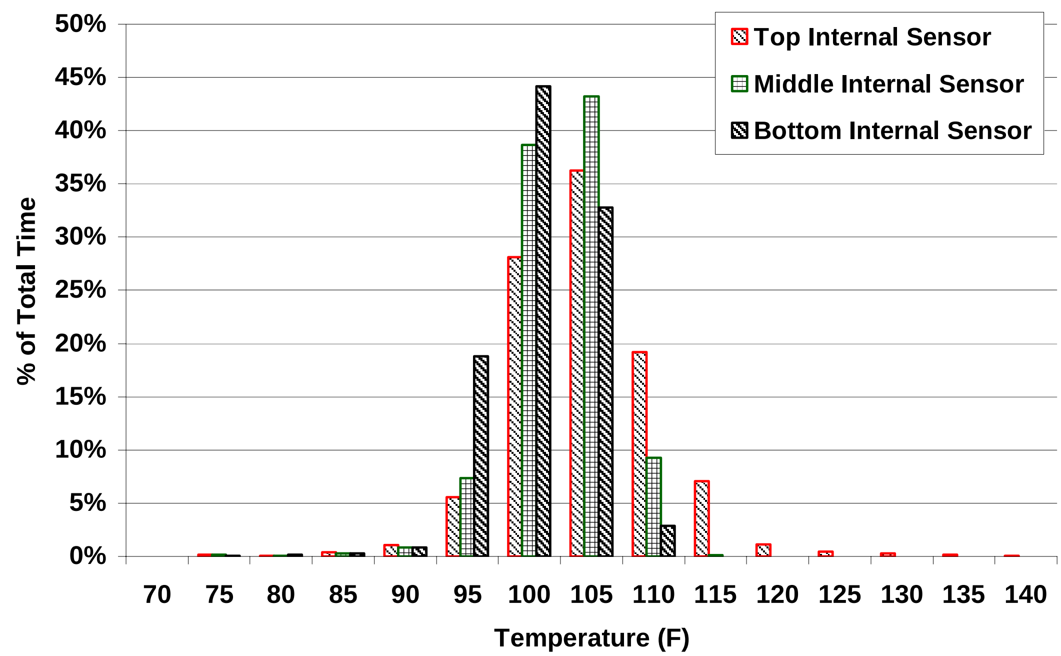


Figure 27: This histogram shows the percentage of total time the internal sensors were within a specific 5 degree temperature range during the one month acquisition period at Nellis AFB. (Day and night inclusive) The temperature on the axis is the low temperature for the bin found above it.