A Simple Analysis of Fuel Addition to the CWT of 747

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Introduction

The National Transportation Safety Board (NTSB) has concluded that a significant factor in the explosion of the center wing tank (CWT) of TWA Flight 800 was the elevated temperature of the fuel. The fuel was warm because: 1) it was a hot day; 2) the air conditioning units ran for about 3 hours prior to take-off, rejecting heat continuously into the tank and fuel; 3) there was a very limited amount of fuel in the tank. One proposed remedy to this situation is to carry more fuel in the center wing tank. The purpose of this short note is to examine the implications of this strategy by using data obtained from flight tests (Ref. 1) with a 747-100 duplicating conditions experienced by TWA Flight 800. This work is part of an ongoing study of fuel behavior and flammability being carried out at Caltech as part of the NTSB investigation into the crash of TWA 800.

The heating of the CWT and its contents is a complicated process, one that is difficult to analyze without approximation. Models have been developed (Ref. 2) to numerically simulate the conditions inside fuel tanks and these models are being used to examine the cost-effectiveness of various mitigation schemes such as fuel addition (Ref. 3). However, despite the attractiveness of a model that captures all the geometrical and heat-transfer characteristics of the tank, such a model is not necessarily an accurate one. For example, the air cycle machines and the hot bleed ducts below the tank exhibit such a wide range of operational conditions, that if these heat sources are modeled, one would expect, at best, to obtain bounds on the heating produced in the air cycle machine (ACM) bay. Furthermore, as it is essential to calibrate any model using actual test data, a detailed model will require detailed measurements, and the adjustment of many parameters. Thus, the accuracy of any model is dependent both on the test data used to calibrate it, as well as on way the test data is used.

A different approach is to analyze the test data itself, in terms of simpler models, before resorting to more complicated ones. This approach does not capture all the physics involved, but it is a direct attempt to gain insight into the test measurements. Such an elementary analysis was carried out, to assess the specific problem of the effect of fuel loaded into to the CWT. The desired end result is the amount and initial temperature of fuel that must be added to the CWT, in order to minimize or eliminate the duration of the flight for which the fuel temperature exceeds the flash point. Using the average ACM bay temperature as the input into the model, an average temperature trace (temperature vs. time) for the fuel in the CWT was calculated, and compared with the measured temperature trace. The calibrated model was then used with different amounts of added fuel and initial fuel temperatures to investigate their effect on the fuel temperature throughout the flight profile.

Method of Calculation

The main premise on which the calculation rests is that the heating and cooling of the tank is driven by the temperature differences between the ACM bay and the fuel only. Neglecting all structural detail of the tank itself, a heat balance can be set-up between the added fuel and the heat output from the ACM bay, as follows:

Rate of heat gained (or lost) by fuel = heat transfer rate from (or to) the ACM bay

This can be cast in terms of a simple differential equation using the traditional formulation of convection heat transfer (Ref. 4):

$$M_{fuel} C_{fuel} \frac{dT_{fuel}}{dt} = (hA)(T_{bay} - T_{fuel}) \tag{1}$$

where,

T_{fuel} is the average temperature of the fuel in the CWT (to be calculated)

T_{bay} is the average temperature of the air in the ACM bay (measured profiles to be used)

M_{fuel} is the mass of the fuel

C_{fuel} is the heat capacity of the fuel, about 2000 J/Kg/K (900 J/lb/K).

(hA) is the product of the heat transfer coefficient, *h*, and the surface area, *A*, over which heat transfer occurs. As both *h* and *A* are unknown and appear in the equation as a product, *hA* is treated as a single parameter.

To get a feel for the magnitudes involved, (dT_{fuel}/dt) can be estimated from the flight test data on the initial heating rate just after the fuel was added to the CWT. This was observed to be approximately 8.5 F/hr or 0.0013 K/sec for the flight test in which 12000 lb of fuel were used. The left-hand side of

Eqn. 1 can be evaluated to obtain 14 kW as a rough estimate of the total heat input provided by the ACM bay to the CWT. Simple engineering estimates suggest that losses from the air cycle machines amount to about 8 kW for 2 units (only packs 2 and 3 were running in flight 6), not including the bleed ducts. Thus the estimated magnitude of heating produced by the ACM bay is not unreasonable. Using a nominal value of 36 K for $T_{bay} - T_{fuel}$ in the right hand side of the equation implies that $hA \approx 400$ W/K. If it is assumed that heat transfer is over the tank bottom only, A has a value of about 34 m^2 (excluding the dry bay), making $h \approx 12$ W/m^2/K which is comparable to values typically obtained (Ref. 4) in flows driven by natural convection. Furthermore, the radiation heat transfer has not been accounted for, which may explain the higher value of h. However, this is not an upper limit, as losses to the tank structure, tank ullage and structural components (wing tank, cabin etc) in contact with the CWT have been not been taken into account, which would increase the actual total heat transfer associated with the tank bottom.

Numerical Procedure

The idea is to use measured values of the ACM bay temperature and Eqn. (1) to determine the fuel temperature as a function of time. The bay temperatures were measured at discrete times t^i and the temperature at that time is denoted by T^i. With this notation, the energy balance equation can be rearranged to compute the fuel temperature as a function of time

$$T_{fuel}^{i+1} = T_{fuel}^{i} + \frac{hA}{M_{fuel} C_{fuel}} (T_{bay}^{i} - T_{fuel}^{i}) \Delta t \qquad (2)$$

where the superscript i indicates the current value of that quantity, the superscript $i+1$ indicates the value of the quantity at the subsequent time point and Dt is the time increment ($t^{i+1} - t^{i}$). Given the initial fuel temperature, the subsequent values of the fuel temperature corresponding to each known value of T_{bay} can be obtained, provided that hA is known at each point. Both the effect of fuel mass M_{fuel} and initial temperature can then be investigated. The data from flight test 6 were used to find average ACM bay temperatures and values of hA that would reproduce the measured fuel temperatures. The computation was implemented in a simple spreadsheet program.

Results

Flight 6 temperature traces from thermocouples located 4 inches below the CWT bottom were averaged to get a single trace (Fig. 1) representing the temperature in the ACM bay. Similarly, the traces from the lowest thermocouples in the trees inside the CWT were averaged to provide a single trace (Fig. 2) representing the average fuel temperature against which the model was calibrated. The calculation was carried out on a spreadsheet and to calibrate the model, *hA* was adjusted at different points in time such that the calculated fuel temperature appeared close to the average measured fuel temperature (Fig. 3) from flight 6 data. The calculation was started at the point at which the fuel temperature first begins to rise, after the addition of fuel. This point is about 0.9 hr into the test. Table 1 gives the values of the various properties of Jet A fuel used in the calculations.

Table 1 Jet Fuel Properties

PROPERTY	VALUE USED
Heat Capacity of Jet A	2000 J/Kg/K
Jet A Flash point	119 F
Flash point declination	1 F in 800 ft

The flammability of the tank contents was estimated by comparing the fuel temperature to a flash point, corrected for the effect of altitude by using a fixed rate of decrease of the flash point temperature with altitude, due to the decrease in pressure. This is an empirical observation that is commonly used in fuel tank flammability assessments. Using the altitude trace from flight 6 (Fig. 4) and the flash point declination in Table 1, a trace of the flash point as a function of time was obtained (see Fig. 3). It can be seen that for a portion of flight 6, the fuel temperature was above the flash point.

The variation of *hA* with time (Fig. 5) obtained during calibration was held constant in subsequent parametric studies in which the quantity of added fuel and its initial temperature were varied. The effect of changing the amount of added fuel, for various initial fuel temperatures, is shown in Figs. 6 to 10.

Figure 6 examines the case a fuel starting temperature of 88.7 F (the actual value in flight 6) and fuel masses between 6000 and 48000 lb. Note that the CWT of a 747-100 series airplane has a capacity of approximately 88000 lb of Jet A. As expected, larger masses of fuel heat up and cool down more slowly than smaller amounts of fuel. Flammability is predicted in all cases for a period of the high altitude portion of the flight (2.5 to 3.75 hr). Figures 7, 8 and 9 examine the same situation with fuel temperatures of 80, 70 and 60 F. The results are essentially identical to those of Fig. 6 except that the fuel temperature is about 10, 20 or 30 F lower for most of the flight. These curves illustrate that fuel temperatures 60 F or lower are required in order to eliminate flammability during the entire flight envelope for the particular situation exemplified by flight 6 ACM bay conditions.

Discussion

Although the results support the proposal that enough cold fuel would keep the mixture below the flash point, it is important to appreciate the limitations of the calculation in estimating actual magnitudes. The following points are especially of concern in evaluating the model and the associated results:

1) Heat transfer is considered to be driven by the temperature difference between the CWT and ACM bay, or one identical in magnitude operating over an effective *hA*.

2) The fuel is assumed to respond, in bulk, to the heating and cooling. The lag between the measured ACM bay temperature and the actual measured fuel temperature (Figure 3) shows the limitations of this approximation. Also, the limited communication between the bays and the curved tank bottom make this a crude approximation, especially for small quantities of fuel.

3) The heating of the fuel on addition into the warm CWT has been neglected. This approximation can be expected to improve with increasing amounts of added fuel.

4) Longer ground operation, as well as the number of ACMs in operation, can substantially increase the fuel temperature, especially for the smaller amounts of added fuel. Thus, the calculation comparisons of various amounts of fuel at various temperatures should only be considered to be representative of

a flight profile and operation identical to flight 6 only.

5) The calculation uses average temperatures, in the bay and in the fuel. As can be seen from the measured fuel temperature traces, the temperature in the 12000 lb of fuel varies with position in the CWT.

The parameter *hA* was adjusted to make the calculated curve approach the measured average fuel temperature curve. If the area, *A*, over which the heat transfer takes place, remains the same throughout the flight profile (i.e. the tank bottom only), then the heat transfer coefficient *h* can be interpreted to increase with altitude. This is possible as the heat transfer mechanism (example natural convection) is dependent on the driving potential- the temperature differences. However, it is difficult to estimate how much of the increase is due to this effect. Furthermore, there is increased cooling on the inside of the tank, with the driving temperature differences inside being comparable to that between the bay and the fuel, when that aircraft is at altitude. This increase in cooling could also explain the increase in *hA*, primarily through an increase in the effective *A*. However, the physics of this process, including actual magnitudes of the temperature difference have not been considered.

Numerical experimentation with the model showed that the fuel can remain cool, provided that there is enough of it and if it is at a low temperature to begin with. The thermal inertia of larger amounts of fuel is reflected by the very modest temperature changes that they exhibit over the flight profile. Smaller fuel amounts, e.g., 300 lb (50 gal), respond more quickly to changes in the ACM bay temperature (see Fig. 10). However, this behavior is slightly misleading as can be seen by comparing actual measurements from other flights. Figure 11 shows the calculation of fuel temperature compared with the measured fuel temperature in the first hour of flight test 1, which had 50 gallons of Jet A in the CWT, using flight 1 data for average bay and initial average fuel temperature and the values of *hA* from flight 6. Although the same ACMs were operating as in flight 6, the initial conditions and duration of ground portion differs, and so a very narrow early portion of the test (while the aircraft is on the ground) has been chosen for comparison. The calculated temperature is found to be much higher than that actually measured. A similar calculation using average fuel and bay temperatures from flight 5 (also with 50 gallons of fuel added) again shows that the calculated average fuel temperature is higher than the measured average fuel temperature (see Fig. 12), even though all three ACMs were operating in this test. The detail of the first hour of flight 6 is shown in Fig. 13 for comparison. If the differences in initial temperatures and operating ACMs are neglected, then the trend in Figs. 11 and 12 suggests that there is more thermal mass than is accounted for in these calculations, which is probably a manifestation of both the heat capacity and diffusivity (conduction) of the CWT structure, with an increasing effect on the calculation as the amount of added fuel is decreased.

Conclusion

The effect of adding fuel to the CWT, in an effort towards keeping the temperatures within the tank below the flash point, has been modeled using a simple heat balance. The differential equation, obtained from this balance, is used to extract the effective heating provided by the ACM bay, using actual flight data. This was done by adjusting the single unknown parameter in the model, the product, hA, of the heat transfer coefficient and the effective surface area, yielding a calculated curve that substantially reproduced the actual measured fuel temperature trace. Numerical parameter studies were carried out for various fuel masses, and initial temperatures. It was found that the fuel temperature would remain under the flash point, in the given flight profile, provided that there was enough of it, and at a cool enough initial temperature. This result is useful in evaluating the strategy of added fuel, although the actual magnitudes obtained should be backed by further consideration of the approximations in the model, as well as actual experiments.

References

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3. Anon., Fuel Tank Harmonization Working Group, Draft Report (ARAC), August 3, 1998.

4. Holman, J. P., Heat Transfer, McGraw-Hill Book Company, 1981.

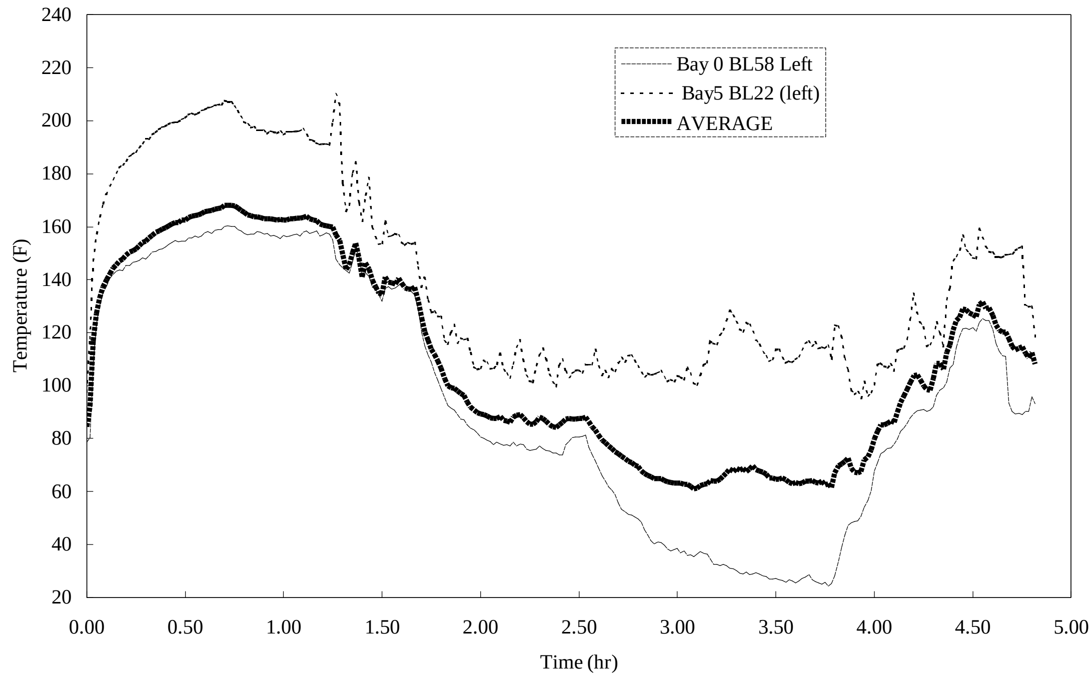

Figure 1: The maximum, minimum and average (over 20 traces) of measured temperatures in the ACM bay. The thermocouples were located 4 inches below the bottom of the tank.

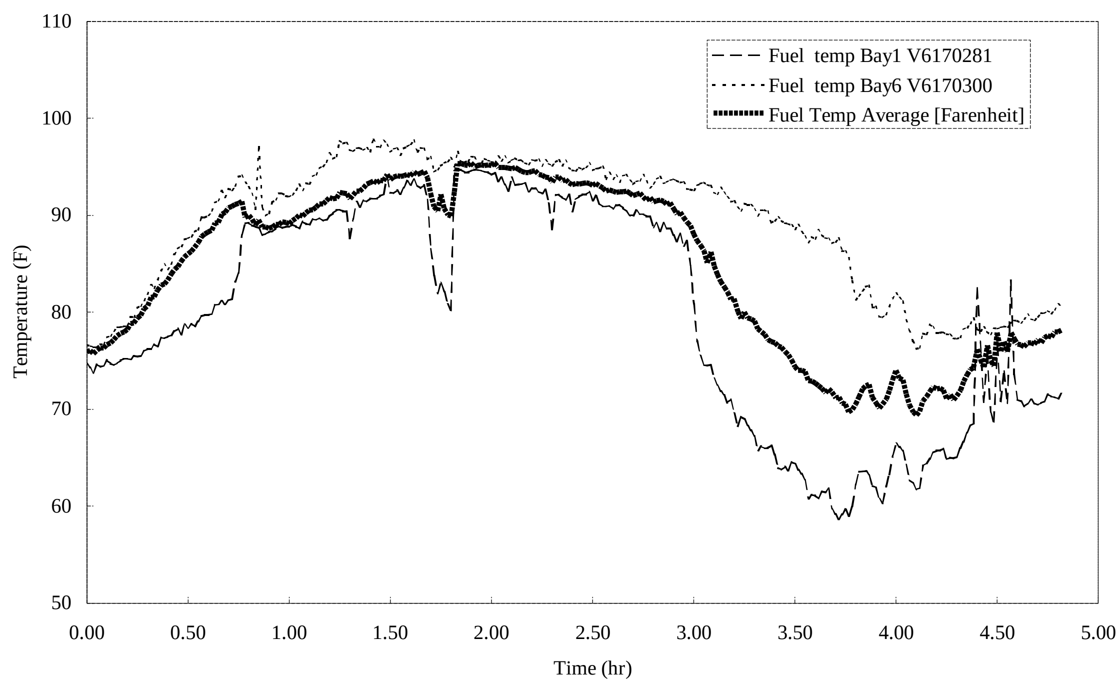

Figure 2: The measured temperatures in the fuel tank. The thermocouples were located within a few inches of the bottom of the CWT.

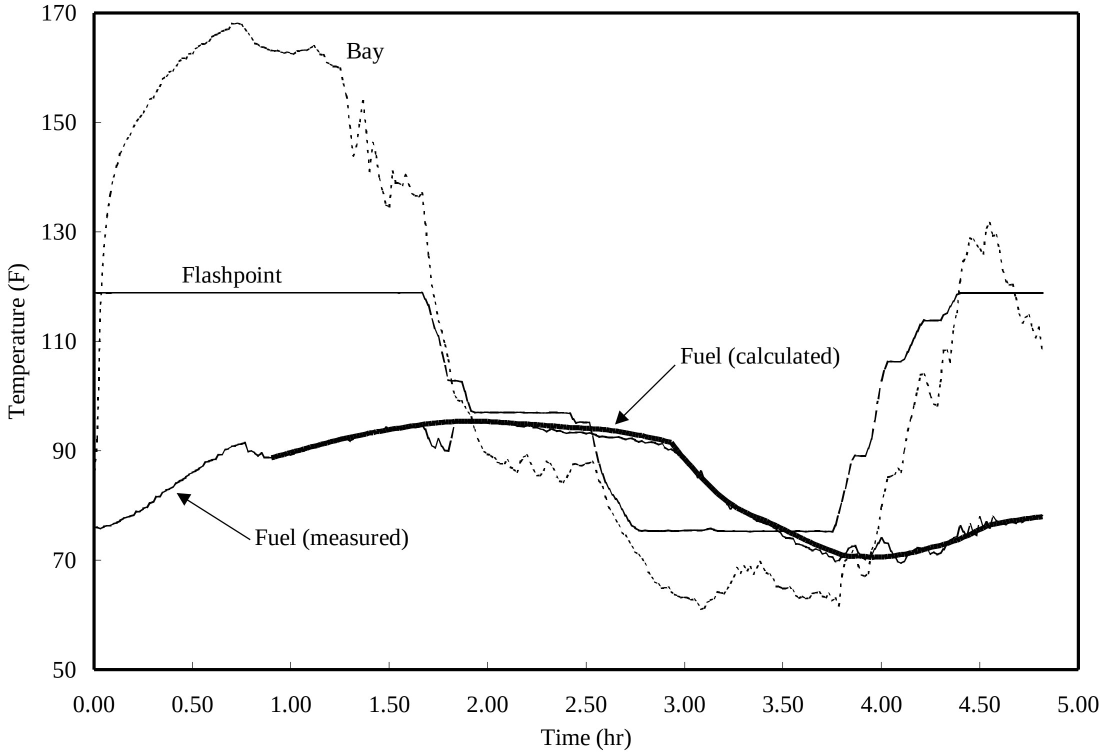

Figure 3: The calculated temperature of the 12000 lb of fuel in flight 6, calibrated with measured data.

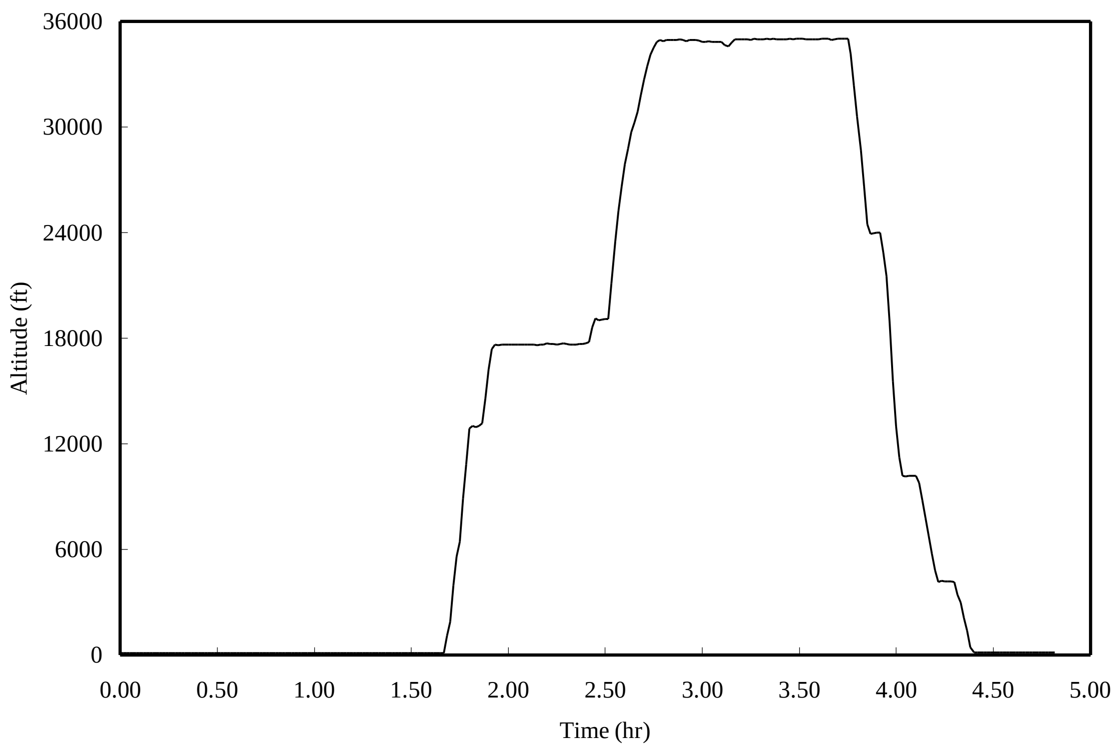

Figure 4: The variation of altitude with time in flight 6.

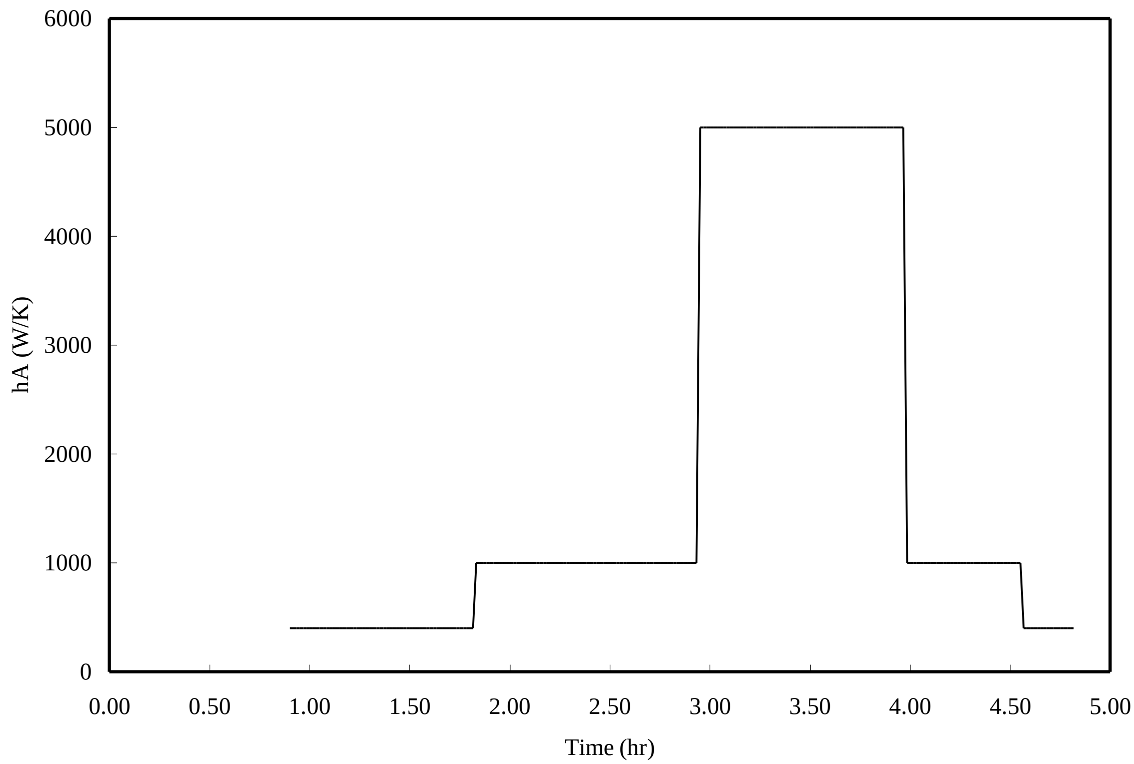

Figure 5: The variation of *hA* with time in flight 6.

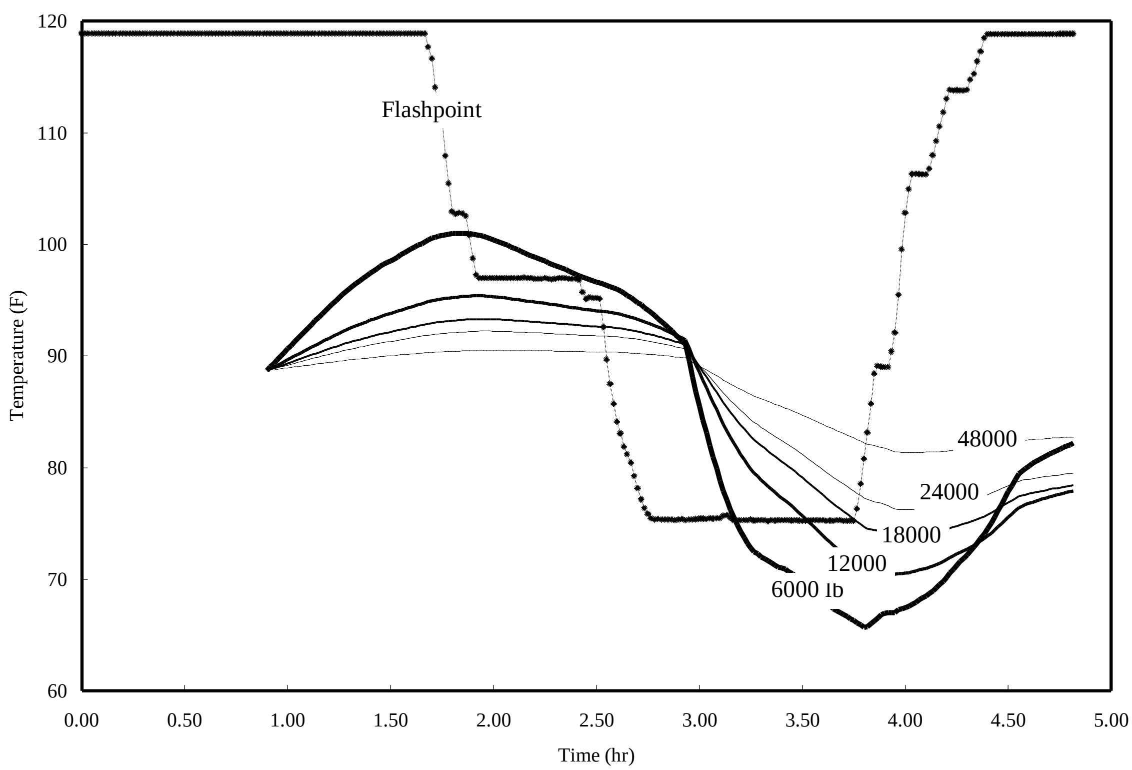

Figure 6: Estimated effect of added fuel mass variation, flight 6 ACM bay conditions. The initial fuel temperature at the beginning of the calculation was 88.7 F, which is taken from the measured fuel temperature in the tank at that time point.

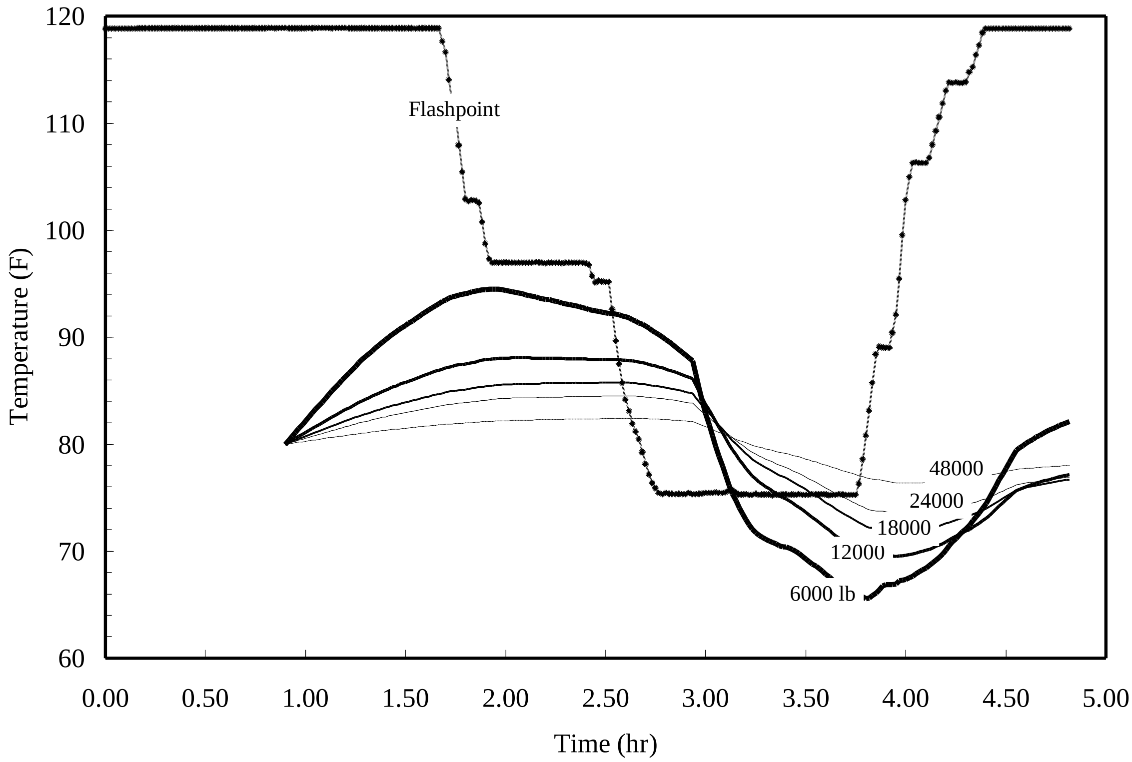

Figure 7: Estimated effect of added fuel mass variation, flight 6 ACM bay conditions. Initial fuel temperature of 80 F.

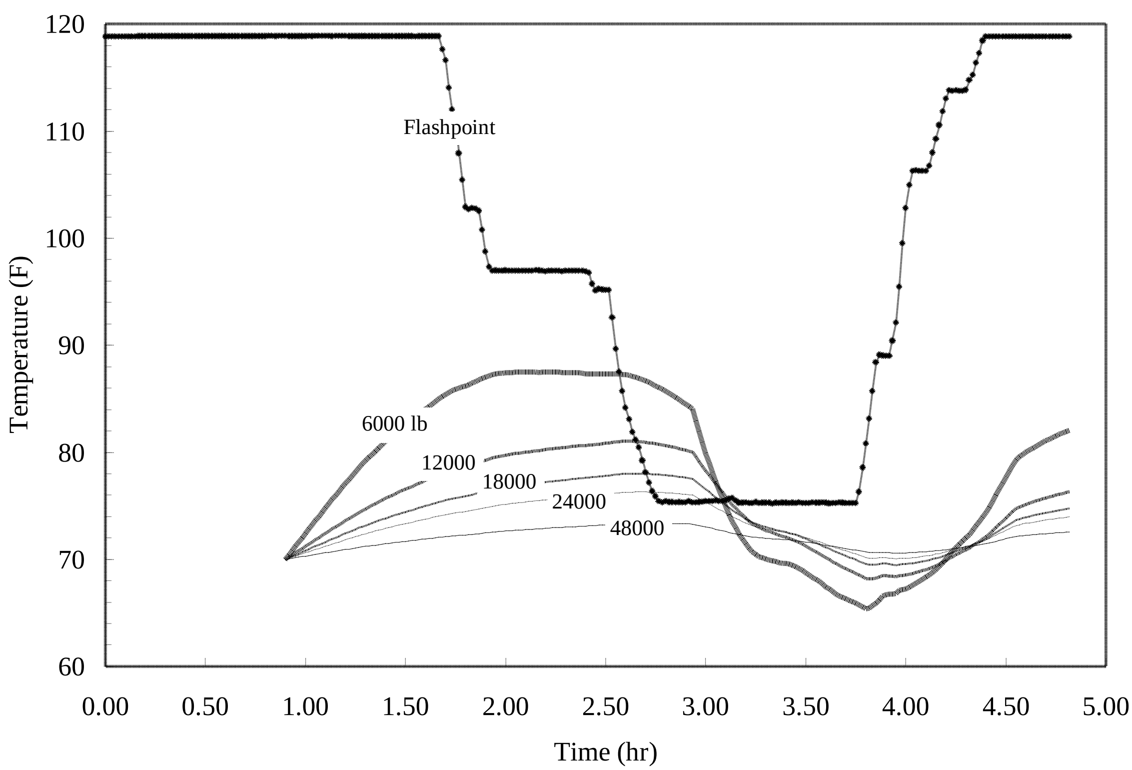

Figure 8: Estimated effect of added fuel mass variation, flight 6 ACM bay conditions. Fuel initial temperature of 70 F.

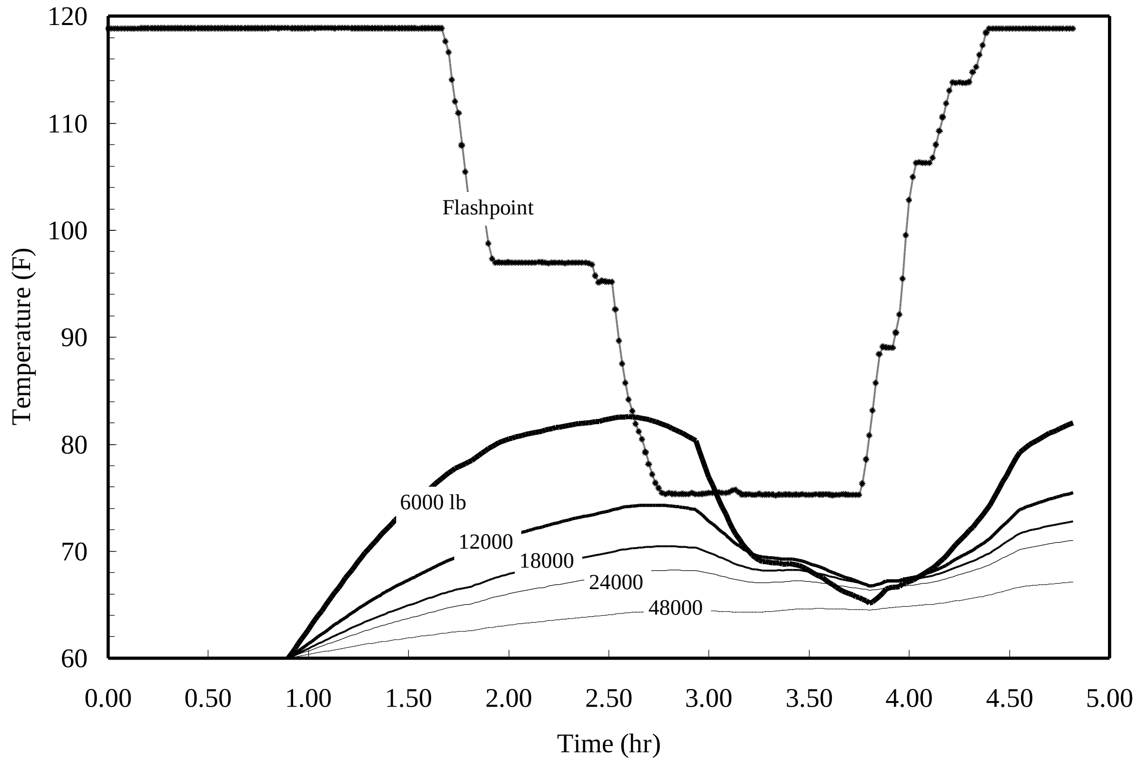

Figure 9: Estimated effect of added fuel mass variation, flight 6 ACM bay conditions. Fuel initial temperature of 60 F.

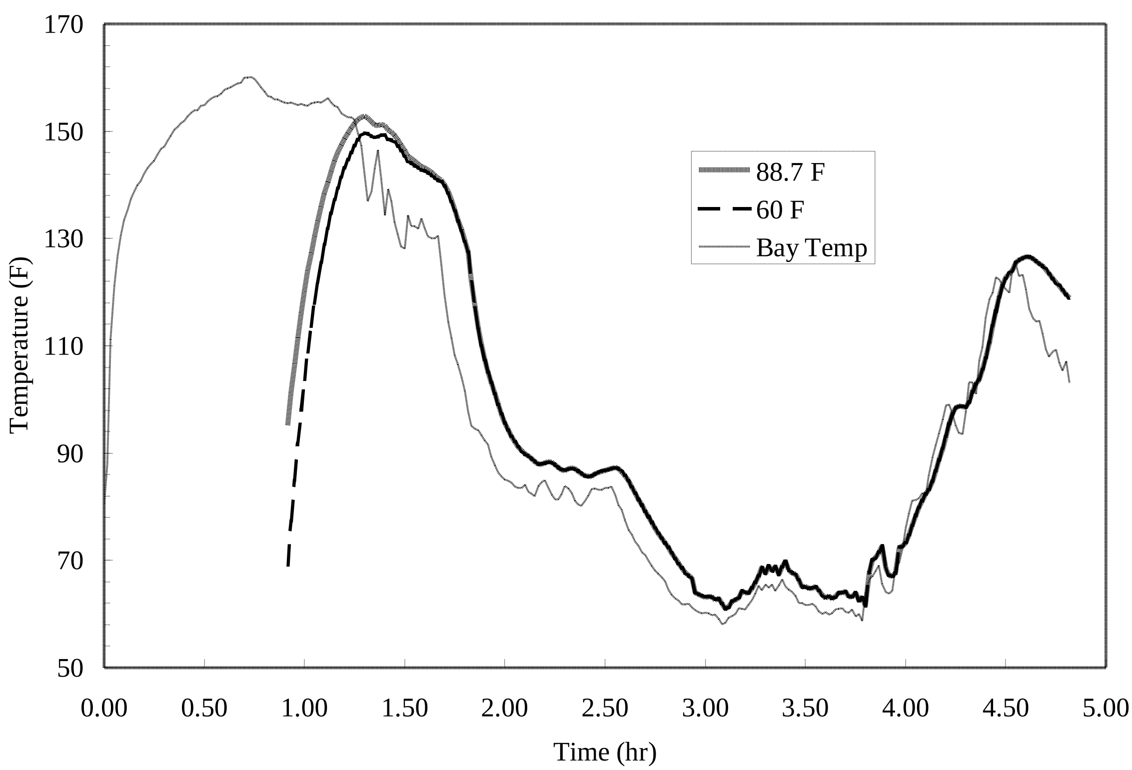

Figure 10: Estimated effect of initial fuel temperature, flight 6 ACM bay conditions. Fuel mass of 300 lb, corresponding to estimated amount in TWA Flight 800.

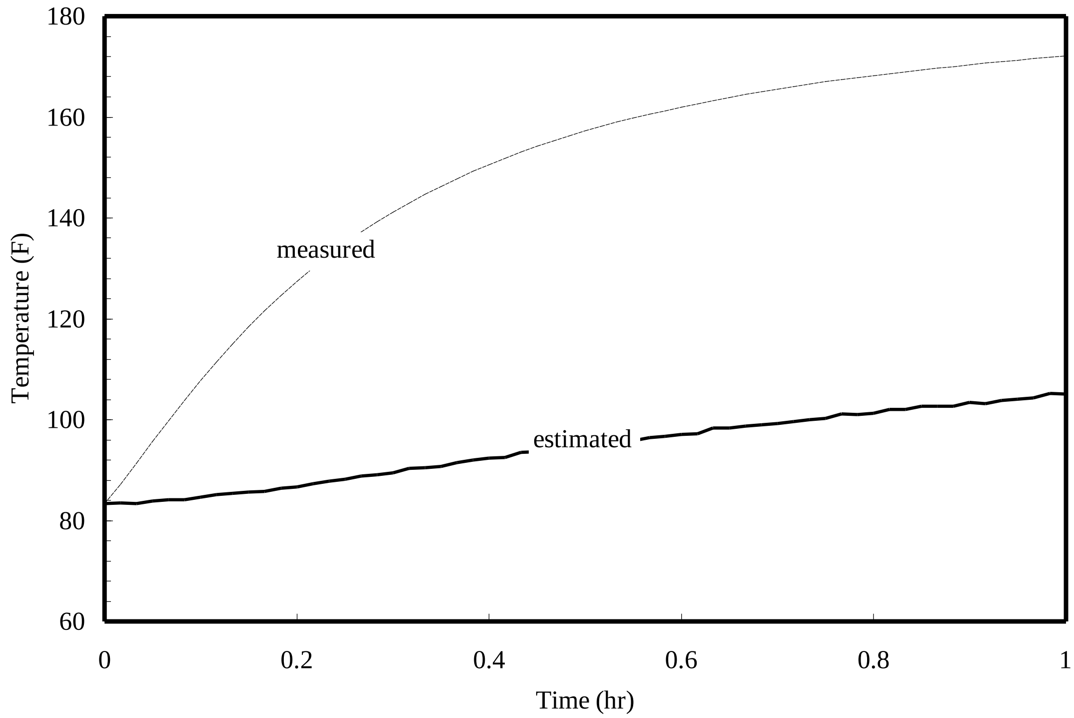

Figure 11: Comparison of measured and estimated fuel temperatures for the initial ground portion of flight 1. 50 gallons of fuel (300lbs). The *hA* used in the calculation is 400W/K, obtained from the flight 6 calibration.

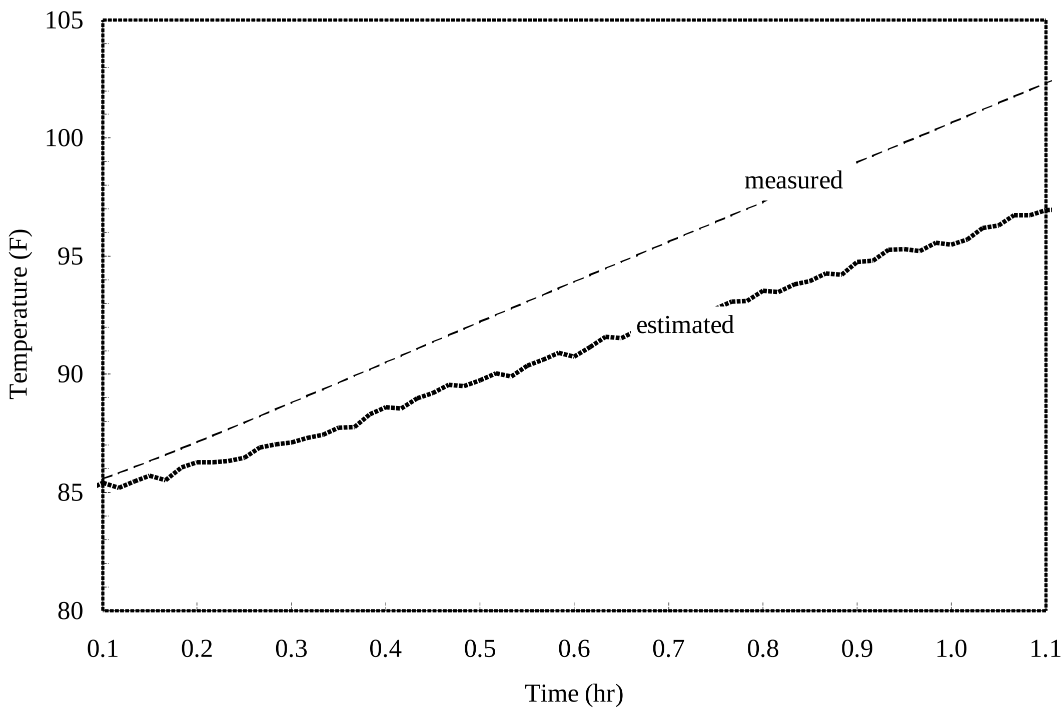

Figure 12: Comparison of measured and estimated fuel temperatures for the initial ground portion of flight 5 with 6000 lb of fuel. The *hA* used in the calculation is 400W/K, obtained from the flight 6 calibration.

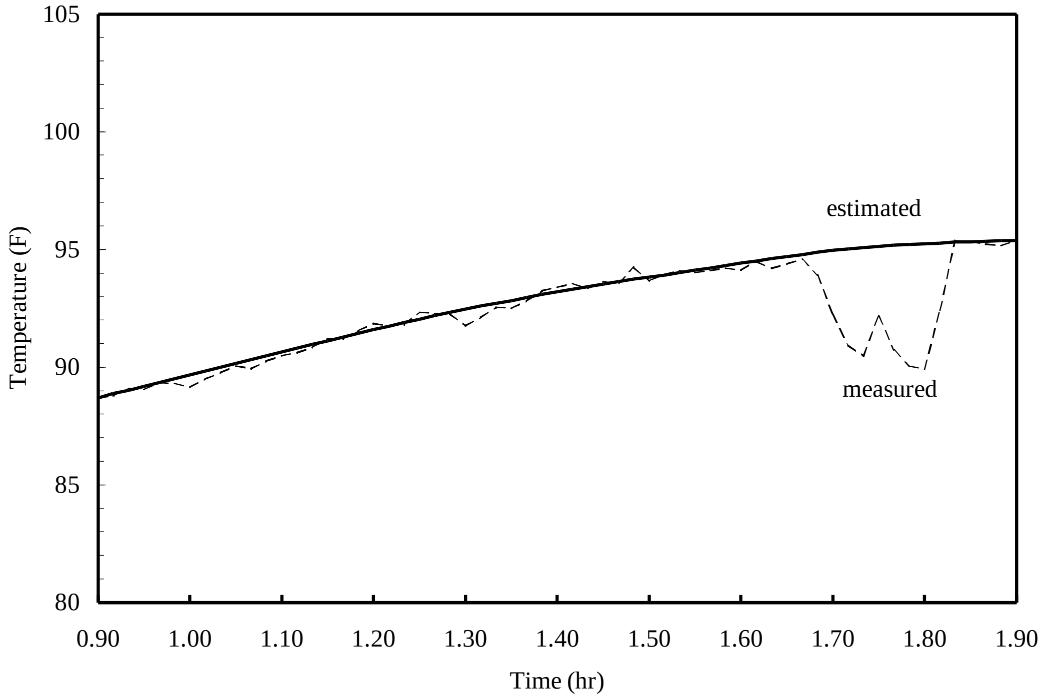

Figure 13: Comparison of measured and estimated temperatures for initial ground portion of flight 6. The value of *hA* used in this portion of the calculation is 400W/K.