Aviation Rulemaking
Advisory Committee

Fuel Vapor Reduction

Task Group 5

1. ABSTRACT

The FAA/JAA initiated a Fuel Tank Harmonisation Working Group in January 1998 by the issuance of a Harmonisation Terms of Reference entitled "Prevention of Fuel Tank Explosions" on December the 16th 1997.

The Working Groups stated task was to study means to mitigate or eliminate fuel tank flammability and to propose regulatory changes to the FAA/JAA Aircraft Rulemaking Advisory Committee (ARAC).

The Working Group established eight Task Groups to report on the following:

1. Service History and Safety Assessment
2. Explosion Suppression
3. Fuel Tank Inerting
4. Fuel Tank Foam
5. Evaluation and mitigation of Fuel Tank Exposure to Flammable Fuel Vapours
6. Fuel Properties Aircraft Effects
7. Fuel Properties Infrastructure Effects
8. Evaluation Standards Advisory and Proposed Regulation Action

This document is the report of Task Group Five whose tasks were:

(i) To evaluate the present exposure of aeroplane fuel tanks to flammable fuel vapour.
(ii) To assess means of mitigating the exposure of aeroplane fuel tanks with adjacent heat sources to flammable fuel vapour.
(iii) To evaluate the exposure of aeroplane fuel tanks to flammable fuel vapour by changing the fuel flashpoint modifications proposed by Task Group Five, or other Task Groups.

Task Group Five had six principle members coming from across the aeronautical transport industry.

▪ Propulsion Systems Design Manager	Aerospatiale
▪ Senior Fuel Systems Engineer	Airbus Industrie
▪ Chemical Engineer, Fuel Systems Safety	Boeing
▪ Senior Engineer, Aircraft and Systems Safety	British Airways
▪ Propulsion/Thermodynamics Staff Scientist	Gulfstream
▪ Independent Transportation Safety Consultant	TRC

Numerous personnel within the six principle members own organisations, other Task Groups and members of the aeronautical transport industry worked for and or contributed to this report.

2. SUMMARY

This report attempts to quantify the exposure of fuel tanks to flammable vapour and evaluate methods to mitigate the exposure considering the related impacts: safety, certification, environmental, aeroplane design, operational and cost. Analysis has also been performed to assess the effects of ground inerting and changing the fuel flashpoint specification in mitigating the exposure to flammable vapours (see reports of Task Groups 6/7 and 3 for the impacts of these modifications). This analysis has been completed for generic aeroplanes and therefore does not relate to any specific aeroplane design.

Thermal analysis has shown that all generic fuel tanks have some exposure to flammable fuel vapour.

- Tanks without adjacent heat sources, independent of location, (wing or fuselage), have equivalent exposure of approximately 5%.
- Tanks with adjacent heat sources have exposure of approximately 30%.

Other factors affecting exposure are:

- Ambient temperature (of which control is not possible)
- Fuel loading (which is discussed further, see option 3)
- Altitude (which is not discussed within this report)

Following from the above, thirteen methods of mitigating the effects of heat sources adjacent to fuel tanks have been analysed. Only one eliminates exposure to fuel vapours. This is achieved by disabling the fuel tank and thus has severe operational consequences that can only be evaluated for individual airlines operations, and thus no conclusion is provided within this report.

Five options considered reduce the exposure to flammable fuel vapour, and have been evaluated for the Small, Medium and Large transport Aeroplanes:

1. Insulate the heat source adjacent to fuel tanks
2. Ventilate the space between fuel tanks and adjacent heat sources
3. Redistribute mission fuel into fuel tanks adjacent to heat sources
4. Locate significant heat sources away from fuel tanks.
5. Sweep the ullage of empty fuel tanks

Options 2 and 4 have been shown to reduce the exposure of fuel tanks with adjacent heat sources to a level similar to fuel tanks without adjacent heat sources. (Option 4 is only applicable to new aeroplane designs).

Option 5 requires significant further research before a conclusion on its feasibility can be reached.

Table 2.1 summarises the effects and impact of the five options.

In addition the effects of ground inerting and changing the fuel flashpoint were assessed. Either method could reduce the exposure of fuel tanks with adjacent heat sources to a level similar to fuel tanks without adjacent heat sources.

Table 2.2 summarises the effects on exposure of ground inerting, changing the flash point specification, and some potential combinations of modifications (that could be evaluated in the timeframe available).

Table 2.1 Summary of impacts and applicability of the five methods evaluated

Centre Wing Tanks With Adjacent Heat Sources Exposure to Flammable Vapours **30%**							
Fuel Tanks Without Adjacent Heat Sources Exposure to Flammable Vapours **5 %**							
OPTION **IMPACT**		1. Insulate Heat Sources	2. Ventilate (Directed)	3. Redistribute Fuel	4. Locate Heat Sources	5. Sweep Ullage
Estimated Exposure to Flammable Vapours after Modification		**20%**	**5%**	**20%**	**5%**	Not quantified
New safety Concerns		*minor*	*None*	**Medium**	*none*	**Medium**
Certification Impact		*minor*	*Minor*	*Minor*	*none*	**MAJOR**
Environmental Impact		*none*	*None*	*None*	*none*	**YES**
Aeroplane Impact		*minor*	**Medium**	*Minor*	**MAJOR**	**Medium**
Operational Impact		*minor*	*Minor*	**MAJOR**	*minor*	**MAJOR**
One Time Fleet Costs ($ x 10^6)	Small	160	500	4	160	2,000
	Medium	50	60	2	50	650
	Large	100	300	3	100	1,200
Annual Fleet Costs ($ x 10^6)	Small	10	170	7	?	370
	Medium	2	20	3	?	80
	Large	2	70	14	?	180
10 Year Fleet Costs ($ x 10^6)		**450**	**3,500**	**250**	**?**	**10,000**
Applicability		MOST	MOST	MOST	**NEW DESIGNS**	MOST

Table 2.2 Summary of the effects of changing the fuel flashpoint, ground inerting and combinations of different modifications.

Modification	Wing Tanks Without heat sources	Centre Tanks without heat sources	Centre Tanks with heat sources
Current Aeroplanes	*5%*	*5%*	*30%*
120°F Flashpoint Fuel	**< 1%**	**< 1%**	**10 to 20%**
130°F Flashpoint Fuel	**< 1%**	**< 1%**	**5 to 10%**
140°F Flashpoint Fuel	**< 1%**	**< 1%**	**1 to 5%**
150°F Flashpoint Fuel	**< 1%**	**< 1%**	**1%**
Ground Based Inerting of Fuel Tanks	*Not applicable*	**< 1%**	**1%**
Combinations of Modifications			
Direct Ventilate and 120°F	*Not applicable*	*Not applicable*	**< 1%**
Insulate and 120°F	*Not applicable*	*Not applicable*	**5%**
Insulate and 130°F	*Not applicable*	*Not applicable*	**1%**

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4. INTRODUCTION

4.1. Objective

The objective of this report is to quantify the exposure of fuel tanks to flammable vapour and to discuss different methods by which that exposure can be minimised including the related; safety, certification, environmental, aeroplane, operational and cost impacts.

4.2. Scope

The methods of reducing the exposure considered are:

(a) Minimise Effects of Onboard Heat Sources
(b) Cooling
(c) Pressurisation
(d) Eliminating the Ullage
(e) Sweeping Ullage

This report does not concern itself with:

(i) The safety, certification, environmental, aeroplane, operational and cost impacts of the reduction of oxygen concentration, e.g. nitrogen inerting, (see Task Group 3 report).
(ii) The safety, certification, environmental, aeroplane, operational and cost impacts of the change to the specification of flash point for JET A/A1, (see Task Group 6 report).
(iii) Ignition sources (see the terms of reference for this ARAC FTHWG).

4.3. Assumptions, Definitions and Limitations

For the purposes of this report in order to quantify the exposure of fuel tanks to flammable vapour the following assumptions and limitations have been made:

(a) The lower flammability limit in terms of fuel vapour concentration in air is defined as 0.6% by volume or 0.35% by mass (reference "Handbook of Properties of Common Petroleum Fuels").

(b) The lower flammability limit in terms of temperature, (as defined by the fuel flash point as defined in the specification of JET A/A1 fuel, (reference ASTM D56)), is used as the basis for quantifying the flammability of fuel vapour and hence the flammability of fuel tanks.

(c) The fuel flash point, (as defined above), is assumed to decrease linearly at the rate of 1°F for every 800ft increase in altitude, (1°C for every 439m increase in altitude), (reference "Handbook of Aviation Fuel Properties", published by the Co-ordinating Research Council Inc.).

* *(The definition and assumption stated above, (a), (b) and (c) cover static conditions).*

(d) Investigations into dynamic flammability of fuel have been performed with no consistent or conclusive definition at the date of writing this report. Therefore dynamic conditions have not been used to quantify the exposure of fuel tanks to flammable fuel vapour.

(e) Probability profiles of ambient static air temperatures, based on historical measurements, have been used, (reference Task Group 8).

(f) The ground refuel temperature is assumed to be the same as the ambient air temperature.

(g) The distribution of JET A/A1 flash points has been compiled from petroleum industry data, (reference Task Group 6/7).

(h) The world fleet of aeroplanes has been divided into size categories, (reference Task Group 8).

(i) For each of these generic aeroplane categories, fuel tank volumes, fuel usage and flight profiles have been defined for the thermal model analysis.

5. EVALUATION OF EXPOSURE TO FLAMMABLE VAPOURS

5.1 Thermal Modelling

To quantify the current fleet exposure of fuel tanks to flammable vapour a process was developed to quantify the amount of time that the fuel temperature is above the flash point of the fuel on a fleet wide basis.

To predict fuel temperatures, the worldwide fleet of transport aeroplanes was divided into six generic size categories of aeroplanes (from Task Group 8). A representative aeroplane from each of the six categories was then chosen for development of a specific thermal model. The choice aeroplane to model was dependent upon three factors:

1. Availability of an existing thermal model, (preference given to those validated by flight test).
2. Number of aeroplanes that model represents in that size category.
3. Involvement in past events, (from Task Group 1).

For the Large and Small aeroplane, both the main wing tanks and the centre wing tank were modelled. For the Medium aeroplane a model was developed for the centre wing tank and results from an inactive model were available for the main wing tanks. A second Small aeroplane was also modelled, which had a centre wing tank without adjacent heat sources. A matrix of the aeroplane sizes and fuel tank configurations modelled is shown Table 5.1.

Table 5.1 Aeroplane sizes and fuel tank configurations modelled

Large	Main Wing Tank	Centre Wing Tank (with adjacent heat source)	*(no thermal model results available)*
Medium	Main Wing Tank (inactive model)	Centre Wing Tank (with adjacent heat source)	*(no thermal model results available)*
Small	Main Wing Tank	Centre Wing Tank (with adjacent heat source)	Centre Wing Tank (without adjacent heat source)
Regional Turbofan	Main Wing Tank	*(no thermal model results available)*	Centre Wing Tank (without adjacent heat source)
Regional Turboprop	*(no thermal model results available)*		
Business Jet	Main Wing Tank	(not applicable)	

5.1 Thermal Modelling (cont.)

The thermal models were developed independently by six different aeroplane manufacturers using seven different thermal codes, and therefore represent a wide range of complexity, from simple differential equation solutions to one-dimensional heat transfer balances, to complex finite element fluid/thermal codes. Because of this wide diversity, the assumptions made in each model were not always the same, but are documented in the descriptions of each thermal model in the Appendix in section 15.1, (with the exception of the Medium aeroplane main wing tank).

In order to produce consistent results, the inputs to and results from each model were processed through Task Group 5 and Task Group 8.

Each model was run through three generic flight profiles representing short, medium and long missions for that size aeroplane. Each flight profile included altitude, Mach number, fuel remaining in each tank and body angle as a function of time. Each model was then run for seven cases, for each mission length, representing a wide range of ambient temperature conditions. The seven ambient temperature profiles ranged from cold (1% cumulative probability) to extremely hot (99.9% cumulative probability). Each model therefore ran a total of 21 cases for each aeroplane/tank configuration and the results, (predicted fuel temperature profiles versus time), were then formatted in a consistent manor.

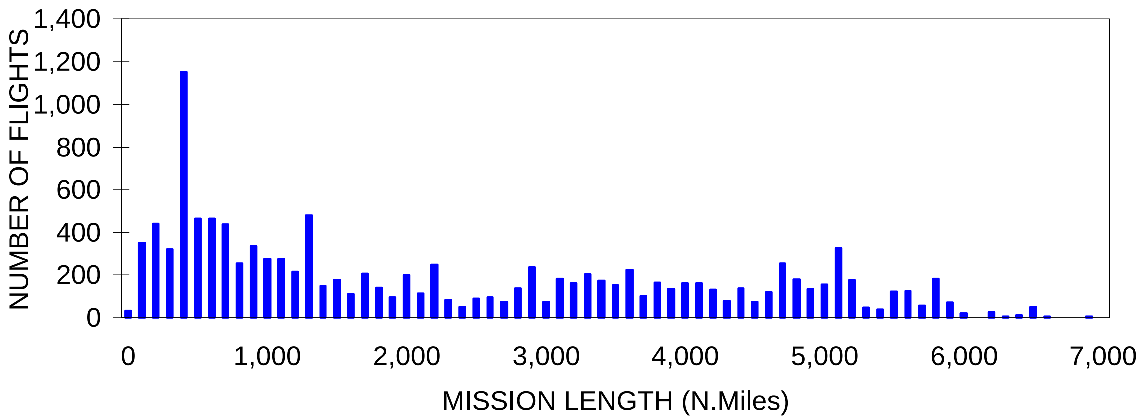
(For the Medium aeroplane main wing tank the model was no longer active and so the 21 cases above could not be run. The data available covered four representative missions with two fuel temperatures and two ambient air temperatures. This data was used to do a simple comparison to verify that the main wing tanks of the Medium aeroplane have a similar exposure to the Large and Small aeroplanes. The exposure analysis, described below was not applied to this model).

5.2 Exposure Analysis

To quantify the current fleet exposure of the fuel tanks to flammable vapour, a process was developed to quantify the amount of time that the fuel temperature is above the flash point of the fuel on a fleet wide basis.
A statistical process was developed using three key variables; mission length, fuel temperature, and flash point, all of which have a defined distribution.

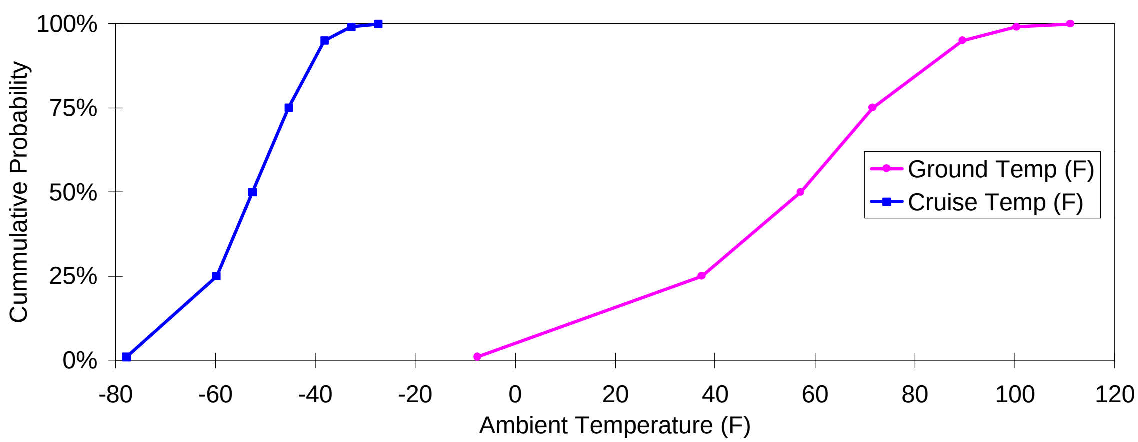
Mission length - Task Group 8 used current fleet statistics to predict the percentage of flights for the three mission lengths, for each size aeroplane. For example; the large aeroplane fleet is estimated to have 63% short missions, 25% medium missions, and 12% long missions, (see Chart 5.2.1).

Chart 5.2.1 Distribution of Mission Lengths (Large Aeroplane)



Fuel temperature - The air ambient temperature profiles used as thermal model inputs were derived from ground and in-flight atmospheric data, based on the probability of a flight encountering that ambient condition, (see Chart 5.2.2).

Chart 5.2.2 Fleetwide Distribution of Ambient Ground and Cruise Temperatures



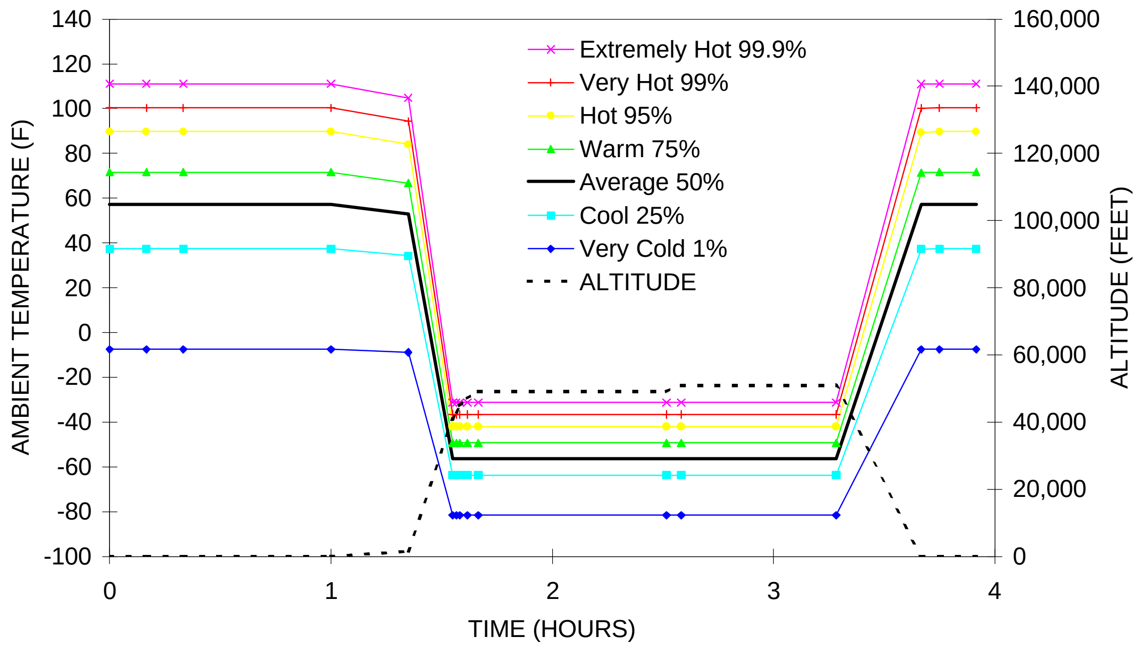
It can be seen that the distribution of ground temperatures is broader than the distribution of cruise temperatures. Seven points on the distributions, (as shown), were chosen to represent a wide range of conditions. Profiles were developed for these conditions. (See Table 5.2.3 below).

Table 5.2.3 Distribution of Ground and Cruise Ambient Temperatures

Condition of Day	Cumulative Probability	Ground Temp Sea Level	Cruise Temp 35,000 feet
Very Cold	1%	-8°F	-78°F
Cold	25%	37°F	-60°F
Average	50%	57°F	-53°F
Warm	75%	72°F	-45°F
Hot	95%	90°F	-38°F
Very Hot	99%	100°F	-33°F
Extremely Hot	99.9%	111°F	-27°F

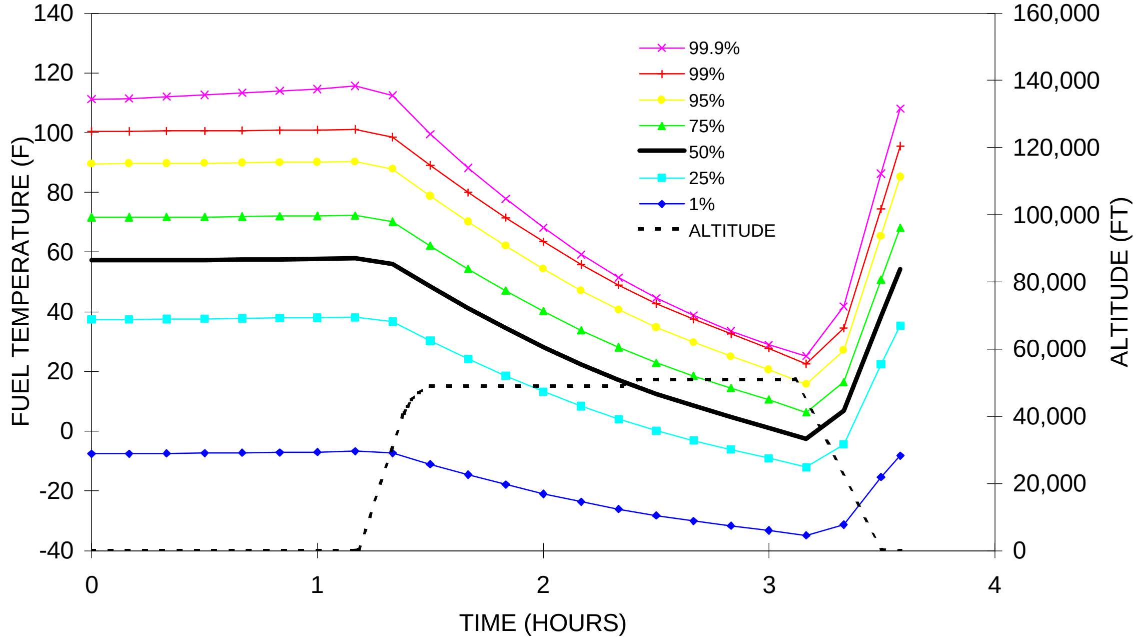
For each aeroplane mission, the seven ambient temperature profiles versus time were developed. For example; the Business Jet – Short Mission ambient temperature profiles are shown below in chart 5.2.4.

Chart 5.2.4 Business Jet – Short Mission. Range of Ambient Temperatures



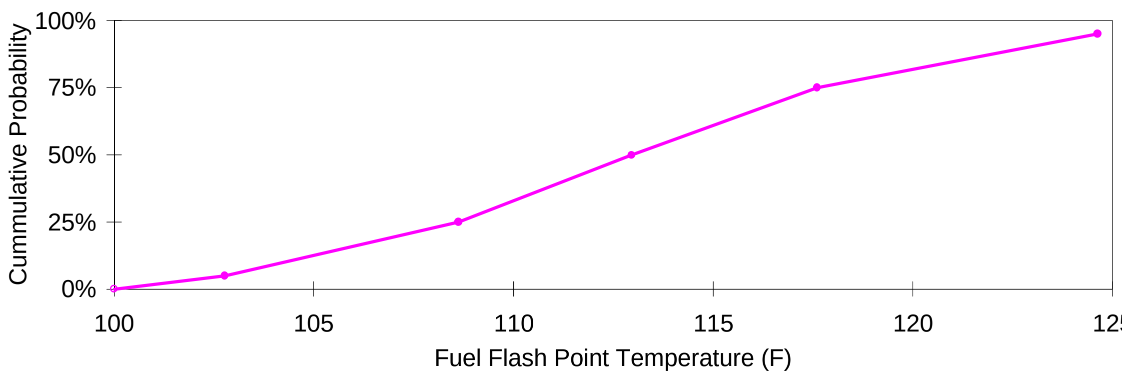
Using these ambient temperature profiles as the input to the thermal model, the output from the thermal model will also be a range of fuel temperatures. The results will be seven profiles with the same probabilities as the ambient temperature profiles. For example; the fuel temperature profiles predicted from the Business Jet – Short Mission thermal model are shown in Chart 5.2.5.

Chart 5.2.5 Business Jet – Short Mission. Predicted Fuel Temperatures for a Range of Ambient Temperatures



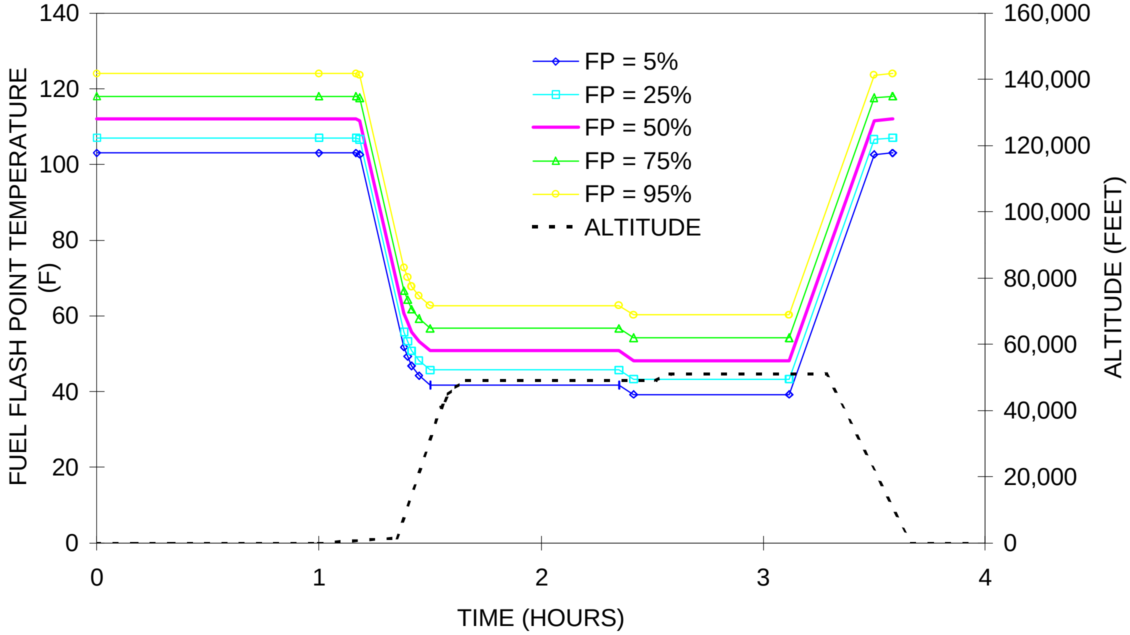
<u>Flash point</u> - To define the flash point of the fuel, the initial assumption was to use the specification limit of 100°F. However, as the objective was to define the exposure of the current fleet of aeroplanes as they actually operate, it was decided to increase the accuracy of the analysis by using the flash point of the fuel that is loaded onto the aeroplane. Task Group 6 provided data on the current distribution of flash points delivered worldwide and assigned probabilities of a specific mission being fuelled with a fuel at a specific flash point. See Chart 5.2.6 below.

Chart 5.2.6 Fleetwide Distribution of Fuel Flashpoint



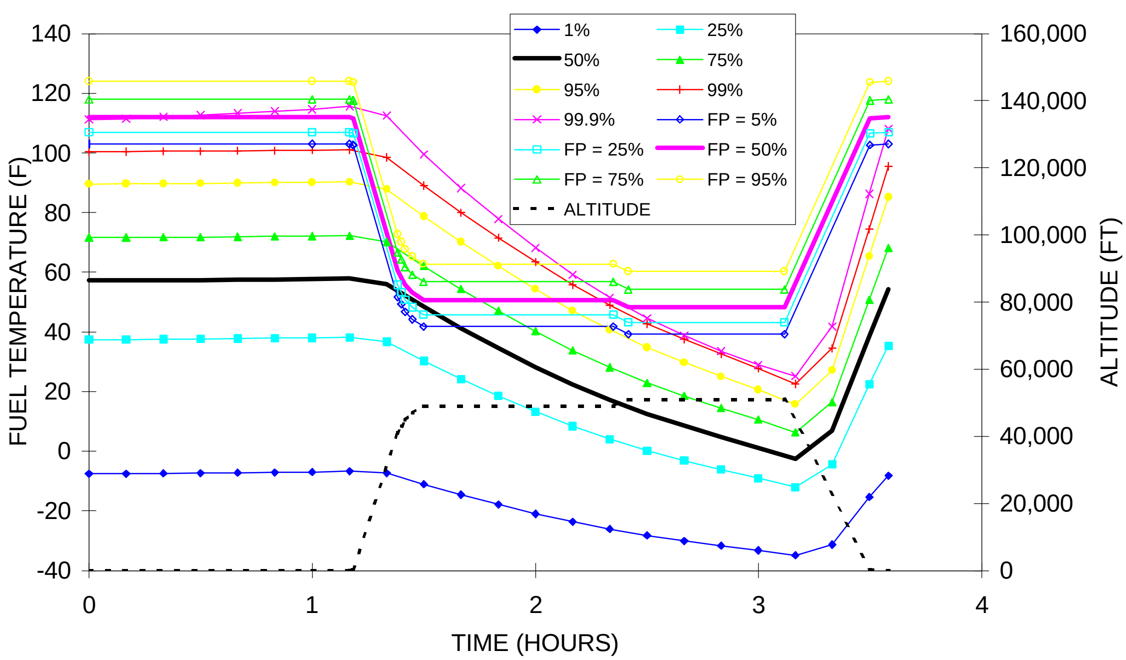
Task Group 5 then used this data to derive the flashpoint versus time profiles that correspond to each fuel temperature profile, for each mission profile of each aeroplane tank configuration. For example; the Business Jet – Short Mission flashpoint profiles are shown in Chart 5.2.7.

Chart 5.2.7 Business Jet – Short Mission. Range of Fuel Flashpoints



The next step was to over lay the fuel temperature profiles with the corresponding flashpoint profiles for each mission profile and for each aeroplane tank configuration. For example; the Business Jet – Short Mission profiles are shown in Chart 5.2.8.

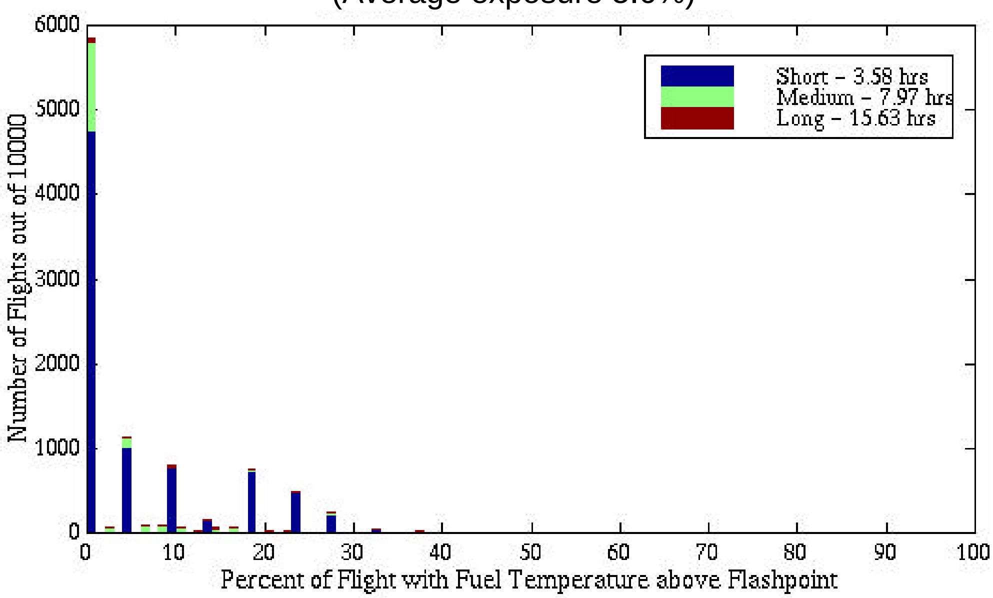
Chart 5.2.8 Business Jet – Short Mission. Predicted Fuel Temperatures for a Range of Ambient Temperatures and Flashpoints.



The time of exposure can be visualised by looking at the part of the mission where the band of fuel temperature lines (filled in symbols) are above the band on flash point line (open symbols). Another way to visualise the time of exposure is to focus only on the overlap of the two solid lines representing the average fuel temperature and the average flash point.

To quantify the fleet exposure, a statistical analysis approach was applied to a statistically significant number (10,000) of randomly selected flights. The flights were then selected to be representative of the fleet using the defined distributions of the three variables. For example, flight one may be a short mission on a cold day with an average flash point fuel, and flight two may be a long mission on an average day with a low flash point fuel, and on and on until 10,000 flights have been defined in this manner. For every one of the 10,000 flights, the time that the fuel temperature was above the flash points was calculated.
These statistical analysis results are best displayed in the form of a histogram showing the number of flights at each percentage of flight time. For example; a histogram the Business Jet which accounts for all three mission lengths is shown in Chart 5.2.9.

Chart 5.2.9 Histogram of 10,000 Business Jet Flights
(Average exposure 5.6%)



Averaging the results for all 10,000 flights provides an average percentage of the flight time that any particular flight could be expected to be exposed to a fuel temperature above the fuel flash point. These fleet average exposure results are given for each aeroplane size/tank configuration in table 5.2.10.

Table 5.2.10 Exposure Analysis Results For Centre and Wing Tanks

Wing Tanks				CentreTanks				
WITHOUT adjacent heat sources				WITHOUT adjacent heat sources		WITH adjacent heat sources		WITH adjacent heat sources and directed ventilation
large	small	regional turbofan	bizjet	small	regional turbofan	large	small	medium
5%				5%		**30%**		5%

(Due to differences between the various thermal models and thus differences in the possible errors in calculation the analysis results have been rounded to within 5%).

Once the current fleet exposures to fuel tanks with flammable vapours are calculated, the same method of thermal analysis is used to systematically study methods to reduce the exposure in fuel tanks.

6. METHODS CONSIDERED

6.1. Reducing the Evolution of Fuel Vapours

Fuel flammability is dependent upon fuel vapour-air ratios which are a function of temperature and pressure. Therefore by controlling either of these two parameters the flammability of fuel tanks can be manipulated. The methods considered in this section are therefore separated between controlling temperature, (6.1.1. and 6.1.2.), and controlling pressure, (6.1.3.), (the control of temperature is sub-divided into minimising the effects of heat sources, (6.1.1.), and active cooling, (6.1.2.).

6.1.1. Controlling Temperature

These methods have only been considered for Large, Medium and Small jet transport aeroplanes as these are the only aeroplanes identified by Task Group One as having centre wing tanks with adjacent heat sources.

6.1.1.1. Insulate Fuel Tanks from Adjacent Heat Sources

For fuel tanks located in aeroplane wings, apart from solar radiation, they are not materially affected by heat sources therefore the insulation of these tanks is not considered appropriate. However for centre wing tanks with adjacent heat sources, insulation is considered.

Thermal analysis shows that the benefits that could be achieved on the ground by thermal insulation of the bottom surface of centre wing tanks, (reducing the heating effects from air-conditioning packs, e.t.c.), would be offset by the lower cooling rate experienced in flight, (prolonging the exposure during flight).

Due to;

a) the questionable benefits such a modification would provide

b) a comparison to other options discussed in this report

this option is not considered further within this report.

6.1.1.2. Insulate Heat Sources Adjacent to Fuel Tanks

Insulation of heat sources adjacent to centre wing tanks would reduce the heating of the contained fuel on the ground without being detrimental to the cooling of that fuel in flight. The potential modifications could be relatively simple to design and retrofit onto many, (but not all), existing aeroplanes, however the affect on the operation of the systems insulated requires specific evaluation. Thermal analysis predicts this modification will reduce the exposure of the Large generic centre wing tank from 27% to 19%.

The benefits of this method of reducing the heating effects on the centre wing tank are considered further by means of thermal analysis within section 8 of this report.

6.1.1.3. Ventilate Heat Sources Adjacent to Fuel Tanks

Ventilation of heat sources with ambient air in flight will reduce the heating of the fuel tank. Thermal modelling and flight testing on a large aeroplane has shown that this method provides only minimal reductions in fuel temperature. Thermal analysis predicts this modification will reduce the exposure of the Large generic centre wing tank from 27% to 22%.

The analysis suggests that for a ventilation system to be effective, it must operate on the ground with a cooler source of air and must be directed effectively between the heat source and the fuel tank. (See section 6.1.1.4.).

Due to;

a) the results of thermal analysis

b) a comparison to 6.1.1.4. discussed in this report

this option is not considered further within this report.

6.1.1.4. Ventilate the Space Between Fuel Tanks and Adjacent Heat Sources

Directed forced ventilation in the space between heat sources and fuel tanks is implemented on some aircraft today to limit the temperature of the aircraft structure. The cooling effect is equally effective on the ground and flight. The systems presently used are simple in principle, but implementation on existing aeroplanes, which do not have such a system, would require significant modifications.

Thermal analysis predicts the exposure of the Medium generic centre wing tank with this modification will be 4%.

The benefits of this system in reducing the heating effects of the centre wing tank are considered further by means of thermal analysis within section 9 of this report.

6.1.1.5. Redistribute Mission Fuel into Fuel Tanks Adjacent to Heat Sources

Increasing the quantity of fuel uplifted into the centre wing tank has been shown, by thermal analysis, to slow the effective rate of temperature increase of the contained fuel on the ground. This approach could involve significant changes to the operation of the aeroplane and require re-examination of the aeroplane strength criteria, which affects the effective life of an aeroplane.

The benefits of this method in reducing the heating effects in the centre wing tank are considered further by means of thermal analysis within section 10 of this report.

6.1.1.6. Locate Significant Heat Sources Away From Fuel Tanks

On most, (but not all), aeroplanes the main heat sources are the environmental control system packs and the associated pneumatic ducts, normally situated beneath the centre wing tank. The packs can not be removed from the aeroplane, as they are essential for flight, to provide pressurised air for heating/cooling and pressurisation of the cabin/fuselage/equipment.

For those aeroplanes with environmental control system packs and the associated pneumatic ducts situated beneath the centre wing tank their relocation is impractical. This is due to the utilisation and optimisation of all available space on an aeroplane. The relocation of such large components would disrupt many other aeroplane components and systems.

Thermal analysis predicts the exposure of a Small generic centre wing tank without adjacent heat sources to be 1%.

For existing aeroplanes this option is not considered further within this report, due to;

(a) the fact that aeroplane design is optimised leaving no practicable location to reposition the equipment
(b) that if the necessary space was available the estimated significant costs of redesign, certification and retrofit are prohibitive.
(c) a comparison to other options discussed in this report

New aeroplane designs could locate the environmental control system packs away from the fuel tanks. However this would have a very significant effect becoming a principle driver in the overall configuration and design of the aeroplane, (due to the significant mass and volume environmental control systems occupy.

The benefits of this approach are considered further by means of thermal analysis within section 11 of this report.

6.1.2. Active Cooling

6.1.2.1. Cool the Fuel During Refuelling

Loading cooled fuel is already proposed for very small business aeroplanes. This is done not as a method of reducing fuel tank flammability, but as a means of increasing range by enabling the uplift of additional fuel mass. The exposure of empty fuel tanks is not significantly affected.

If such a measure was required for all commercial flights, (as a means of reducing the exposure of fuel tanks to flammable vapours), it would necessitate a massive capital investment at all the world's airports, to purchase and install cooling equipment. The cooling equipment would need to cool the fuel very fast to prevent impacting on the aeroplane dispatch time, and thus would be physically large. For airports having fuel hydrant systems then the cooling equipment could be stored underground. However for airports using fuelling trucks then the cooling equipment would need to be towed on a trailer which would increase further the congestion around the aeroplane.

Additionally cooling would increase the operational costs associated with uplifting fuel:

- It requires approximately 45kJ to cool 1kg of JETA from 40°C to 20°C, (104°F to 68°F).
- A medium size aircraft flying a medium length mission requires 25,000kg of fuel and therefore an energy requirement of 1,125,000kJ.

Present certification regulations require that each fuel tank must have an expansion space not less than 2% of the tank capacity. The loading of fuel cooler than the ambient air temperature would result in either;

(i) A restriction on the maximum fuel volume that could be uplifted.

(ii) A time limitation between refuelling and take-off which if exceeded due to airport constraints, would require defuelling of the aeroplane.

These are due to the fact that the fuel will heat up inside the fuel tank and thus expand with the potential of a fuel spillage onto the ground, which would represent a very real fire hazard.

Due to;

(a) This option would not be effective for empty fuel tanks.

(b) The significant capital investment which would be required at all airports.

(c) The estimation that a significant increase in operational costs related to cooling would be incurred with (present technology).

(d) The significant limitations that this option could impose on aeroplane operation.

(e) A comparison to other options discussed in this report.

this option is not considered further within this report.

6.1.2.2. Cool the Fuel in the Fuel Tanks

The cooling of fuel tanks, together with the contained fuel, would require a very significant cooling capability, which is currently not available from any existing aeroplane system. Further the ability to use ground equipment to cool the tank would require the introduction of a new dedicated aeroplane subsystem and a massive investment in ground equipment. This, in turn, would lead to further ramp congestion and be detrimental to the environment. It would also introduce, under failure conditions, the possibility of fuel being dumped overboard due to expansion.

Due to;

- **(a) the impracticalities of providing the necessary energy to cool the fuel**
- **(b) the estimation that a significant increase in operational costs related to cooling would be incurred**
- **(c) a comparison to other options discussed in this report**

this option is not considered further within this report.

6.1.2.3. Cool the Heat Sources Adjacent to Fuel Tanks

The main heat sources on most aeroplanes are the environmental control system packs and the associated pneumatic ducts situated beneath the centre wing tank. Under high ambient temperatures, when the necessity to cool these sources would be greatest, the packs would be working hardest and running hottest. Thus maximum heat rejection from the packs/ducts would coincide with the requirement for maximum cooling of the heat sources.

Due to;

- **(a) the impracticalities of providing the necessary energy to cool**
- **(b) a comparison to other options discussed in this report**

this option is not considered further within this report.

6.1.3. Controlling Pressure

6.1.3.1. Pressurise the Fuel Tanks

The aim of this measure is to increase the flammability lean limit temperature by increasing the pressure, with respect to the ambient pressure, within fuel tanks.

Examples of the possible increase in the flammability lean limit temperature that could be obtained if a fuel tank is pressurised to 200 mb above the ambient pressure are approximately; 5°C (from 37°C to 42°C) at 6,000ft; 12°C (from 10°C

To pressurise fuel tanks to 200mb would require;

a) a pressurisation system.
b) an over-pressurisation protection system.
c) structural reinforcement.

The majority of present aeroplanes have structural limitations restricting the pressurisation of fuel tanks to approximately +/- 35 mb. (Aeroplanes with pressurised fuel tanks do exist today but this is mainly small business jets and the pressurisation constituted part of the initial design).

Due to;

(a) requirements for large structural reinforcements
(b) new hazards such a system would introduce
(c) a comparison to other options discussed in this report

this option is not considered further within this report.

6.2. Eliminating the Ullage

The elimination of the ullage removes the flammable fuel vapour air mixture and thus significantly reduces the potential of ignition within a fuel tank.

6.2.1. Actively Minimise the Ullage space

The aim of this measure is to minimise the ullage so that there is virtually no space for fuel vapours. This principle is used in some ground storage tanks.

The two principle means considered are:

(i) To cover the fuel surface with a sheet of impermeable material.
(ii) To fill the ullage space with an inflatable bag.

The main problem with both approaches is that, (unlike ground storage tanks), there is considerable structure within aeroplane fuel tanks. This structure causes the fuel surface to change shape as fuel is used. These changes in shape are such that it is not practicable to use a semi-rigid sheet or inflatable bag due to the snagging of structure. The use of a large number of low density impermeable “balls” would overcome the problems of snagging. However this solution would have problems of ensuring the tank vent system does not become blocked and that the “balls” do not become heaped in one corner. The heaping of balls in one corner would allow fuel vapour to fill the ullage space. (The above issues would be compounded further on aeroplanes where fuel transfers between tanks occur).

(Some military aeroplanes use collapsible fuel tanks. These eliminate the ullage by collapsing as fuel is used. Installing such devices into commercial transport aeroplanes is not practicable for similar reasons as filing the ullage space with inflatable bags).

This option is considered impractical and is not considered further within this report.

6.2.2. Remove Residual Fuel from Unused Fuel Tanks

The aim of this measure is that by removing all residual fuel you eliminate fuel vapours.

Aeroplane maintenance manuals specify that several days are required to clean and vent fuel tanks to eliminate fuel vapours. It is therefore considered impracticable to perform this task on aeroplane operations where tanks are nominally empty only intermittently.

However, for a limited number of aeroplane operations where fuel tanks are never (or extremely infrequently) used conversion from a fuel tank to a dry bay may be possible. Though preventing fuel vapours from other tanks being drawn into the “tank” during descent is a significant issue that would need to be solved. The actual conversion would require measures that, not only prevent the “tank” from being fuelled, but also prevent fuel leaks and/or provide means of detection of fuel leakage into the “tank”. Maintenance procedures would also have to be put in place to prevent any seal within the “tank” drying out. This is to prevent heavy maintenance action if the tank was to be reactivated.

For most aeroplane operations the only tank which is frequently left empty is the centre wing tank.

This measure is only practicable for fuel tanks that are intermittently if ever used. To analyse the economic impact of such a modification it would be necessary for each individual airline to analyse it’s operations.

6.3. Sweeping the Ullage

Sweeping the ullage is a method of purging the fuel vapours from the ullage space in a fuel tank with ambient air. The aim of this process is to reduce the concentration of fuel vapours to below the lower flammability limit.

6.3.1. Sweeping the Ullage of Empty Fuel Tanks

Laboratory testing of this concept has shown significant fuel evaporation. Therefore, the evaluation of this method has specifically considered only empty tanks (defined as containing only unusable fuel).

The source of air would be different for ground and flight and would depend on the specific aeroplane design. The source of air on the ground could either be a fan (on the aeroplane or on ground equipment), or the source could be pressurised air bottles. The source of air in flight could be a ram air inlet, or modifications to the vent system. To be effective, the air would have to be correctly distributed within the bays of the tank to prevent direct through flow which could leave flammable ullage. The swept air, containing fuel vapour, could exit the tank via the existing vent system.

To minimise the exposure, both a ground and flight system would be required.
Fuel that is lost through evaporation, could be condensed out in a heat exchanger and drained into a main wing tank minimising the environmental impact and waste of fuel. Testing has been conducted on a laboratory scale to evaluate this concept. Details of the testing are described in the appendix section 15.3.

The benefits of this approach have been the subject of specific testing and are considered further within section 12 of this report.

7. METHODS SELECTED FOR FURTHER EVALUATION

7.1. Insulate Heat Sources Adjacent to Fuel Tanks

The evaluation of this method has specifically considered the installation of insulation blankets around environmental control system pneumatic ducts under centre wing tanks. This evaluation was performed for the large generic aeroplane only. The results are therefore not directly applicable to any specific design.

7.2. Ventilate the Space Between Fuel Tanks and Adjacent Heat Sources

The evaluation of this method has specifically considered forced ventilation directed into the area between the environmental control system packs and the lower surface of the centre wing tanks on the ground and in flight. This evaluation was performed for the medium generic aeroplane only. The results are therefore not directly applicable to any specific design.

7.3. Redistribute Mission Fuel into Fuel Tanks Adjacent to Heat Sources

The evaluation of this method has specifically considered a change to the fuelling procedures to re-distribute a portion of mission fuel from the main wing tanks to the centre wing tank. The fuel in the centre wing tank would then be used during the initial stages of flight as part of the mission fuel. This evaluation was performed for the large generic aeroplane only. The results are therefore not directly applicable to any specific design and the potential impact on the fatigue life of the aeroplane has not been included in the assessment.

7.4. Locate Significant Heat Sources Away From Fuel Tanks

This method is only applicable for new designs of aeroplanes.

7.5. Sweeping the Ullage of Empty Fuel Tanks

The evaluation of this method has specifically considered an aeroplane system using a fan to supply air on the ground and a ram air inlet in flight.

8. INSULATE HEAT SOURCES ADJACENT TO FUEL TANKS

8.1. Safety Impact

8.1.1. Effectiveness in minimising the hazard

This method is effective in reducing the exposure of centre wing tanks to flammable vapour by limiting the heating effects of environmental control system packs, but does not eliminate the exposure. This conclusion is supported by thermal analysis of the large and small generic aeroplanes with environmental control system packs beneath the centre wing tank and insulation blankets on the pneumatic ducts in the air-conditioning pack bay. Analysis for these generic aeroplanes predicts the fleet average exposures to be reduced from **27% to 19%** for the large aeroplane.

8.1.2. Negative impacts

Specific studies of the affect on insulated equipment would need to be performed for each aeroplane model. This is necessary to ensure that there are no detrimental effects on the related system. To date there have been no negative impacts on safety identified.

8.2. Certification Impact

This method would have minimal certification impact using already approved insulation materials, but may require additional certification for new optimised insulation materials.

8.2. Environmental Impact

No additional environmental impact identified.

8.4. Aeroplane Impact

- Increased weight.
- Some aeroplanes may require system modifications to compensate for adverse effects.
- A new dedicated leak detection system may be required due to reduced accessibility.
- Insulation may not be possible in some confined spaces.

8.5. Operational Impact

- Increased maintenance of the environmental control system or other effected systems.
- Insulation could result in a reduction in the reliability of some environmental control system components due to increased running temperatures.

8.6. Cost Impact

The following estimated costs are for modifying existing aeroplane designs:

Reason for costs	Estimated cost	Conversion to $	Cost $
Evaluation and Design	750 man hrs	1 man hour = $85	$63,750
Flight Tests Required to Verify System effects	10 flight test hrs	1 flight test hour = $100,000	$1,000,000
Development Costs per Aeroplane Design			**$1,063,750**

Hardware, (insulation material and fixings)	$4,000	$1 = $1	$4,000
Installation Time	8 man hrs	1 man hour = $60	$480
Installation Costs per Production Aeroplane			**$4,480**

Hardware, (insulation material and fixings)	$4,000	$1 = $1	$4,000
Installation Time	80 man hrs	1 man hour = $60	$4,800
Lost Revenue due to down time	2 days	1 day = $6,700 S 1 day = $15,350 M 1 day = $26,800 L	$13,400 $30,700 $53,600
Retrofit Costs per In-Service Aeroplane		Small Medium Large	**$22,200** **$39,500** **$62,400**

Additional Weight of Hardware	30lbs	1lb = $9,35 S 1lb = $14,10 M 1lb = $9, 55 L	$281 $423 $287
Additional Maintenance	20 man hrs	1man hour = $60	$1,200
Additional Aeroplane Operational Costs per Aeroplane per year		Small Medium Large	**$1,481** **$1,623** **$1,487**

Total Fleet Costs to Insulate Heat Sources Adjacent to Fuel Tanks			
	Small	Medium	Large
N° aeroplanes affected	*6203*	*1091*	*1350*
N° models affected	*17*	*9*	*12*
New production per year	*200*	*50*	*100*
Design (1 off)	$18,083,750	$9,573,750	$12,765,000
Retrofit costs (1 off)	$137,706,600	$43,094,500	$84,240,000
Total one time costs	**$155,790,350**	**$52,668,250**	**$97,005,000**
Production (per year)	$896,000	$224,000	$448,000
Operation (per year)	$9,186,643	$1,770,693	$2,007,450
Total annual costs	**$10,082,643**	**$1,994,693**	**$2,455,450**

9. VENTILATE THE SPACE BETWEEN FUEL TANKS AND ADJACENT HEAT SOURCES

9.1. Safety Impact

9.1.1. Effectiveness of minimising the hazard

This method is effective in minimising the exposure of centre wing tanks to flammable vapour by limiting the heating effects of environmental control system packs, but does not eliminate the exposure. This conclusion is supported by thermal analysis of the medium generic aeroplane with centre wing tank with environmental control system packs beneath the centre wing tank, with forced ventilation directed to the area between the environmental control system packs and the lower surface of the with centre wing tank. Analysis for these generic aeroplanes predicts the fleet average exposures to be **4**% for the medium aeroplane.

9.1.2. Negative impacts

There have been no negative impacts on safety identified.

9.2. Certification Impact

There is flight experience with this type of system on current aeroplanes. Specific aeroplane designs would have to be certified with some minimal ground and flight-testing.

9.3. Environmental Impact

No additional environmental impact identified.

9.4. Aeroplane Impact

- Increased weight
- Performance drag penalty
- Effective ventilation may not be possible in some confined spaces

9.5. Operational Impact

- Increased maintenance of new system

9.6. Cost Impact

The following costs have been estimated for present aeroplane designs:

Reason for costs	Estimated cost	Conversion to $	Cost $
Evaluation and Design	10,000 man hrs	1 man hour = $80	$800,000
Flight Tests Required to Verify System effects	20 flight test hrs	1 flight test hour = $100,000	$2,000,000
Development Costs per Aeroplane Design			**$2,800,000**
Hardware, (equipment ducts and fixings)	$20,000	$1 = $1	$20,000
Installation Time	20 man hrs	1 man hour = $60	$1,200
Installation Costs per Production Aeroplane			**$21,200**
Hardware, (insulation material and fixings)	$20,000	$1 = $1	$20,000
Installation Time	300 man hrs	1 man hour = $60	$18,000
Lost Revenue due to down time	7 days	1 day = $6,700 S 1 day = $15,350 M 1 day = $26,800 L	$46,900 $107,450 $187,600
Training of Personnel	3 man hrs	1 man hour = $60	$180
Retrofit Costs per In-Service Aeroplane		Small Medium Large	**$85,080** **$145,630** **$225,780**
Operational Delays	8 hrs	I hour = $2,875	$23,000
Additional Weight of Hardware	50lbs	1lb = $9,35 S 1lb = $14,10 M 1lb = $9, 55 L	$468 $705 $478
Additional Maintenance	40 man hrs	1 man hour = $60	$240
Lost Revenue due to down time	1 day	1 day = $6,700 S 1 day = $15,350 M 1 day = $26,800 L	$6,700 $15,350 $26,800
Additional Aeroplane Operational Costs per Aeroplane per year		Small Medium Large	**$30,408** **$39,295** **$50,518**

9.6. Cost Impact (cont.)

Total fleet costs to ventilate the space between fuel tanks and adjacent heat sources			
	Small	Medium	Large
N° aeroplanes affected	*5448*	*445*	*1350*
N° models affected	*14*	*4*	*12*
New production per year	*200*	*50*	*100*
Design (1 off)	$39,200,000	$11,200,000	$33,600,000
Retrofit costs (1 off)	$463,515,840	$43,094,500	$84,240,000
Total one time costs	**$502,715,840**	**$64,805,350**	**$304,803,000**
Production (per year)	$4,240,000	$1,060,000	$2,120,000
Operation (per year)	$165,662,784	$17,486,275	$68,199,300
Total annual costs	**$169,902,784**	**$18,546,275**	**$70,319,300**

10. REDISTRIBUTE MISSION FUEL INTO FUEL TANKS ADJACENT TO HEAT SOURCES

10.1. Safety Impact

10.1.1. Effectiveness in minimising the hazard
This method is effective in reducing the exposure of centre wing tanks to flammable vapour by limiting the heating effects of environmental control system packs, but does not eliminate the exposure. This conclusion is supported by thermal analysis of the large generic aeroplane with centre wing tanks with environmental control system packs beneath the centre wing tank. With a portion of mission the fuel initially loaded into the centre wing tank (10-15% full), analysis for this generic aeroplane predicts the fleet average exposure to be reduced from **27% to 20%** for the large aeroplane.

10.1.2. Negative impacts
The possibility of fuel system mismanagement could have a negative impact on safety. There would also be increased crew workload, which for short missions would occur during already heavy workload periods.

10.2. Certification Impact
There would be some structural analysis required to assess the impact on structural fatigue and system analysis/flight testing to verify the behaviour of the aeroplane.

10.3. Environmental Impact
No additional environmental impact identified.

10.4. Aeroplane Impact
- Structural impacts would need to be analysed for each aeroplane model to verify the impact on the fatigue life of the wing structure
- New procedures would need to be written and approved
- Changes to system warnings and alarms may be required
- Re-programming of fuelling systems may be required

10.5. Operational Impact
- Ground crews and flight crews would have to be retrained on the new procedures for all operations worldwide.
- Dependant on the optimised fuel mass to be loaded into the centre wing tank and the resultant structural impact analysis, some operations may be cargo and/or fuel load restricted. The costs associated with this payload penalty have been estimated assuming (a) an optimum fuel load would be approx. 7% of a full tank and (b) approximately 90% flights are normally operated without fuel in the centre tank of which 10% would be payload limited.

10.6. Cost Impact

The following costs have been estimated for applying this procedural modification to existing aeroplane designs:

Reason for costs	Estimated cost	Conversion to $	Cost $
Evaluation and Design of Installation	750 man hrs	1 man hour = $80	$60,000
Flight Tests Required to Verify System effects	2 flight test hrs	1 flight test hour = $100,000	$200,000
Development Costs per Aeroplane Design			**$260,000**

Training of Personnel	5 man hrs	1 man hour = $60	$300
Lost Revenue due to Payload Penalty	S 1,500 lbs M 4,500 lbs L 12,000 lbs	1lb = $9,35 S 1lb = $14,10 M 1lb = $9, 55 L	$14,025 $63,450 $114,600
Additional Aeroplane Operational Costs per Aeroplane per year		Small Medium Large	**$14,325** **$63,750** **$114,900**

Total fleet costs to redistribute mission fuel into fuel tanks adjacent to heat sources			
	Small	Medium	Large
N° aeroplanes affected	*5,448*	*445*	*1350*
N° flights affected	*9.5%*	*9.0%*	*8.8%*
N° models affected	*17*	*6*	*12*
New production per year	*200*	*50*	*100*
Design (1 off)	$4,420,000	$1,560,000	$3,120,000
Total one time costs	**$4,420,000**	**$1,560,000**	**$3,120,000**
Operation (per year)	$ 7,414,047	$2,553,188	$13,650,120
Total annual costs	**$ 7,414,047**	**$2,553,188**	**$13,650,120**

11. LOCATE SIGNIFICANT HEAT SOURCES AWAY FROM FUEL TANKS

11.1. Safety Impact

11.1.1. Effectiveness in minimising the hazard
This method is effective in minimising the exposure of centre wing tanks to flammable vapour by removing the heating effects of environmental control system packs, but does not eliminate the exposure. This conclusion is supported by thermal analysis of a small aeroplane without environmental control system packs beneath the centre wing tank. The fleet average exposure for this generic aeroplane is estimated to be **1%.**

11.1.2. Negative impacts
There have been no negative safety impacts identified.

11.2. Certification Impact
No additional certification work required for new aeroplane designs.

11.3. Environmental Impact
No additional environmental impact identified.

11.4. Aeroplane Impact
Space is a precious commodity on all aircraft. The use of any space is optimised particularly on the issues of system weight and complexity.

Recent aeroplane designs have been affected by the size of jet engines, the effect of which has lead to designs with wing mounted engines. On such aeroplanes it has been shown that the optimised location for environmental control system packs is beneath the centre wing tank. Relocation of the environmental control system packs would be a significant driver for the total aeroplane configuration as well as increasing the weight and complexity of the systems. Quantifying the impact of this method would only be possible for specific new designs.

11.5. Operational Impact
The operation of the aircraft could be impacted by the location of the ground service ports, (dependent on the specific designs).

11.6. Cost Impact

The following costs have been estimated for applying this requirement to New aeroplane designs:

Reason for costs	Estimated cost	Conversion to $	Cost $
Reconfiguration of Aeroplane	50,000 man hrs	1 man hour = $80	$4,000,000
Flight Tests Required to Verify System effects	100 flight test hrs	1 flight test hour = $100,000	$10,000,000
Development Costs per Aeroplane Design			**$14,000,000**

Hardware, (additional material and fixings)	$ **?**	$1 = $2,875	$?
Installation Costs per Production Aeroplane			**$?**

Additional Weight of Hardware	**?** lbs	1lb = $9,35 S 1lb = $14,10 M 1lb = $9, 55 L	$? $? $?
Additional Aeroplane Operational Costs per Aeroplane per year		Small Medium Large	**$?** **$?** **$?**

Total fleet costs to locate significant heat sources away from fuel tanks			
	Small	Medium	Large
N° models affected	*2*	*1*	*1*
New production per year	*50*	*50*	*50*
Design (1 off)	$28,000,000	$14,000,000	$14,000,000
Total one time costs	**$155,790,350**	**$52,668,250**	**$97,005,000**
Production (per year)	$?	$?	$?
Operation (per year)	$?	$?	$?
Total annual costs	**$?**	**$?**	**$?**

12. SWEEP THE ULLAGE OF EMPTY FUEL TANKS

12.1. Safety Impact

12.1.1. Effectiveness of minimising the hazard
Quantifying the reduction in exposure that could be achieved in an actual aeroplane environment will require further testing and analyses.

12.1.2. Negative impacts
By introducing a new system into the fuel system, there are increased risks of failure conditions. One such risk is over-pressurisation of the fuel tanks if fuelling and sweeping occur at the same time. A second risk is the loss of mission fuel if sweeping occurs in a non-empty tank, due to evaporation.

12.2. Certification Impact

This method would require further laboratory, and aeroplane testing, (both ground and flight), and would require complete system certification. Proving the tank to be in a non-flammable condition requires vapour sampling instrumentation, for which speciality equipment is available for laboratory use, but no such equipment is available for aeroplane installations.

12.3. Environmental Impact

Sweeping the ullage would increase fuel vapour emissions out of the fuel tank. A system could be designed to collect the fuel vapour, but would add system complexity.

12.4. Aeroplane Impact

- There would be additional weight of an air distribution system in the fuel tank.
- There may also be additional weight if a fuel vapour collection system is required.
- The addition of a new sweeping system would require additional fire protection systems.

12.5. Operational Impact

- A source of air would be required, both on the ground and in flight. A ground system could increase ground time and involve ground crew training. A flight system would incur a drag penalty to the aircraft performance.

12.6. Cost Impact

The following costs have been estimated for applying this modification to existing aeroplane designs:

Reason for costs	Estimated cost	Conversion to $	Cost $
Evaluation and Design	20,000 man hrs	1 man hour = $80	$1,600,000
Flight Tests Required to Verify System effect	100 flight test hrs	1 flight test hour = $100,000	$10,000,000
Development Costs per Aeroplane Design			**$11,600,000**
Hardware, (equipment, pipe-work and fixings)	$60,000	$1 = $1	$60,000
Installation Time	50 man hrs	1man hour = $60	$3,000
Installation Costs per Production Aeroplane			**$63,000**
Hardware, (equipment, pipe-work and fixings)	$60,000	$1 = $1	$60,000
Installation Time	1,000 man hrs	1 man hour = $60	$60,000
Lost Revenue due to down time	25 days	1 day = $6,700 S 1 day = $15,350 M 1 day = $26,800 L	$167,500 $383,750 $670,000
One Time Training of Personnel	3 man hrs	1 man hour = $60	$180
Retrofit Costs per In-Service Aeroplane		Small Medium Large	**$287,680** **$503,930** **$790,180**
Operational Delays	16 hrs	I hour = $2,875	$46,000
Additional Weight of Hardware	70lbs	1lb = $9.35 S 1lb = $14.10 M 1lb = $9.55 L	$655 $987 $669
Additional Maintenance	60 man hrs	1 man hour = $60	$3,600
Lost Revenue due to down time	1 day	1 day = $6,700 S 1 day = $15,350 M 1 day = $26,800 L	$6,700 $15,350 $26,800
Additional Aeroplane Operational Costs per Aeroplane per year		Small Medium Large	**$56,955** **$65,937** **$77,069**

12.6. Cost Impact (cont.)

Total fleet costs to sweep the ullage of empty fuel tanks			
	Small	Medium	Large
N° aeroplanes affected	*6203*	*1091*	*1350*
N° models affected	*17*	*9*	*12*
New production per year	*200*	*50*	*100*
Design (1 off)	$197,200,000	$104,400,000	$139,200,000
Retrofit costs (1 off)	$1,784,479,040	$549,787,630	$1,066,743,000
Total one time costs	**$1,981,679,040**	**$654,187,630**	**$1,205,943,000**
Production (per year)	$12,600,000	$3,150,000	$6,300,000
Operation (per year)	$353,291,865	$71,937,267	$175,980,417
Total annual costs	**$365,891,865**	**$75,087,267**	**$182,280,417**

13. CONCLUSIONS

Thermal analysis has shown that all generic fuel tank designs have some exposure to flammable fuel vapour.

- Tanks without adjacent heat sources, independent of their location in the aeroplane, (wing or fuselage), have equivalent exposure of approximately 5%.
- Tanks that have adjacent heat sources have exposure of approximately 30%.

Thirteen options have been considered. Only one eliminates exposure to fuel vapours. This is achieved by disabling the fuel tank and thus has severe operational consequences that can only be evaluated for individual airlines operations, and thus no conclusion is provided within this report.

Five of the methods considered reduce the exposure to flammable fuel vapour, and have been evaluated for the Small, Medium and Large transport Aeroplanes:

1. Insulate the heat source adjacent to fuel tanks
2. Ventilate the space between fuel tanks and adjacent heat sources
3. Redistribute mission fuel into fuel tanks adjacent to heat sources
4. Locate significant heat sources away from fuel tanks.
5. Sweep the ullage of empty fuel tanks

Options 2 and 4 have been shown to reduce the exposure of fuel tanks with adjacent heat sources to a level similar to fuel tanks without adjacent heat sources. (Option 4 is only applicable to new aeroplane designs).

Option 5 requires significant further research before a conclusion on its feasibility can be reached. (Table 13.1 summarises the effects and impact of the five options).

In addition the effects of ground inerting and changing the fuel flashpoint specification have been assessed. Either of these methods could reduce the exposure of fuel tanks with adjacent heat sources to a level similar to fuel tanks without adjacent heat sources. (Table 13.2 summarises the effects on exposure of ground inerting, changing the flashpoint, and some potential combinations of modifications (that could be evaluated in the timeframe available).

Table 13.1 Summary of impacts and applicability of the five methods evaluated

Centre Wing Tanks With Adjacent Heat Sources Exposure to Flammable Vapours **30%**					
Fuel Tanks Without Adjacent Heat Sources Exposure to Flammable Vapours **5 %**					
OPTION **IMPACT**	1. Insulate	2. Ventilate	3. Redistribute	4. Locate	5. Sweep
Estimated Exposure to Flammable Vapours after Modification	**20%**	**5%**	**20%**	**5%**	Not quantified
New safety Concerns	*minor*	*none*	**Medium**	*none*	**Medium**
Certification Impact	*minor*	*minor*	*minor*	*none*	**MAJOR**
Environmental Impact	*none*	*none*	*none*	*none*	**YES**
Aeroplane Impact	*minor*	**Medium**	*minor*	**MAJOR**	**Medium**
Operational Impact	*minor*	*minor*	**MAJOR**	*minor*	**MAJOR**
One Time Fleet Costs ($ x 10^6) Small Medium Large	160 50 100	500 60 300	4 2 3	160 50 100	2,000 650 1,200
Annual Fleet Costs ($ x 10^6) Small Medium Large	10 2 2	170 20 70	7 3 14	? ? ?	370 80 180
Applicability	MOST	MOST	MOST	**NEW DESIGNS**	MOST

Table 13.2 Summary of the effects of changing the fuel flashpoint, ground inerting and combinations of different modifications.

Modification	**Wing Tanks Without heat sources**	**Centre Tanks without heat sources**	**Centre Tanks with heat sources**
Current Aeroplanes	***5%***	***5%***	*30%*
120°F Flashpoint Fuel	**< 1%**	**< 1%**	**10 to 20%**
130°F Flashpoint Fuel	**< 1%**	**< 1%**	**5 to 10%**
140°F Flashpoint Fuel	**< 1%**	**< 1%**	**1 to 5%**
150°F Flashpoint Fuel	**< 1%**	**< 1%**	**1%**
Ground Based Inerting of Fuel Tanks	*Not applicable*	**< 1%**	**1%**
Combinations of Modifications			
Ventilate and 120°F	*Not applicable*	*Not applicable*	**< 1%**
Insulate and 120°F	*Not applicable*	*Not applicable*	**5%**
Insulate and 130°F	*Not applicable*	*Not applicable*	**1%**

14. REFERENCES

Boeing Document, D6-52754, “Handbook of Properties of Common Petroleum Fuels,” John E. Schmidt, Dec. 1984, Boeing Commercial Airplane Group, Seattle, WA.

Handbook of Aviation Fuel Properties
(Co-ordinating Research Council, Inc)

15. APPENDIX

15.1 Thermal Model Descriptions

15.1.1 Centre Wing Tank (Large Aeroplane)

A thermal model was developed and correlated for a large aeroplane centre fuel tank. It predicts liquid & ullage temperatures on the ground and during flight for various ambient and operational conditions. Operational conditions include tank fuel volumes, aeroplane pitch, environmental control system pack component temperatures, and mission length. The model also assesses the effect of aeroplane structural and operational changes on fuel and ullage temperature profiles for a range of ambient temperature profiles. The model can handle the following changes:

1. Environmental control system pack surfaces with and without insulation.
2. Environmental control system pack ventilation
3. Varying fuel volumes in tanks
4. Varying aeroplane attitude

The model evaluates the effect of the following operational and design modifications on centre wing tank, fuel and ullage temperatures for 3 mission lengths and 7 ambient air temperature profiles:

1. Existing aeroplane configuration
2. Ventilating the environmental control system pack bay with ambient air
3. Insulating the environmental control system pack bay ducts.

The model is transient and includes the following elements and influences:

1. centre wing tank
2. inboard wing tanks
3. wing structure
4. body structure
5. air conditioning (a/c) packs
6. heat transfer to and from ambient

<u>Analytical Tools</u>

Computer modelling was performed using the SINDA85 / FLUINT thermal/fluid analysis program. This program is an industry standard finite difference code, designed to handle lumped parameter thermal/fluid systems that include radiation, convection, and conduction heat transfer and single, or two-phase, fluid flow.

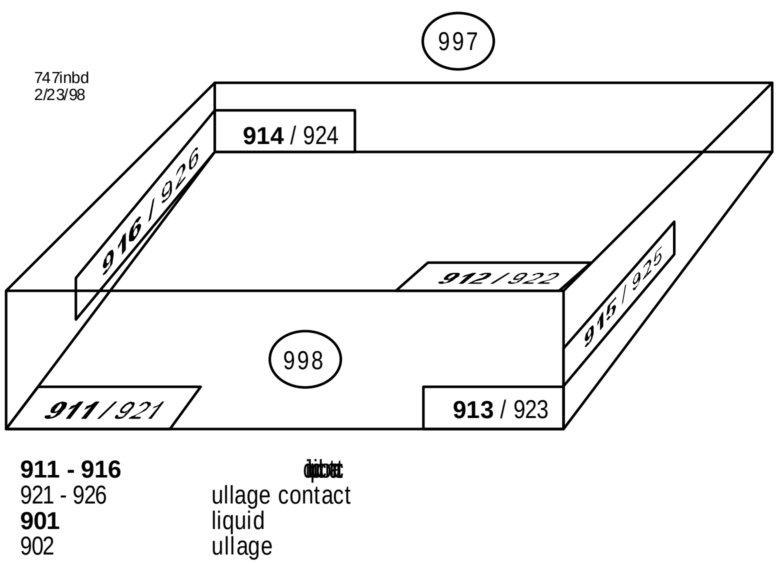
The overall model was created using three sub-models for fluid flow and one sub-model for thermal transfer. The fluid sub-models analyse air movement between the inboard wing tank and ambient, centre wing tanks and ambient, and between the pack bay and ambient through drainage holes in the environmental control system pack bay fairing.

The thermal sub-model analyses the conduction and radiation heat transfer within and between the centre wing tank, environmental control system packs and bay, and the inboard wing tanks. This high level of detail is driven by the need to identify the relative influence of a large number of variables on tank fuel temperatures.

<u>Inboard Wing Tank</u>

The inboard wing tank was included in the thermal/fluid model in order to provide a centre tank side boundary temperature. It consists of a six-sided box, as shown in figure 15.1.1.1, below. In order to capture temperature differences between surfaces in contact with the ullage and liquid each tank surface has two nodes corresponding to the surface areas in contact with ullage and liquid.

Figure 15.1.1.1



Depending on the volume of fuel in the tank and the aeroplane pitch and roll, each side of the box may be in contact with liquid or vapour, or both liquid and vapour. For example, on the ground before takeoff the lower and inboard surfaces are typically completely covered with liquid while the remaining surfaces are in contact with both liquid and ullage. During flight as fuel is withdrawn from the tank the program automatically changes the fuel and tank node thermal capacitance and conductor values to account for the new wetted contact areas. If a surface becomes completely dry during a mission then the corresponding liquid node is mathematically isolated from the model.

Tank internal heat transfer includes free convection between the tank surfaces and the liquid and ullage, and between the liquid surface and ullage and

radiation from the liquid to the upper wing surface not in contact with the liquid. A discussion of the heat transfer calculation occurs later in this write up. Internal radiation is only analysed between the liquid surface and the upper tank (wing) surface.
Tank external heat transfer includes forced convection to a total air temperature node, radiation to sky and/or ground temperature nodes and a solar load on the upper wing surface.

The ullage is modelled in the fluid sub-model as a single air node connected to ambient, which allows airflow into and out of the tank through the tank vent system as the aeroplane altitude changes. The liquid is modelled in the thermal sub-model as a single thermal node.

Center Wing Tank

The centre tank model consists of a thermal sub-model, and ullage and environmental control system pack air fluid sub-models.

The centre wing tank thermal sub-model includes the tank bottom & top, spanwise beams, front & rear spars, environmental control system pack components and, environmental control system pack bay fairing. Nodal density is greatest on the tank bottom surfaces, with 140 nodes, since these surfaces have the greatest effect on fuel temperatures, and temperature gradients are large due to uneven heating from the environmental control system packs located directly below. The node density on the remaining surfaces is less in order to minimise model run times. Nodal maps for the thermal sub-models are provided in figures 15.1.1.2 through 15.1.1.4.

The tank ullage fluid sub-model simulates ullage movement between the tank compartments and through the tank venting ducts to ambient. The environmental control system pack bay fluid sub-model models pack leakage into the environmental control system pack bay, airflow between the environmental control system pack bay and the adjacent dry bay, and ambient air leakage into and out of the pack bay through drainage holes in the pack bay fairing.

The tank bottom was divided into the 7 by 20 node grid. Unlike the inboard wing tank model the centre tank model assumes each node is in contact with either the liquid or ullage. FORTRAN control logic ensures that radiation and free convection occurs from either the liquid or tank surface for each tank bottom surface node depending on the fuel location through out the mission.

The frequency of nodes along the axis of the aeroplane is greater in order to capture the effect of fuel movement within the tank caused by changes in aeroplane pitch. Because the slope of the tank bottom is so gradual small variations in aeroplane pitch can have a large effect on the location of the fuel within the tank and more important, the total contact area between the fuel and tank bottom. As the contact area increases total heat transfer to the fuel increases since the convective heat transfer from the fuel to the tank bottom is larger than the convective heat transfer and radiation from the fuel surface to the tank ullage and inner surfaces.

The location of the fuel within the tank and the amount of fuel remaining in the tank also have a large effect on the fuel temperature. This is due to variations in heat transfer between the environmental control system pack surfaces and the tank bottom surface. To capture the effect of fuel location on fuel temperature, the fuel location and total fuel to tank bottom surface contact area is input in the model array data block. The wetted surface area between the centre wing tank fuel and tank bottom, tank side and spanwise beams which also varies with aeroplane pitch and the amount of fuel remaining in the tank is calculated on an Excel spreadsheet and imported in data arrays.

CWT Thermal Nodal Maps

Figure 15.1.1.2 Centre Wing Tank Bottom Surface Nodes

forward spar

111	112	113	114	115	116	117
121	122	123	124	125	126	127
131	132	133	134	135	136	137
141	142	143	144	145	146	147
211	212	213	214	215	216	217
221	222	223	224	225	226	227
231	232	233	234	235	236	237
241	242	243	244	245	246	247
311	312	313	314	315	316	317
321	322	323	324	325	326	327
331	332	333	334	335	336	337
341	342	343	344	345	346	347
411	412	413	414	415	416	417
421	422	423	424	425	426	427
431	432	433	434	435	436	437
441	442	443	444	445	446	447
511	512	513	514	515	516	517
521	522	523	524	525	526	527
531	532	533	534	535	536	537
541	542	543	544	545	546	547

rear spar

Figure 15.1.1.3 Centre Wing Tank Vapour and Vertical Surface Nodes

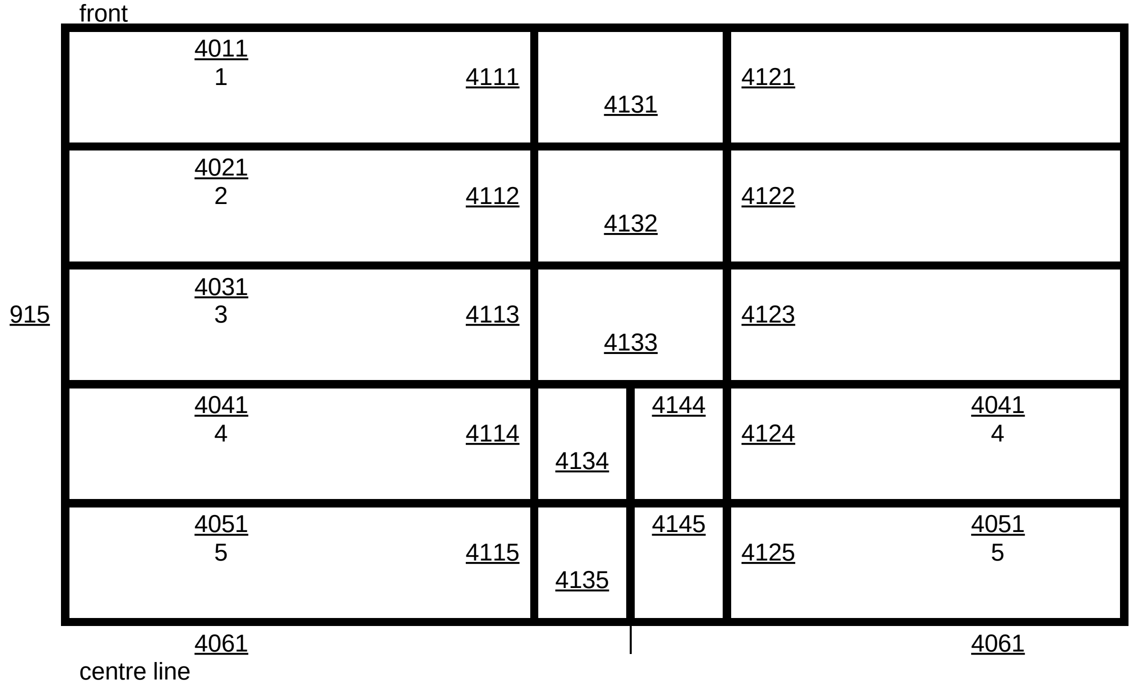


Figure 15.1.1.4 Fairing Interior and Exterior Nodes

forward spar

2811 3811	2812 3812	2813 3813	2814 3814	2815 3815	2816 3816	2817 3817
2111 3111	2112 3112	2113 3113	2114 3114	2115 3115	2116 3116	2117 3117
2211 3211	2212 3212	2213 3213	2214 3214	2215 3215	2216 3216	2217 3217
2311 3311	2312 3312	2313	2314 3314	2315 3315	2316 3316	2317 3317
2411 3411	2412 3412	2413 3413	2414 3414	2415 3415	2416 3416	2417 3417
2511 3511	2512 3512	2513 3513	2514 3514	2515 3515	2516 3516	2517 3517
2611 3611	2612 3612	2613 3613	2614 3614	2615 3615	2616 3616	2617 3617
2711 3711	2712	2713	2714	2715	2716	2717 3717

rear spar

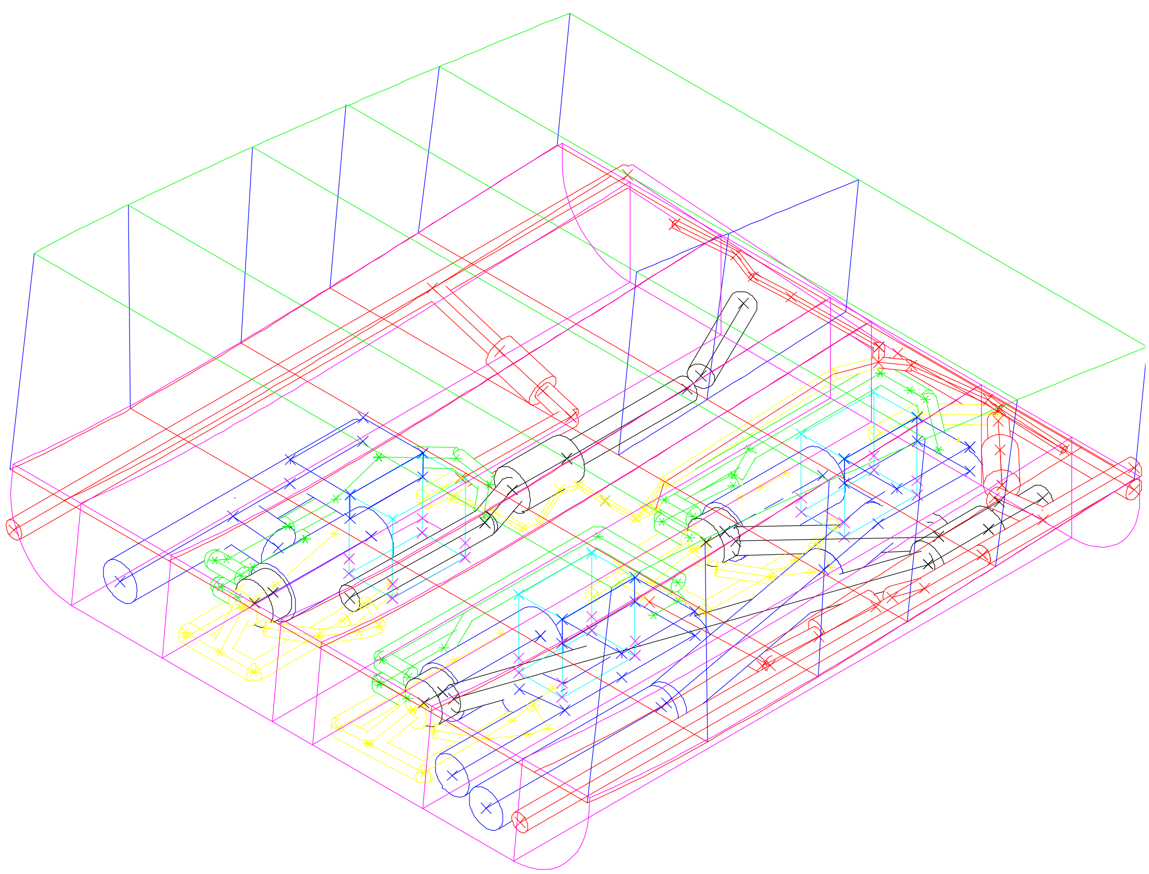
Radiation Models

The environmental control system pack bay and centre wing tank internal thermal sub-models include about 900 and 2600 radiation conductors respectively, (see figure 15.1.1.5). Radiation conductors inside the environmental control system pack bay and centre wing tank internal tank were created using Radsim, a Boeing proprietary radiation simulation program.

The environmental control system pack, bleed air, APU and supply air duct are broken up into 32 surfaces which radiate to the centre wing tank bottom and pack bay fairing interior surfaces. Each surface is assigned a unique boundary temperature, which varies during and between missions due to changes in ambient temperature and predicted pack performance. Environmental control system pack surface boundary temperatures are based on test data and predictions from a pack computer model.

Insulated ducts are modelled with an additional insulation outer surface arithmetic node connected to the duct boundary node through a conduction heat transfer path.

Figure 15.1.1.5 Environmental Control System Pack Bay Radiation Model



Convective Heat Transfer

Convection heat transfer from the exterior surfaces outside the inboard wing tank and pack bay fairing is modelled using a standard forced convection heat transfer correlation for flow over a flat plate. The program models convection heat transfer from the aeroplane exterior surfaces to a boundary ambient total air temperature node. The total air temperature assumes a 100% temperature recovery factor. For the ground conditions a 3 mile per hour wind speed is used in calculating the heat transfer coefficient.

Natural convection heat transfer coefficients are calculated for all model surfaces not in contact with the aeroplane exterior, which includes tank inner surfaces and a/c pack components. For natural convection, the heat transfer correlations are a function of temperature difference between the fluid and surface, surface orientation, fluid properties and (for horizontal surfaces) whether the surface is warmer then adjacent fluid. The program chooses the appropriate correlation, based on the above mentioned information and continuously updates all natural convection heat transfer coefficients.

Fuel Properties

The program was designed to model various fuels, (JET A, Aviation Gas, JP-4, JP-5), by setting the fuel type flag. Jet A was used for this study.

15.1.2 Main Wing Tank (Small and Large Aeroplane)

The wing tank thermal model simulates heat transfer between a fuel system and its surroundings during an aeroplane flight. This model was designed to predict in-flight fuel temperatures for (main) integral wing tanks of commercial aeroplanes using quasi-steady state equations of heat transfer.

A fuel system consists of fuel tanks, plumbing lines and components such as pumps, valves, pressure switches and the like for fuel management. There may be several fuel tanks with a provision of fuel transfer between tanks.

The time dependent heat transfer process is influenced by factors including the environment and the aeroplane flight profile. The initial fuel tank quantity also changes depending on the engine feed rate and fuel transfers from other tanks.

The principal mechanisms of heat transfer considered in this model are:

- Convective heat transfer from the aerodynamic boundary layer outside the tank to/from the tank surface
- Conductive heat transfer through the tank wall
- Convective heat transfer from the wetted tank inside wall to/from bulk fuel
- Radiative heat transfer from the fuel surface to the dry areas of tank inside wall
- Conductive heat transfer through the dry area of tank wall
- Radiative heat loss/gain from the tank outside surfaces to sky or ground
- Solar radiation to the tank surfaces

Assumption

The thermodynamic properties do not change rapidly so that the heat transfer process can be considered quasi-steady state.

Method of Solution

The generalised mass and energy conservation equations are developed for a tank. These are applied for a small time increment Δt. At each time step, recovery temperature for the aerodynamic boundary layer and Reynolds number at the tank leading edge (for determining the aerodynamic heat transfer coefficient) are calculated based on the flight profile. Similarly, tank wetted and dry areas based on fuel quantity remaining are determined. The equations are solved numerically to obtain the bulk fuel temperature at the end of the time interval for all the tanks. The process is repeated to cover the entire flight profile.

Inputs

Inputs required include:

- Fuel System Details - Number of tanks, fuel volume versus tank wetted area for each tank, tank material properties

- Atmospheric Data - Altitude versus pressure, air temperature, sky and ground temperatures
- Flight Profile - Aeroplane speed and altitude as a function of time
- Fuel Management Data - Engine feed rate and tank-to-tank fuel transfer schedules
- Internal Heat Sources - Heat inputs as a function of time
- Initial Conditions - Fuel quantity and temperature in each tank, specific gravity

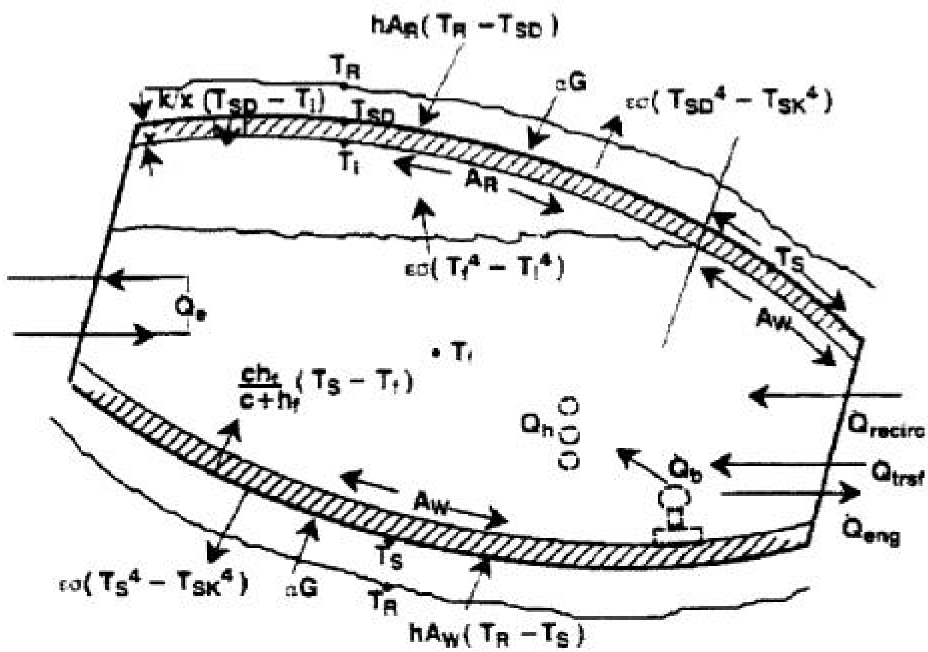
Output

The main output of the computer program is a history of fuel quantity and temperature in each tank of the fuel system.

The model described above has evolved over many years. It is highly versatile in dealing with fuel systems with a large number of tanks and complex fuel management schemes. It can also predict fuel temperature variation while the aeroplane is on the ground. The only major is its inability to provide any information on fuel temperature stratification within tanks. It is well known that such stratification, principally in the vertical plane, does occur. Fuel is mixed in flight, but not nearly enough to maintain thermal continuity. However, the model has not been designed to address this behaviour mainly to avoid complexity and to keep run times short.

Schematic

The following sketch shows various modes of heat transfer.



In addition to the heat transfer mechanisms listed above, there also is a provision for heat sources internal to the tank.

15.1.3 Centre Wing Tank (Small Aeroplane)

Model Assumptions

The wing tank thermal model described in Section 15.1.2 was used as the basis for the development of a thermal model for centre wing tanks. The centre wing tank thermal model is simplified from the main tank model by the following assumptions:

- Aerodynamic heating or cooling of the tank surfaces is not applicable.
- The tank is a basic cube, six flat surfaces without internal structure (bays).

Both models utilise the following assumptions:

- Steady state equations apply over a short time interval (0.5 minutes).
- Constant heat transfer coefficients and emissivities.
- The surface temperatures of the tank walls are uniform (uniform boundary conditions).
- Calculated fuel temperature is uniform throughout the fuel layer.
- Calculated ullage temperature is uniform throughout the ullage space.
- Ambient temperature and pressure gradients with altitude are standard atmosphere.

Boundary Conditions

For the tank wall surface temperatures, the model assumes a constant 70°F for the top wall (floor of the passenger cabin) and front wall (cargo bay). Over the flight profile, the sidewalls track the main tank fuel temperature (input from the wing tank thermal model), and the rear wall (wheel well) tracks total air temperature. The bottom wall surface temperature is calculated in the model as the boundary between the environmental control system bay and fuel tank. The bottom surface of the environmental control system bay tracks total air temperature.

Initial Conditions

For the initial conditions, the model assumes that the initial fuel, ullage, and environmental control system bay air temperatures equal the initial ambient temperature.

Model Inputs

The inputs to the program by the user are:

- Dimensions and volumes of the centre wing tank and environmental control system bay for the specific model aeroplane
- Flight profile - Altitude vs. time, including Mach No., vs. time (used to calculate total air temperature)
- environmental control system pack surface temperature vs. time
- Fuel temperature of main wing tanks vs. time

- Fuel load vs. time, including the area of the bottom surface wetted by the fuel (for small quantities only)
- Initial ambient temperature on the ground (default of 60°F)
- Initial fuel temperature (default is equal to initial ambient temperature)
- The type of fuel in the tank (specifically the flash point)
- Addition of a layer of insulation, with specified thermal conductivity and thickness, onto the bottom of the tank to study the thermal effects.

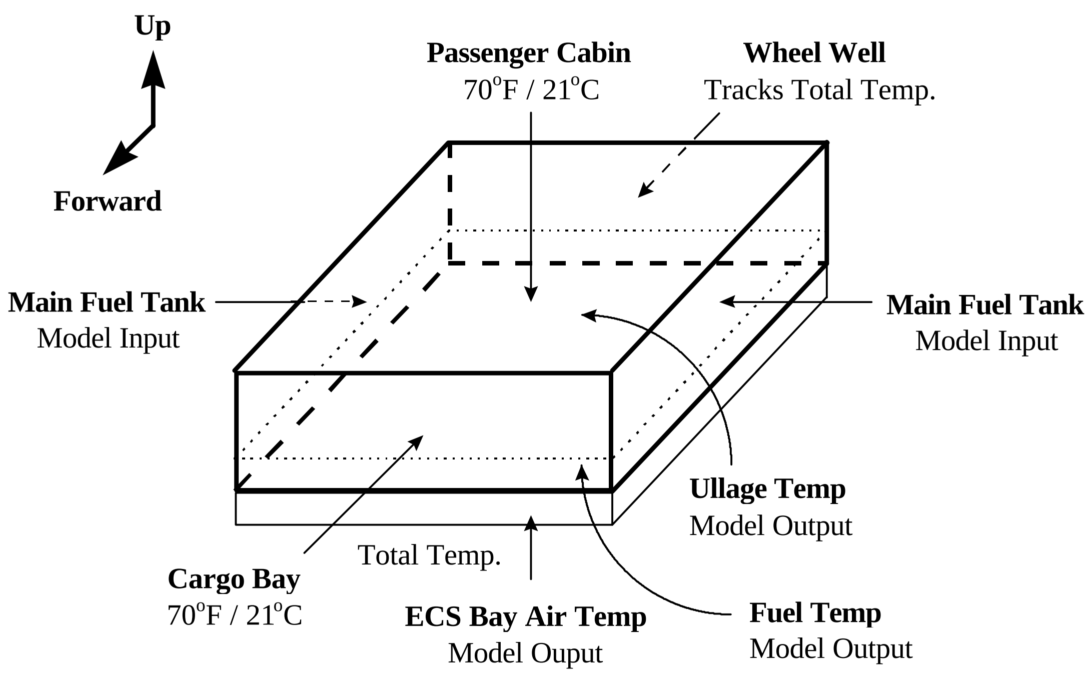
Model Output

The output of the thermal model is the predicted fuel, ullage, and environmental control system bay air temperatures over time.

Model Validation

The model has been validated with average fuel, ullage, and environmental control system bay air temperatures measured in ground and flight tests on a large aeroplane. The model does not always track the data exactly, but always predicts the trends accurately. Therefore, this simple model used in this study provides adequately accurate results to compare the effect of several options.

Center Wing Tank Thermal Model



15.1.4 Main Wing Tank (Medium Aeroplane)

A fuel wing tank model was created within British Aerospace to study the evolution of fuel temperatures during flight for both subsonic and supersonic flight. This model is presently inactive but results for a medium aeroplane both inner and outer tanks are shown in 15.2.4.

Though the model has not been used to calculate a total fleet wide exposure figure it has been used to estimate that Medium aeroplanes do not have an exposure to flammable fuel vapours significantly different to Small are Large aeroplanes.

The model calculated skin and the bulk mean fuel temperature by solving the steady state heat transfer equations for consecutive short time intervals. The results were validated against flight test and found to be within +/- 2°C.

The model considers three variables; flight profile, ground fuel temperature and ambient air temperature. The results shown in 15.2.4 use; four different flight profiles, two ground fuel temperatures and two ambient air temperatures. By use of data shown in 15.2.4 figure 7 it is possible to correct the data for other ambient air temperatures.

15.1.5 Centre Wing Tank (Medium Aeroplane)

A thermal model has been developed for a centre wing tank of generic medium size aeroplane, with directed ventilation of the space beneath the tank and a vapour seal. The model determines the temperature of fuel and ullage within the centre wing tank and the air in the compartments adjacent to the centre wing tank.

The model uses basic thermodynamic principles, in particular heat transfer by;

- convection
- conduction
- radiation

The relevant aeroplane compartments considered are;

- the environmental control system pack bay beneath the centre wing tank
- the vapour seal directly beneath the centre wing tank
- the fuel volume within the centre wing tank
- the ullage within the centre wing tank

and are shown in figure 15.1.5.1.

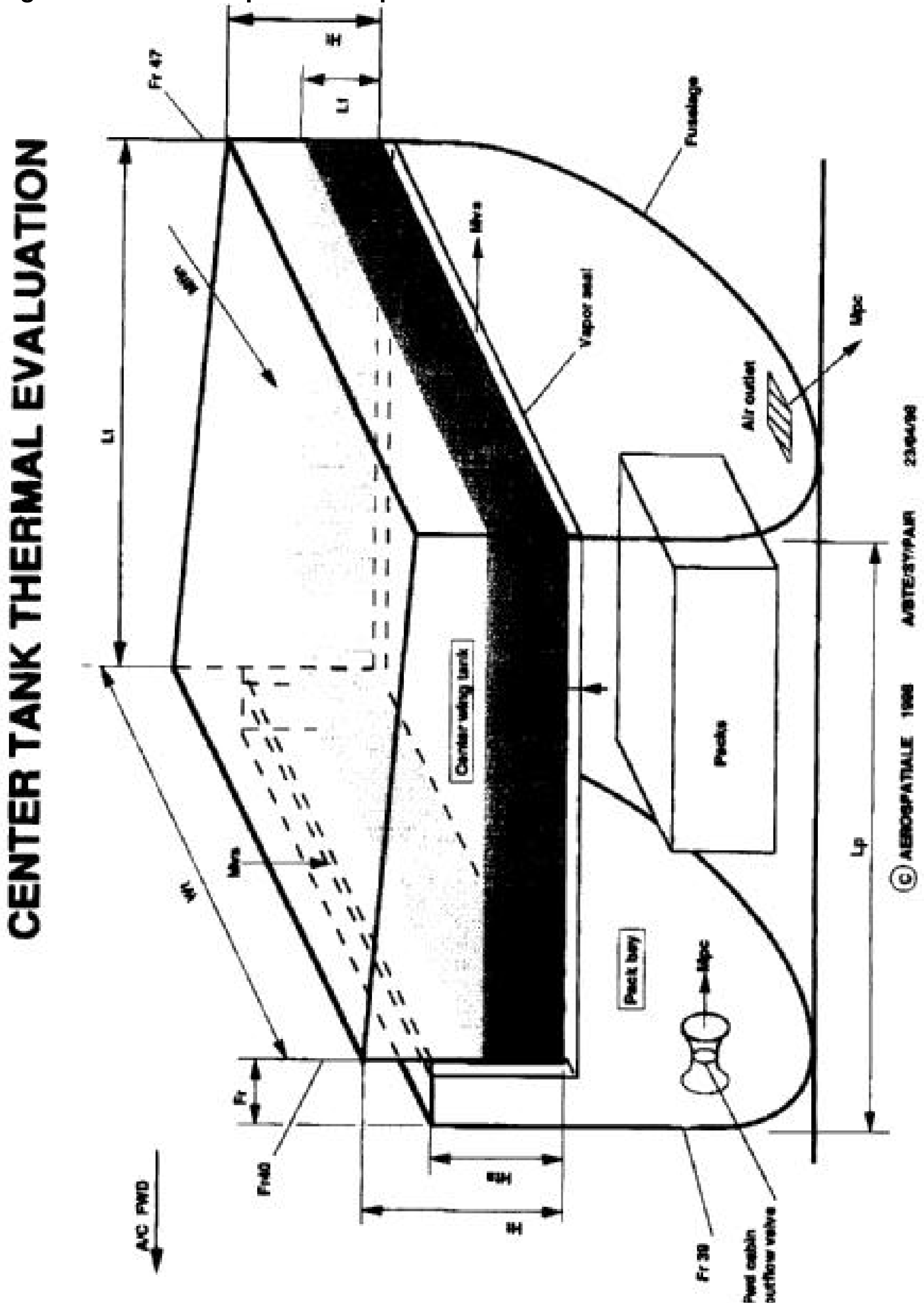
For each compartment a differential thermal balance equation has been established considering a global heat transfer of the fluid, (air, fuel and ullage), within the compartment, with the relevant surfaces in contact with the fluid.

Four thermal differential equations have been used to determine the required temperature variations during aircraft operations. These equations are resolved by use of a MATLAB software programme.

The programme takes into account the fuel consumption and hence the variation in fuel mass and level, within the centre tank during flight. Flight test data has been used to provide the temperatures of the fuel masses in the left and right wings.

The various convection coefficients of air and ullage have been corrected for changes in aeroplane altitude.

Figure 15.1.5.1 Aeroplane Compartments Considered



15.1.6 Main Wing Tank (Business Jet and Regional Turbofan)

A Thermal/Fluid fuel tank model was created to evaluate the effects of a Heated Fuel Return System (HFRS) in a bizjet wing fuel tank, (the same model was adapted to asses a generic regional turbofan). It was developed using a transient Thermal analysis program. This technique utilises the finite difference method and applies a forward time stepping approach to solve a matrix of non-linear simultaneous equations. The model is made up of a number of lumped parameters (nodes) that represent selected masses associated with the physical problem.

The program is capable of addressing conduction, convection and radiation heat transfer as well as heat sources and sinks. Subroutines are provided internally that enable the user to code detailed physical logic into the analytical model. Because of the fluid nature of the HFRS, major innovations were made in the Thermal technique in order to model in detail, the predicted fuel flows/levels throughout the tank. This has the effect of modifying both the fuel node masses and dimensions with time.

The Thermal network also utilises this embedded Fluid nodal model to account for the heat flux resulting from the liquid mass transfer. Each Thermal fuel node has an associated Fluid conductor. The model is made up of:

- 57 iterated nodes (to be solved for),
- 24 zero capacitance nodes (air nodes, to limit calculation time),
- 245 boundary nodes (used for boundary conditions, input ports or fluid links),
- 376 thermal and fluid conduction links,
- one internal heat source
- Eight external solar inputs.

The model is divided into an external reheated fuel segment and eight internal regions representing partitioned wing bays #0 through #6 and the inboard located hopper. The internal segments are connected in a series loop via fluid conductors with an internal parallel link existing between the hopper and bay #0 to account for its continuous fuel overflow.

Each bay is divided into upper and lower aluminium skins, an internal air node above the fuel and five fuel nodes. The skins are connected to the ambient turbulent recovery temperature by a turbulent forced convection coupling. The fuel nodes are connected internally by conduction and convection couplings and an additional flow couplings to allow heat to flow, (due to the fuel flow mass transfer), to connect them.

As fuel is depleted, the nodes reduce in size (height/mass) from the uppermost one, and collapse onto each other and eventually down to the lower skin. The bays are connected to each other only by flow couplings (i.e., no conduction through the ribs which is insignificant). The model utilises fuel loading/burn data in tabular form to define the amount of fuel present in any bay at any instant.

The internal convective fluid heat transfer coefficients were modified based on data obtained from two flight tests (they essentially represent the mixing caused by vibration). The first case had the HFRS off and the second had the HFRS turned on. The modified coefficients enabled the model to accurately predict the recorded data with the system both operating and not operating. The model was then applied to the second flight test with the HFRS "turned" off in the model. There was a significant difference in the results, indicating that the system was working as designed and that the model was capable of handling a broad spectrum of cases.

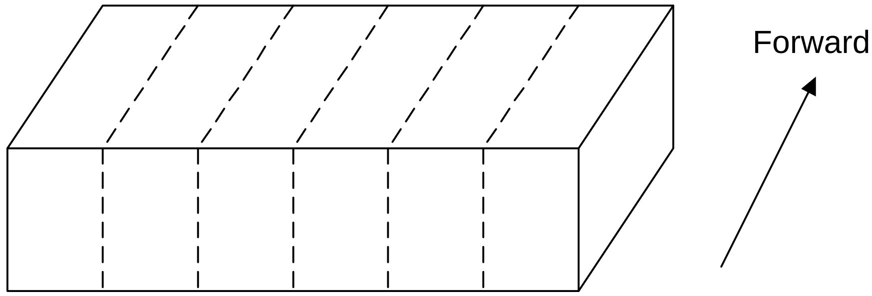
Based on these empirical/analytical results, additional test instrumentation was added to the non-heated wing (LH) and an extended flight was conducted. The results of this test were analysed using the model without further modification and the results were in good agreement with the data for both wings. As a result, it has been demonstrated that the Thermal model satisfactorily predicts the bizjet fuel temperatures and temperature stratification throughout the entire wing tank.

The model described above was used to predict the Thermal response of the fuel in the bizjet wing tank for three mission profiles and seven different temperature atmospheres. The reported results are for the innermost wing tank section (bay#1) which by virtue of containing the most fuel, cools down the slowest and results in the most severe exposure condition.

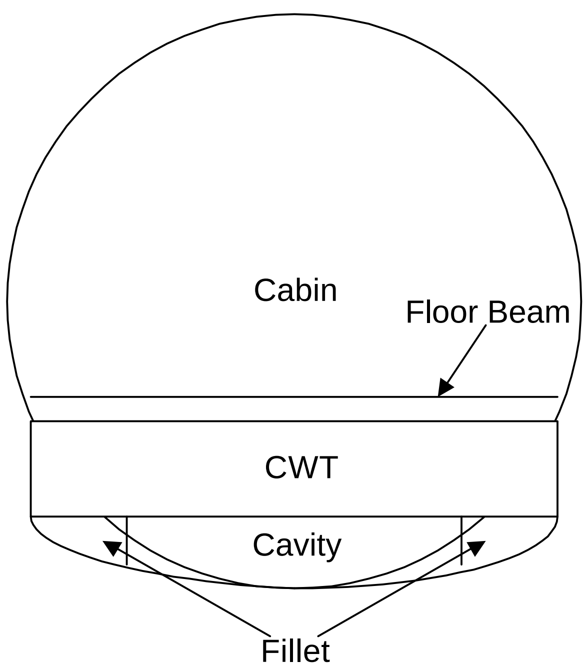
**15.1.7 Centre Wing Tank
(Small Aeroplane without Adjacent Heat Source)**

Centre Wing Tank

The centre wing tank is simulated as a basic cube with 6 fuel cells.



The following figure shows the relative position of the centre wing tank.



Analysis Tools

The System Improved Numerical Differencing Analyser (SINDA/G) thermal modelling system was used to model the centre wing tank. SINDA/G is a software system for solving lumped parameter representations of physical problems governed by diffusion-type equations. It is a general thermal analyser accepting conductor-capacitor (G-C) network representations of thermal systems.

A transient model was built to calculate the fuel temperature history inside the centre wing tank with various flight profiles. Microsoft Excel spreadsheet is used to calculate the adiabatic wall temperature vs. time.

Model Assumptions

- The surface temperatures of the tank walls are uniform.
- Radiation heat transfer is not considered.
- No heat transferred from fuel to the ullage or from ullage to fuel.
- Calculated fuel temperature and ullage temperature are uniform throughout the centre wing tank.
- Adiabatic wall temperature is used to simulate the air in the wheel well compartment and in the fillet.
- Top of the centre wing tank was exposed to the warm air between the floor beam and the centre wing tank, the heat transfer coefficient from the air to the top of the centre wing tank wall is constant.
- Both the left and right side of the centre wing tank walls were exposed to the fuel in the main fuel tank. Natural convection is assumed for the heat transfer from these walls to the fuel in the main tank.
- The Centre Auxiliary Compartment is forward of the centre wing tank, the heat transfer coefficient from the air in Centre Auxiliary Compartment to the centre wing tank wall is constant.
- The wheel well compartment is located aft of the centre wing tank, the fillets are connected to the wheel well compartment. The heat transfer coefficient is varied with time in flight depending on Mach number.
- Underneath the centre wing tank is the cavity. The air temperature in the cavity is assumed to be the adiabatic wall temperature and the heat transfer from the cavity to the bottom of the centre wing tank is assumed to natural convection.
- Ambient temperature and pressure gradients with altitude are standard atmosphere.

Boundary Conditions

For the air temperature between the floor beam and the top of the centre wing tank wall is 75° Fahrenheit. The air temperature in the Centre Auxiliary Compartment (forward of the centre wing tank) is also 75°F. Over the flight profile, the side walls tract the main tank fuel temperature (average temperature of the fuel in the centre wing tank and the main tank in the previous time step). The air temperature in the wheel well and the tunnels is equal to the adiabatic wall temperature. The air temperature under the centre wing tank wall is equal to the air temperature in the wheel well compartment.

Initial Conditions

The model assumes that the initial fuel, ullage temperatures are equal to the ambient temperature. Packs are operating on the ground before the flight. The air temperature in Centre Auxiliary Compartment and between the floor beam and the centre wing tank top wall is 75°F.

Model Inputs

- Dimensions and volumes of the centre wing tank.
- Flight profile - Fuel quantity in centre wing tank vs. time, adiabatic wall temperature vs. time, heat transfer coefficient vs. time.
- Initial ambient temperature on the ground.
- Initial fuel temperature.
- Centre Auxiliary Compartment air temperature and air temperature under the floor beam.

Model Output

The outputs of the model are the predicted fuel temperature and tank wall temperature vs. time.

15.1.8 Centre Wing Tank (Regional Turbofan)

The mission profiles considered were short and long mission lengths of 400 and 800 nautical miles. These were chosen as the proportion of flights with mission lengths between 0- 650 N.M is estimated to be 85% (short mission), and mission lengths between 650-1000 N.M at 15% (long mission).

Flight profiles were based on the delta ISA condition in flight as specified by Task Group 8 for the altitude range 20,000ft and above. For the altitude range below 20,000ft an incremental approximation was made starting at the specified ground delta ISA condition and finishing at specified delta ISA condition at 20,000ft.

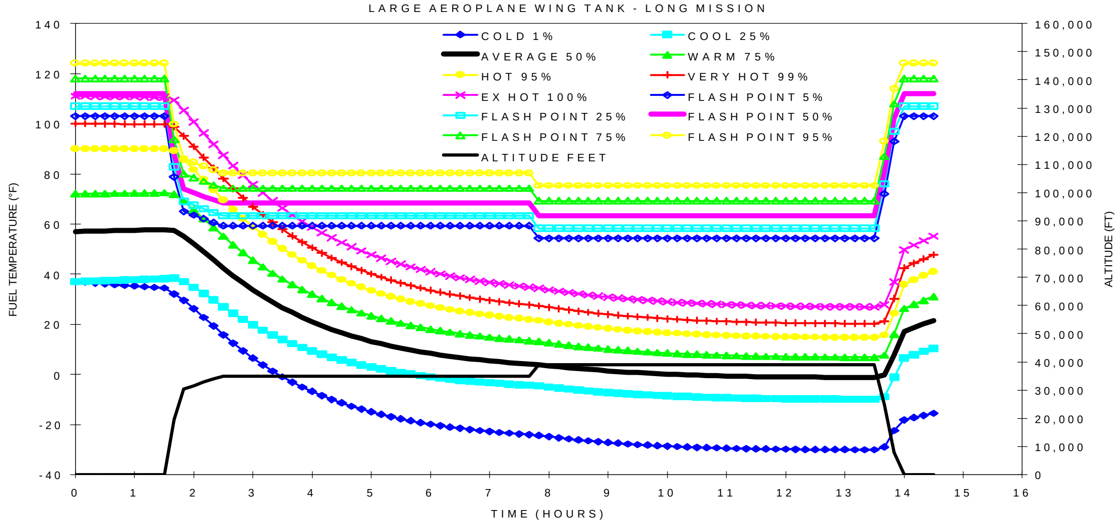
The rate of climb is based on actual engine performance for these temperatures. Ground time is 15 minutes before takeoff and 15 minutes after landing.

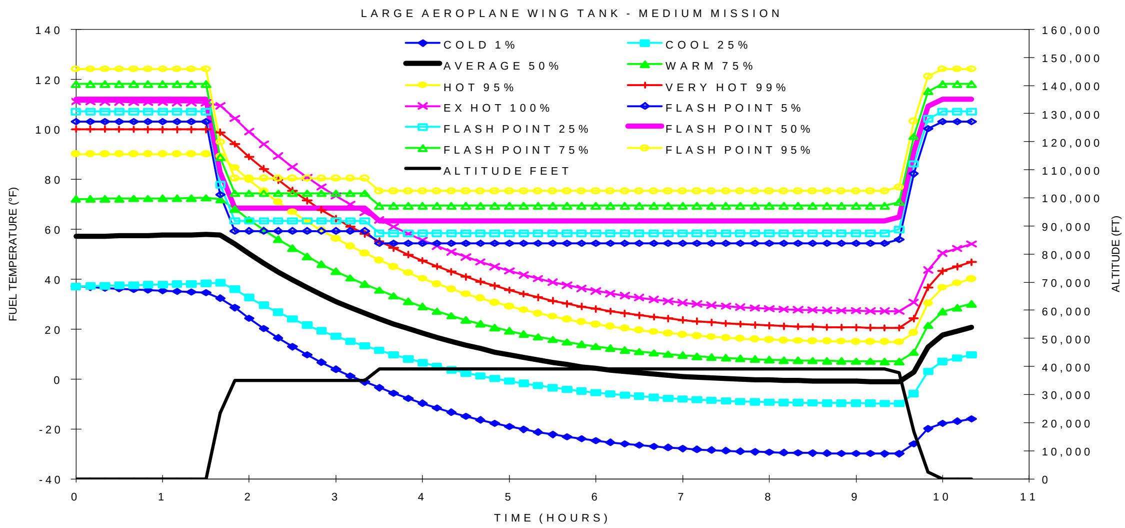
Fuel load in the centre wing tank is assumed for both mission lengths. This is very conservative and only representative for fuel tankering, i.e. flying several hops without refuelling. Normally the centre wing tank is not filled for mission lengths below 950 N.M but it may be assumed that 5% of all missions are with fuel in the centre wing tank to account for tankering. To indicate the effect of an empty centre wing tank the flight profiles are also given for 400 and 800 nautical miles for the "extremely hot" condition. For lower ambient temperature conditions the exposure % is close to zero hence not of interest in this regard.

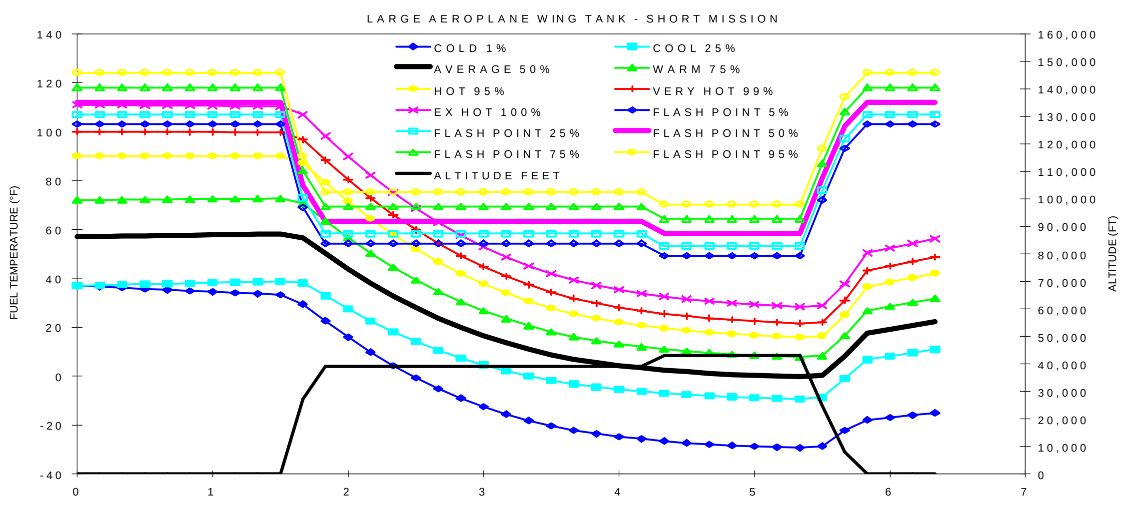
The fuel temperature always equals the ambient temperature at the start of flight. The thermal model does not account for the radiation effects because of the low temperature of air and equipment surrounding the centre wing tank. In the future, the model may need some refinement to correctly address time constants of tank structure etc.

15.2 Thermal Model Predicted Bulk Fuel Temperatures Results Charts

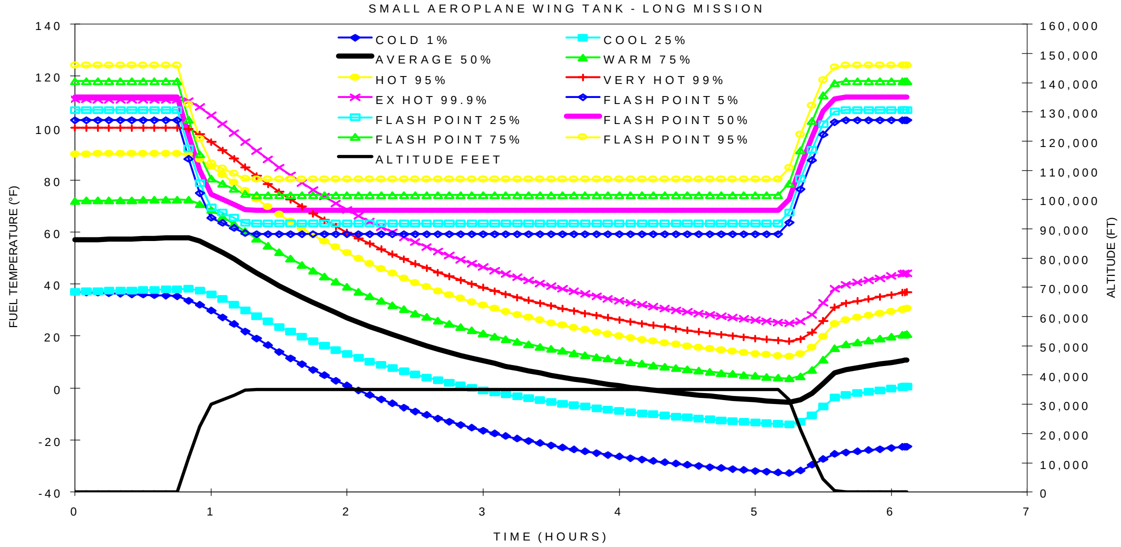
15.2.1 Large Aeroplane Wing Tank

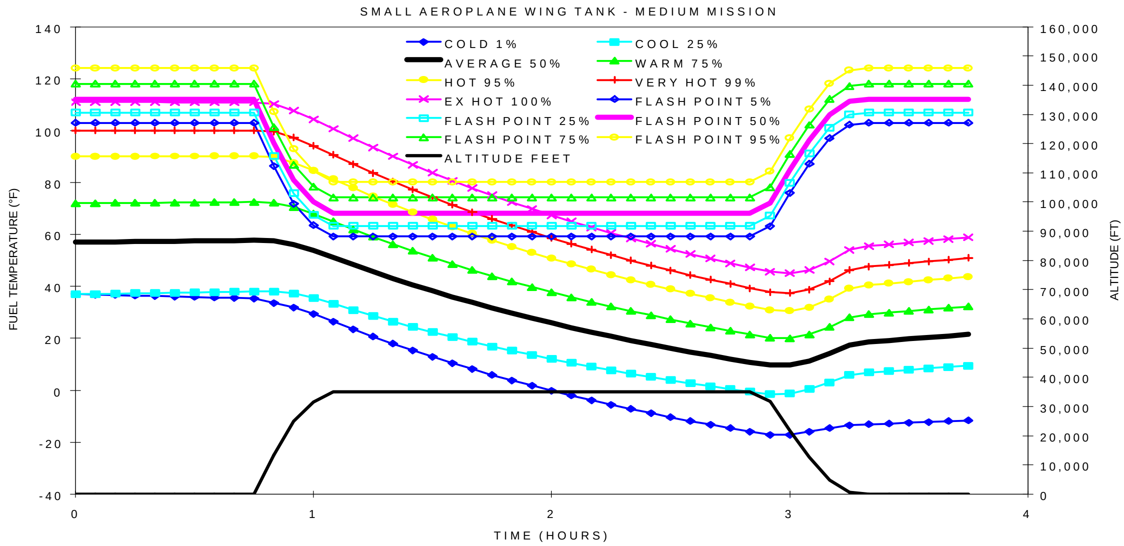


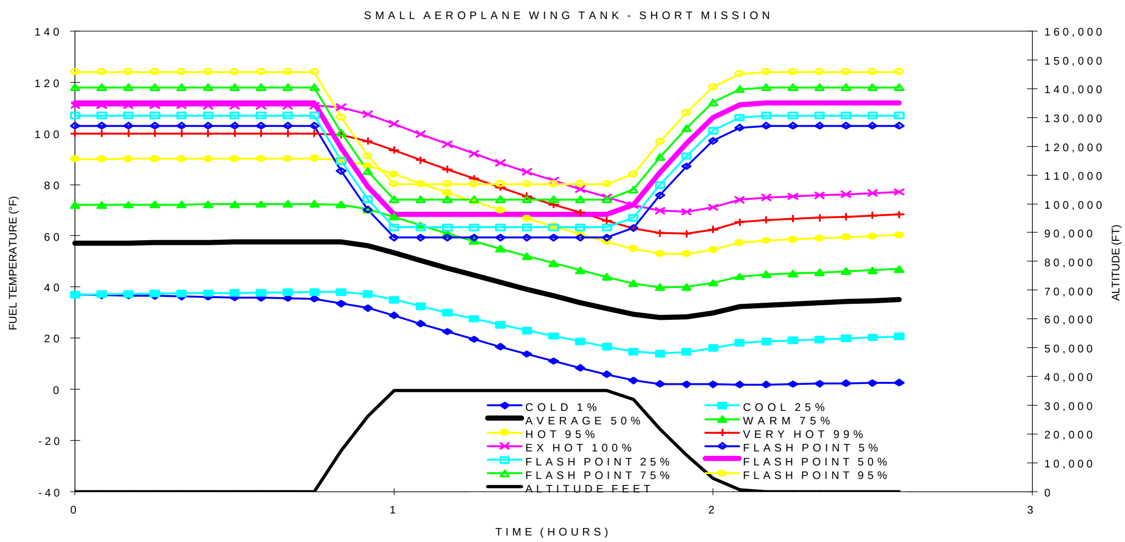




15.2.2 Small Aeroplane Wing Tank

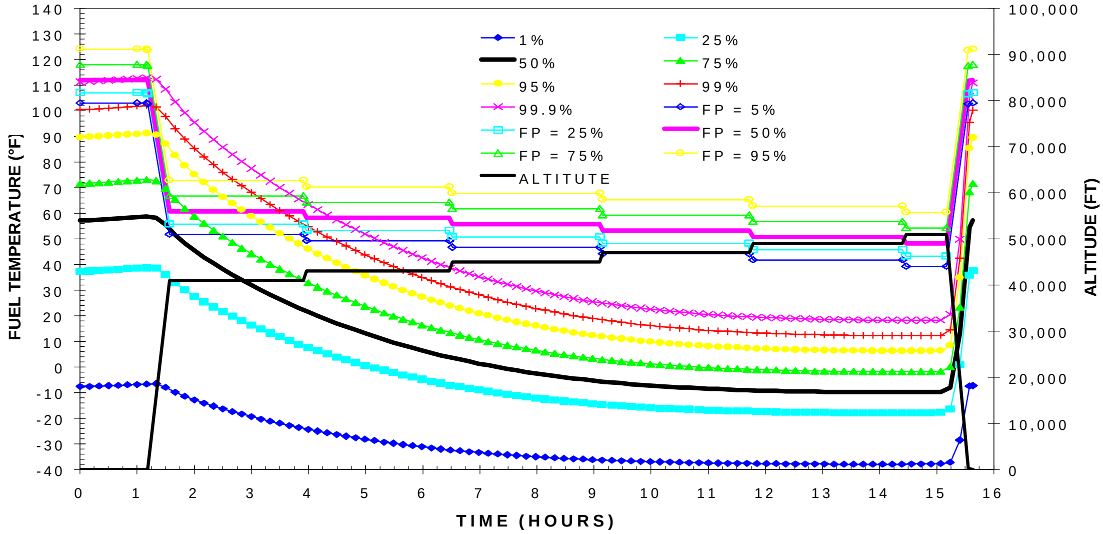




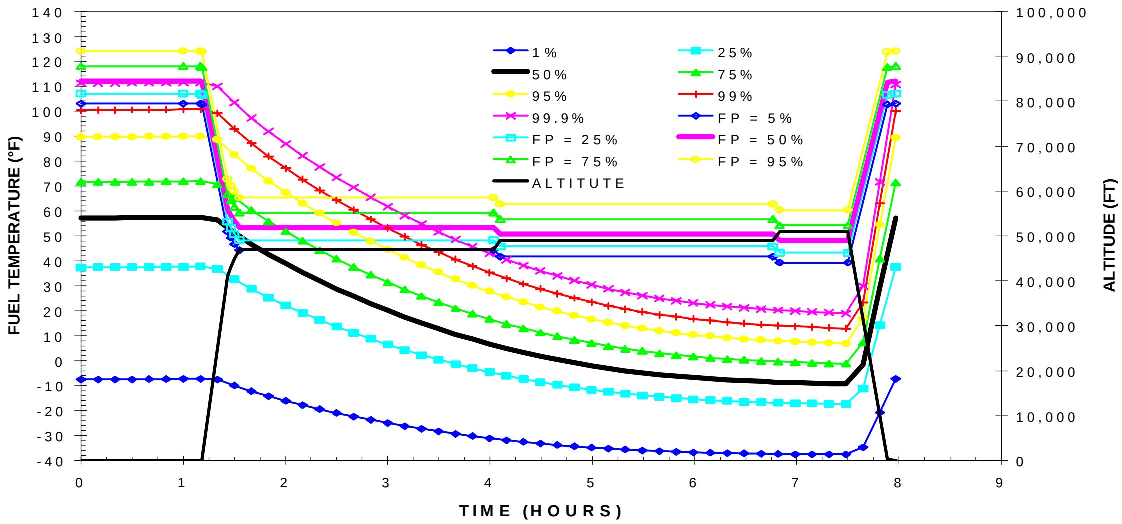


15.2.3 Business Jet Wing Tank

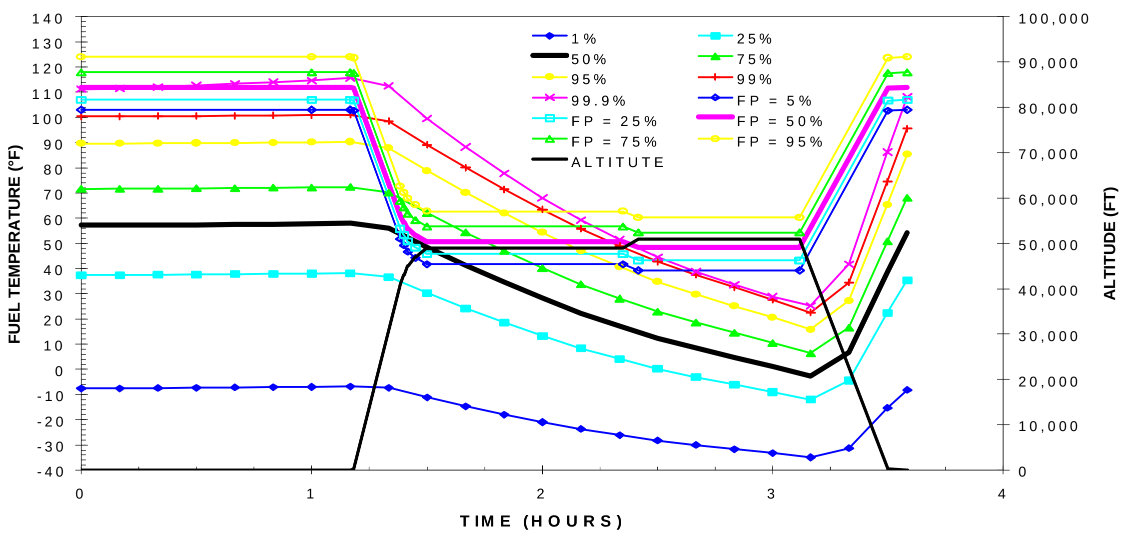
BUSINESS JET - LONG MISSION



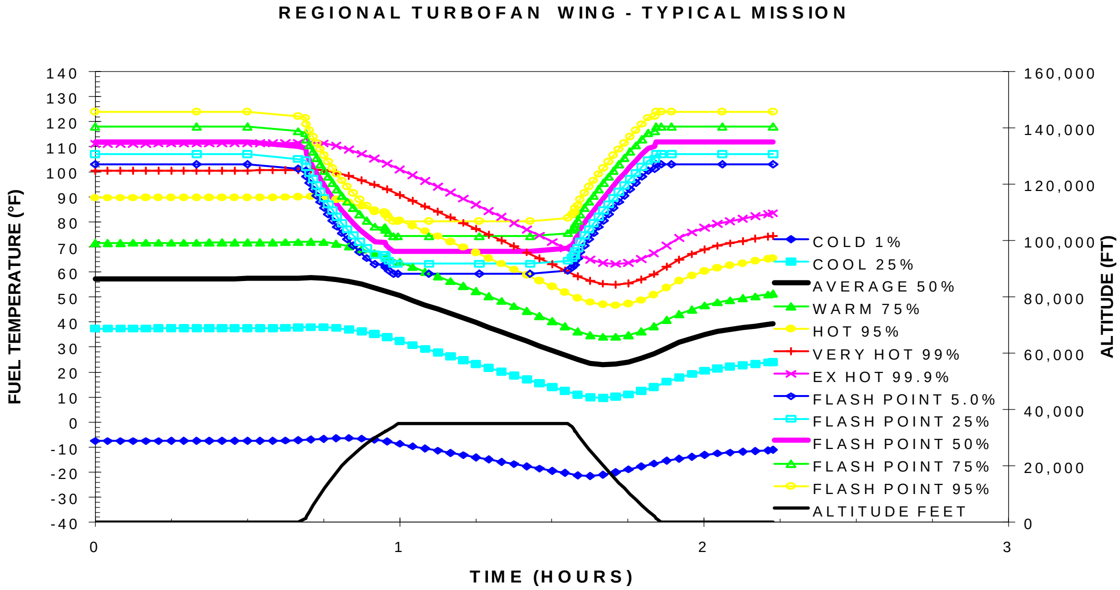
BUSINESS JET - MEDIUM MISSION



BUSINESS JET - SHORT MISSION

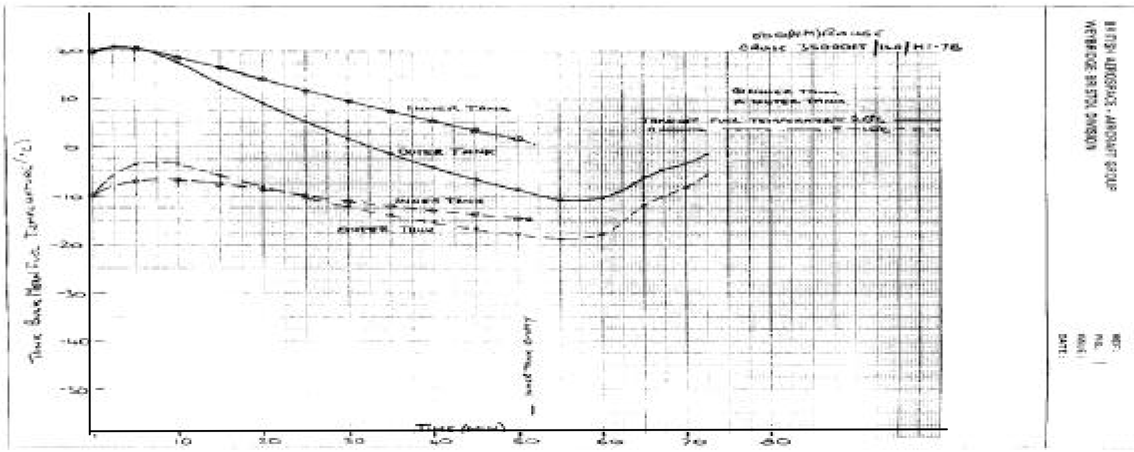


15.2.4 Regional Turbofan Wing Tank

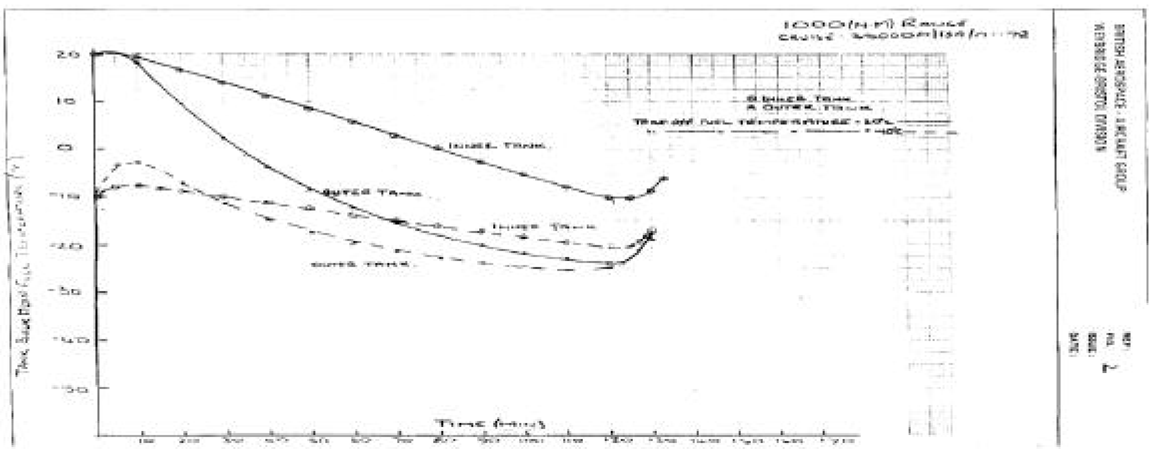


15.2.5 Medium Aeroplane Wing Tank

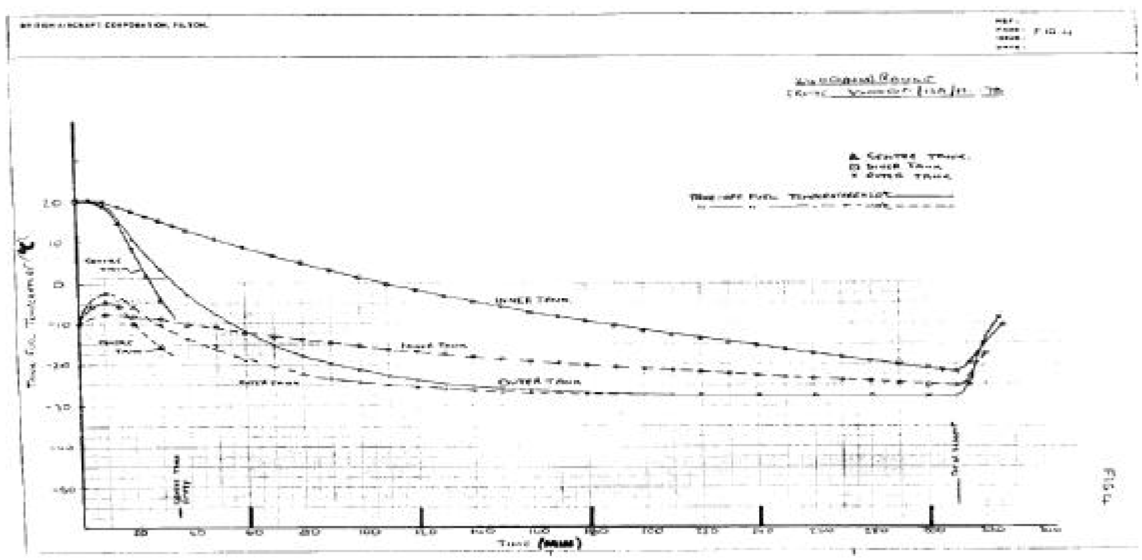
(short mission 500 nm)



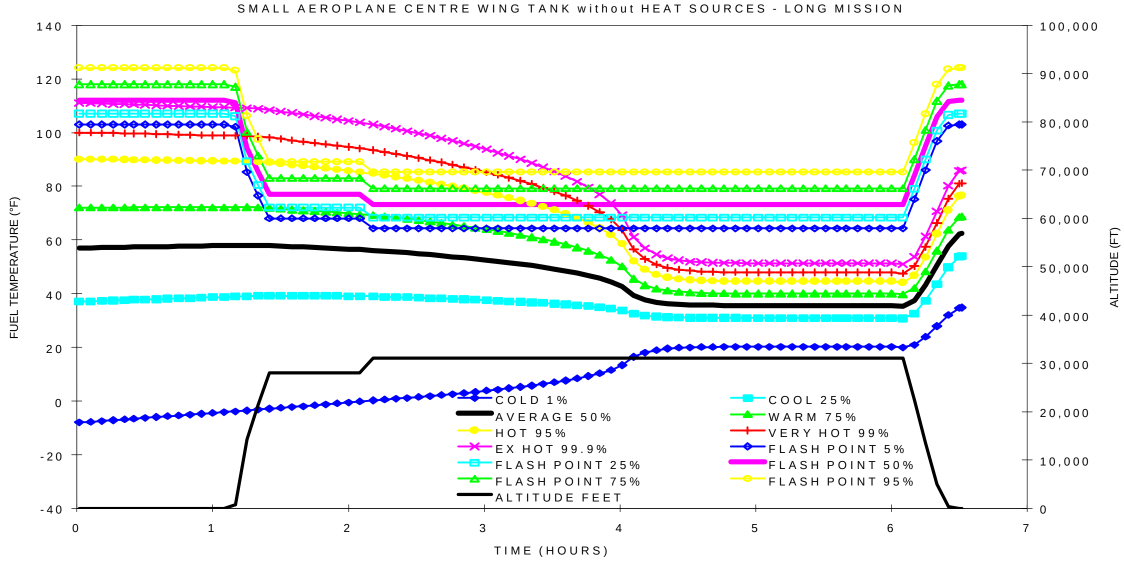
(medium mission 1,000 nm)

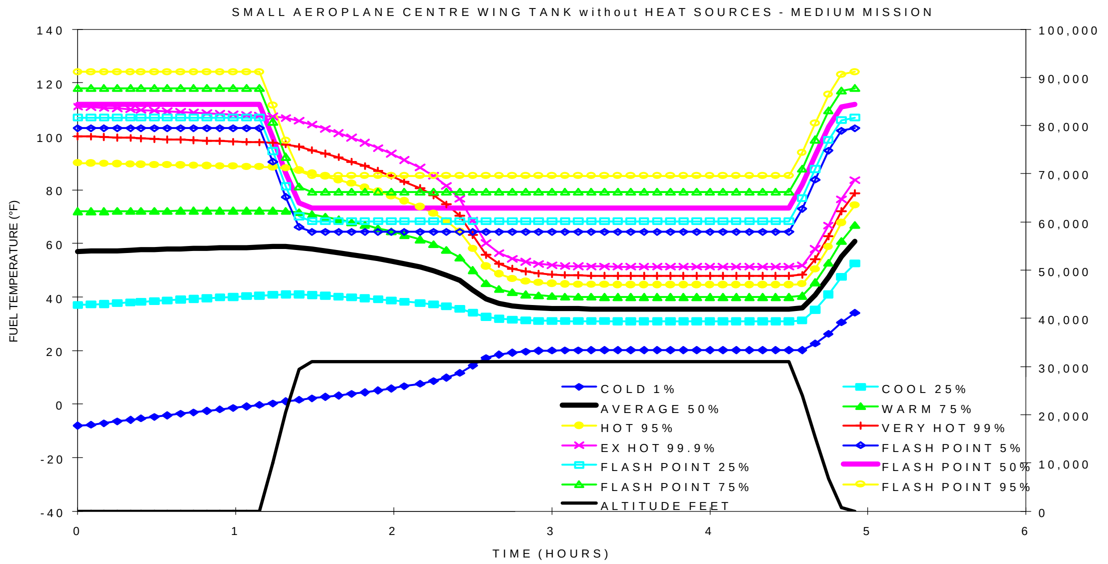


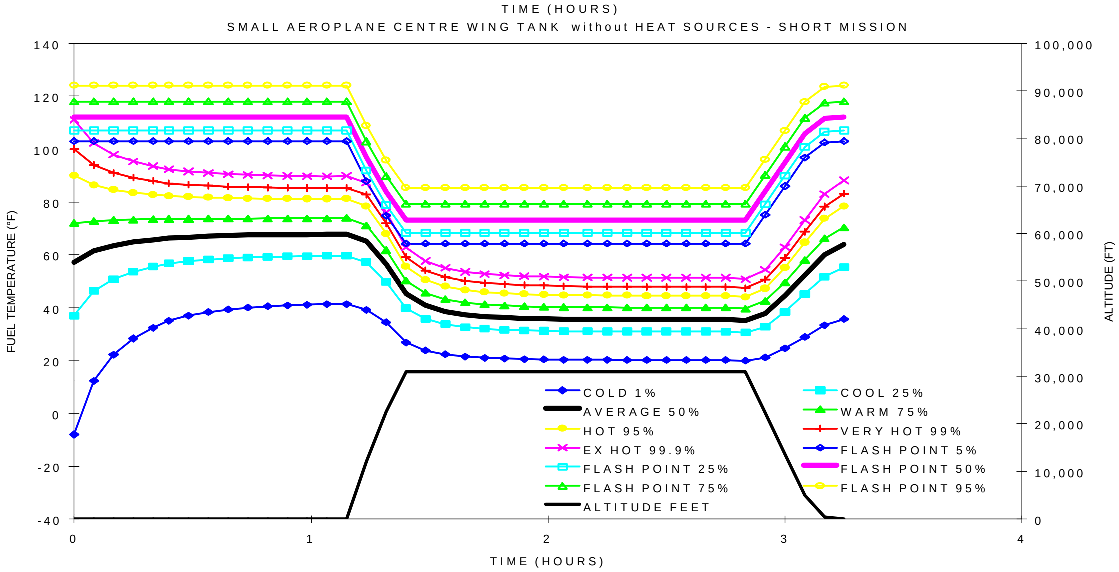
(long mission 2,400 nm)



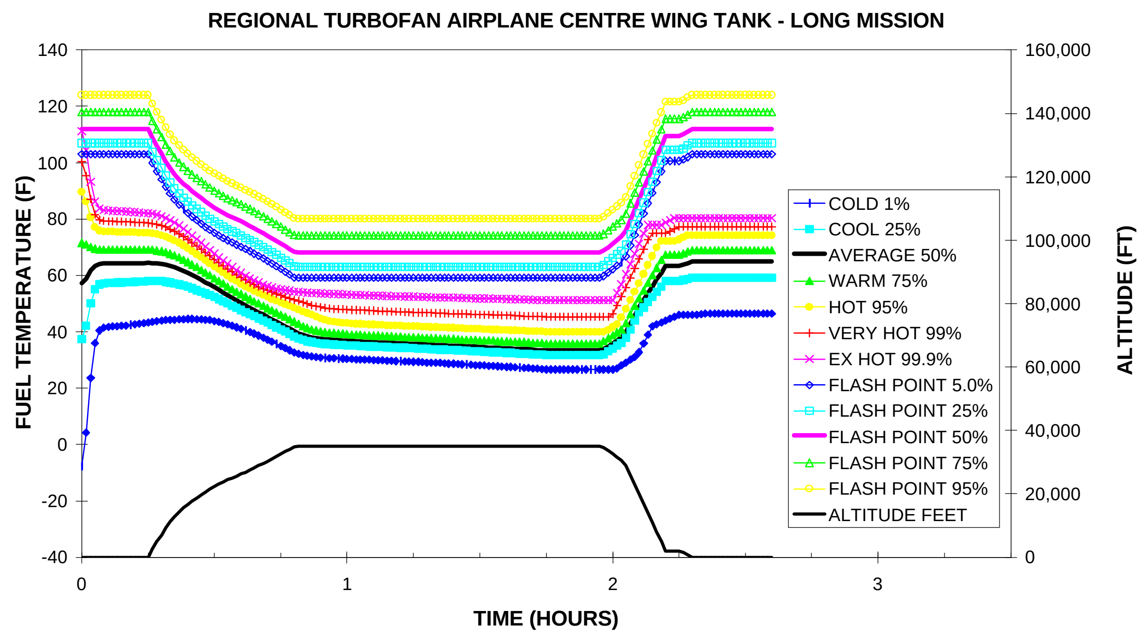
15.2.6 Small Aeroplane Centre Wing Tank (without heat source)

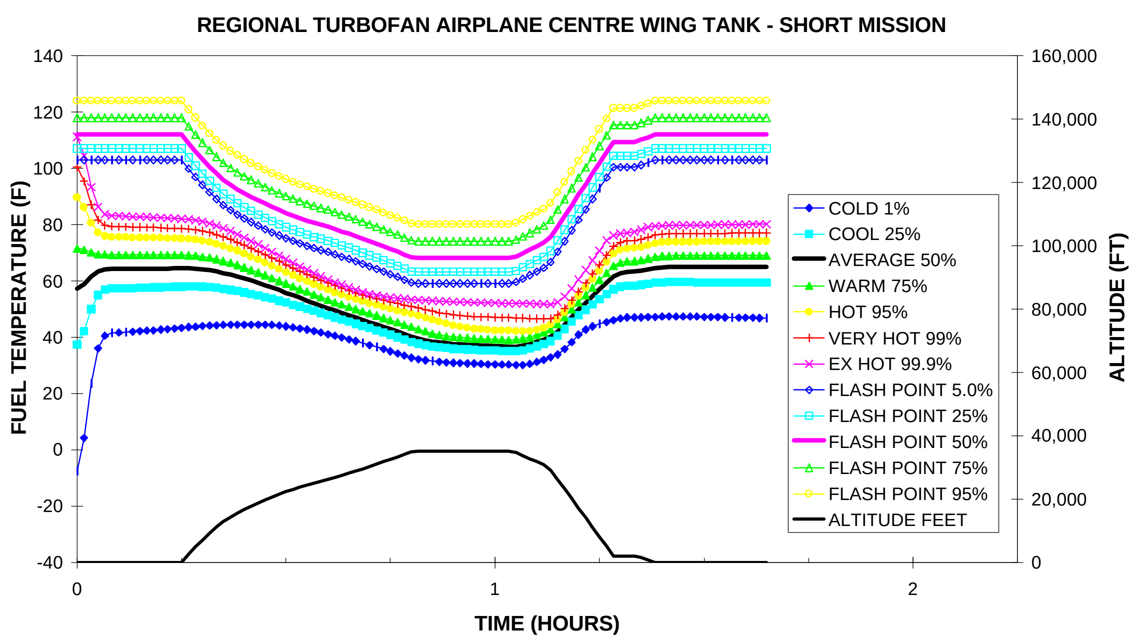




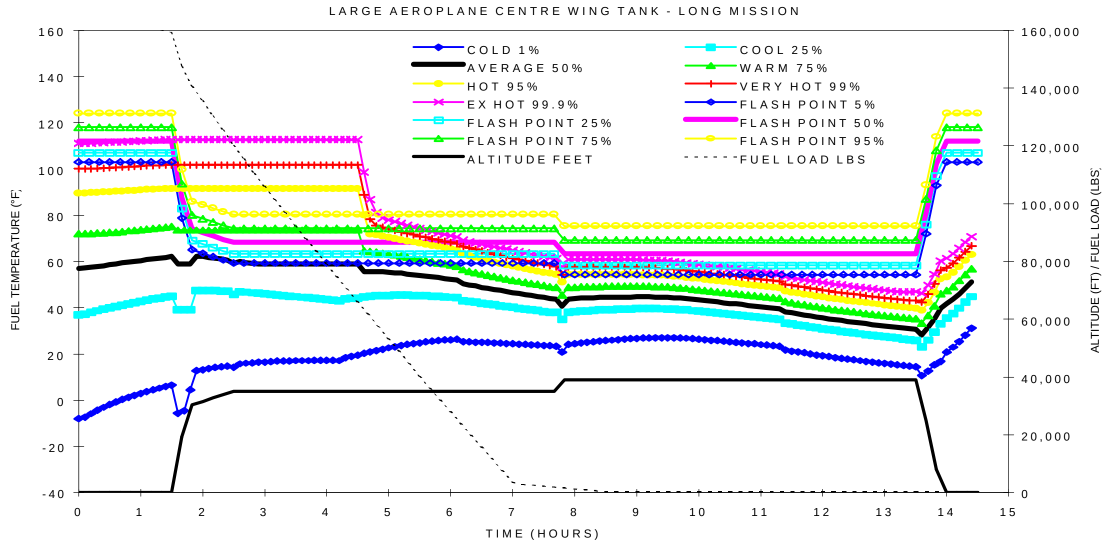


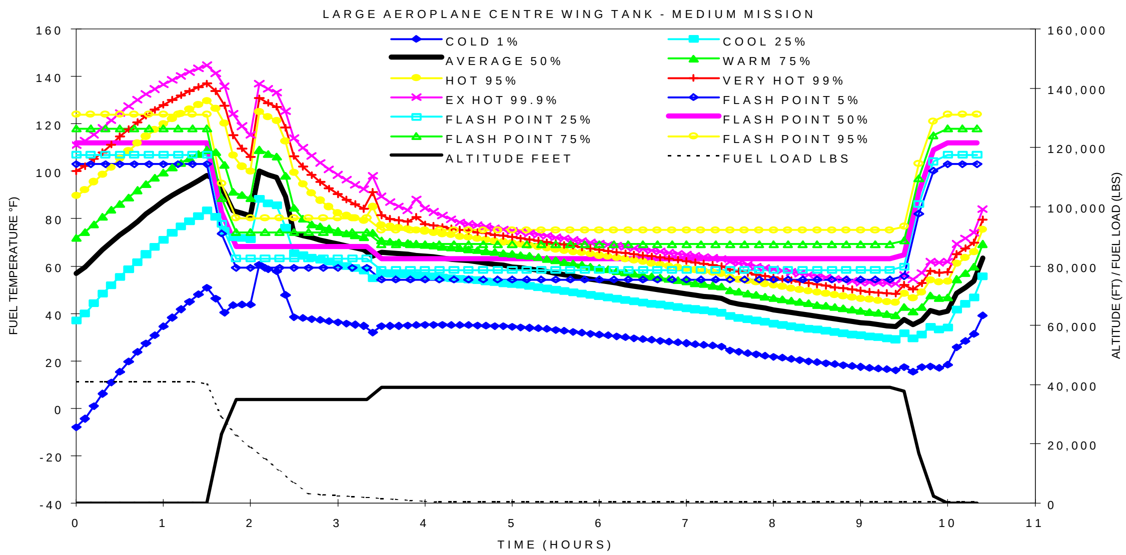
15.2.7 Regional Turbofan Centre Wing Tank (without heat source)

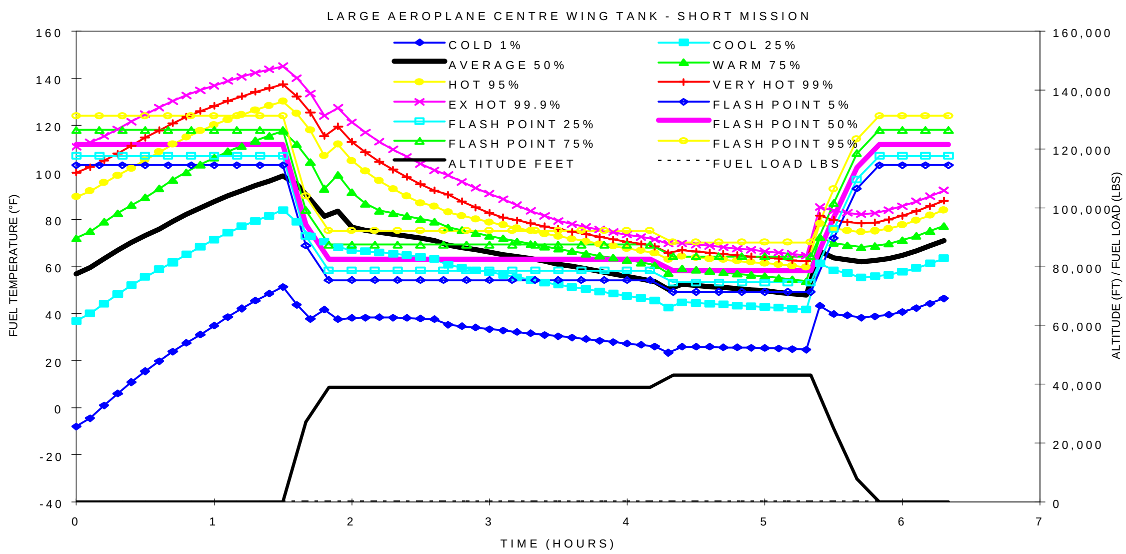




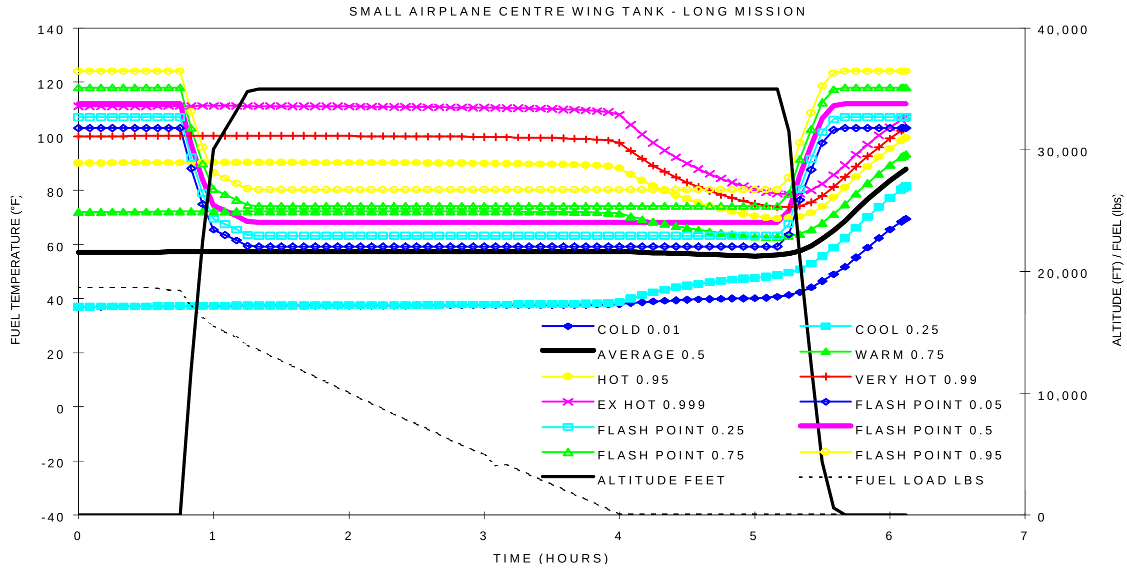
15.2.8 Large Aeroplane Centre Wing Tank (with heat source)

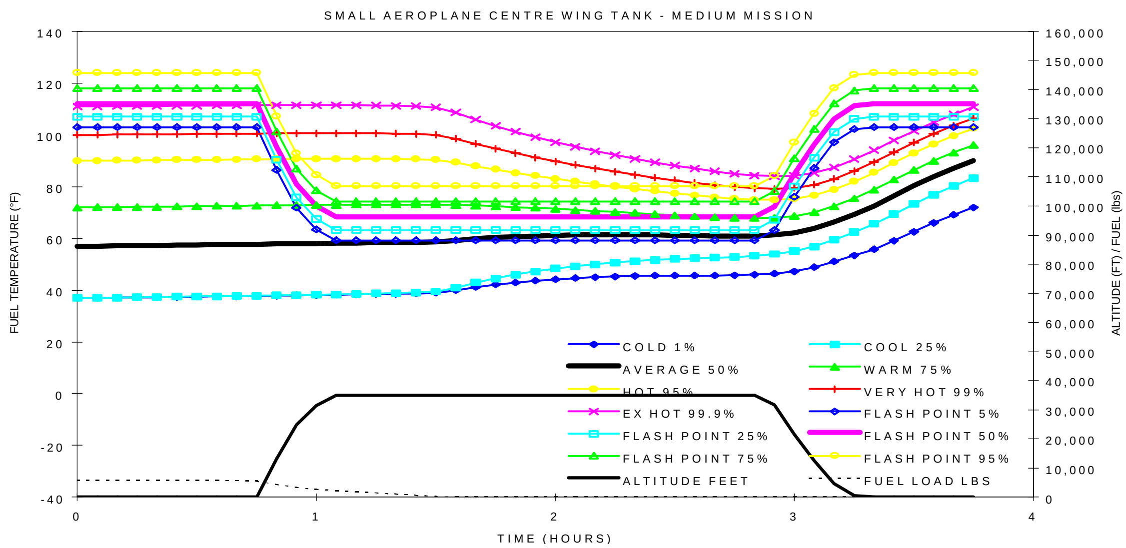


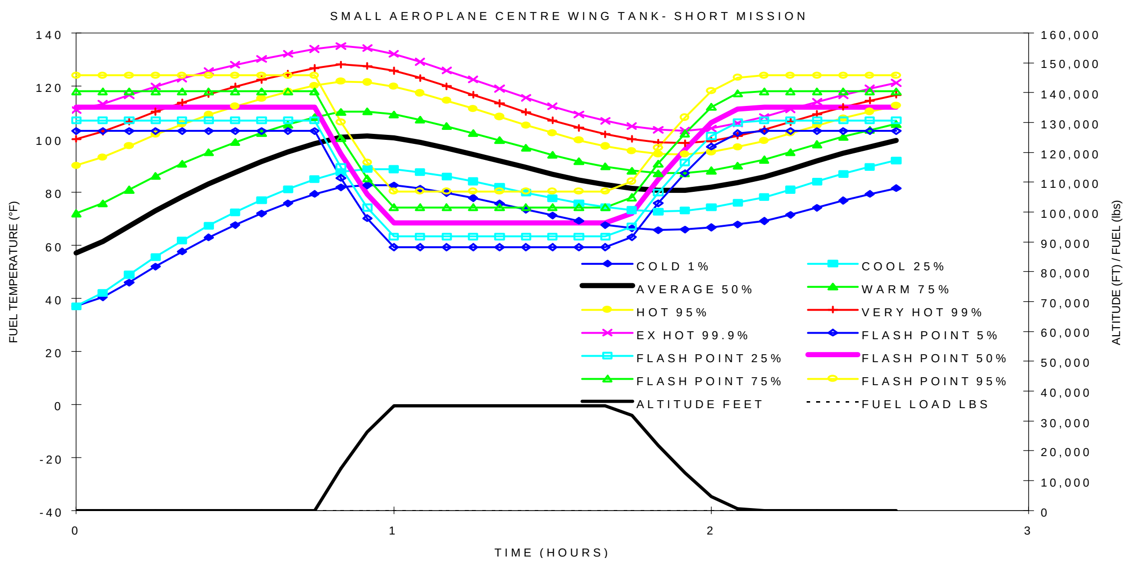




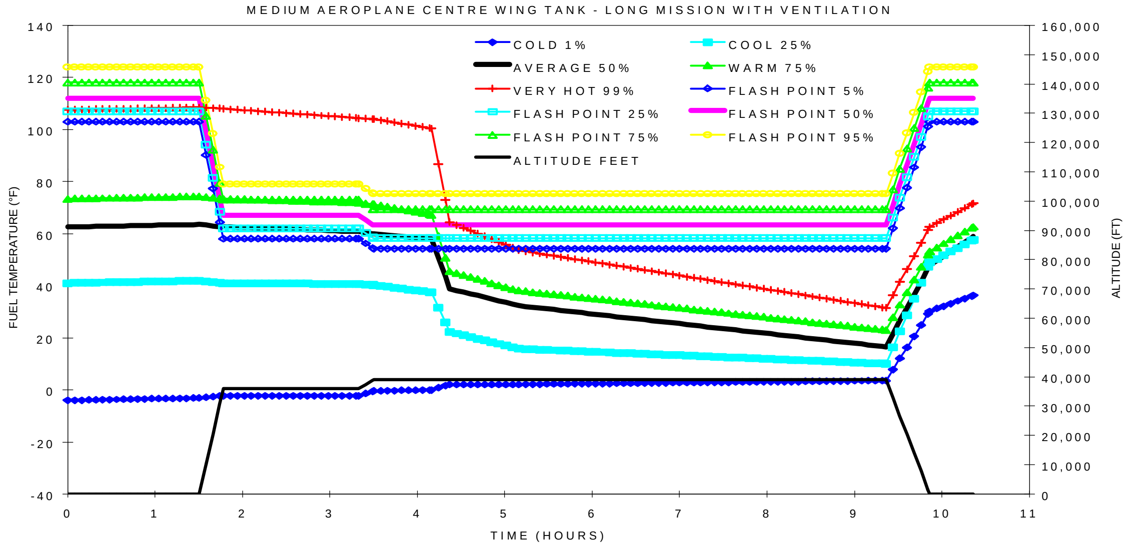
15.2.9 Small Aeroplane Centre Wing Tank (with heat source)

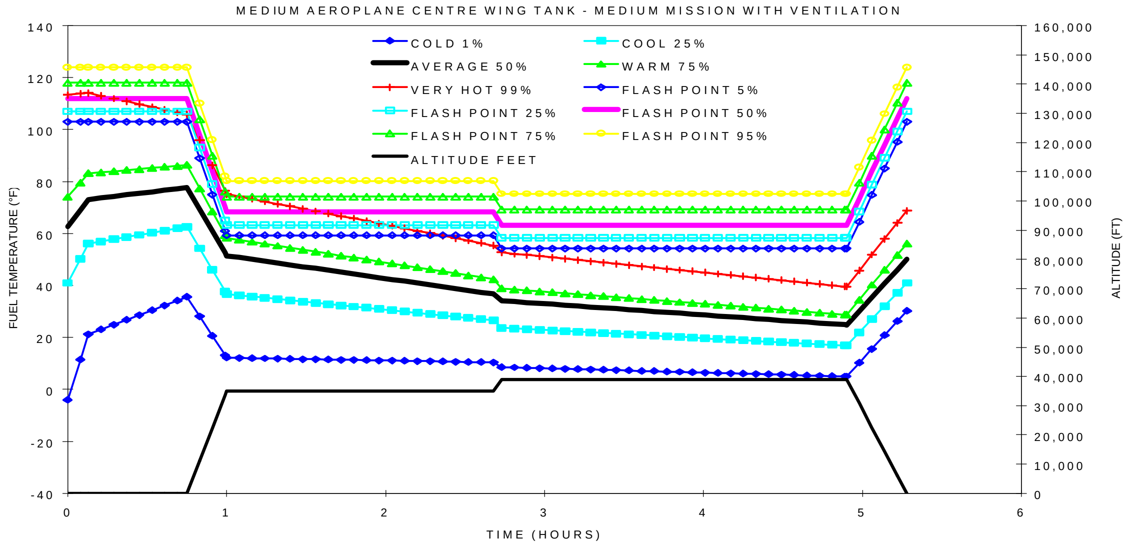


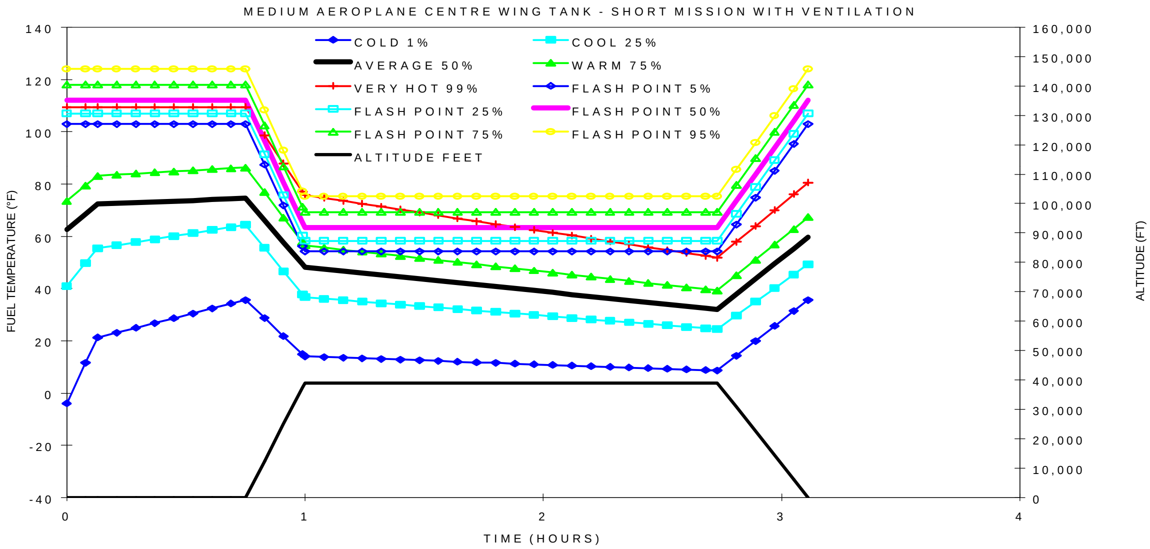




15.2.10 Medium Aeroplane Centre Wing Tank (with heat source)



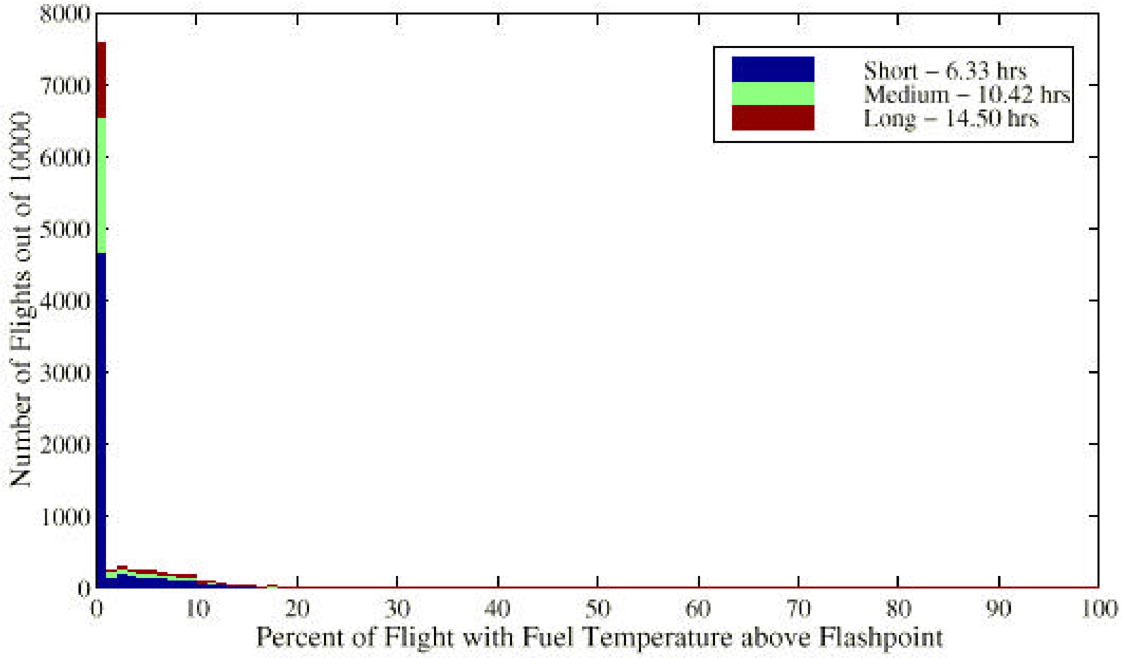




15.3 Exposure Analysis Results Charts

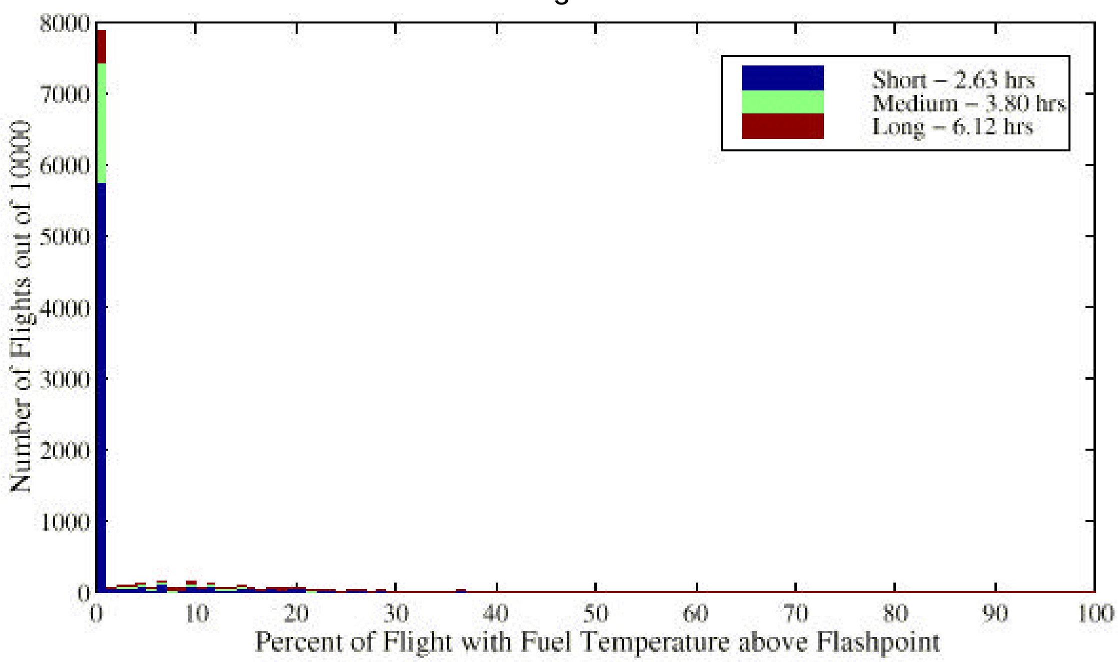
15.3.1 Large Aeroplane Wing Tank

average 1.6%



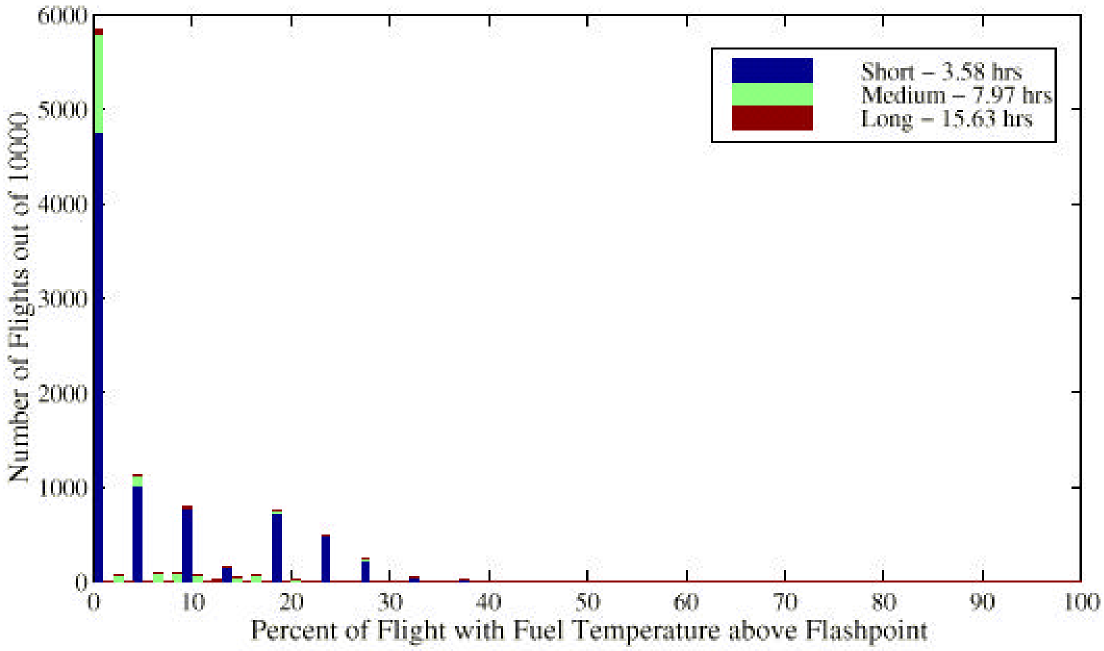
15.3.2 Small Aeroplane Wing Tank

average 3.0%



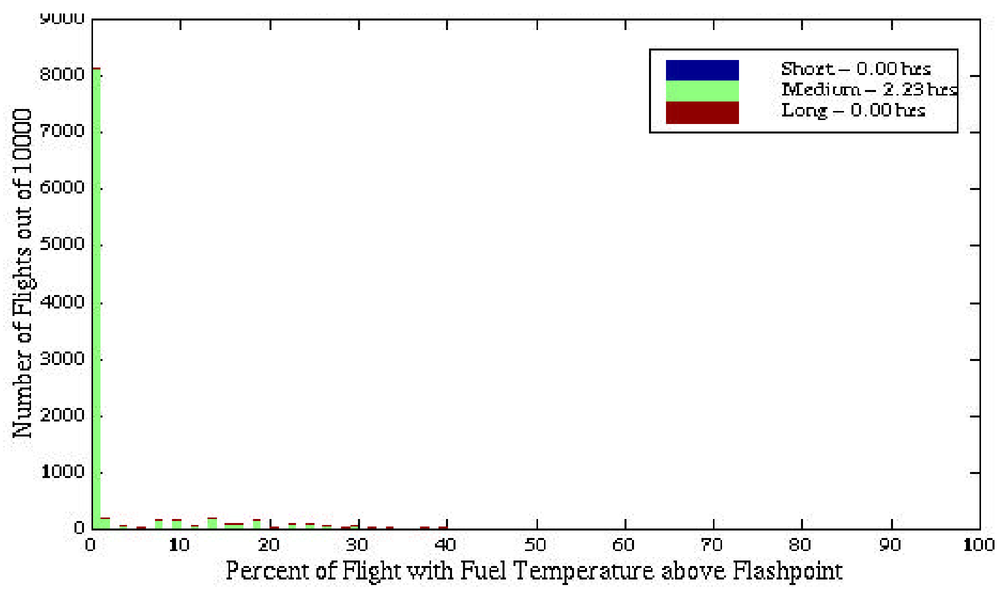
15.3.3 Business Jet Wing Tank

average 5.6%

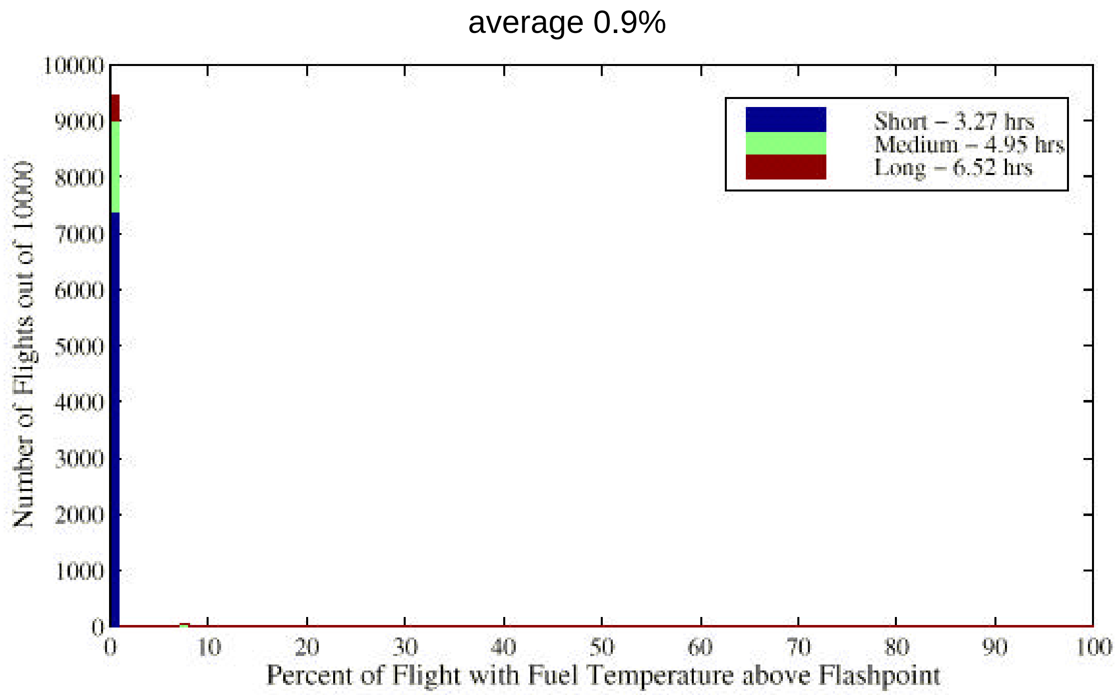


15.3.4 Regional Turbofan Wing Tank

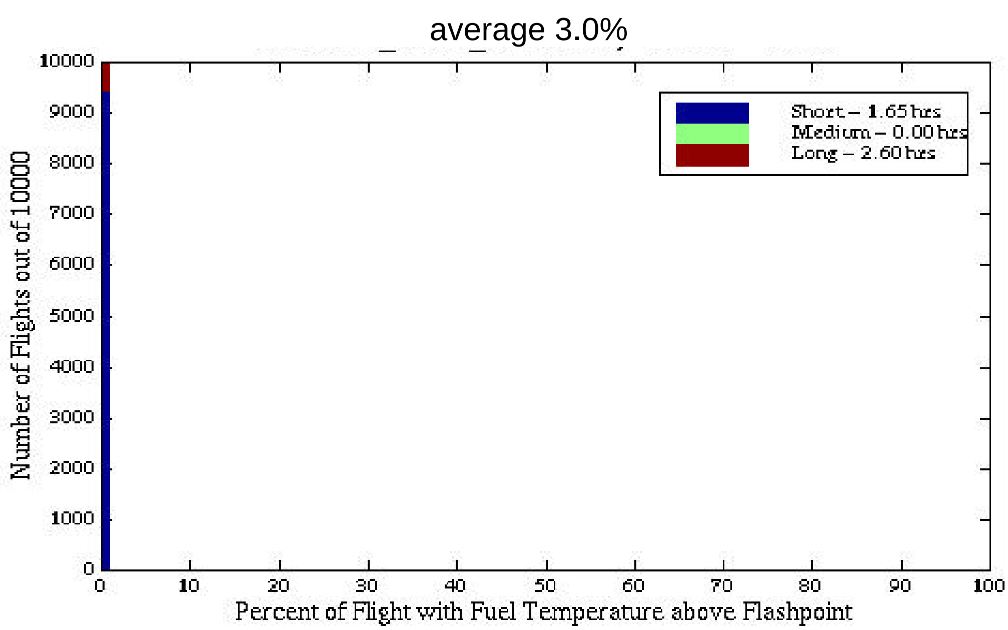
average < 0.1%



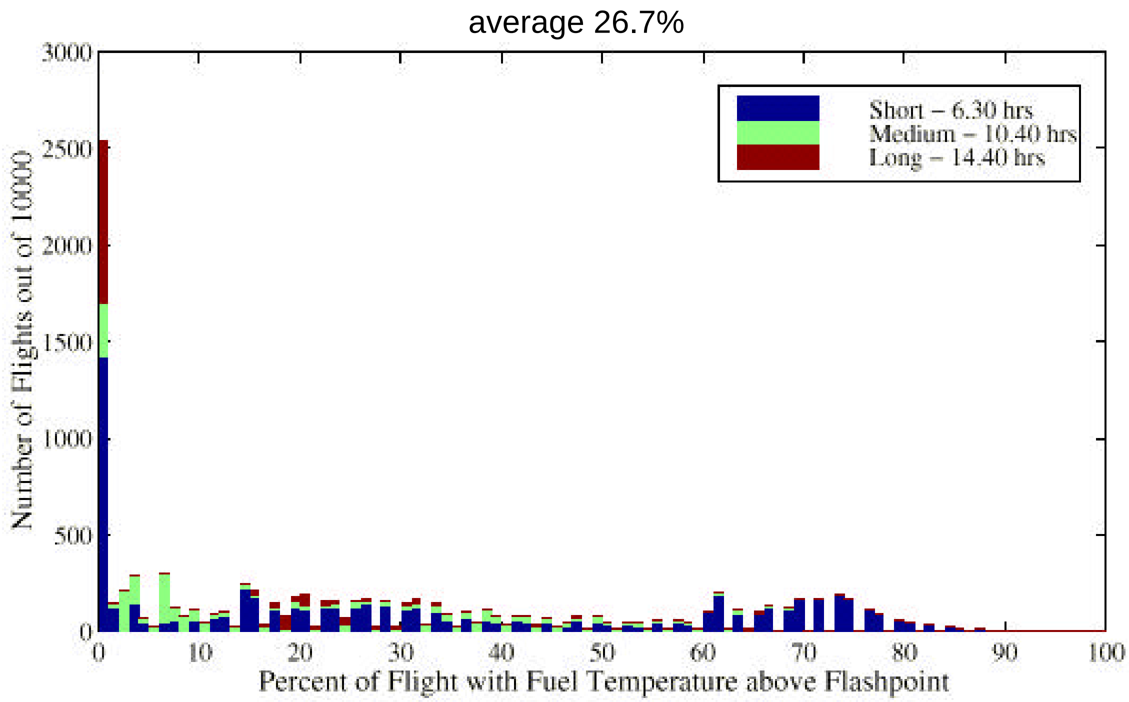
15.3.5 Small Aeroplane Centre Wing Tank (without heat source)



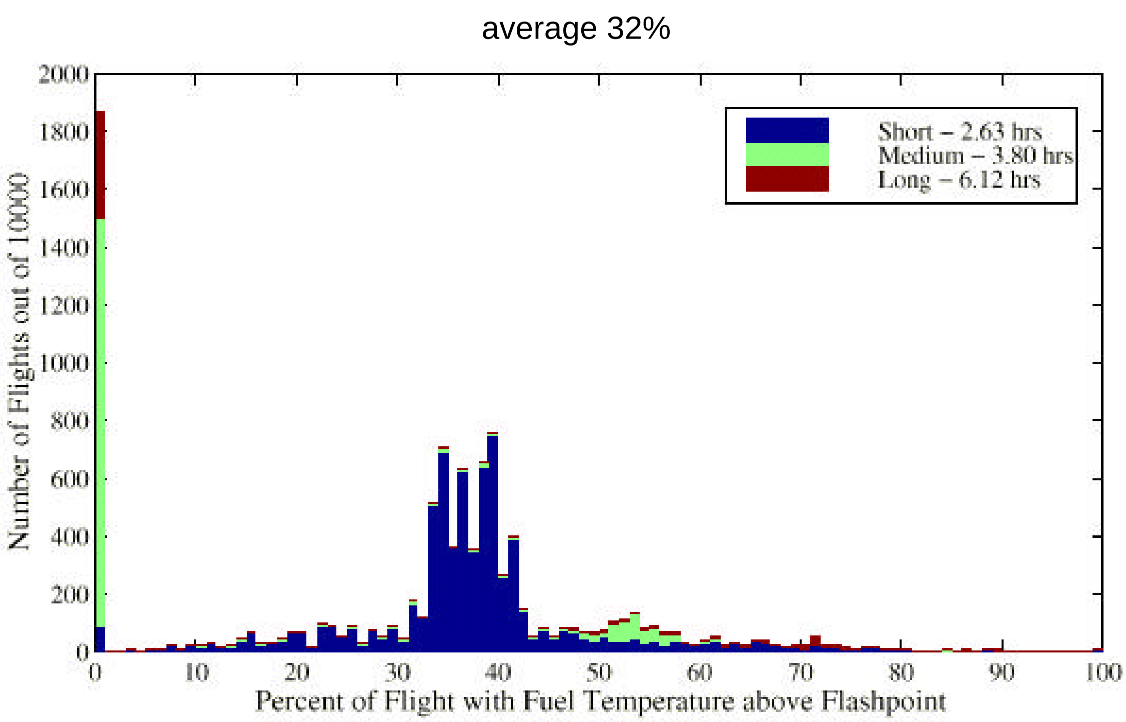
15.3.6 Regional Turbofan Centre Wing Tank (without heat source)



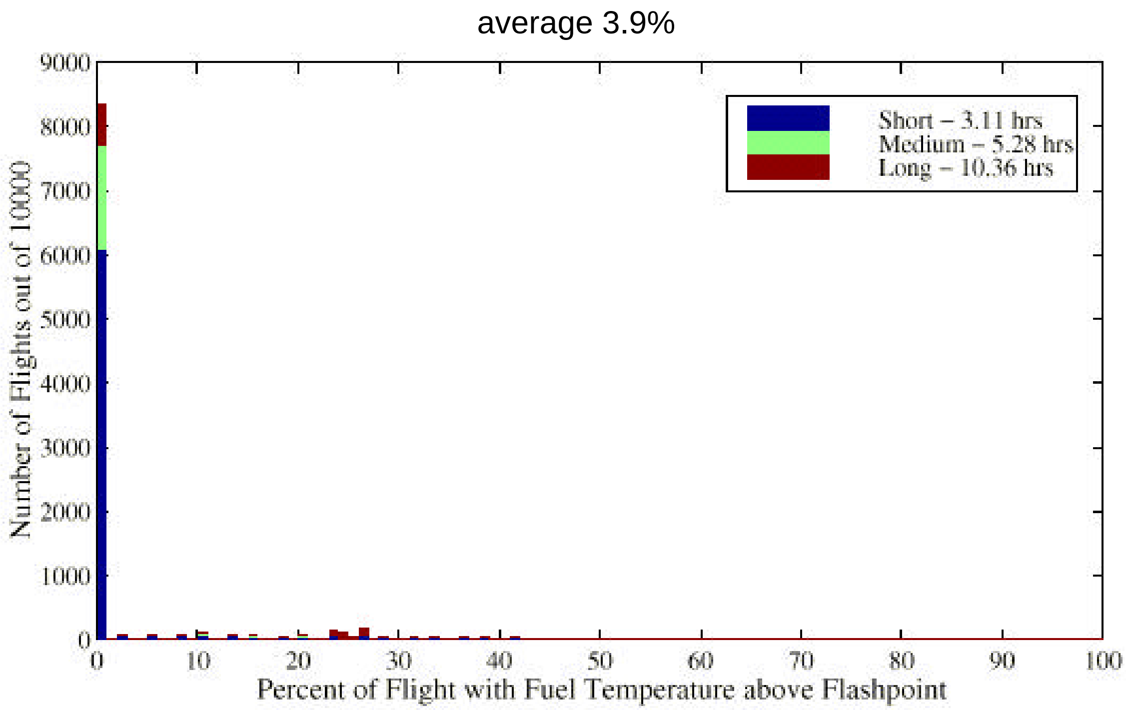
15.3.7 Large Aeroplane Centre Wing Tank (with heat source)



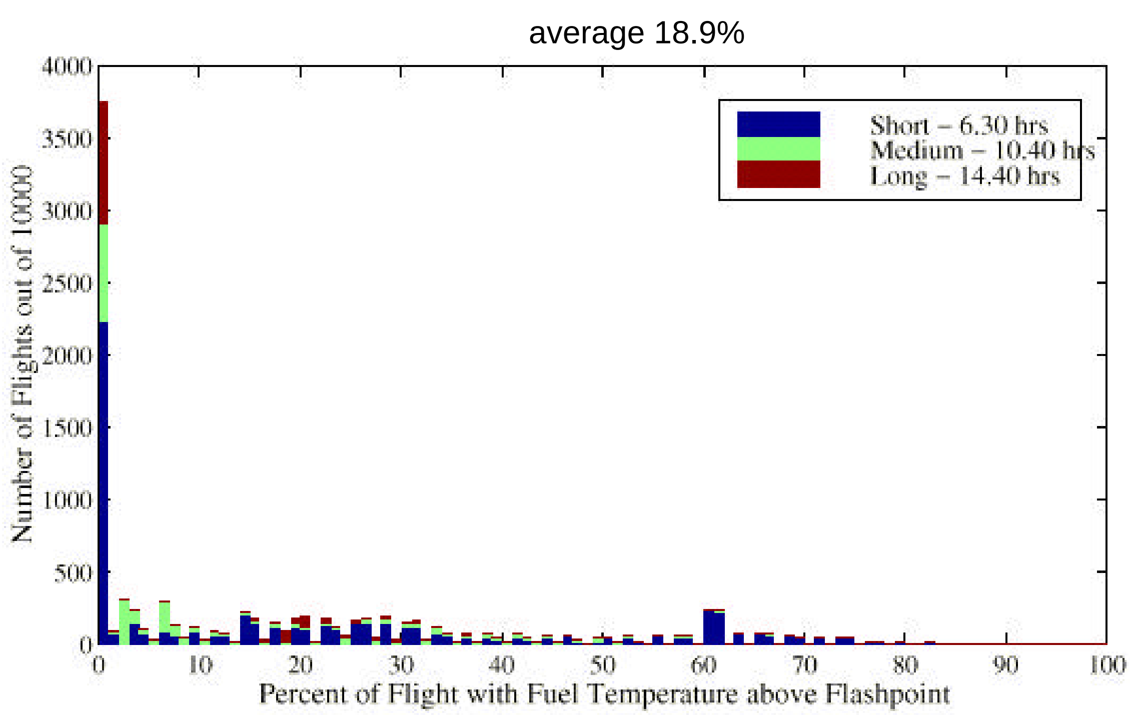
15.3.8 Small Aeroplane Centre Wing Tank (with heat source)



15.3.9 Medium Aeroplane Centre Wing Tank (with heat source and directed forced ventilation)

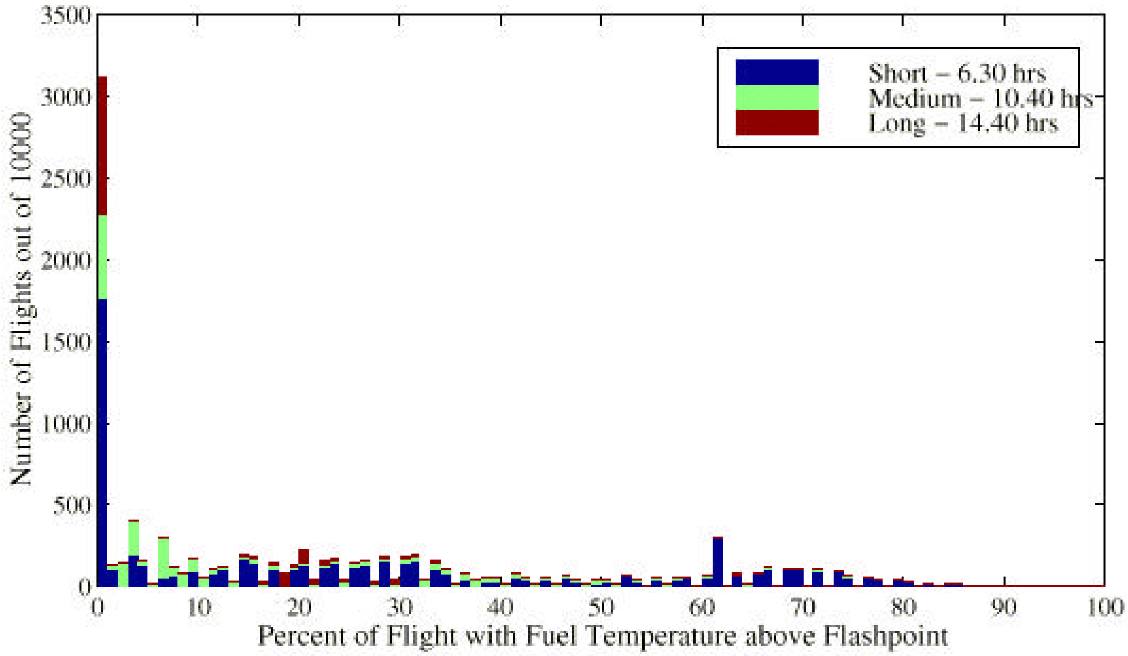


15.3.10 Large Aeroplane Centre Wing Tank With Insulation (of heat sources)



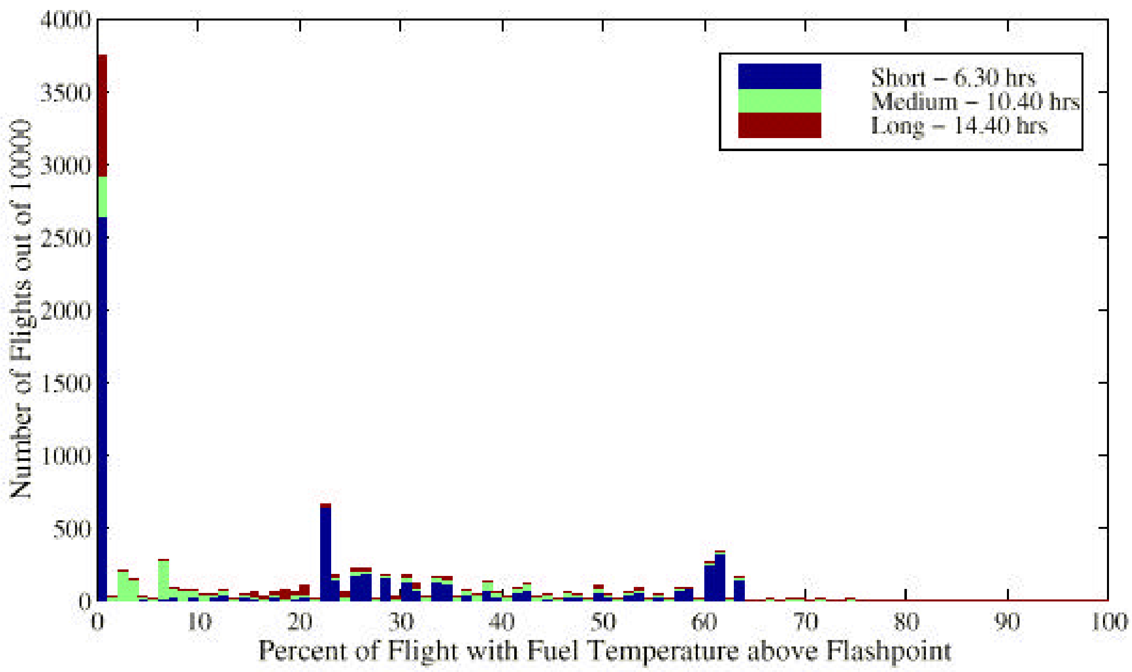
15.3.11 Large Aeroplane Centre Wing Tank With Ventilation (of heat source)

average 22%



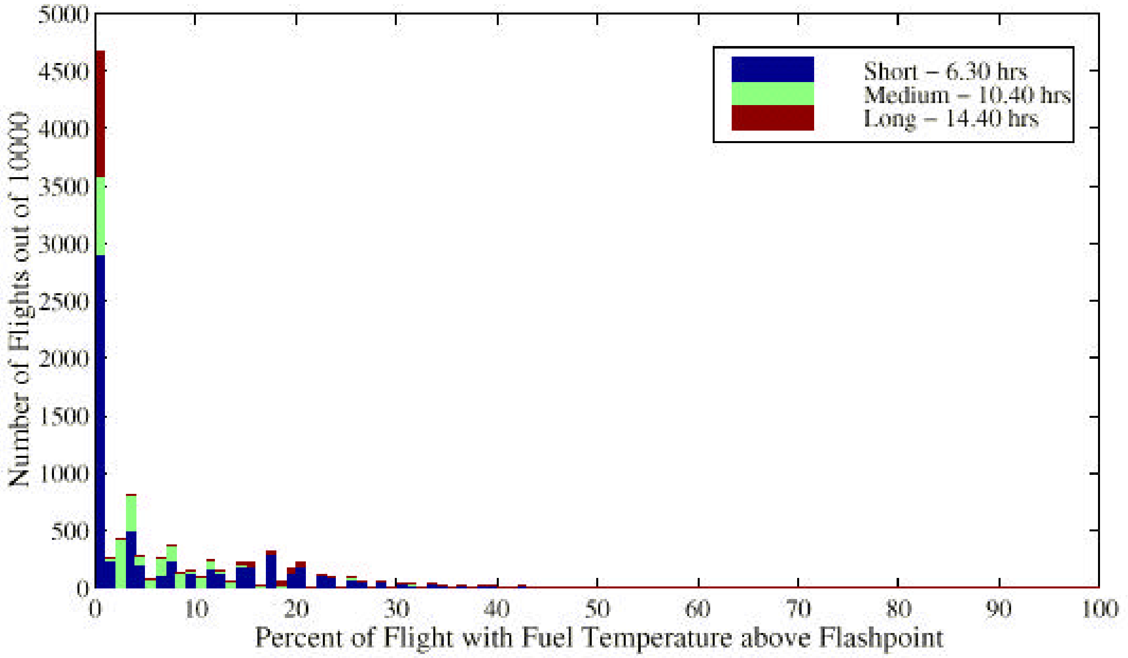
15.3.12 Large Aeroplane Centre Wing Tank With Redistributed Fuel

average 20.3%



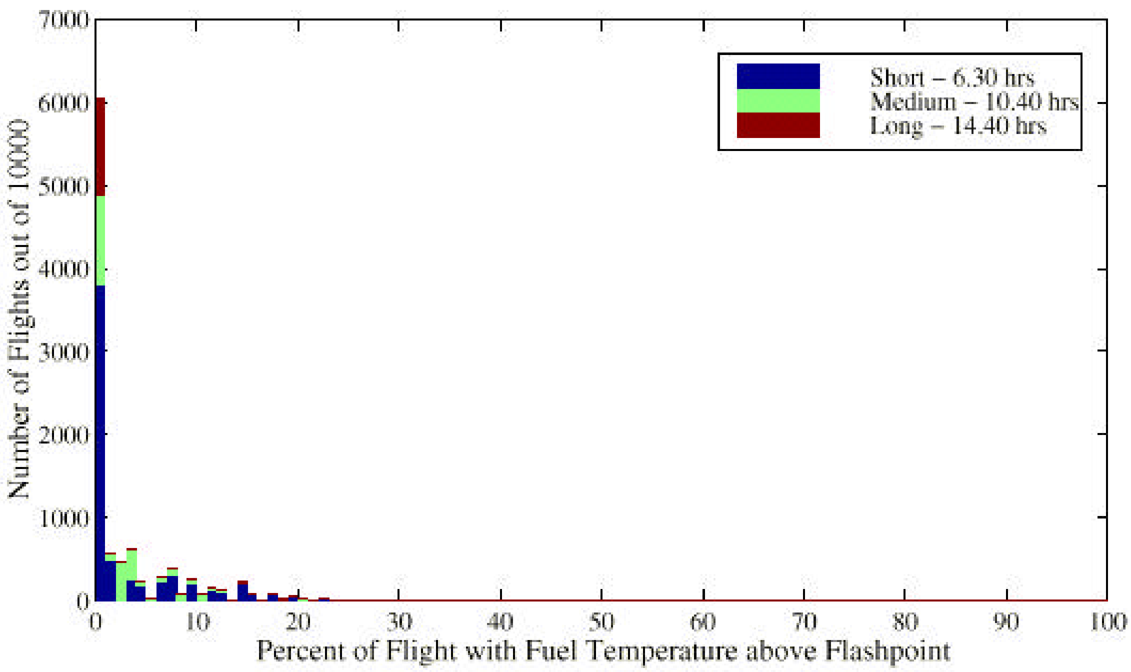
15.3.13 Large Aeroplane Centre Wing Tank With 120°F Flashpoint

average 6.5%



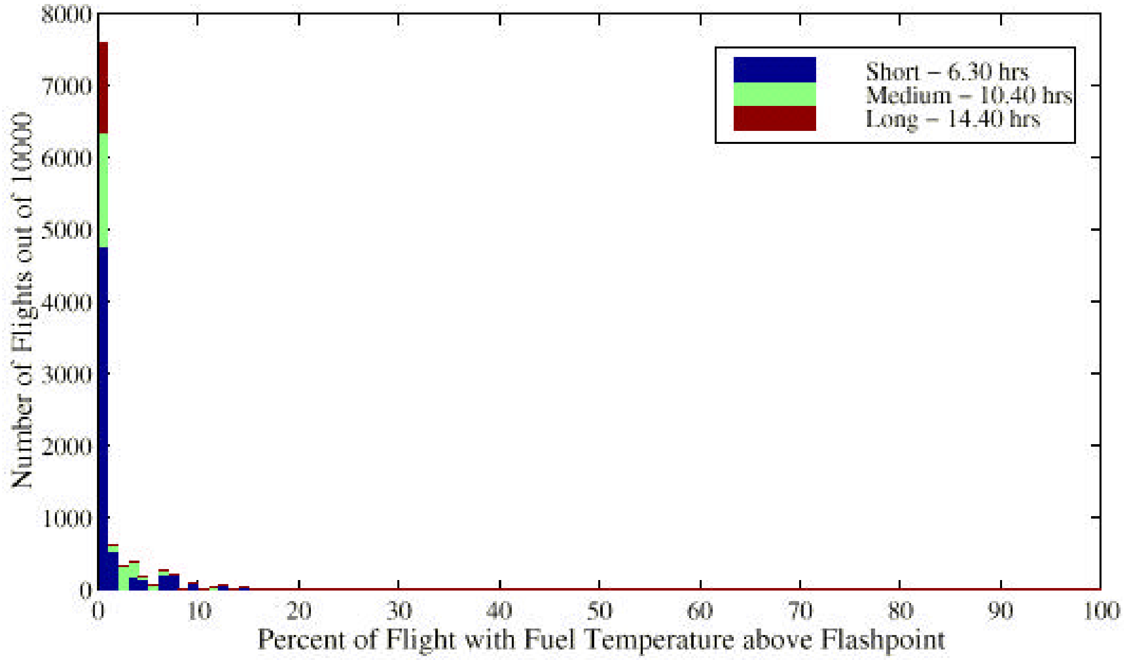
15.3.14 Large Aeroplane Centre Wing Tank With 130°F Flashpoint

average 3%



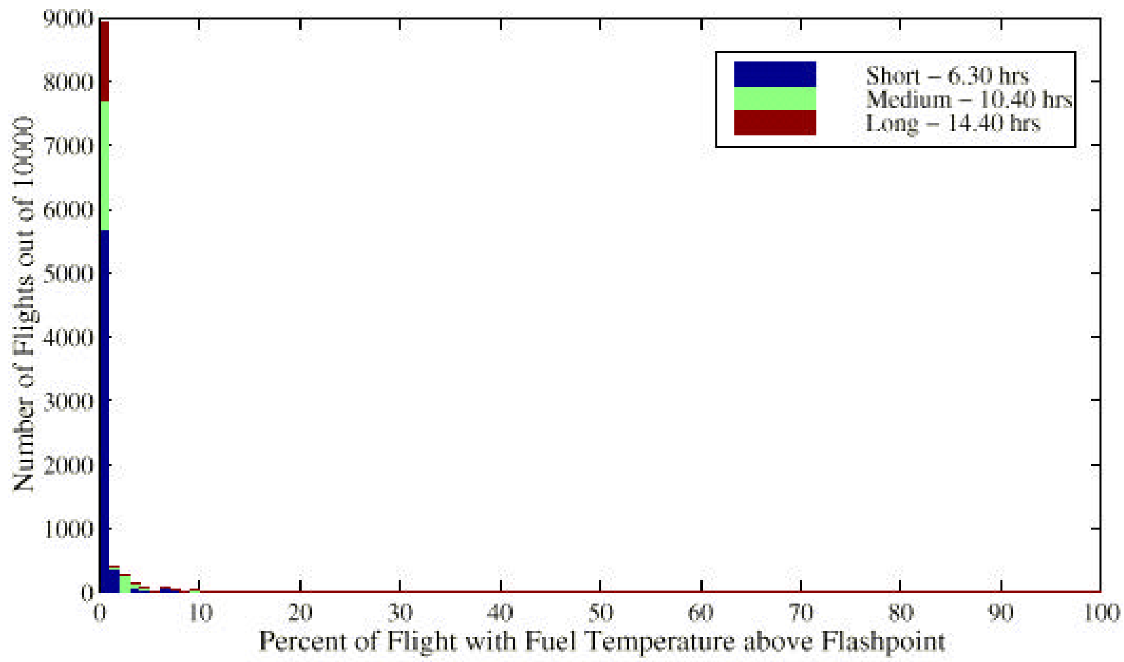
15.3.15 Large Aeroplane Centre Wing Tank With 140°F Flashpoint

average 1.2%

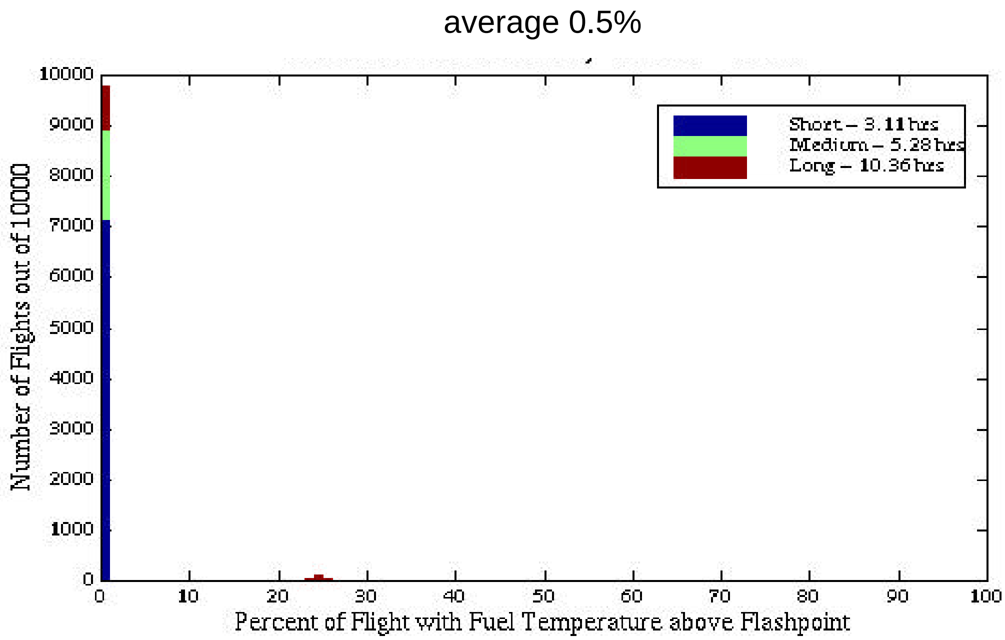


15.3.16 Large Aeroplane Centre Wing Tank With 150°F Flashpoint

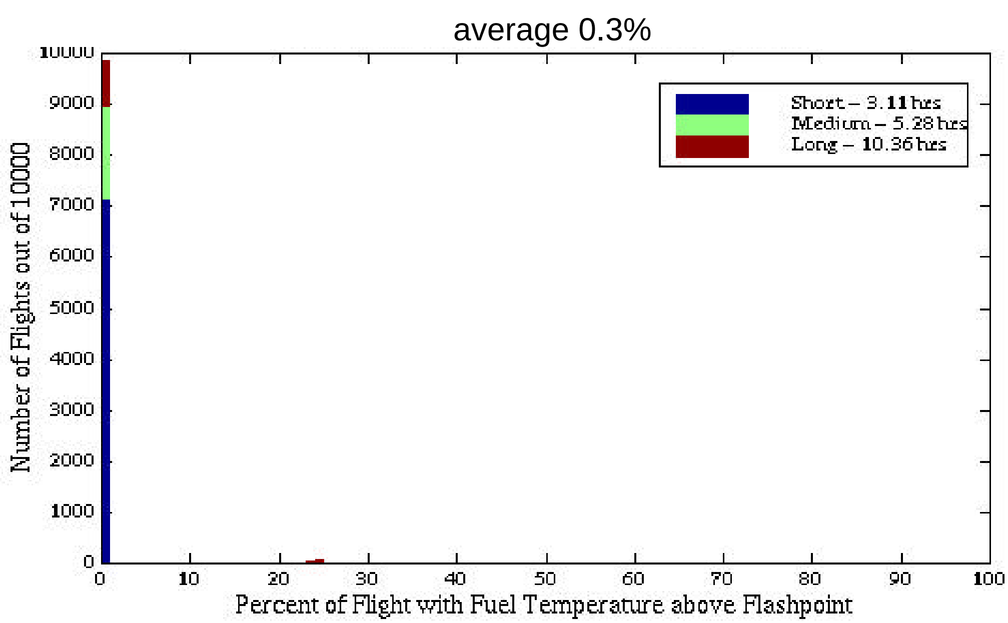
average 0.4%



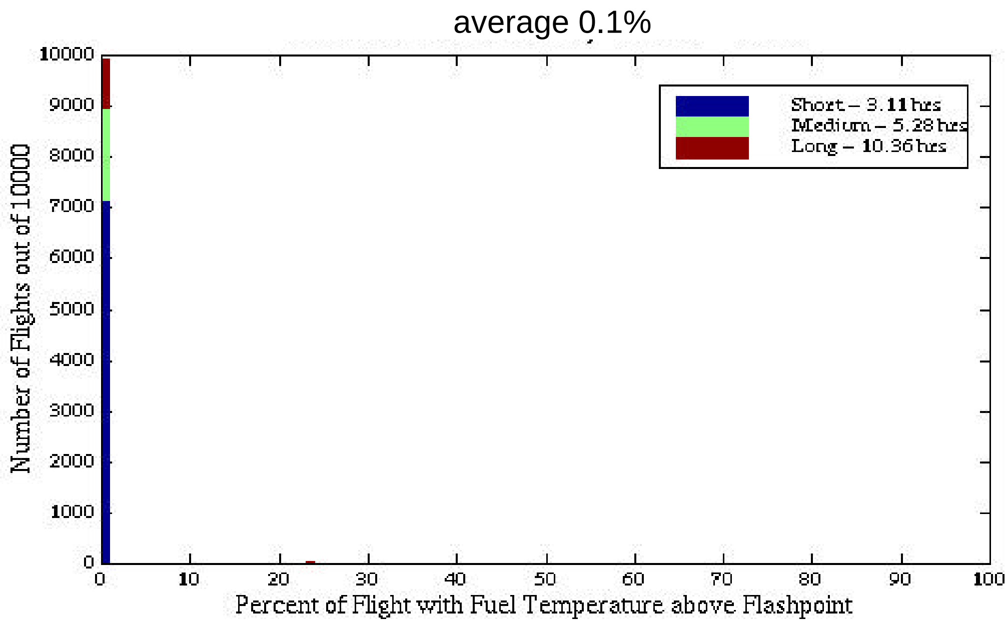
15.3.17 Medium Aeroplane Centre Wing Tank With 120°F Flashpoint



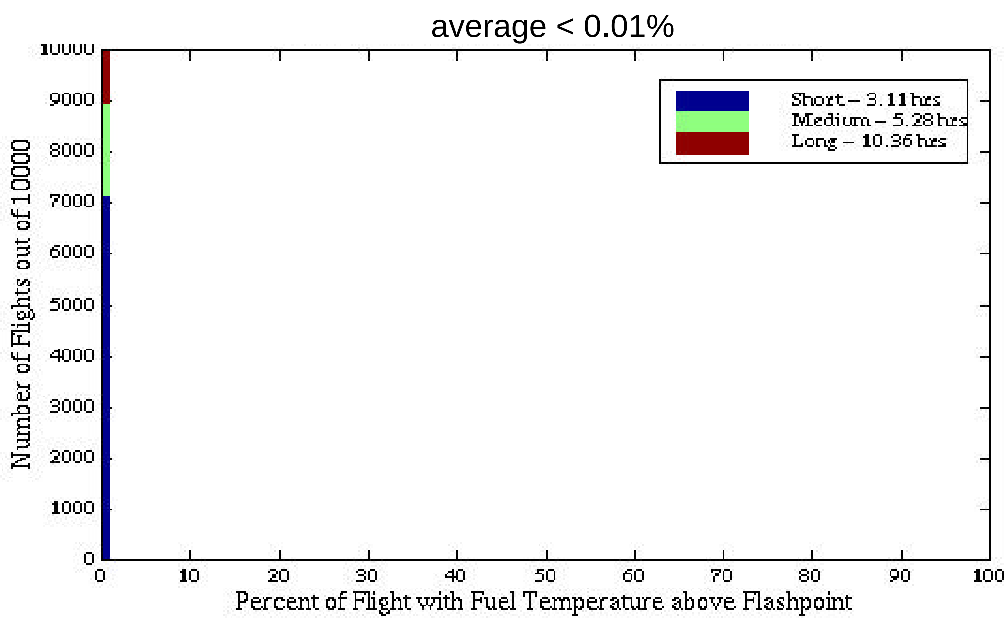
15.3.18 Medium Aeroplane Centre Wing Tank With 130°F Flashpoint



15.3.19 Medium Aeroplane Centre Wing Tank With 140°F Flashpoint

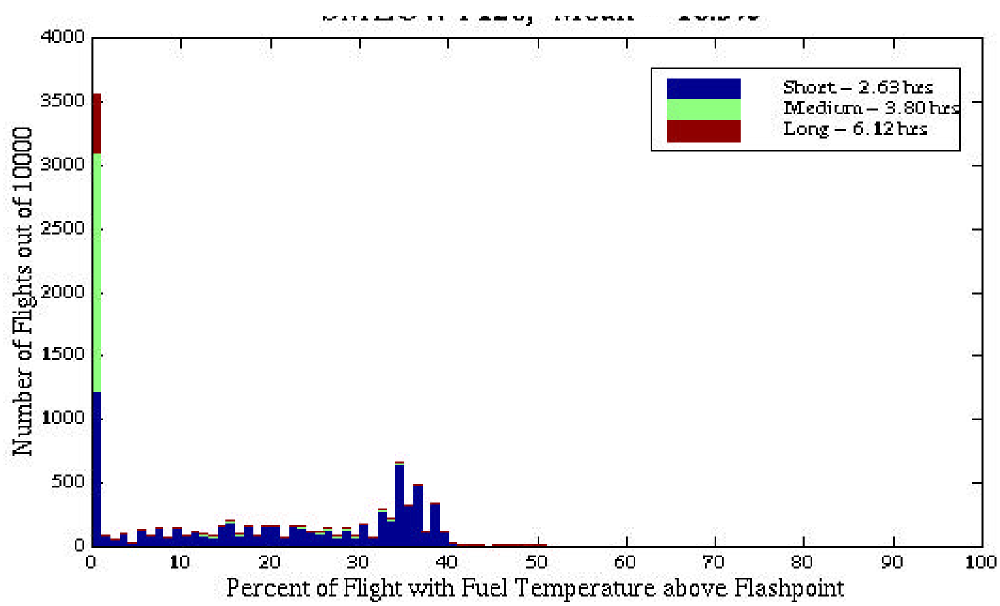


15.3.20 Medium Aeroplane Centre Wing Tank With 150°F Flashpoint



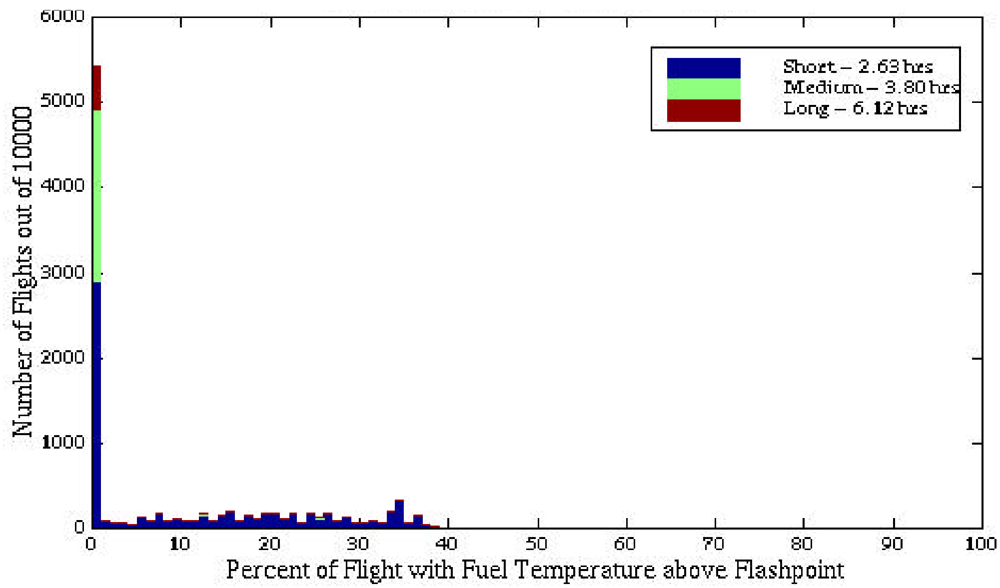
15.3.21 Small Aeroplane Centre Wing Tank With 120°F Flashpoint

average 16.5%



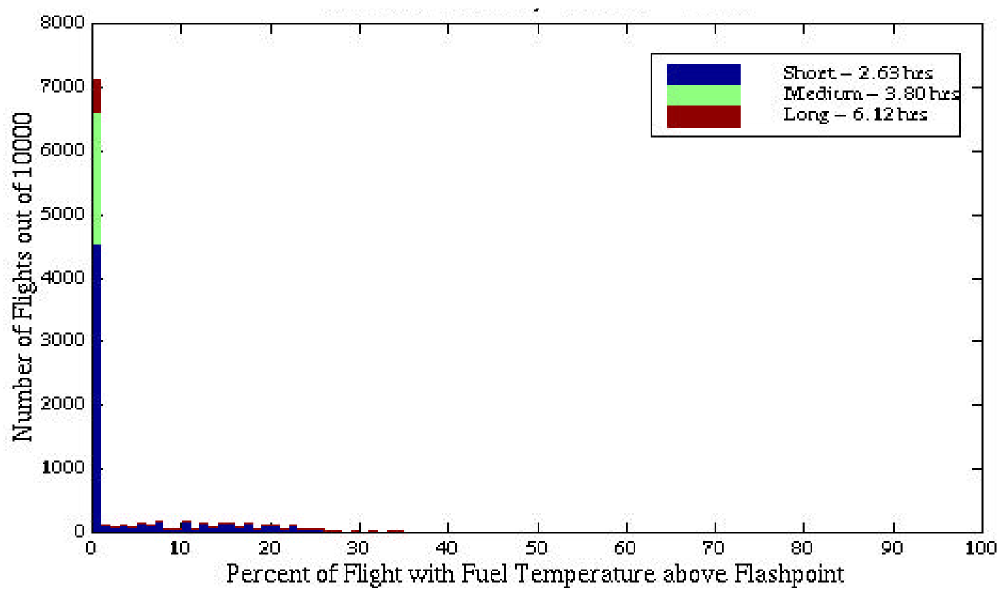
Flashpoint

average 9.5%



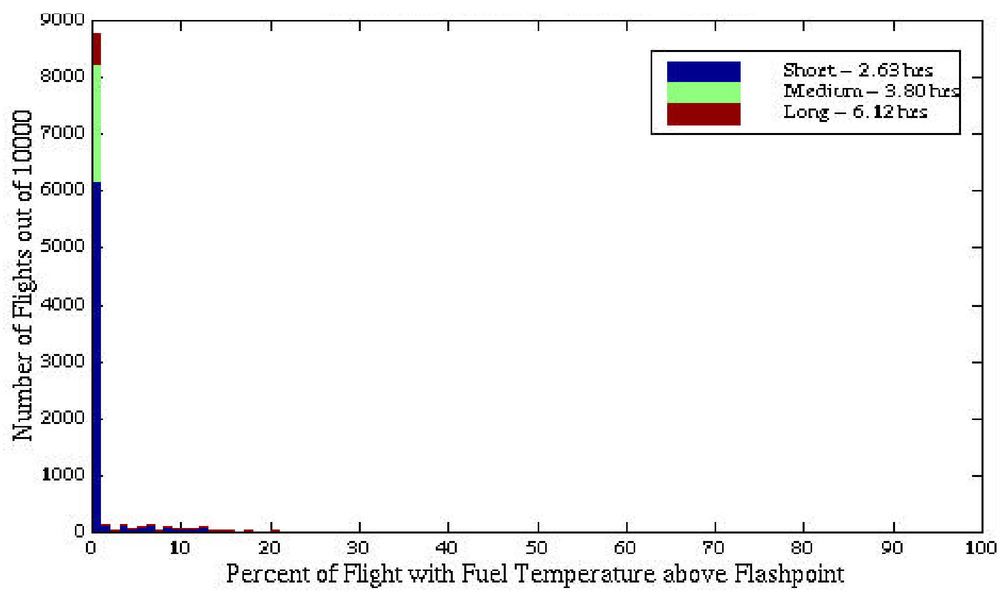
15.3.23 Small Aeroplane Centre Wing Tank With 140°F Flashpoint

average 4.0%



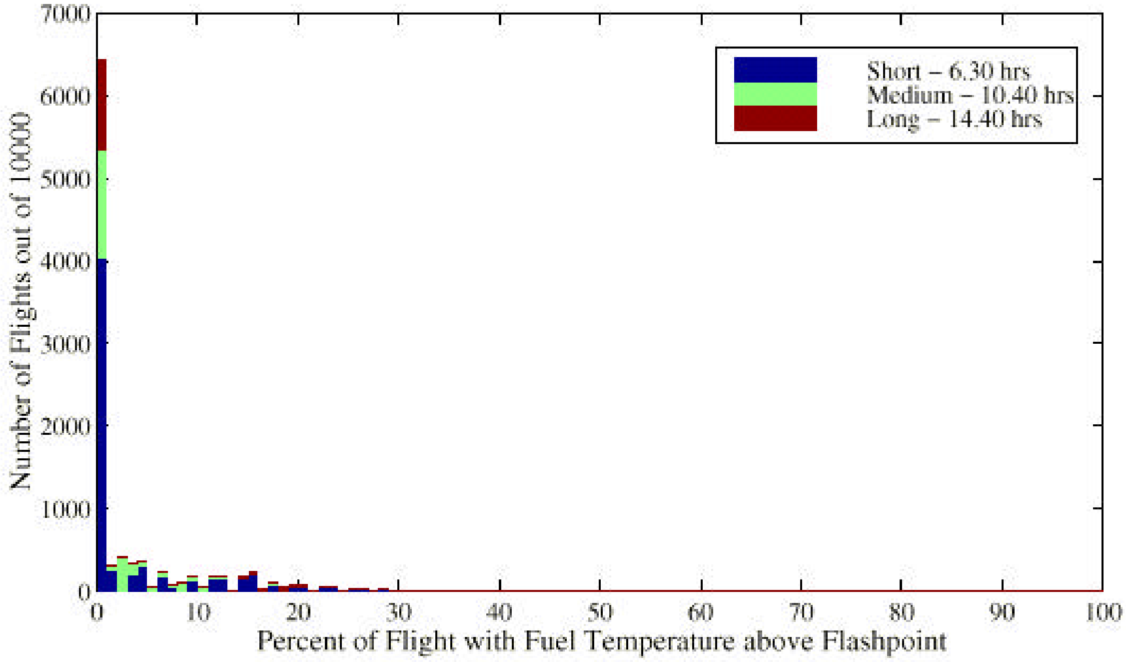
Flashpoint

average 1.1%



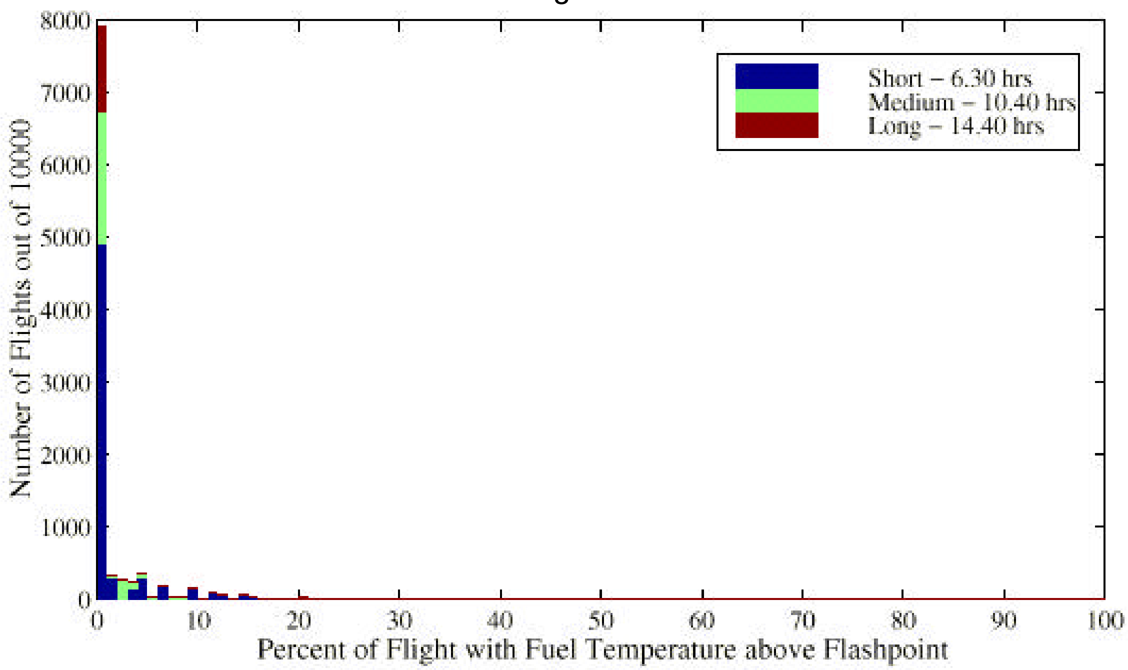
15.3.25 Large Aeroplane Centre Wing Tank COMBINATION of Insulate Heat Sources AND 120°F Flashpoint

average 3.5%

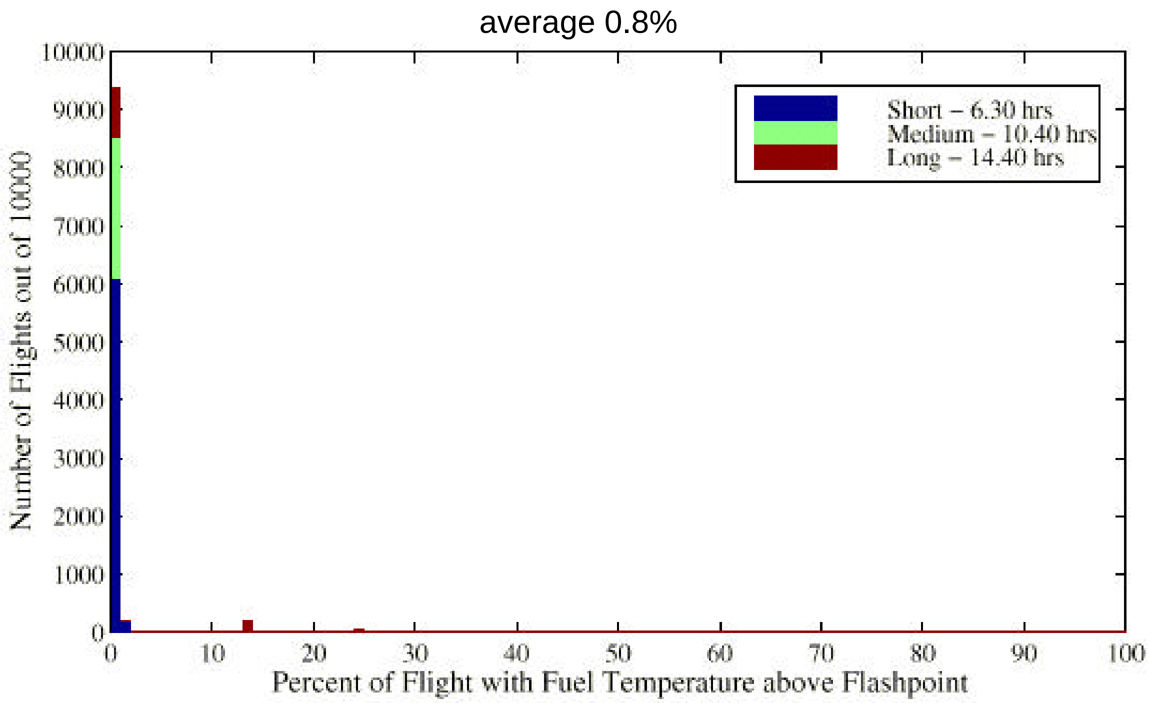


15.3.26 Large Aeroplane Centre Wing Tank COMBINATION of Insulate Heat Sources AND 130°F Flashpoint

average 1.3%



15.3.27 Large Aeroplane Centre Wing Tank With Ground Inerting



15.4 Exposure Analysis Process

A Monte Carlo analysis was run to determine the percent of fuel tank temperature above flashpoint. The randomised variables were; flight length, ground temperature and flashpoint. The fuel tank temperature was input to the Monte Carlo analysis. Models of different aeroplane fuel tanks were developed and run for specified ground temperatures.

Input Data

There were four data inputs into the Monte Carlo analysis:

a) Aeroplane type; this is needed to determine the set of flight lengths to use. Task Group 8 provided this data.

b) Fuel tank temperature; this file determines which data file to load. This is independent of the aeroplane type as there are various models for the same aeroplane type such as; wing tank, centre wing tank with heating and centre wing tank without heating. This data was generated from various sources.

c) Flashpoint; this is needed to determine the range of flashpoints used. The basic flashpoint range was received from Task Group 6. The other ranges used were generated within Task Group 5 and have less spread. The basic flashpoint data was used for most analyses.

d) The final input is the seed for the random number generator. The same seed was used for basic analyses of different models. Several seeds were used to determine the variance of the random numbers generated.

Load Aeroplane Data

With the fuel tank temperature file defined, loading the data is a matter of using the correct format and assigning the data to the correct variables.

Random Numbers Generation

The analysis was started assuming 10,000 runs were required, with 3 randomised variables, this became 30,000 random numbers. A uniform random number generator that gave numbers between 0 and 1 generated the numbers.

The first 10,000 numbers were assigned to the ground temperature probability. As the distribution for these did not have data below 1% or above 99.9%, any numbers outside of this range were assigned to these values. The values were left as probability since the temperature files data were listed as probability.

The second 10,000 numbers were assigned to the flashpoint probability. Using the appropriate flashpoint distribution and the random numbers, flashpoints were generated for the 10,000 runs.

The last set of 10,000 was assigned to mission length. Using the appropriate mission length distribution and the random numbers, mission lengths were determined (short, medium or long).

Percentage Calculation

For each of the 10,000 runs, the ground temperature for each run is used to interpolate the fuel temperature profile from the appropriate fuel temperature data for each run's flight length. Using the altitude data for each run's flight length and the run's flashpoint, the flashpoint for each segment of the flight is calculated.

With the fuel temperature and flashpoint profiles created, the flight segments where the fuel temperature is above the flashpoint are determined. The time spent in each segment is summed and divided by the total length of the flight. This gives the percent of each particular flight where the average fuel temperature is above the flashpoint. The percentages are then averaged, for the 10,000 runs, to produce the average percentage of time that the average fuel temperature is above the flashpoint.

Process Flow Charts

Chart 15.4.1 Monte Carlo Analysis of Fuel Tank Temperature

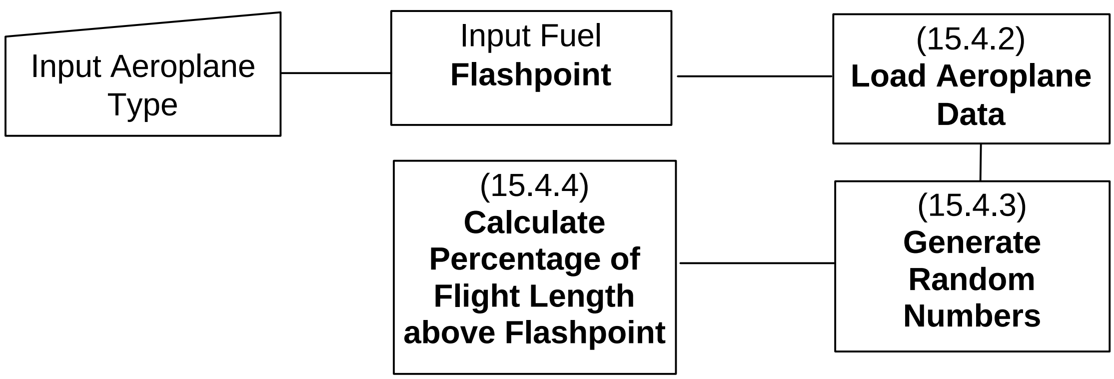


Chart 15.4.2 Load Aeroplane Data

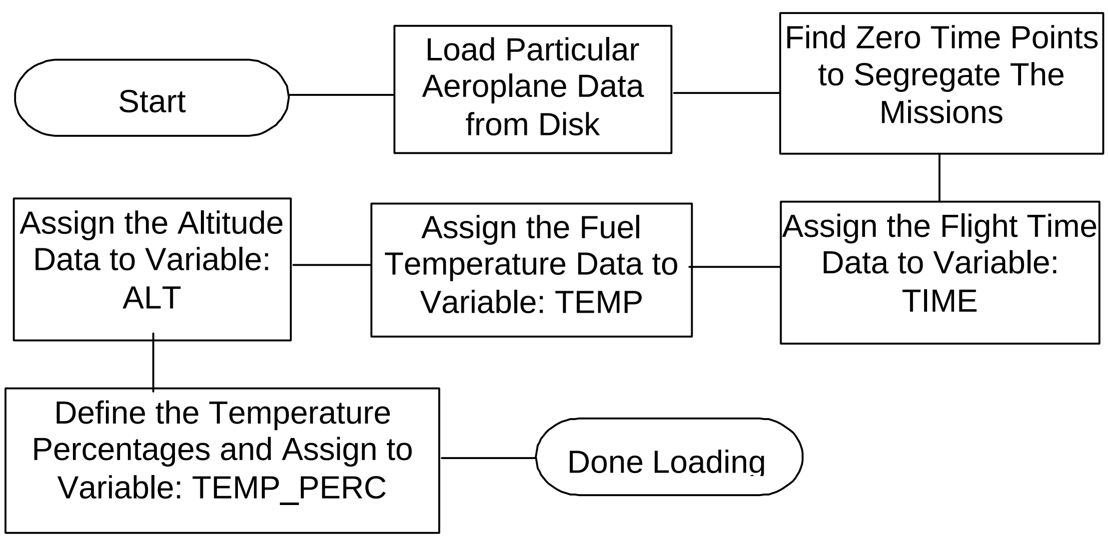


Chart 15.4.3 Generate Random Numbers

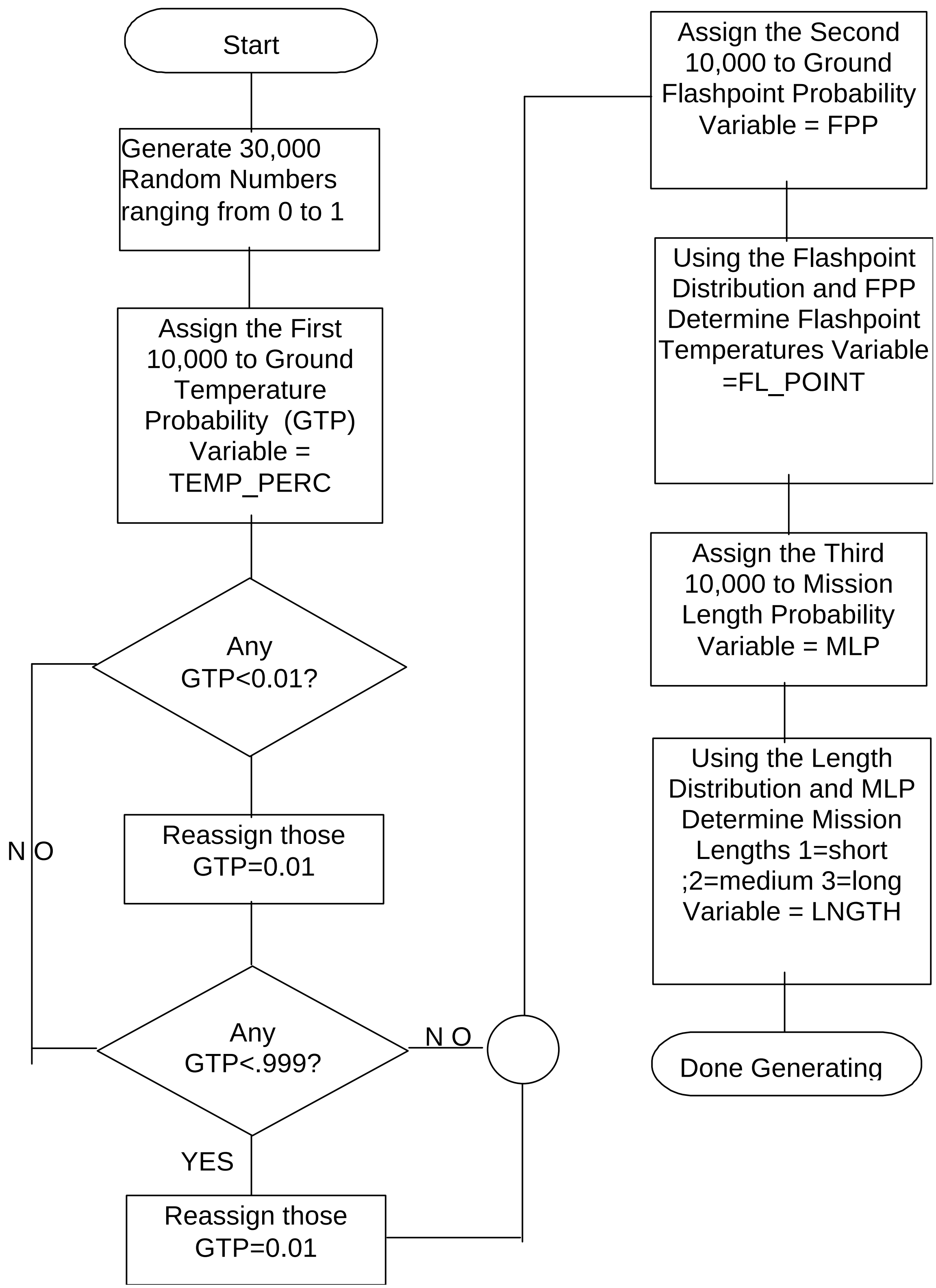
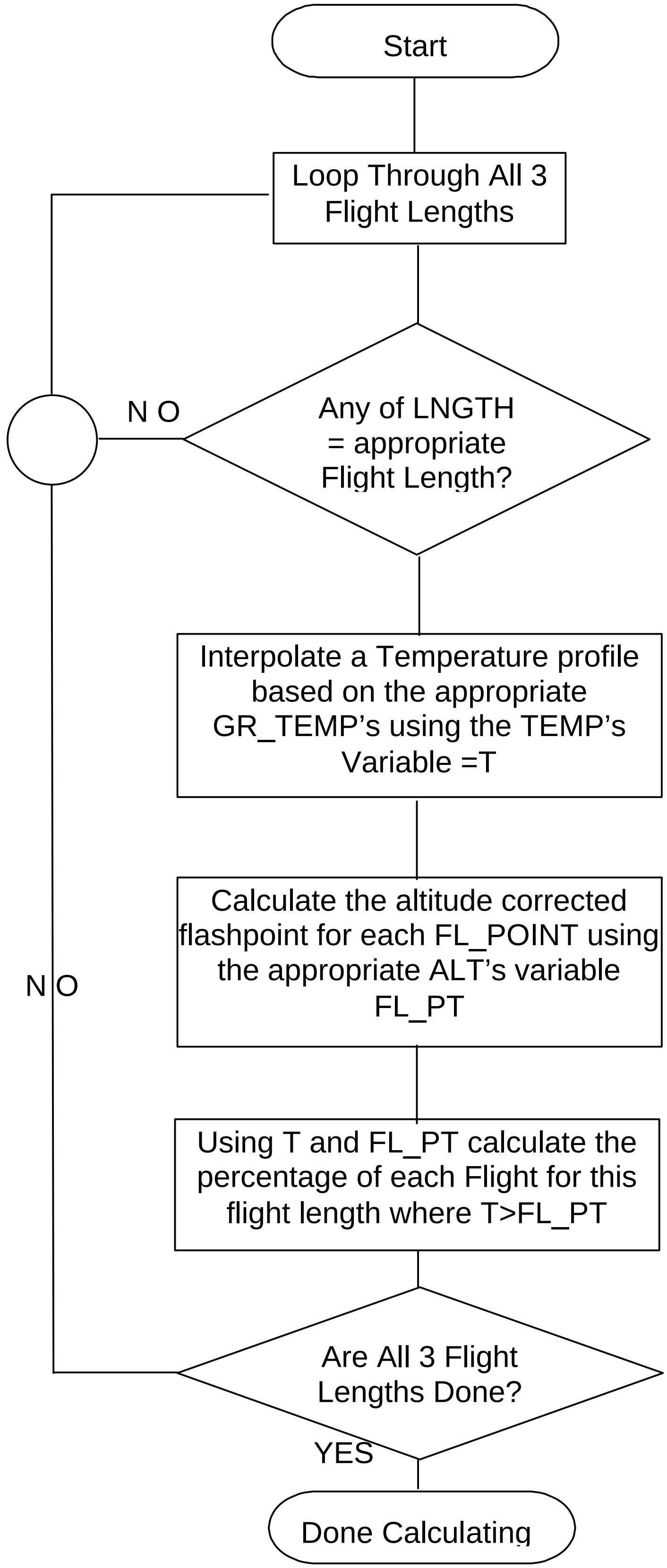


Chart 15.4.4 Calculate Percentage of Flight Length Above Flashpoint



15.5 ULLAGE SWEEPING TESTING

Preliminary laboratory scale tests were conducted to study the concept of ullage sweeping. The test set up was a 55-gallon (US) drum loaded with 1 gallon (US) of fuel. See Figure 15.5.1. The test tank was heated for four hours to a fuel temperature of 120°F which was 14°F above the flashpoint of the fuel. The fuel vapour concentration was measured at two locations within the test tank and several times during the test. The concentration meter gave results in terms of %LFL which is the fuel vapour concentration as a fraction of the lower flammability limit of 0.6% by volume. For example, 100%LFL on the meter equals 0.6% by volume, and so 50%LFL equals 0.3% by volume. Results of the heating test are shown in figure 15.5.2.

After the tank had been heated for four hours, the ullage was swept with ambient air for 1½ hours. The flow rate of the air was 25 standard cubic feet per hour, (SCFH), which simulates 1 test tank volume change in 20 minutes. The fuel vapour concentration was reduced to 80%LFL in the first 30 minutes and to 60%LFL after 1½ hours. Test results are shown in Figure 15.5.3. During this test approximately 3% of the fuel mass was evaporated and lost through the vent.

The fuel vapour concentration was measured with a custom built, 10 channel combustible gas monitoring system from Mine Safety Appliance Corp. The gas samples are measured with a low temperature catalytic bead sensor utilising Ultima combustible gas transmitters. The unit measures percent lower flammability limit by sampling the fuel vapour at rates of one litre per minute. The unit was acquired from Autoline Controls of Redmond, Washington, USA.

Figure 15.5.1 Fuel Tank Ullage Sweeping / Vapour Condensing Test Set-up

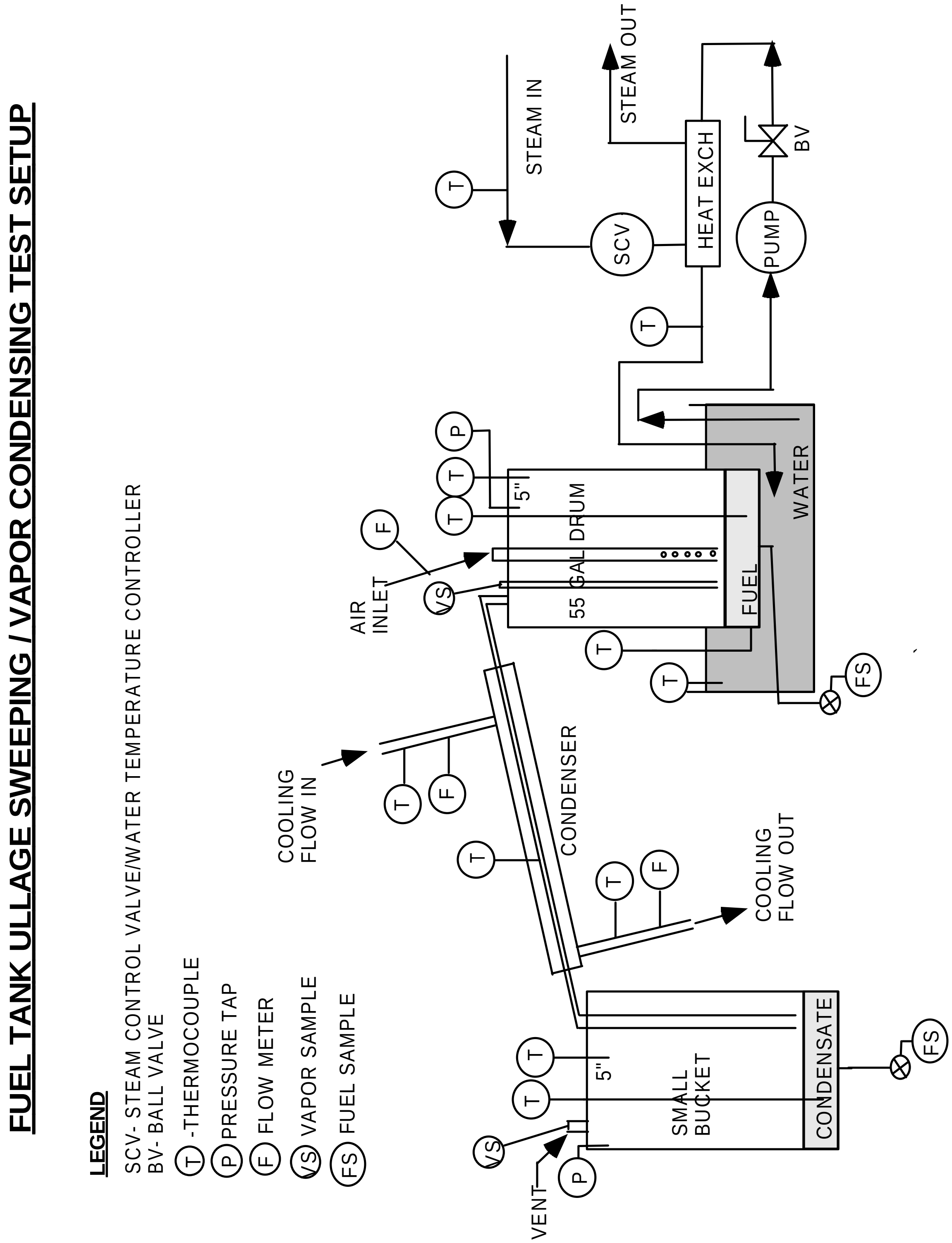


Figure 15.5.2 Flammability of a Nearly Empty Fuel Tank

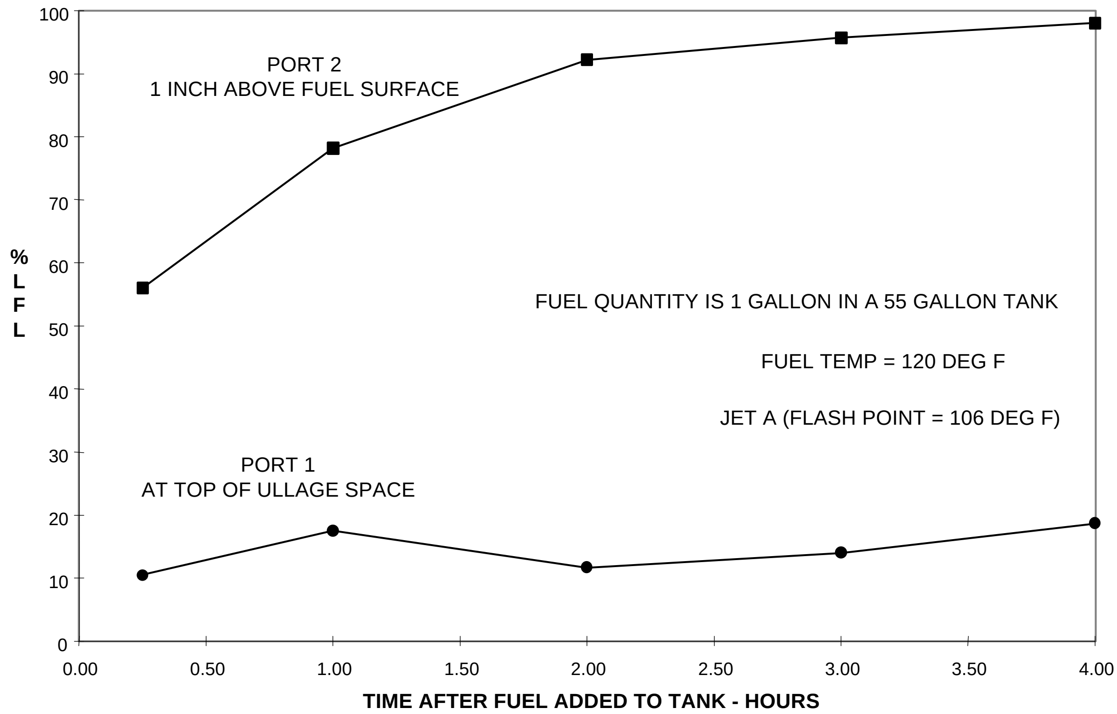


Figure 15.5.3 Effect of Ullage Sweeping by Ambient Airflow of 25 SCFH