Helicopter Fuel Burn Modeling in AEDT

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13. ABSTRACT (Maximum 200 words)

This report documents work done to enhance helicopter fuel consumption modeling in the Federal Aviation Administration's Aviation Environmental Design Tool (AEDT). Fuel consumption and flight performance data were collected from helicopter flight manuals and from in-service operations. These data were used to develop methods for predicting helicopter fuel consumption as a function of the helicopter flight state. The primary method developed for this report showed a difference from the flight manual reported fuel consumption of about 4% in cruise mode for the utilized helicopter weight.

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HELICOPTER FUEL BURN MODELING IN AEDT *

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Preface

As students of the faculty of Aerospace Engineering at the Technical University of Delft, The Netherlands, it is mandatory to do an internship in the first or second year of the Masters track. The total duration of the internship is set to a minimum of 3 months and is rewarded upon completion with 18 ECTS. The goal of the internship is to put the knowledge gained at the Technical University of Delft into a practical use, being either the aviation or the space field, and to familiarize students with working for a company in preparation of their professional life.

There are numerous options available, but working for the Volpe center in the United States of America is an opportunity not to be missed. It presents a great chance to work for an ambitious research center and to get to know the country as a bonus. It is the land of opportunity indeed.

We would like to thank Mr. David Senzig for guidance and help during the project. Furthermore, we would like to thank Dr. Amar Choudry for the assistance in getting settled and facilitation of numerous thing. Mister Eric Lincoln, from Blue Hawaiian Helicopters is thanked for facilitating the only flight data available to us. And finally, we would like to thank everyone who made it possible for us to work at the Volpe Center and provide us with everything we needed.

Cambridge, February 3, 2010
Alexander Haagsma and Elgar van Veggel

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Summary

As an introductory part of the internship the evaluation of new BADA 3.7 fuel burn data was performed. This data was optimized for terminal operations. The execution of AEDT has been automated and performed for thousands of flights with the old BADA 3.6 and the new BADA 3.7 data. It was shown that for ten of the 12 aircraft evaluated, the new BADA 3.7 data improved the calculations by AEDT considerably.

The main part of this report describes the process of obtaining a calculation model of helicopter fuel burn to allow fuel burn calculations of real life flights in AEDT. In this project, the focus has been on flights across the National Parks of United States of America. Because the helicopter part of AEDT does not work with a performance module which could easily calculate fuel burn, another approach has to be found to calculate the fuel burn in the different procedural steps a flight is divided.

In this approach, four methods have been evaluated. The first method assumes a fixed thrust specific fuel consumption of 0.5 lbs/HP/hr for the complete flight. The second method features a relation between fuel flow and torque setting of the Bell 407. In this method different torque settings for different flight phases have been defined. The third method involves the extensive fuel burn data from the flight manual of the Bell 407. For different flight phases, different fractions of the fuel flow in cruise are determined. The last method is based on the theoretical required power in the different flight phases. The power required is then related to fuel flow.

Of these four methods, the third: “fuel flow data from flight manual” has been chosen based on a comparison of the four with the available data. The first method, which is not more than a reference method, is around 50% off. The second was found to be around 7% off. The third method is closest with 2% off and the last theoretical method is around 16% off.

The chosen method has been developed into a model which is presented compatibly with the excising AEDT architecture. Unfortunately, it was not possible to confirm the model’s accuracy with flight data, as this was not available.

Glossary and abbreviations

Glossary

C_1	Flight phase constant	-
C_2	Helicopter constant	-
$C_{Deq}S$	Equivalent flat plat area	m²
$\overline{C}_{Dp}$	Profile drag coefficient	-
D	Drag	N
d	AEDT horizontal coordinate	ft
FF	Fuel flow	lbs/hr
FF_{cruise}	Fuel flow of cruise phase	lbs/hr
$FF_{flight\ phase}$	Fuel flow of flight phase	lbs/hr
FM	Figure of Merit	-
H	Altitude	ft
$HP_{installed}$	Power installed	HP
k_{dl}	Disc loading constant	-
M_{fuel}	Fuel burned	lbs
$M_{fuel,Bell\ 407}$	Fuel burned by Bell 407	lbs
$M_{fuel,flight\ phase}$	Fuel burned in flight phase	lbs
$M_{fuel,helicopter}$	Fuel burned by any helicopter	lbs
μ	Advance ratio	-
N_g	Gas turbine speed	%
P_d	Drag power	W
$P_{forward\ flight}$	Forward flight power	W
P_{hover}	Hover power	W
P_i	Induced power	W
P_{ideal}	Ideal power	W
P_p	Profile power	W
P_{phov}	Profile power in hover phase	W
P_{req}	Power required	W
P_s	Parasite power	W
R	Rotor radius	m
ρ	Density	kg/m³
SFC	Specific Fuel Consumption	lbs/HP/hr
σ	Solidity ratio	-
Ω	Rotational speed	rad/s
T	Thrust	N
$T_{flight\ phase}$	Torque in flight phase	Nm

$t_{flight\ phase}$	Duration of flight phase	s
$t_{mission}$	Duration of mission	s
V	Velocity	m/s
$\overline{V}$	Velocity parameter	m/s
V_{cruise}	Cruise velocity	kts
V_T	True airspeed	kts
v_i	Induced velocity	m/s
$\overline{v}_i$	Dimensionless induced velocity	-
v_{i_h}	Induced velocity parameter	m/s
V_{max}	Maximum velocity	m/s
V_{ne}	Never exceed velocity	m/s
V_{tip}	Rotor tip velocity	m/s
W	Weight	N
$\dot{W}_{fuel}$	Fuel flow	lbs/hr
z	AEDT altitude above helipad	ft AFE

Abbreviations

AEDT	Aviation Environmental Design Tool
AFE	Above Field Elevation
APP	Approach
BADA	Base of Aircraft Data
CSV	Comma Separated Value
DEP	Depart
ECTS	European Credit Transfer System
FAA	Federal Aviation Administration
FDR	Flight Data Recorder
INM	Integrated Noise Model
ISA	International Standard Atmosphere
OVF	Over flight
SFC	Specific Fuel Consumption
SHP	Shaft Horse Power
SQL	Structured Query Language
TAX	Taxi
TSFC	Thrust Specific Fuel Consumption
WBF	Windows Batch File

1 Introduction

The Volpe Center is continuously developing the Aviation Environmental Design Tool (AEDT). This tool is developed to incorporate both emissions and noise of specific flights. For jet airliners, the tool is well developed. For helicopters and turboprop aircraft the emissions part of the model has not been developed yet. The Volpe Center is focusing on noise and emissions in the United States National Parks, where mostly helicopters and turboprop aircraft are used for air tours. Therefore the development of an emissions part to be implemented in the AEDT tool is of importance. The assignment given by the Volpe Center is to create a software model which can estimate the fuel burned by a helicopter on a specific flight. Fuel burn can then be directly linked with emissions(7). The model must be able to handle different helicopter types and different flight profiles.

To get acquainted with AEDT and modeling, first an introduction in working with AEDT was given. For this small project the AEDT model was used to compare the old BADA 3.6 fuel burn data which is used in AEDT with the new BADA 3.7 fuel burn data. This has been done to verify whether the improvements in terminal phases indeed lead to better accuracy.

The details on the introductory project on the BADA 3.6 and 3.7 data can be found in chapter 2. Then chapter 3 starts with the presentation of the available information on helicopters which is useful for this project. It also shows in what way that information can be used to get to the fuel flow. In chapter 4 the different methods to calculate the fuel flow will be presented resulting from the information available, which was presented in chapter 3. A comparison of these methods can be found in chapter 5 together with the selection of one of these methods to be used in the model and how that model would be defined. In chapter 6 the implementation of the method is explained; inputs are described and a recapitulation of the equations needed is given. This is followed by the conclusion in chapter 7 and the recommendations are found in chapter 8.

2 Introductory project to understand the available models

In this chapter the introductory project will be discussed. The method and results are presented below. This project has been completed with Jef Geudens and Kurt Wils.

2.1 Introduction

In the past, a fair amount of research has already been done on how to model the fuel burn of several types of aircraft in the terminal area. However, there are still different types of aircraft such as the turboprop and helicopters which are not yet covered. To model fuel burn, a combination of two models has been used over the years. These two models are Eurocontrol's Base of Aircraft Data (BADA) and SAE AIR 1845(8). Both are combined in the FAA's AEDT model.
Analysis of Flight Data Recorder (FDR) data has shown that the BADA 3.6 model does not model the fuel burn in the terminal area of airports accurately. The reason for this is that the BADA model was initially designed as an Air Traffic Management (ATM) tool and the Thrust Specific Fuel Coefficients that are used do not extrapolate well to the velocities that are used in the terminal area.
Eurocontrol has released a new version of the BADA model, BADA 3.7. One of the improvements is on the fuel burn in terminal areas(9). To see if these improvements indeed led to a better estimation of fuel burn in terminal areas the 3.6 and 3.7 model will be evaluated using AEDT and be compared with FDR data available. The results will be stated in this paper.

2.2 Project description

The goal of this project is to validate the new BADA 3.7 model. This will provide introductory work with the AEDT model.

The project involves:

- Running BADA 3.6 data in AEDT and compare this with known results for BADA 3.6 (calculated a couple of years ago with INM used to determine the terminal area thrust) and FDR data. The FDR data is obtained from a major European airline.
- Running BADA 3.7 data in AEDT and check whether this new data is an improvement over BADA 3.6 in terminal operations.

The BADA model will be evaluated for twelve commercial airliners, being the:

- Airbus A319
- Airbus A320
- Airbus A321
- Airbus A330-202
- Airbus A330-223
- Airbus A330-243
- Airbus A340-313
- Airbus A340-541
- Boeing 757-200
- Boeing 767-300ER
- Boeing 777-300ER
- British Aerospace BAe-146

To be able to run the same flights in AEDT as those of which FDR data is available, the SQL databases which forms the backbone of AEDT has to be updated every for flight run. Because there are around 3000 flights to be analyzed, all steps needed to run a flight will be automated using SQL scripts combined with Windows Batch Files (WBF).

2.3 Flow diagram

To be able to automate all flights used in the validation the following flowchart has been designed (Figure 1). There are initial procedures required (block 1), then there is a loop in which the procedures are repeated for every flight (block 2-6), concluded with some final procedures (block 7). The whole process is programmed in a Windows Batch File. All steps are also programmed in batch files. If a SQL step is indicated in Figure 1, the SQL script is executed from within another batch file. The actual scripts are given in Appendix A1 for the Boeing 757-200.

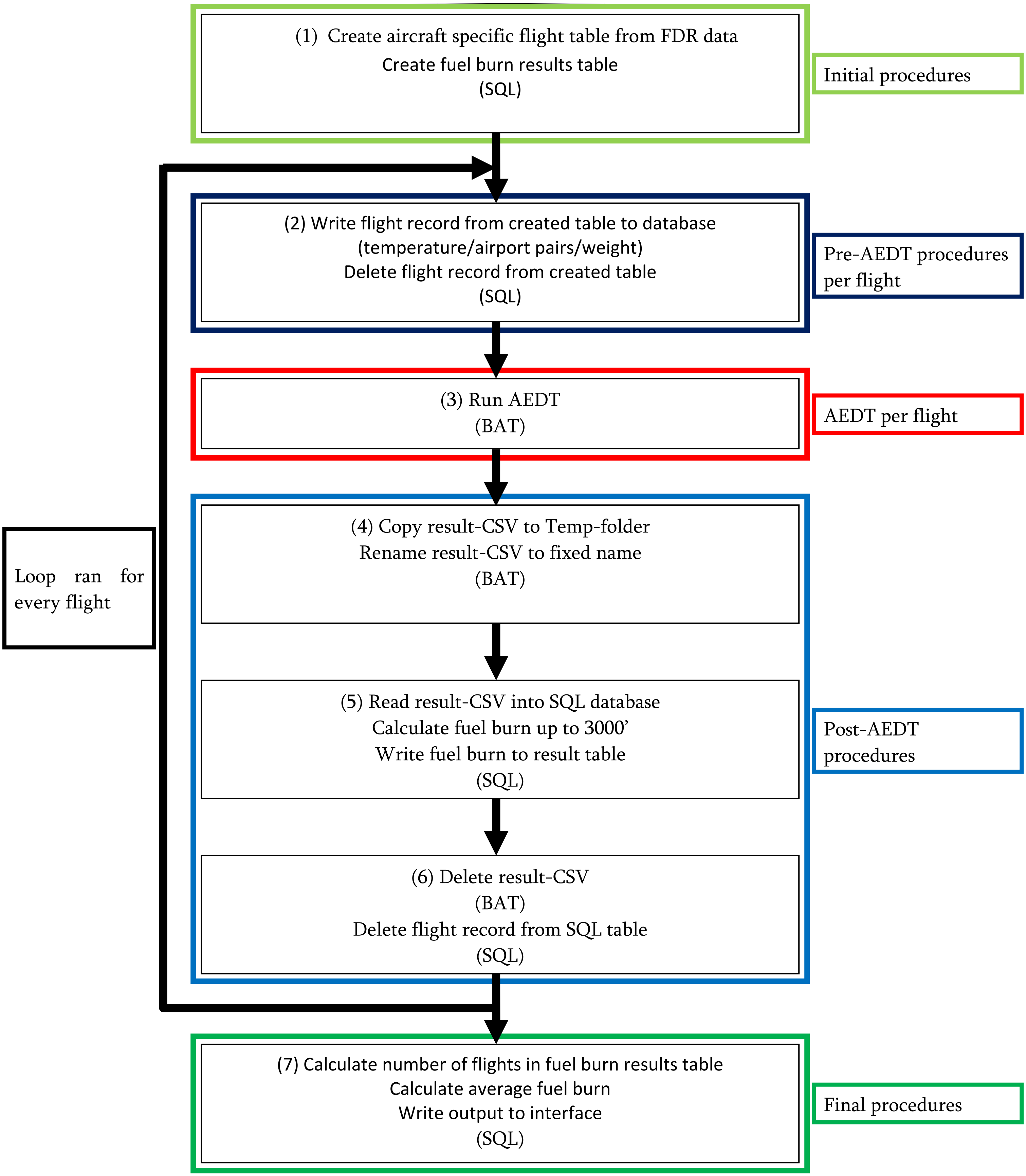

Figure 1: Flow diagram of automated procedure

2.4 Results

The results of the calculations with AEDT and the BADA 3.6 and 3.7 data are given in Table 1. Also the BADA 3.6 data run with the Integrated Noise Model (INM) a couple of years ago is presented as reference[34]. In Table 2 all differences are given.

Table 1: Calculation results

Aircraft	*Measured (FDR) [kg]*	*Modeled (INM + BADA 3.6) [kg]*	*Modeled (AEDT + BADA 3.6) [kg]*	*Modeled (AEDT + BADA 3.7) [kg]*
757-200	328	262	262	349
767-300ER	464	552	545	486
777-300ER	736	1131	1160	822
A319	181	189	202	213
A320	198	278	268	209
A321	241	268	283	266
A330-202	639	769	679	558
A330-223	680	877	725	597
A330-243	539	741	685	562
A340-313	956	1104	1069	842
A340-541	1013	1258	1370	1082
Bae-146	170	388	371	269

Table 2: Differences between calculations

Aircraft	*Difference INM, 3.6 vs FDR [%]*	*Difference AEDT, 3.6 vs FDR [%]*	*Difference AEDT, 3.7 vs FDR [%]*	*Difference INM vs AEDT, 3.6 [%]*
757-200	-20%	-20%	6%	0%
767-300ER	19%	17%	5%	-1%
777-300ER	54%	58%	12%	3%
A319	4%	12%	18%	7%
A320	40%	35%	6%	-4%
A321	11%	17%	10%	6%
A330-202	20%	6%	-13%	-12%
A330-223	29%	7%	-12%	-17%
A330-243	37%	27%	4%	-8%
A340-313	15%	12%	-12%	-3%
A340-541	24%	35%	7%	9%
Bae-146	128%	118%	58%	-4%

2.5 Conclusions

Except for the Airbus A330s the analysis of the BADA 3.6 data with INM does not differ much from the analysis with AEDT. The results for BADA 3.7 are for most aircraft much better than the results based on the BADA 3.6 data. The A330-202, A330-223 and the A319 are an exception on that conclusion.

In general it can be concluded that BADA 3.7 is indeed an improvement with respect to the older 3.6 data in terminal areas.

3 The available information on helicopters

This chapter will explain the relevant information there is on. It displays the helicopter chosen to be the base model in this project and which information sources are used.

3.1 Helicopter models

With the closure of the first part, the second part of the project has been initiated. The goal is to implement a fuel burn model for helicopters in AEDT, since there is no data available at all at this point. Especially the helicopters used at National Parks are important. The Volpe Center is interested in the trade off that has to be made between noise, fuel consumption and the impact of the air tours on the park visitors. The main objective is to let AEDT calculate the fuel burned in a specific flight and be able to get data of various flights and various helicopters, but the focus is on the ones at National Parks. The helicopter types used for air tours particularly at that location have been researched and the most often used types are[18-33]:

- Bell 206
- Bell 407
- Eurocopter AS350
- Eurocopter EC 130 B4

The Eurocopter EC 130 B4 is the latest type from Eurocopter and successor of the Eurocopter AS350. It has been made for low noise levels with its Fenestron tail rotor, which is one of the reasons it is used often in National Parks. The Bell 407 is the derivative of the Bell 206, which is also used regularly for tourist flights. Its main differences between the Bell models are the four bladed rotor on the Bell 407 versus the two bladed rotor on the Bell 206. It is also more powerful and the cabin is 18 cm (about 7 inches) wider[14,15].

3.2 Flight manuals available

An important source of information about an aircraft is the flight manual. It usually provides detailed performance data and, useful in this particular case, the fuel flow or fuel consumption in different situations.

The flight manual of the EC 130 has been found[5], in which relevant fuel burn data and weights as well as performance data is given. It has several figures plotted to indicate the fuel burn for different situations, for example for recommended cruise speed at International Standard Atmosphere (ISA) conditions. This can be seen in Figure 2:

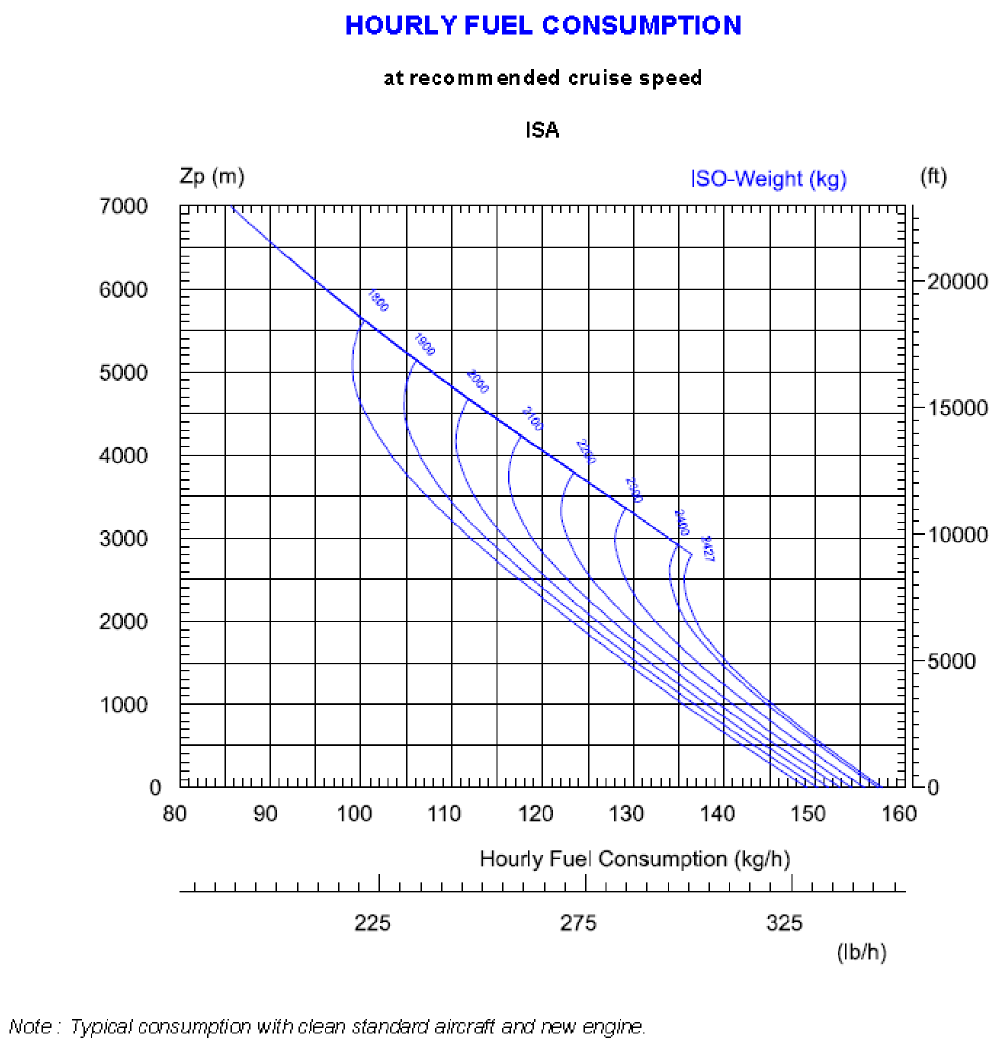

Figure 2: Eurocopter EC 130 Fuel consumption[11]

As can be seen in this figure, there is a relation between helicopter weight, altitude, (fixed) temperature and speed, and hourly fuel consumption. This could therefore be used in cruise when altitude, weight and speed are known to calculate the fuel burned for the duration of the cruise phase. The rest of the figures and the table with performance data for different gross weights are given in Appendix A2.

For the Bell 407, the flight manual was also available[3], which displays the same sort of information. It shows a relation between helicopter weight, (fixed) altitude and temperature, speed and fuel flow. Several figures show the relations for the different temperatures and altitudes. The figure for sea level at 15 °C is shown, the rest of the figures for different conditions are shown in Appendix A3.

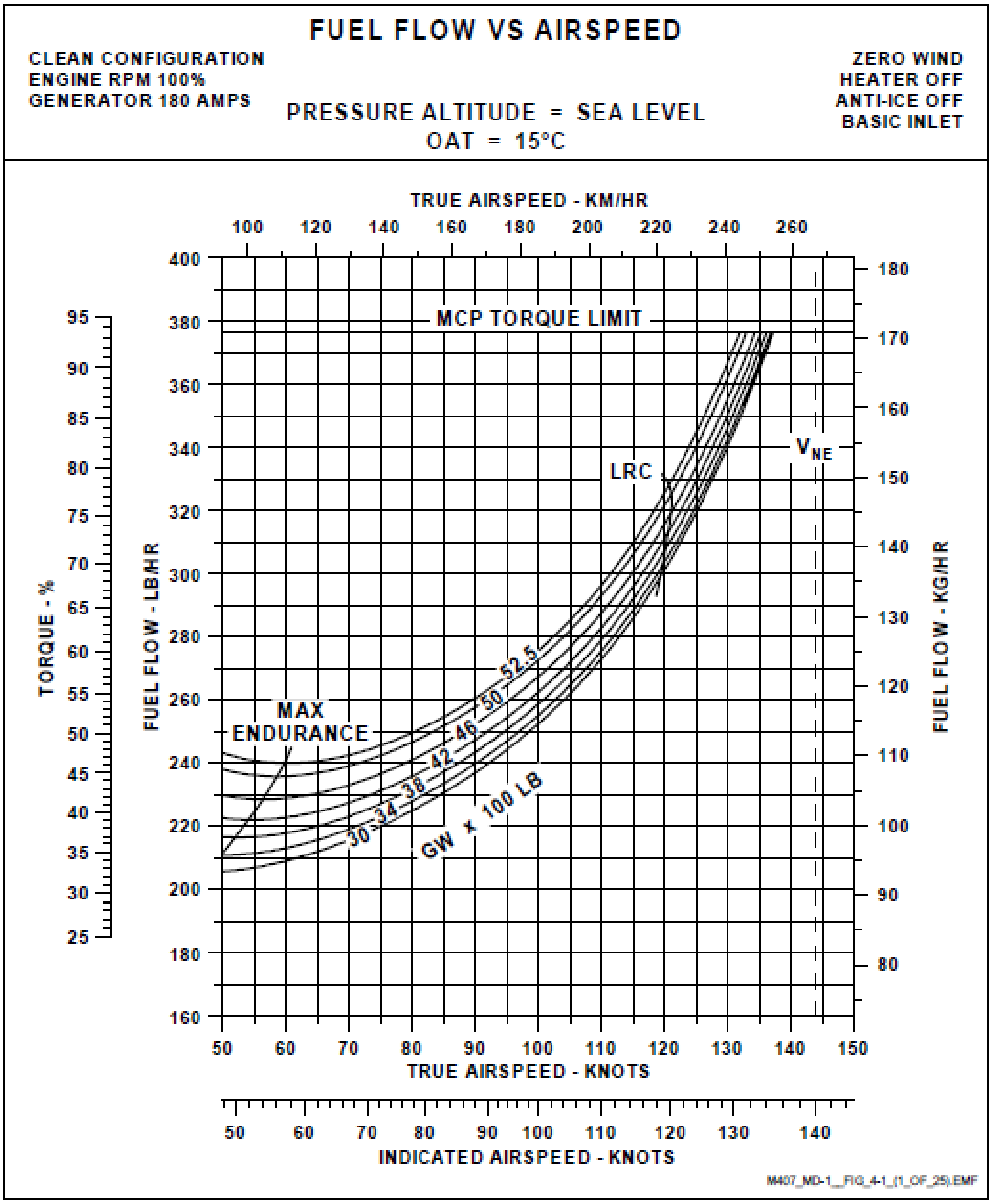

Figure 3: Bell 407 Fuel burn at sea level 15 °C(3)

The difference between this figure and the one from Eurocopter is the addition of the torque relation. It shows, for a particular condition, what percentage of torque equals which amount of fuel flow. Since helicopter profiles could probably be expressed in torque, this is a very important relationship which could come in handy. This is the reason the Bell 407 will be chosen as the reference helicopter over the Eurocopter EC 130 B4, however the EC 130 will be used amongst other helicopter models to verify the eventual model.

3.3 Helicopter literature

A lot can be learned from the available helicopter literature. Methods to determine the power required are obtained from Prouty[1] (in SI units). There is a method to determine the power required to hover, presented in section 3.3.1. Another method is presented to determine the power curve of the helicopter. This power curve indicates the required power to perform a forward flight at every velocity. This method is presented in section 3.3.2.

3.3.1 Hover

The first phase to be discussed is the hover phase. For this phase it is necessary to know the ideal power, which is calculated with equation 3.1:

$$P_{ideal} = W\sqrt{\frac{W}{2\rho\pi R^2}} \qquad (3.1)$$

Where W is the instantaneous weight, ρ is the density and R is the rotor radius. To be able to calculate the ideal power the weight, the density and the radius of the rotor must be specified.

To calculate the power required to hover equation 3.2 is used:

$$P_{Hover} = \frac{P_{ideal}}{FM} \qquad (3.2)$$

The ideal power is divided by the Figure of Merit (FM), which indicates the efficiency of the rotor. Generally the value of the Figure of Merit lays somewhere between 0.7 and 0.8. The Figure of Merit has not significantly improved over the last 20 years and is still found to be between 0.7 and 0.8, which shows 0.8 is around the maximum value obtainable. In this case a value of 0.75 would be a good assumption to cover the modern clean helicopters used in air tours.

3.3.2 Forward Flight

In forward flight, a different approach is taken. Now for example induced drag and pressure drag are taken into account. The basic formula to calculate the power required in forward flight is:

$$P_{Forward\ flight} = P_S + P_d + P_p + P_i \qquad (3.3)$$

In this case, $P_S$is the parasite power, $P_d$is the drag power, P_p is the profile drag power and P_i is the induced power.

To calculate P_S equation 3.4 is used:

$$P_S = DV = \sum(C_{Deq}S)\frac{1}{2}\rho V^3 \qquad (3.4)$$

Where $\sum(C_{Deq}S)$ is the equivalent flat plate area which influences the parasite drag, ρ is the density and V is the velocity.

The calculation of P_d and P_p is combined into equation 3.5:

$$P_p + P_d = P_{phov}(1 + 4.65\mu^2) \tag{3.5}$$

Where P_{phov} is the profile drag in the hover phase and μ is the advance ratio.

The advance ratio is defined by:

$$\mu = \frac{V_{ne}}{V_{tip}} \tag{3.6}$$

With V_{ne} is defined as $1.1 \times V_{max}$

P_{phov} is calculated with equation 3.7:

$$P_{phov} = \frac{\sigma \bar{C}_{Dp}}{8}\rho(\Omega R)^3 \pi R^2 \tag{3.7}$$

In this σ is the solidity ratio, for helicopters in question a value of 0.16 can be assumed, $\bar{C}_{Dp}$ is a profile drag coefficient depending on maximum tip speed which can be assumed to be 0.025, Omega is the rotational speed and R is the rotor radius.

Finally in the forward flight phase P_i needs to be calculated. This is done by using equation 3.8:

$$P_i = kTv_i \tag{3.8}$$

In this equation k is a fixed constant set to 1.15, T is the thrust force determined on the basis of the weight of the helicopter given by equation 3.9 and v_i is the induced velocity given by equation 3.10:

$$T = k_{dl} \times W \tag{3.9}$$

In which k_{dl} can be set to 1.03

$$v_i = \bar{v}_i \times v_{i_h} \tag{3.10}$$

In which $\bar{v}_i$ is the non dimensional form of v_i and v_{i_h} is parameter making v_i non dimensional.

v_{i_h} is defined in equation 3.10:

$$v_{i_h} = \sqrt{\frac{W}{2\rho\pi R^2}} \tag{3.11}$$

$\bar{v}_i$ is depending on the speed, more specifically on $\overline{V}$ which is defined as:

$$\overline{V} = \frac{V}{v_{i_h}} \tag{3.12}$$

For $\overline{V} > 2$, $\bar{v}_i$ is defined as:

$$\bar{v}_i = \frac{1}{\overline{V}} \tag{3.13}$$

For $\overline{V} \leq 2$ $\bar{v}_i$, is defined as:

$$\bar{v}_i = \sqrt{-\frac{1}{2}V^2 + \frac{1}{2}\sqrt{V^4 + 4{v_{i_h}}^4}} \tag{3.14}$$

With equation 3.4-3.14, the power required in forward flight as specified in equation 3.3 can be calculated.

3.4 Real time flight data

The actual fuel burn data would be a good reality check for the model. Furthermore, it would give the opportunity to analyze the differences in fuel burn between the different phases. This will make it possible to find certain factors between the fuel burn of different phases.

There was no flight data available at the Volpe Center and it was not possible to get it through testing. Operators were approached for flight data and Blue Hawaiian Helicopters has been willing to provide some flight data of two flights[35].
Flight 1 took off with 574.6 lbs fuel. The fuel flow and N_g speed is provided for the flight phases with corresponding conditions in Table 3:

Table 3: Flight data of flight 1 (Blue Hawaiian Helicopters Eurocopter EC 130)

Flight phase	*Altitude [ft]*	*Temperature [°F]*	*N_g speed [%]*	*Fuel flow [lbs/hr]*
Hover	0	85	92	307.8
Climb	1000	75	96	348.8
Climb	6000	61.8	96	328.3
Climb	7000	60.8	96	307.8
Cruise	1000	80	86	225.7
Cruise descent	7000	61	92.5	246.2

Flight 2 took 48 minutes and consumed 36 gallons (246.2 lbs) of fuel. The other data obtained during the flight is provided in Table 4:

Table 4: Flight data of flight 2 (Blue Hawaiian Helicopters Eurocopter EC 130)

Flight phase	*Altitude [ft]*	*N_g speed [%]*	*Fuel flow [lbs/hr]*
Flat pitch full throttle	0	80.8	184.7
Hover	0	94.2	362.5
Cruise	2000	95	328.3
Climb	5000	96.5	328.3
Climb	7000	96.5	314.6
Climb	8000	96.5	294.1
Climb	9000	96.5	280.4

The flight data does not give enough information to verify the model with, but it gives some information which might be used in the definition of the model.

4 Possible methods for the model

As seen in chapter 3, four methods have been researched to use in the calculations of the fuel used in an entire helicopter flight. In this chapter, the various calculation methods will be explained leading to a comparison in the next chapter.

Most information used to define the methods in paragraph 4.1 and 4.4 can be found in Prouty[(1)], a well known book on helicopter performance. The flight manual of the Bell 407[(3)] provides several figures showing various relations, which were used for the methods explained in paragraph 4.2 and 4.3.

4.1 Method 1: fixed specific fuel consumption

The first method to be discussed is also the most basic one. An assumption is made on the SFC of modern turbine engines to be 0.5 lbs/HP/hour[(36,37)]. The SFC is given by equation 4.1:

$$SFC = \frac{fuel\ flow}{flight\ power} = \frac{\dot{W}_{fuel}}{P} \tag{4.1}$$

This can be rewritten as equation 4.2:

$$\dot{W}_{fuel} = SFC \times P \tag{4.2}$$

This will give the fuel flow for that specific power setting, but it is assumed that the complete flight is done with maximum flight power, also known as installed power. When this formula is multiplied by the mission time (in hours), this leads to equation 4.3:

$$M_{fuel} = SFC \times HP_{Installed} \times t_{Mission} \tag{4.3}$$

This very simplistic formula will generally give a rough estimation of the used fuel mass (in lbs) since it assumes a fixed SFC and maximum flight power and thus can only be used for a very basic calculation. However, since it can be found quite easily it will be used in the comparison of the methods to check its validity.

4.2 Method 2: fixed torque-fuel flow relation

Another method which can be used is to fix the torque setting for different flight phases and use a formula which relates torque to fuel flow[(38)]. This is based on graphs of the flight manual of the Bell 407[(3)], where the fuel flow axis and the torque percentage axis are given next to each other.

Since the torque depends on various things such as weight, temperature and pressure altitude, this leads to inaccuracy when a standard setting is used. It would be best if the input by the user would include the torque settings for every flight phase for that particular flight.

The starting point for this method is Figure 3 from the Bell 407 flight manual. There it can be seen there is a direct relation between fuel flow and torque. This relation differs for every altitude and corresponding standard temperature. The relation was tabularized, leading to graph with a relation between torque and fuel flow. This can be seen in Figure 4 for sea level:

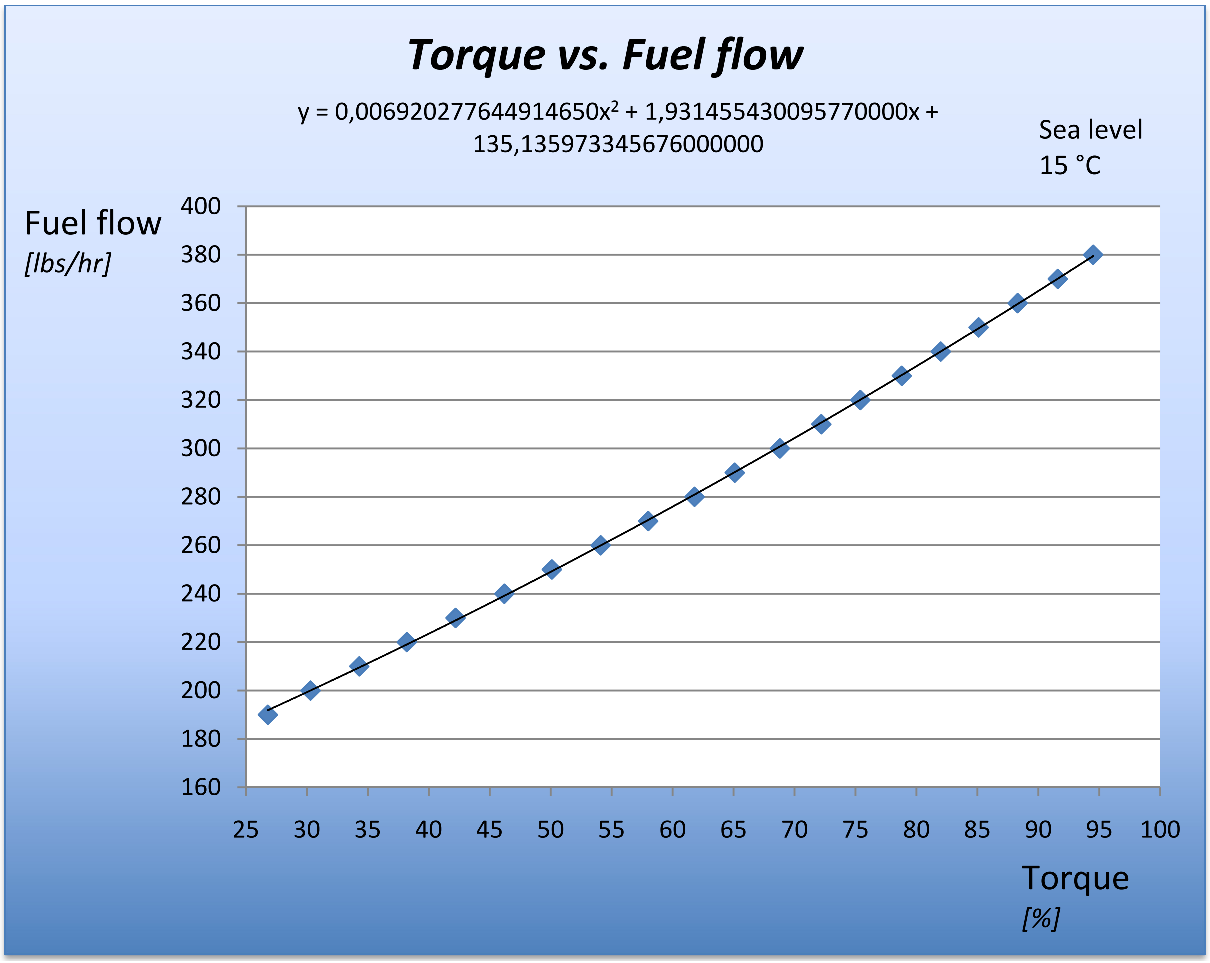

Figure 4: Bell 407 Torque influence on fuel flow

In the figure the formula which relates torque to fuel flow can be seen, which is in the form of equation 4.4:

$$FF_{flight\ phase} = k_1 \times T_{flight\ phase}{}^2 + k_2 \times T_{flight\ phase} + k_3 \qquad (4.4)$$

Such a formula exists for every altitude with different values of the constants. These constants are dependent on altitude, which means $k_1, k_2, k_3 = f(H)$. The fuel flow is presented depending on torque and the altitude (represented in the constants) in Figure 5.

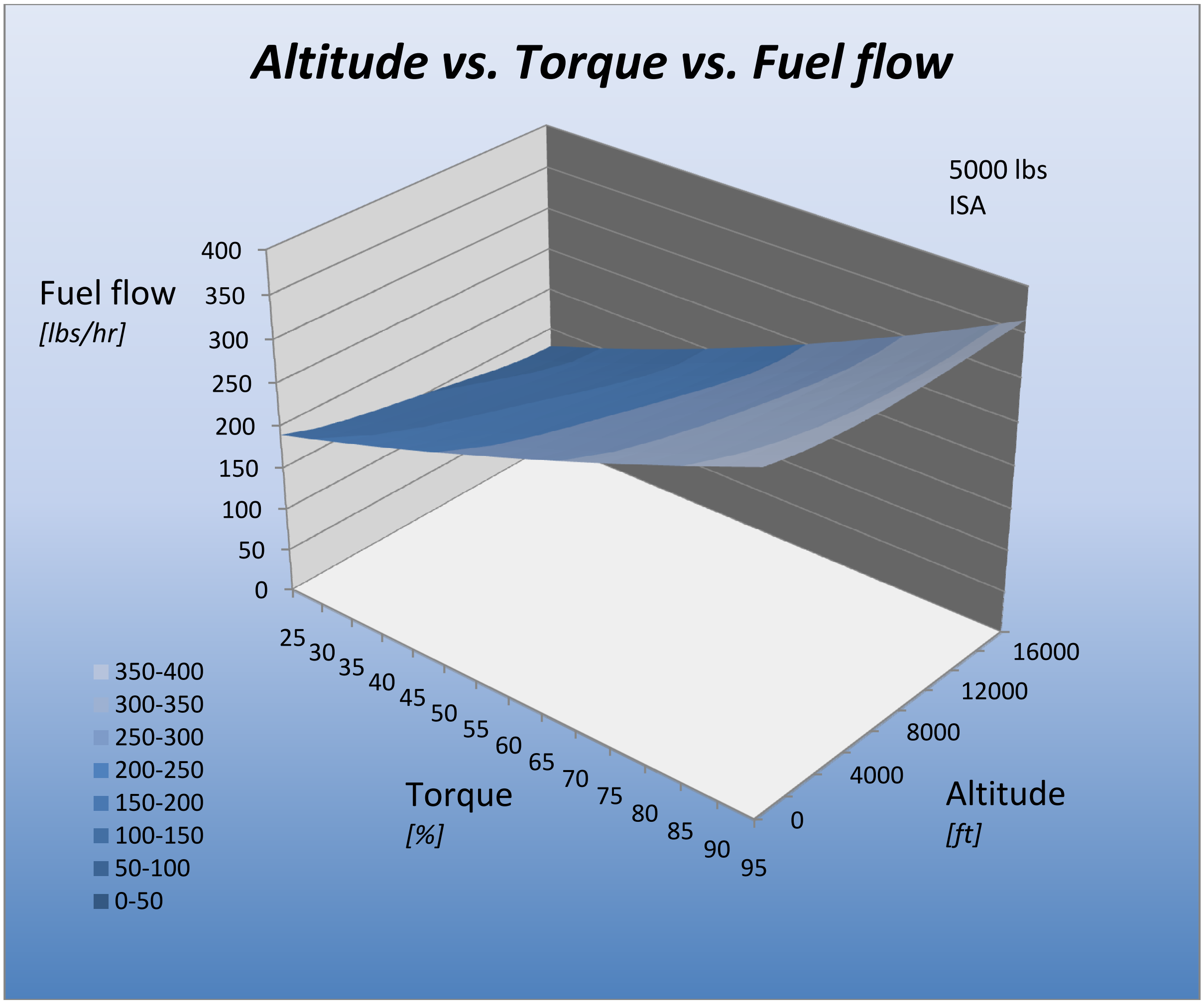

Figure 5: Altitude and torque versus fuel flow

For the different altitudes the values of the constants vary. This variation can be seen in Table 4, rounded to four decimals.

Table 5: Variation of constants with altitude

Altitude [ft]	*k_1*	*k_2*	*k_3*
0	0.0069	1.9315	135.1360
2000	0.0067	2.0045	124.1866
4000	0.0058	2.1869	109.2304
6000	0.0062	2.1780	101.9375
8000	0.0067	2.1753	94.3226
10000	0.0085	2.0386	90.5228
12000	0.0104	1.9028	86.6028
14000	0.0124	1.7888	82.9421
16000	0.0125	1.8594	75.0455
17000	0.0122	1.9266	70.8759

The relations between the altitudes for each of these constants can be put into a figure, seen in Figure 6 for k_1. The figures for $k_2$and k_3 can be found in Appendix A4 (Figure 43 and Figure 44).

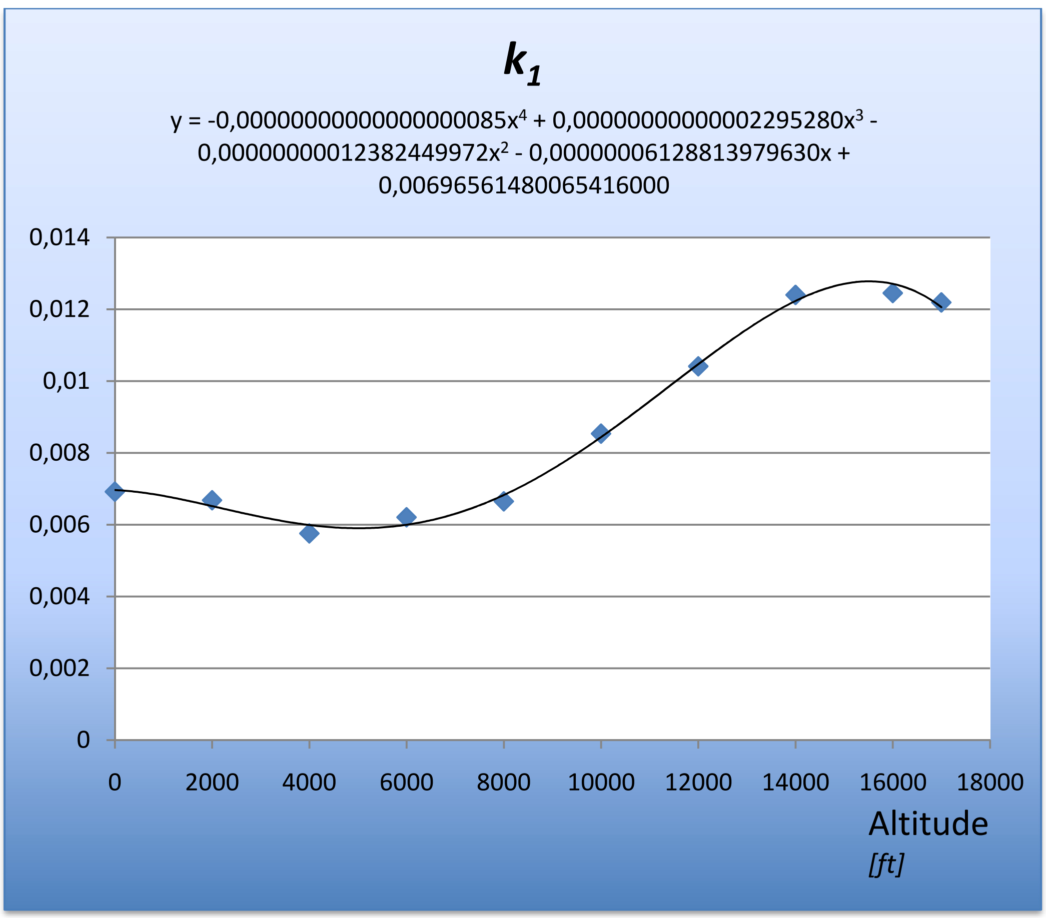

Figure 6: Constant k_1 as function of altitude

The formula's for the constants k_1 and k_2 are 4th order polynomials in the form seen in equation 4.5:

$$k_{1,2} = (k_4 \times H^4 + k_5 \times H^3 + k_6 \times H^2 + k_7 H + k_8) \tag{4.5}$$

Constant k_3 can be expressed in a 3rd order polynomial and is in the form of equation 4.6:

$$k_3 = (k_5 \times H^3 + k_6 \times H^2 + k_7 H + k_8) \tag{4.6}$$

The resulting equations for the three constants are:

$$k_1 = -8.5 \times 10^{-19} \times H^4 + 2.29528 \times 10^{-14} \times H^3 - 1.2382449972 \times 10^{-10} \times H^2 - 6.128813979716 \times 10^{-8} \times H + 6.96561480065416 \times 10^{-3} \tag{4.7}$$

$$k_2 = 8.188 \times 10^{-17} \times H^4 - 2.10162049 \times 10^{-12} \times H^3 - 9.31906852938 \times 10^{-9} \times H^2 + 4.79203407651452 \times 10^{-5} \times H + 1.92128704452732 \tag{4.8}$$

$$k_3 = -1.806013024 \times 10^{-11} \times H^3 + 5.929375582207 \times 10^{-7} \times H^2 - 8.69230435083423 \times 10^{-3} \times H + 136.519824835884 \tag{4.9}$$

Equation 4.7-4.9 can then be inserted into equation 4.4 to obtain the fuel flow by giving an altitude and torque. A check has been done by comparing the fuel flow from the flight manual to the fuel flow resulting from implementing equation 4.7-4.9 into 4.4 for every altitude. The results for several altitudes at a fuel flow of 250 lbs/hr can be found in Table 6 below:

Table 6: Comparison of fuel flow between flight manual and formula

Altitude [ft]	*Torque setting [%]*	*Fuel flow from flight manual [lbs/hr]*	*Fuel flow from formula [lbs/hr]*	*Difference [%]*
0	50.1	250	250.26	0.10
2000	53.2	250	248.28	-0.69
4000	56.2	250	249.75	-0.10
6000	58.1	250	249.67	-0.13
8000	60.1	250	250.16	0.06
10000	61.9	250	249.97	-0.01
12000	63.7	250	250.05	0.02
14000	64.7	250	248.71	-0.52
16000	65.8	250	250.31	0.12
17000	65.9	250	251.13	0.45

As can be seen the deviation is within 0.7%. This is accurate enough to be used, so equation 4.4 can be taken to calculate the fuel burn from torque and altitude.

When equation 4.4 is multiplied by the flight phase time (in hours) the result will be the fuel burned for the flight phase at a specific torque setting. In this, a standard value for torque can be taken if the actual torque is unknown. This will lead to deviations because of the assumption of a standard weight and therefore will be less preferable. It depends on the information the user has whether this method will be accurate or not.

To be able to determine the total fuel burned in a flight the fuel flow in the various flight phases have to be determined. If there is no information available on the specific torque setting this can be done assuming the following torque settings for the different flight phases (Table 7) and using equation 4.4 to calculate the corresponding fuel flow for that particular phase. Torque during continuous operations may vary between 0% and 93.5 %. During take-off (for a maximum of 5 minutes) a setting between 93.5% and 100% is allowed.

Table 7: Typical flight phases with their torque settings and duration

Flight Phase	*Typical Torque setting [%]*
Take-off and initial climb	100
Hover	80
Climb	85
Cruise climb	75
Cruise	60
Cruise Descent	45
Descent	50
Approach and landing	80
Idle	20

To calculate the fuel burned in a phase, equation 4.10 can be used:

$$M_{fuel,flight\ phase} = FF_{flight\ phase} \times t_{flight\ phase} \qquad (4.10)$$

To be able to get the total fuel burned during a flight the summation of all flight phases is taken:

$$M_{fuel} = \sum_{flight\ phases} M_{fuel,flight\ phase} \qquad (4.11)$$

With equation 4.11 method 2 is defined.

4.3 Method 3: fuel flow data from flight manual

The next method, based on the Bell 407 flight manual(3) is a calculation with the use of the many different figures given. For several altitudes and temperatures the graphs of true airspeed versus fuel flow is given for several weights. To have a starting point, values from these graphs were tabularized which lead to the examination of various parameters.

A first approach led to a collection of equations with a total of four unknowns, being altitude, true airspeed, weight and temperature. It was checked if simplifications could be made by looking at the effect of the four parameters on the fuel flow.
By looking at Figure 3 in chapter 3 it is already apparent that the influence of airspeed cannot be disregarded. This is of course as expected since an increased airspeed will require more power from the engine and thus more fuel flow.
The second check is done on the influence of weight on the fuel flow. As with airspeed, the weight will have a significant impact on fuel flow. However, in the case of these national park flights it is improbable that the flights will be done without maximizing the capacity of the helicopter. It would be more beneficial to fly with a maximum passenger load or payload. When this is assumed, it is only necessary to take the heaviest settings into account when looking at the influence of weight. To see the variation the 4600 lbs, 5000 lbs and 5250 lbs weight entries have been selected to have an idea about the relation between weight and fuel flow. This is seen in Figure 7:

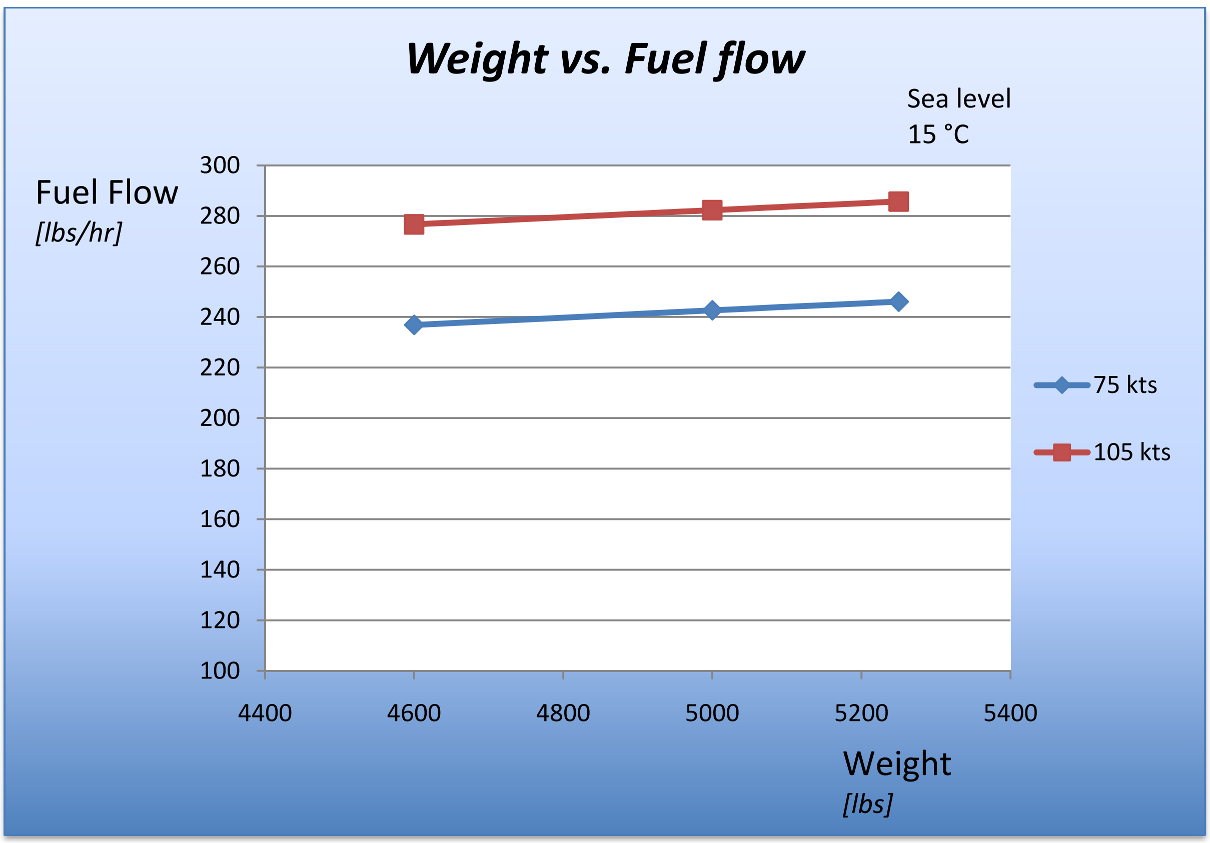

Figure 7: Weight influence on fuel flow for different true airspeeds

For these three weights it is obvious that the difference is small (within 5%) which will not have a big effect on the result. So, a reference weight for the Bell 407 of 5000 lbs was selected. This is assumed based on the maximum payload with some margin.

The next thing to check is the effect temperature variation has on the fuel flow. In the flight manual the fuel flow for the various true airspeeds is given at sea level for a temperature of 15°C, 35°C and 45°C. This can be seen in Figure 8 for various airspeeds which are commonly used in cruise:

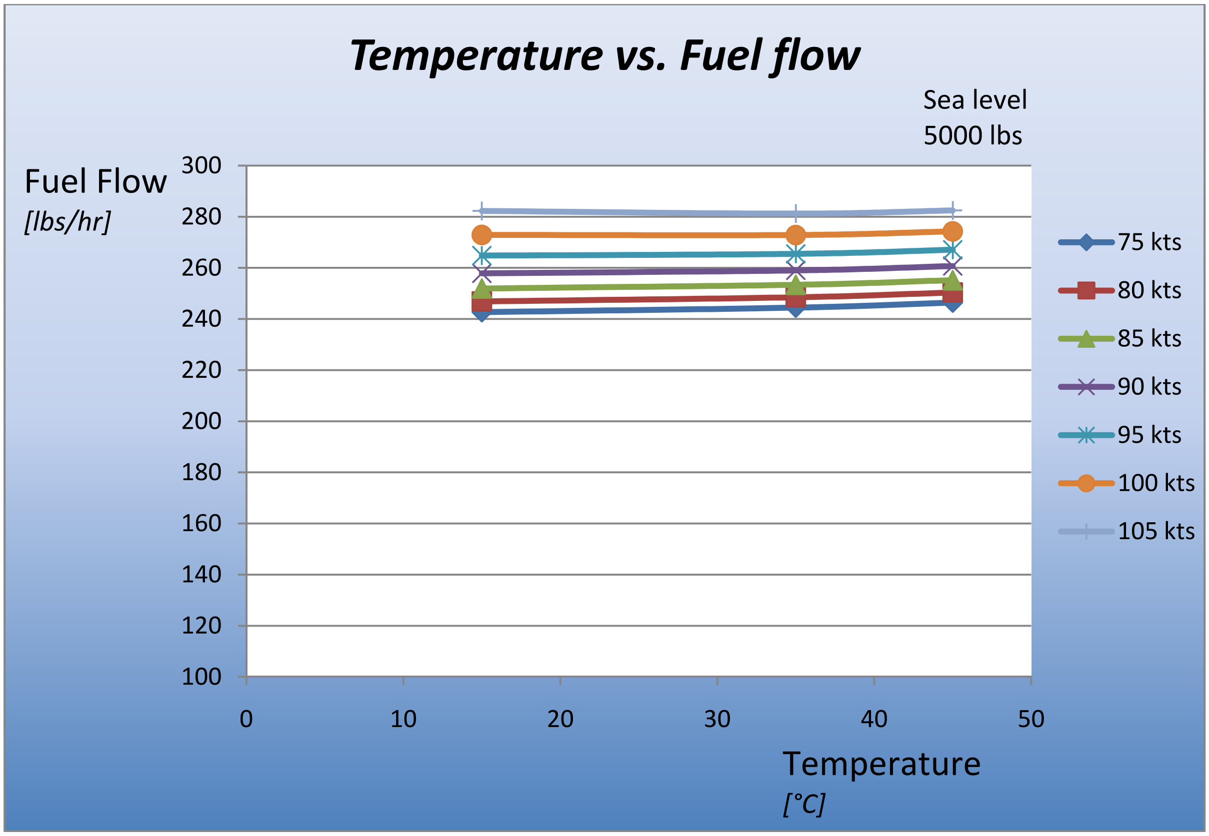

Figure 8: Temperature influence on fuel flow for different true airspeeds

It is clear that temperature has an influence, but it is small enough to disregard it in calculations. The error resulting from this will not be significant in the total calculation.

The next parameter is altitude. In the flight manual of the Bell 407 a lot of figures are given for various altitudes (and resulting from that also a different temperature), so beforehand it seems that altitude variation has a important influence on fuel flow. The influence of altitude on the fuel flow can be seen in Figure 9.

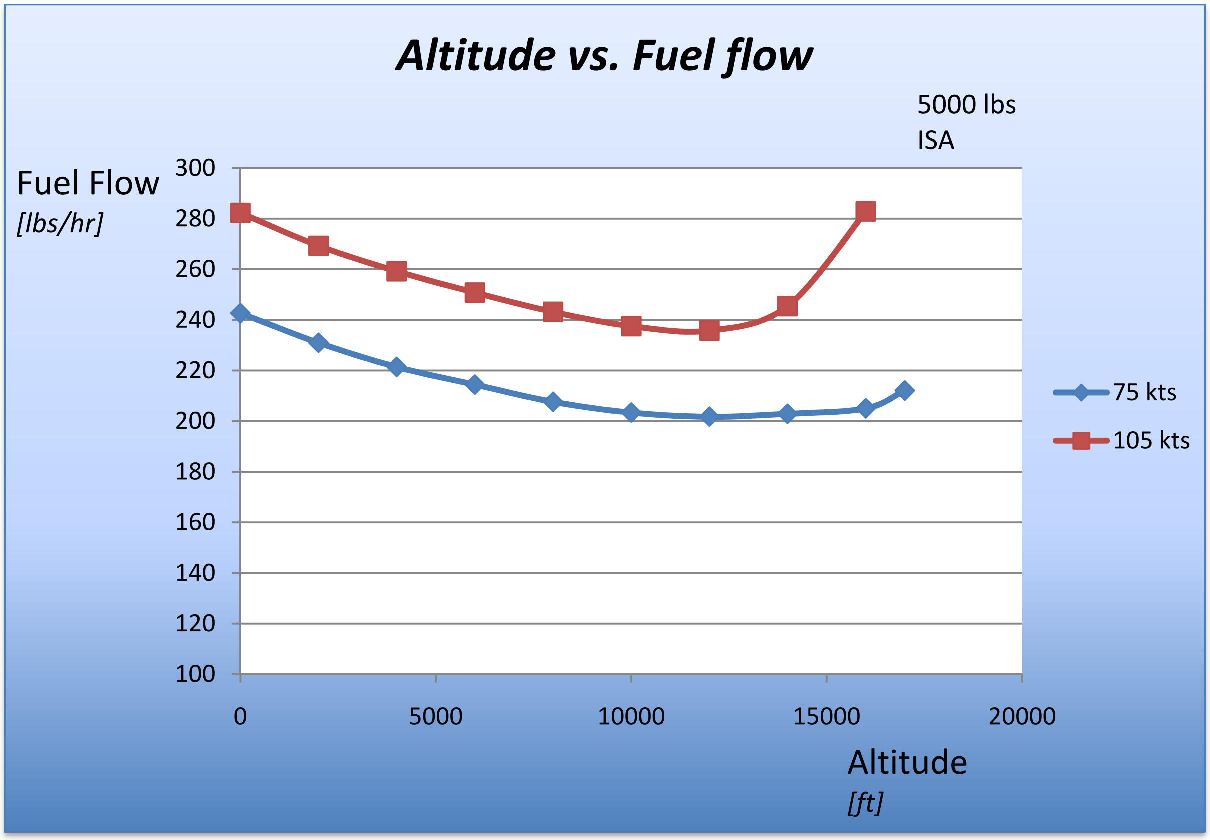

Figure 9: Altitude influence on fuel flow for different true airspeeds

From this it is indeed clear that altitude has too much of an influence to be disregarded. It will therefore be the parameters together with airspeed which will have to be accounted for in the fuel flow calculation.

Now that there are only two parameters left to get to the fuel flow, a formula with these two variables can be created. This is initiated by plotting the graphs for 5000 lbs as found in the manual which can be seen in Figure 10.

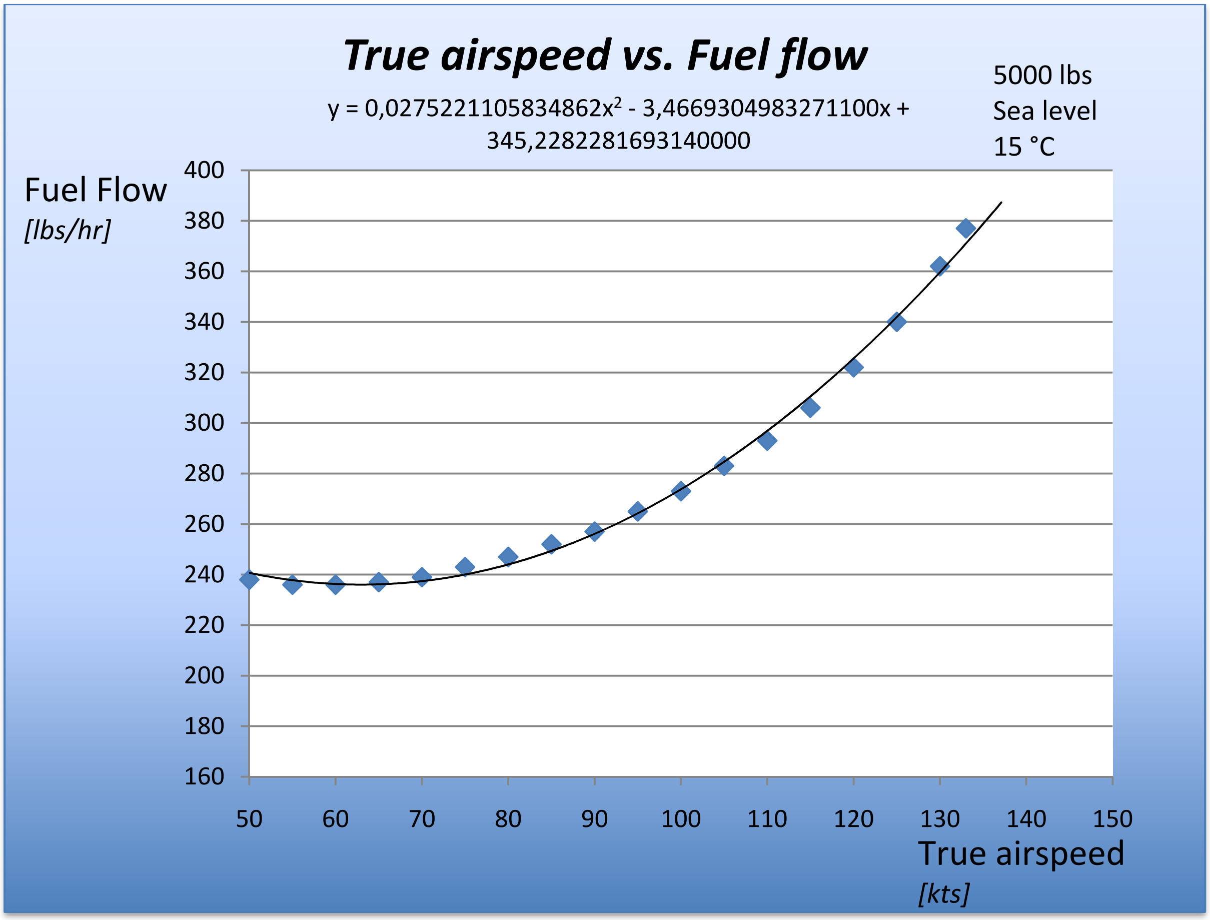

Figure 10: True airspeed versus fuel flow for 5000 lbs

In this figure a 2nd order polynomial can be seen, with its formula below it. This formula is in the form of equation 4.12:

$$FF_{cruise} = k_1 \times V_{cruise}^{\;\;2} + k_2 \times V_{cruise} + k_3 \tag{4.12}$$

In this formula the y has been replaced by fuel flow (FF) and the x by true airspeed (V). The constants k_1, k_2 and k_3 are given in the equation in the figure. A check has been done between the read value from the flight manual and the value following from the equation. This can be seen in Table 8 for sea level.

Table 8: Comparison of fuel flow between flight manual and equation 4.12 at sea level

Airspeed (TAS) [kts]	*Fuel flow from flight manual [lbs/hr]*	*Fuel flow from equation 4.12 [lbs/hr]*	*Difference [%]*
50	238	240.69	-1.13
55	236	237.80	-0.76
60	236	236.29	-0.12
65	237	236.16	0.35
70	239	237.40	0.67
75	243	240.02	1.23
80	247	244.02	1.21
85	252	249.39	1.04
90	257	256.13	0.34
95	265	264.26	0.28
100	273	273.76	-0.28
105	283	284.63	-0.58
110	293	296.88	-1.33
115	306	310.51	-1.47
120	322	325.51	-1.09
125	340	341.89	-0.56
130	362	359.65	0.65

From Table 8 it is clear that the formula is a good enough approximation of the values read from the flight manual. Since altitude is the other parameter this has been done for every altitude from the flight manual. The difference was no more than 3.5% for any case.

The constants from equation 4.12 are in fact a function of the altitude: $k_1, k_2, k_3 = f(H)$, so these constants were found for every altitude. For altitude another limitation was set. Even though the flight manual shows graphs until 17000 feet, it is unlikely that helicopter tour flights will reach these altitudes. It has been noticed that the relation between altitude and fuel flow is smooth till 12000 feet, when there is a rapid increase in fuel flow per altitude change as was already seen in Figure 9. Since 12000 feet seems to be quite reasonable as ceiling for these types of flights, this has been chosen as maximum value. This leads to an adaptation of Figure 9 which can be seen in Figure 11 for a true airspeed of 90 knots.

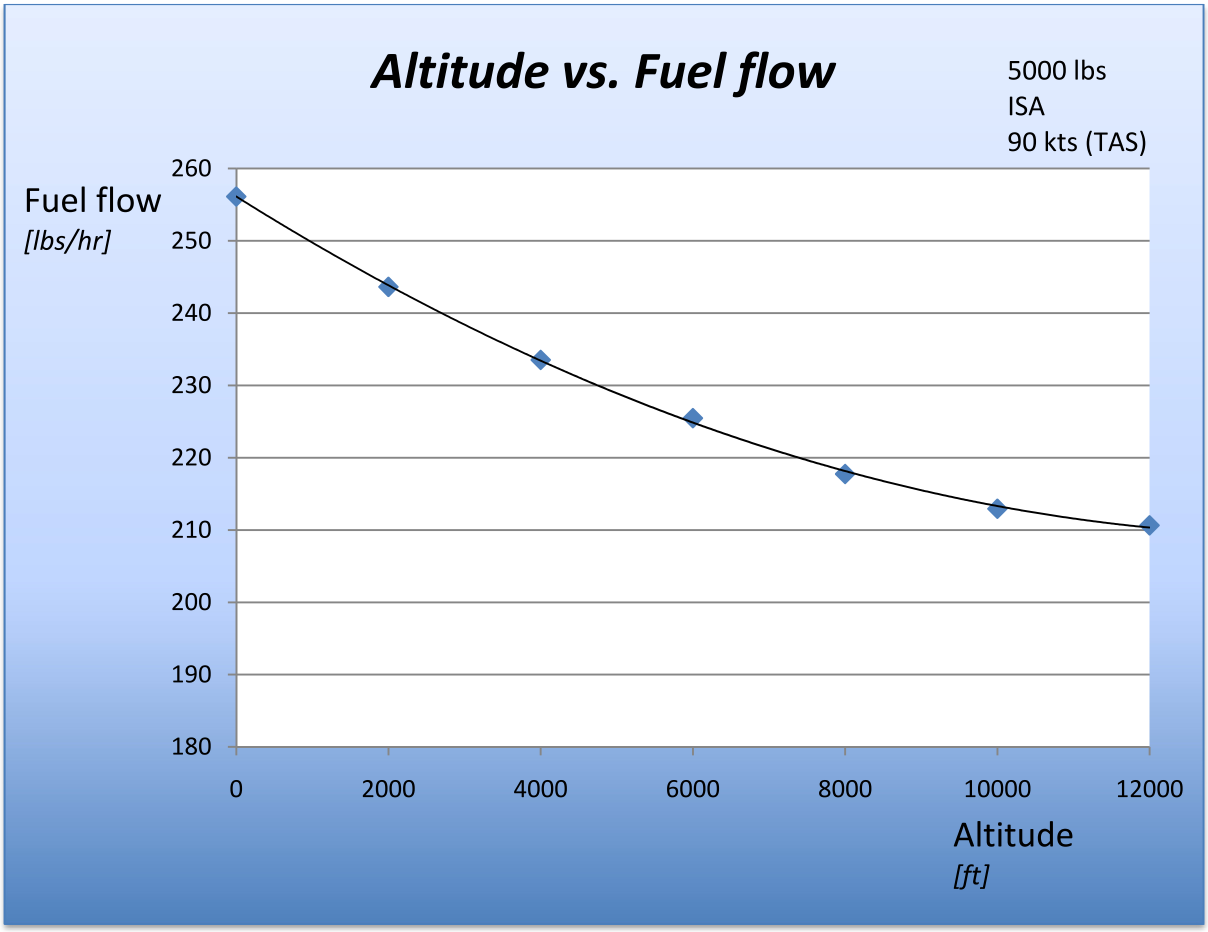

Figure 11: Influence of altitude on fuel flow at 90 knots

This figure can be combined with Figure 10 for all altitudes until 12000 feet and all airspeeds, creating the 3D-plot found in Figure 12.

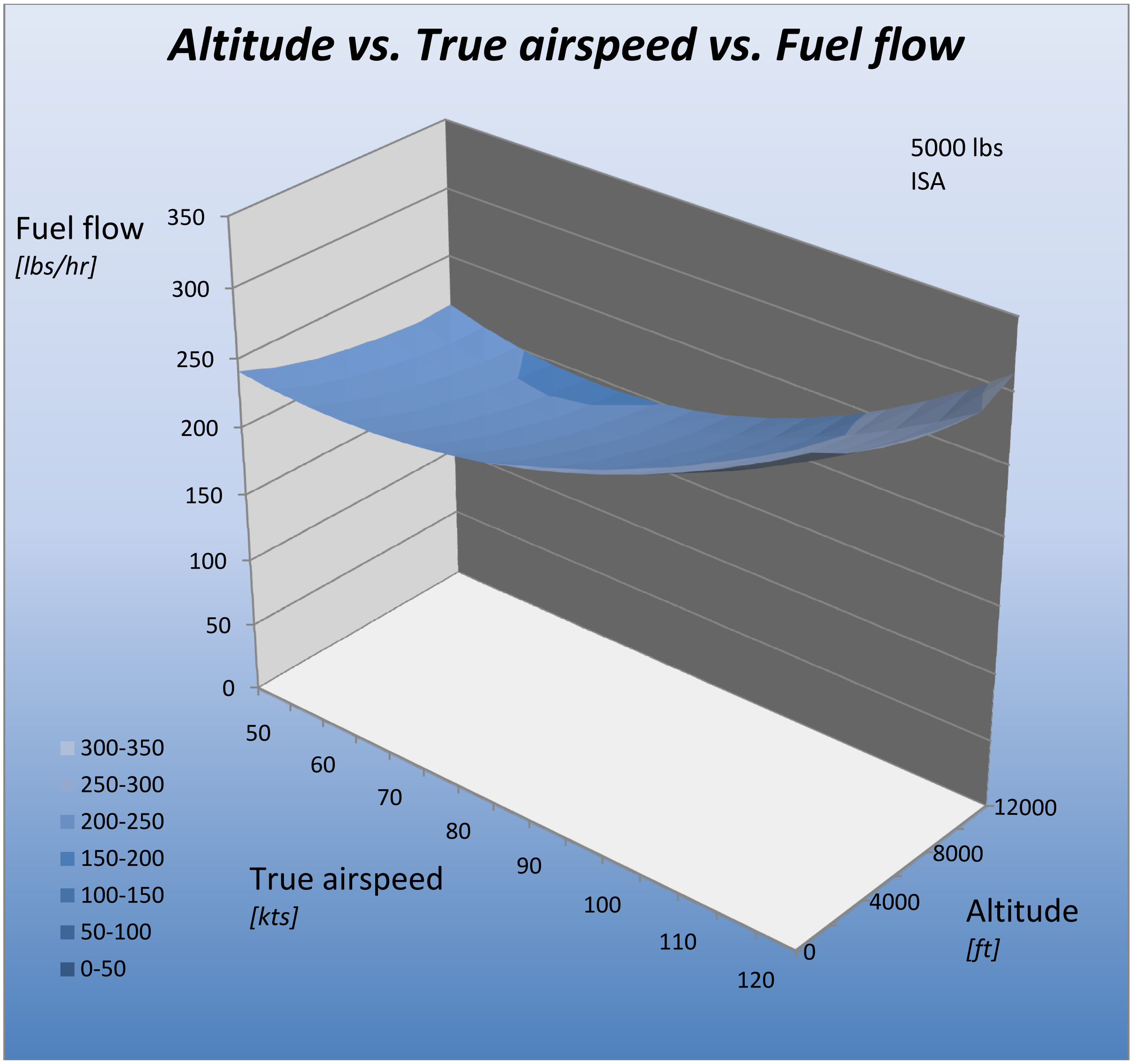

Figure 12: Altitude and true airspeed versus fuel flow

What is needed now is a formula which fits this 3D curve. This is done by looking at the variation of the constants in equation 4.12 for every altitude, seen in Table 9, where the values are rounded off to four decimals.

Table 9: Variation of constants with altitude

Altitude [ft]	*k_1*	*k_2*	*k_3*
0	0.0275	-3.4669	345.2282
2000	0.0276	-3.5414	338.7909
4000	0.0284	-3.7143	337.7745
6000	0.0294	-3.9368	341.4882
8000	0.0314	-4.3173	351.6456
10000	0.0328	-4.5565	357.7102
12000	0.0395	-5.5932	393.9953
14000	0.0471	-6.6224	429.6516
16000	0.0601	-8.2192	480.1569
17000	0.0727	-9.5737	520.6317

When the relations between the constants and the altitude are plotted separately, an equation can be found as seen in Figure 13:

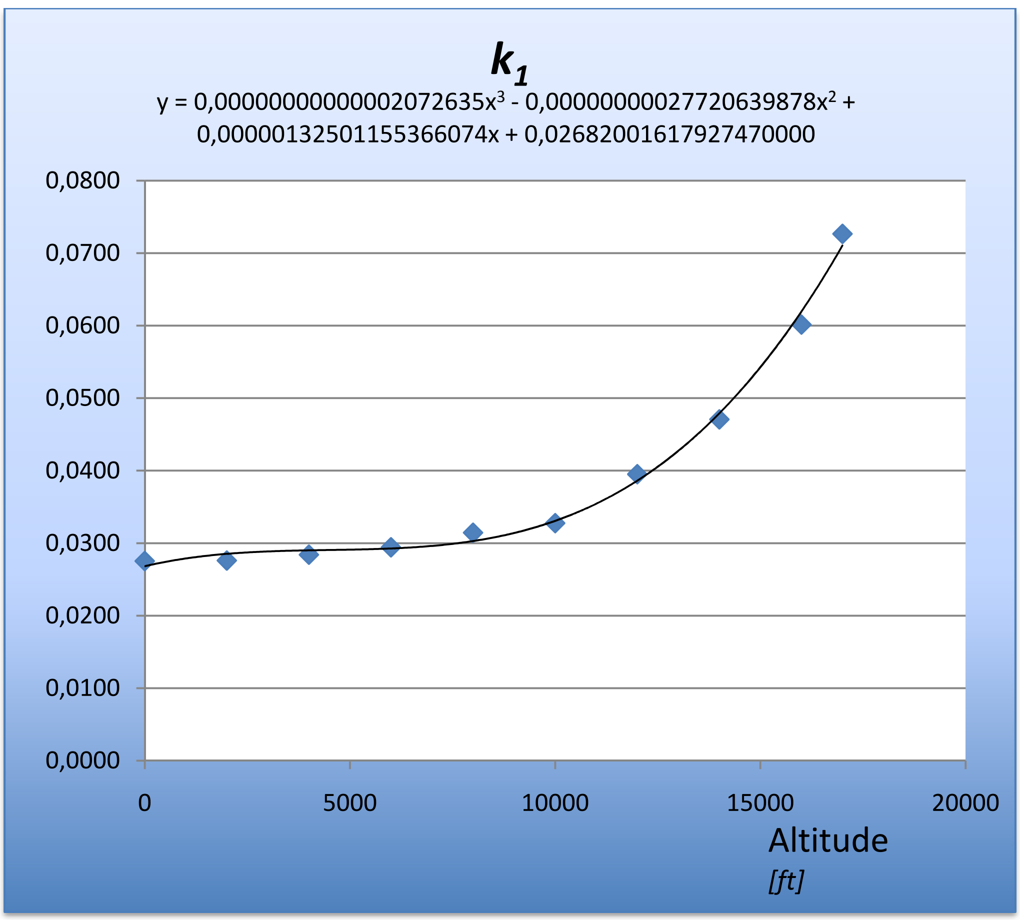

Figure 13: Constant k_1 as function of altitude

The equation in the graph links the variation in altitude to the value of the constant k_1 which is used in equation 4.12. This is also done for the other two constants k_2 and k_3. The figures of the constants k_2 and k_3 can be found in Appendix A5 (Figure 45 and Figure 46). The equations for the constants are all in the form seen in equation 4.13:

$$k_{1,2,3} = (k_4 \times H^3 + k_5 \times H^2 + k_6 H + k_7) \tag{4.13}$$

The resulting formula's for the three constants are (equation 4.14-4.16):

$$k_1 = 2.072635 \times 10^{-14} \times H^3 - 2.7720639878 \times 10^{-10} \times H^2 + 1.32501155366053 \times 10^{-6} \times H + 2.68200161792742 \times 10^{-2} \tag{4.14}$$

$$k_2 = -2.0018239 \times 10^{-12} \times H^3 + 2.142268418042 \times 10^{-8} \times H^2 - 1.40647794810267 \times 10^{-4} \times H + 3.41063633469128 \tag{4.15}$$

$$k_3 = 4.853244569 \times 10^{-11} \times H^3 - 1.2962315278217 \times 10^{-7} \times H^2 - 1.59288842093197 \times 10^{-3} \times H + 344.044935485974 \tag{4.16}$$

Equations 4.14-4.16 can then be inserted into equation 4.12 to be able to calculate the fuel flow by specifying an altitude and airspeed. A check has been done by comparing the fuel flow from the flight manual to the fuel flow resulting from implementing equations 4.14-4.16 into 4.12 for every altitude. The result for sea level can be found in Table 10 below.

Table 10: Comparison of fuel flow between flight manual and equation 4.12 at sea level

Airspeed (TAS) [kts]	*Fuel flow from flight manual [lbs/hr]*	*Fuel flow from equation 4.12 [lbs/hr]*	*Difference [%]*
50	238	240.56	-1.08
55	236	237.59	-0.67
60	236	235.96	0.017
65	237	235.67	0.56
70	239	236.72	0.95
75	243	239.11	1.60
80	247	242.84	1.68
85	252	247.92	1.62
90	257	254.33	1.04
95	265	262.09	1.10
100	273	271.18	0.67
105	283	281.62	0.49
110	293	293.40	-0.14
115	306	306.52	-0.17
120	322	320.98	0.32
125	340	336.78	0.95

As can be seen the deviation is within 1.7%. When every altitude is checked the largest deviation is found to be 3.3%, which is accurate enough for these calculations.

With equation 4.12 the fuel flow in the cruise phase can be calculated. To be able to determine the fuel flow of other flight phases this value can be multiplied with a constant as can be seen in equation 4.17:

$$FF_{flight\ phase} = C_1 \times FF_{cruise} \tag{4.17}$$

There is no source in literature which gives the value of C_1 for the different flight phases. This could be obtained from flight tests or from Bell for the 407, because there certainly will be information available on this with Bell. However it was not possible to obtain this information. Therefore the values for C_1 are assumed, based on the available flight data (see Table 11)[35].

Table 11: Values of C_1 for different flight phases

Flight phase	C_1
Take-off and initial climb	2
Hover	1.6
Climb	1.7
Cruise climb	1.4
Cruise	1
Cruise Descent	0.7
Descent	0.8
Approach and landing	0.8
Idle	0.3

When the fuel flow of each flight phase is know this can be used to calculate the fuel burned per flight phase:

$$M_{fuel,flight\ phase} = FF_{flight\ phase} \times t_{flight\ phase} \tag{4.18}$$

To be able to get the total fuel burned during a flight the summation of all flight phases is taken:

$$M_{fuel} = \sum_{flight\ phases} M_{fuel,flight\ phase} \tag{4.19}$$

With equation 4.19 method 3 is defined.

4.4 Method 4: Power required equations

The final approach discussed involves the horsepower the engine has to deliver. This power is related to the fuel flow, which gives the opportunity to calculate the fuel burn over a flight.

An exact relation between fuel flow and horsepower has to be known with engine manufactures, but was not made available[(12,13,16,17)]. A relation is therefore assumed, leading to a less accurate method than intended.

Although the relation was not provided by engine manufacturers, the power required in every phase is determined on the basis of the literature described in section 3.3. In section 4.4.5 a relation between the horse power and fuel flow is determined in a different manner.

4.4.1 Hover

In the hover phase the method specified in equation 3.2 in section 3.3.1 can be used:

$$P_{Hover} = \frac{P_{ideal}}{FM} \qquad (3.2)$$

To be able to calculate the power required for hover, P_{ideal} is needed, which requires the weight, the density of the air and the radius of the rotor (W, ρ, R).

4.4.2 Cruise

In cruise the method from section 3.3.2 can be used (equation 3.3):

$$P_{Forward\ flight} = P_S + P_d + P_p + P_i \qquad (3.3)$$

As can be seen in section 3.3.2, this method would involve a lot of theoretical calculations. Input needed would be weight velocity, maximum velocity, density of the air, maximum RPM of rotor, radius of rotor ($W, V, V_{max}, \rho, RPM, R$).

4.4.3 Climb and descent

It can be assumed that for every 450ft/min of rate of climb an additional 10% of the power is needed on top of the hover power. For descent the reverse is assumed; 10% less power required for every 450ft/min rate of descent[36].

For cruise climb the same can be assumed based on the cruise power needed. So 10% more power for a climb rate of 450 ft/min. For the cruise descent it is also assumed that for every 450 ft/min rate of descent, 10% less than the power to cruise with that velocity is needed.

4.4.4 Take-off and landing

Take-off is one of the most demanding flight phases. It is assumed that for this phase 100% of the available power is required.

There is no specific power required available for landing in literature. Therefore landing will be part of the hover and descent phases.

4.4.5 Fuel flow to power relation

With the equations and assumptions in section 4.4, the required power at all phases can be calculated. This however has to be translated to fuel flow.

From the flight manual of the Bell 407 the relation between fuel flow and true airspeed is known. Together with the relation between available power and true airspeed, obtained in section 4.4.1-4.4.4, a relation between available power and fuel flow is determined. This is based on the specifications of the Bell 407, with a take-off weight of 5000 lbs and ISA conditions at sea level. The values of fuel flow from the Bell 407 flight manual and the power required calculated for the Bell 407 are presented in Table 12.

Table 12: Fuel flow and power required for cruise of Bell 407

Airspeed (TAS) [kts]	*Fuel flow from flight manual [lbs/hr]*	*Power required [W]*
50	238	264548
55	236	267585
60	236	271227
65	237	275530
70	239	280548
75	243	286337
80	247	292952
85	252	300448
90	258	308879
95	265	318301
100	273	328769
105	282	340338
110	293	353063
115	306	366999
120	322	382201
125	340	398724
130	362	416623

Fuel flow is then coupled with power required through true airspeed and presented as a simple equation in Figure 14.

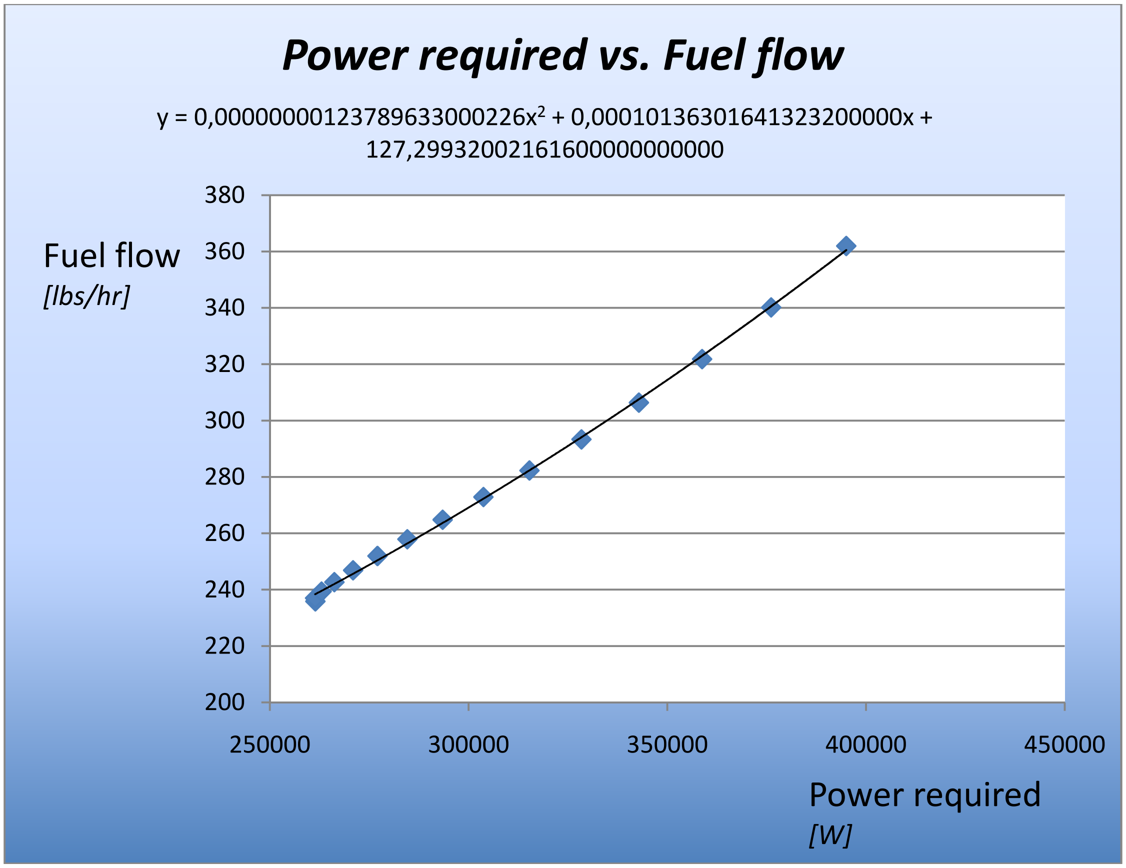

Figure 14: Fuel flow in terms of power required for the Bell 407

The following relation between fuel flow and power required is found based on the data for sea level:

$$FF = 1.2378963300023 \times 10^{-9} \times {P_{req}}^{2} + 1.363016413149 \times 10^{-4} \times P_{req} + 127.29932002163 \qquad (4.20)$$

A check has been done by comparing the fuel flow from the flight manual to the fuel flow resulting from calculating the required horse power in the cruise phase combined with equation 4.20. The result of this comparison at sea level can be found in Table 13.

Table 13: Comparison of fuel flow between flight manual and equation 4.20 at sea level

Airspeed (TAS) [kts]	*Fuel flow from flight manual [lbs/hr]*	*Fuel flow from required horsepower [lbs/hr]*	*Difference [%]*
50	238	242,16	-1,75
55	236	238,88	-1,22
60	236	237,34	-0,57
65	237	237,26	-0,11
70	239	238,46	0,22
75	243	240,87	0,88
80	247	244,44	1,04
85	252	249,18	1,12
90	257	255,12	0,73
95	265	262,33	1,01
100	273	270,89	0,77
105	283	280,91	0,74
110	293	292,54	0,16
115	306	305,93	0,02
120	322	321,26	0,23
125	340	338,73	0,37

To determine the fuel burned during a flight the following procedure has to be performed. For every flight phase the fuel flow has to be calculated with equation 4.16 based on the calculated power required in that flight phase. This is followed by the calculation of the fuel burned in that phase (see equation 4.21):

$$M_{fuel,flight\ phase} = FF_{flight\ phase} \times t_{flight\ phase} \tag{4.21}$$

To be able to get the total fuel burned during a flight the summation of all flight phases is taken:

$$M_{fuel} = \sum_{flight\ phases} M_{fuel,flight\ phase} \tag{4.22}$$

With equation 4.22 method 4 is defined.

5 Definition of the model

In this chapter the four methods will be compared after which one of them is chosen. The model will be described based on the chosen method for the Bell 407, followed by an adaption to other helicopters.

5.1 Comparison of the four methods for the Bell 407

To be able to compare the different models, an arbitrary flight profile has been chosen to calculate the corresponding fuel burn of the different models. This flight profile is shown in Table 14. The flight is performed with a Bell 407 with a 700 SHP engine. The gross weight is 5000 lbs. Standard conditions are assumed: ISA atmosphere with 59 °F at 0 ft altitude. The origin of the flight will be at sea level. The total flight time of this flight would be 60 minutes.

Table 14: Definition of arbitrary flight profile

Flight phase	*Start altitude [ft]*	*End altitude [ft]*	*Phase time [s]*	*Airspeed (TAS) [kts]*
Take-off and initial climb	0	20	120	0
Hover	20	20	120	0
Cruise climb	20	8000	660	80
Cruise	8000	8000	2100	100
Cruise descent	8000	20	480	75
Approach and landing	20	0	120	0

The results of these calculations are shown in Table 15:

Table 15: Result of fuel burn calculations with the 4 presented methods

Flight phase	*Fuel burn Method 1 [lbs]*	*Fuel burn Method 2 [lbs]*	*Fuel burn Method 3 [lbs]*	*Fuel burn Method 4 [lbs]*
Take-off and initial climb	12	11	23	17
Hover	12	13	18	10
Cruise climb	64	56	57	52
Cruise	204	146	135	159
Cruise descent	47	29	21	27
Approach and landing	12	11	9	10
Total	**350**	**266**	**264**	**276**

In Table 15, the differences between the methods can be seen which will be evaluated in the next section.

5.2 Check with actual data

As can be seen in section 3.4, there has been some flight data received from Blue Hawaiian Helicopters. Unfortunately, this data is not sufficient to make a good comparison with the different methods because it is not complete enough. For example, there are no velocities recorded.

However, it is possible to check the data with the figure from the flight manual of Bell found in Appendix A3, Figure 22. This data is applicable to the flight conditions of the arbitrary flight. A fuel flow of 235 lbs/hr is specified by Bell for the cruise phase. A cruise segment of 35 minutes has been specified which would give a fuel burn in the cruise phase of 137 lbs. The comparison of the four methods and the fuel burn according to the Bell flight manual is given in Table 16:

Table 16: Comparison of fuel burn in cruise phase of 4 methods with flight manual

Method	*Fuel Burn [lbs]*	*Difference w.r.t. flight manual [%]*
Method 1: fixed specific fuel consumption	204	48.9
Method 2: fixed torque-fuel flow relation	146	6.6
Method 3: fuel flow data from flight manual	135	-1.5
Method 4: power required equations	159	16.1
Bell Flight Manual	137	-

In this comparison, method 3: “fuel flow data from flight manual” gives the best result.

5.3 Selection of the method

At this stage one of the four methods must be chosen to be implemented in AEDT. There is no flight data and no better data from Bell on the Bell 407 than the flight manual data. Therefore the decision has to be made on the basis of the definition of the methods and the results of the calculations and comparison made in section 5.1 and 5.2. Based on the analysis in these sections method 3: “fuel flow data from flight manual” seems to be the best option. In the rest of this section all methods will be discussed.

Method 1 is nothing but a rough estimation, which is not meant for fuel burn modeling. It can be seen that the results deviate a lot (in the order of 50%) from the other methods and the values found in the flight manual (see Table 16). Therefore this method is good to be a reference, but not good enough to be implemented.

The result of the calculation of the arbitrary flight with method 2 is close to the values found in the flight manual (within 10%). There are some drawbacks to this method though. The method uses the relation between fuel flow and torque from the flight manual of the Bell 407, but not the actual data. The results are based on the values of the torque during the various phases. When there is flight data available featuring torque values, this method could be more accurate. Unfortunately, this is not available at this moment. If the torque setting would be known during other flight phases, this method would give correct values in those other flight phases as well. In this point this method distinguishes itself from method 3, which needs factors to determine the fuel burn of other phases.

As mentioned in the first part of this section, method 3 is the most accurate of the methods evaluated (135 lbs vs. 137 lbs in the flight manual, a difference of 1.5%). This is to be expected since the method is directly based on the information of the flight manual. A drawback of this method is that for all other phases than cruise, the fuel burn is calculated with a factor over the fuel burn in cruise. There are no sources for these factors and they should be based on flight tests.

Method 4 deviates more from the data in the flight manual than method 2 and 3. One of the reasons for this is the fact that this method is very theoretical. There are multiple characteristics of the helicopter which are translated into constants of which the real value is not known and is estimated using averages and generalizations. However, an advantage of this method is that the power required is calculated for multiple phases, although there are still assumptions made (for example the 10% more/less power for a rate of climb of 450 feet/minute). Furthermore the relation between fuel flow and available power is assumed and not obtained from the engine manufacturers.

Concluding, based on the information available at this time, method 3 gives the best results and will be chosen to be implemented into AEDT.

5.4 Applying the method to other helicopters

The chosen method is developed based on the performance data of the Bell 407, therefore the coefficients will be accurate only for the Bell 407. To be able to make it possible to use the method for different types of helicopters, a factor will be determined for other helicopters to be able to translate the Bell 407 results to be applicable for that particular helicopter. Information is found for the other important helicopters used for air tours in National Parks: the Bell 206, Eurocopter EC 130 and Aerospatiale AS350, and the Eurocopter EC 120[2,4-6].

Because there is limited data of other helicopters than the Bell 407, only two points of cruise at maximum endurance speed (minimum fuel consumption) have been evaluated for different helicopters. Both points are, for all the helicopters, taken at a weight of 4000 lbs. However the Atmospheric conditions differ; for the first point sea level at 59 °F, the second point 6000 feet at 37.4 °F. The comparison between the helicopters can be seen in Table 17:

Table 17: Comparison of fuel flow at maximum endurance for different helicopters

Helicopter	*Fuel flow, Point 1 [lbs]*	*Fuel flow, Point 2 [lbs]*	*Difference Bell 407, Pt.1 [%]*	*Difference Bell 407, Pt.2 [%]*	*Average difference [%]*
Bell 407	219	189	-	-	-
Bell 206L	201.5	177.2	-8.0	-6.3	-7.2
Eurocopter EC 120	165 (extrap.)	150 (extrap.)	-24.7	-20.6	-22.7
Eurocopter EC 130	240	207	9.6	9.5	9.6
Aerospatiale AS350	249	211	13.7	11.6	12.7

To be able to incorporate these differences into the model, a simple factor is applied to the result of the method. The method calculates the mass of the fuel of the complete flight based on equation 5.1:

$$M_{fuel,Bell\ 407} = \sum_{flight\ phases} M_{fuel,flight\ phase} \tag{5.1}$$

The factor will be applied as shown in equation 5.2:

$$M_{fuel,helicopter} = C_2 \times M_{fuel,Bell\ 407} \tag{5.2}$$

The factor C_2 is simply based on the difference found in Table 17 and can be found in Table 18:

Table 18: Factor C_2 for different helicopters

Helicopter	*Average difference [%]*	*Factor C_2*
Bell 407	-	1
Bell 206L	-7.2	0.928
Eurocopter EC 120	-22.7	0.773
Eurocopter EC 130	9.6	1.096
Aerospatiale AS350	12.7	1.127

Now that this factor is known, equation 5.2 gives the fuel burned for the other important helicopter types.

6 Implementation of the method and user input

To be able to implement the fuel burn calculations in AEDT, the flight trajectory with its corresponding state variables must be defined similar in AEDT and the model. AEDT uses the definition of INM(34), which does not use helicopter performance calculations to determine its trajectory, noise or performance as there are no thrust, altitude, or speed performance calculations(10). In this chapter, the implementation of the model is described. First definitions of AEDT will be given, followed by the link of AEDT with the model.

6.1 Definition of helicopter flights in AEDT

INM and thus AEDT uses a ordered set of procedure steps. Helicopter procedure steps are modal; they are defined as a set of procedure steps that each represents a helicopter flight operational mode(10). A helicopter flight must be specified in terms of those procedure steps. They are processed one at a time to calculate profile points. Those profile points generate a two dimensional trajectory. At every point the following variables are specified:

- d : horizontal coordinate relative to an origin [ft]
- z : altitude of the helicopter above the helipad [ft AFE]
- V_T : helicopter true airspeed at the point [kts]
- Mode : helicopter operational mode
- t_{seg} : time spent at a location for static operational modes [s]

There are four types of helicopter flight operations (APP, DEP, TAX, OVF). They are based on 14 types of procedure steps (Table 19):

Table 19: Definition of procedural steps in AEDT (INM)(10)

#	*Mode*	*Description*
1	Start Altitude	Used to start a profile at a given altitude and speed. The starting altitude and speed are inputs.
2	Level Fly	Used to maintain altitude and speed for a given distance. The track distance covered by the step is the only input. Altitude and speed are defined by the previous step.
3	App Const Speed	Used to descend at constant speed to a given altitude over a given distance. The track distance covered by the step and the final altitude are inputs. The initial altitude and speed are defined by the previous step.
4	App Desc Decel	Used to descend and decelerate to a final altitude and speed over a given distance. The track distance covered by the step, the final altitude, and the final speed are inputs. The initial altitude and speed are defined by the previous step.

5	App Horiz Decel	Used to decelerate to a final speed at constant altitude over a given distance. The track distance covered by the step and the final speed are inputs. The altitude and initial speed are defined by the previous step.
6	App Vertical	Used to maintain horizontal position while descending to a final altitude over a given duration. The duration of the step and the final altitude are inputs. The horizontal position of the step is calculated from the previous step and the horizontal speed is zero.
7	Hover	used to maintain altitude and horizontal position for a given duration. The duration of the step is the only input. The altitude is defined by the previous step, the horizontal position of the step is calculated from the previous step, and the horizontal speed is zero.
8	Ground Idle	used to maintain ground idle for a given duration. The duration of the step is the only input. The altitude is zero, the horizontal position of the step is calculated from the previous step, and the horizontal speed is zero.
9	Flight Idle	used to maintain flight idle for a given duration. The duration of the step is the only input. The altitude is zero, the horizontal position of the step is calculated from the previous step, and the horizontal speed is zero.
10	Dep Vertical	used to maintain horizontal position while ascending to a final altitude over a given duration. The duration of the step and the final altitude are inputs. The horizontal position of the step is calculated from the previous step and the horizontal speed is zero.
11	Dep Horiz Accel	used to accelerate to a final speed over a given distance. The track distance covered by the step and the final speed are inputs. The altitude and initial speed are defined by the previous step.
12	Dep Climb Accel	used to climb and accelerate to a final altitude and speed over a given distance. The track distance covered by the step, the final altitude, and the final speed are inputs. The initial altitude and speed are defined by the previous step.
13	Dep Const Speed	used to climb at constant speed to a given altitude over a given distance. The track distance covered by the step and the final altitude are inputs. The initial altitude and speed are defined by the previous step.
14	Taxi	used to taxi at a given constant speed. The speed is the only input. The track distance is calculated based on the assigned taxi ground track, and the altitude is defined by the previous step. INM allows helicopters defined as having wheels to taxi at zero altitude. Helicopters defined as not having wheels must taxi at an altitude greater than zero.

In the following section these procedure steps will be coupled with the model.

6.2 Model coupled with AEDT definitions

As described in section 5.3, method 3: “fuel flow data from flight manual” has been chosen. The calculations which have to be made will be repeated here. All calculations are based on the main calculation of fuel burn in cruise. This is given in equation 4.12:

$$FF_{cruise} = k_1 \times V_{cruise}^{\ 2} + k_2 \times V_{cruise} + k_3 \tag{4.12}$$

With the Bell 407 constants:

$$k_1 = 2.072635 \times 10^{-14} \times H^3 - 2.7720639878 \times 10^{-10} \times H^2 + 1.32501155366053 \times 10^{-6} \times H + 2.68200161792742 \times 10^{-2} \quad (4.14)$$

$$k_2 = -2.0018239 \times 10^{-12} \times H^3 + 2.142268418042 \times 10^{-8} \times H^2 - 1.40647794810267 \times 10^{-4} \times H + 3.41063633469128 \quad (4.15)$$

$$k_3 = 4.853244569 \times 10^{-11} \times H^3 - 1.2962315278217 \times 10^{-7} \times H^2 - 1.59288842093197 \times 10^{-3} \times H + 344.044935485974 \quad (4.16)$$

The velocity and the altitude are the inputs for these calculations. The fuel flow of any phase is calculated with equation 4.17:

$$FF_{flight\ phase} = C_1 \times FF_{cruise} \quad (4.17)$$

The inputs for this equation is the result from equation 4.12 and the constant C_1, which can be found in Table 11:

Table 11: Values of C_1 for different flight phases

Flight phase	C_1
Take-off and initial climb	2
Hover	1.6
Climb	1.7
Cruise climb	1.4
Cruise	1
Cruise Descent	0.7
Descent	0.8
Approach and landing	0.8
Idle	0.3

Then, to obtain the fuel burned during a phase, equation 4.18 is applied:

$$M_{fuel,flight\ phase} = FF_{flight\ phase} \times t_{flight\ phase} \quad (4.18)$$

The inputs needed for the calculations for every of the 14 procedure steps mentioned above will be given in Table 20.

Table 20: Inputs for the 14 procedure steps in AEDT

#	*Mode*	*Input H*	*Input V*	*Input t*	*Input C_1*
1	Start Altitude	H	V	$t_{flight\ phase}$	NA
2	Level Fly	H	V	$t_{flight\ phase}$	1
3	App Const Speed	H_{avg}	V	$t_{flight\ phase}$	0.8
4	App Desc Decel	H_{avg}	V_{avg}	$t_{flight\ phase}$	0.8
5	App Horiz Decel	H	V_{avg}	$t_{flight\ phase}$	1
6	App Vertical	H_{avg}	90	$t_{flight\ phase}$	0.8
7	Hover	H	90	$t_{flight\ phase}$	1.6
8	Ground Idle	H	90	$t_{flight\ phase}$	0.3
9	Flight Idle	H	V	$t_{flight\ phase}$	0.3
10	Dep Vertical	H_{avg}	90	$t_{flight\ phase}$	1.7
11	Dep Horiz Accel	H	V_{avg}	$t_{flight\ phase}$	1
12	Dep Climb Accel	H_{avg}	V_{avg}	$t_{flight\ phase}$	1.4
13	Dep Const Speed	H_{avg}	V	$t_{flight\ phase}$	1.4
14	Taxi	H	90	$t_{flight\ phase}$	0.3

The inputs for V in steps 6-8, 10 and 14 are set to a standard cruise speed. To be able to calculate a fuel flow in the model and these steps have a velocity of zero, a cruise velocity input is required. The standard velocity chosen is fixed for these steps on all possible flights simulated with the model.
To be able to calculate the fuel burned during the complete flight, equation 5.1 is used:

$$M_{fuel,Bell\ 407} = \sum\nolimits_{flight\ phases} M_{fuel,flight\ phase} \tag{5.1}$$

Finally, the helicopter type has to be an input as well (which is the case already), and has to be linked with the values of the constant C_2, this way, C_2 can be an input into the final equation to account for different helicopter types (equation 5.2):

$$M_{fuel,helicopter} = C_2 \times M_{fuel,Bell\ 407} \tag{5.2}$$

With the values for C_2 specified in Table 21:

Table 21: Values of C_2

Helicopter	*Factor C_2*
Bell 407	1
Bell 206L	0.928
Eurocopter EC 120	0.773
Eurocopter EC 130	1.096
Aerospatiale AS350	1.127

7 Conclusions

The introductory project gave a good understanding of AEDT. The calculations done on the BADA 3.6 and 3.7 fuel burn data showed that the newer 3.7 data gives a better solution for the large majority of the aircraft. The claim by Eurocontrol that the fuel burn constants have been optimized for terminal operations is backed up by these calculations. The future use of the BADA 3.7 fuel burn constants in AEDT will therefore give more accurate fuel burn results.

The goal of the main project was to develop a model to calculate fuel burn of a helicopter for a complete flight which could be integrated in the AEDT. Because the helicopter part of AEDT does not feature a performance module, another method is found which is compatible with the way AEDT simulates a helicopter flight. Because AEDT calculates a flight based on multiple procedural steps, like take-off, hover, climb, cruise etc, the method had to be able to calculate fuel burn for all those steps, so that every possible flight in AEDT could be run with a resulting fuel burn.

Of the four methods evaluated in this report, method 3: “fuel flow data from the flight manual” based on the Bell 407 was chosen. Because there is little fuel burn information available for helicopters, and there was an absence of real flight data, the fuel flow data from the flight manuals is the best information available. The method chosen incorporates this information in a formula depending on velocity and altitude. Because the fuel flow data is only available in cruise, the method calculates the fuel burn in the cruise phase only. Therefore a set of factors (C_1) has been determined to calculate the fuel burn in other phases based on the fuel burn in cruise. These factors are not based on flight data, and therefore should be reevaluated when real flight data becomes available.
So for every procedural step the fuel flow in cruise is determined. This is then multiplied with the corresponding factor, C_1, of the procedural step to obtain the fuel flow of that specific step. This is multiplied with the time of the procedural step to obtain the total fuel burn of that step. Ultimately the fuel burn of all procedural steps must be summed to obtain the total fuel burn of the complete flight.

Because the method depends on the fuel flow data of the Bell 407, it is in principle only valid for that type of helicopter. Unfortunately for most other helicopters, such extensive fuel flow data was not available. However, most helicopter flight manuals show the fuel flow during cruise at maximum endurance speed. Therefore the fuel flows of different helicopters in cruise at maximum endurance have been compared for similar conditions. Based on this comparison a set of factors (C_2) has been determined to be able to calculate the fuel burn of other helicopters than the Bell 407.
To calculate the fuel burn for different helicopters, first the fuel flow of the complete flight is calculated based on the Bell 407 data. This is followed by the multiplication with the factor corresponding with the helicopter the flight is performed with. The result is the fuel burn for the complete flight of the helicopter type chosen.

It should be noted that the model developed in this project has not been validated with actual flight data. It is however compared with the fuel flow data from the Bell 407 flight manual and has proven be very accurate in the cruise phase (within 2%).

With the information in this report, the method as described in chapter 6 can be programmed and implemented in AEDT.

8 Recommendations for future development

As mentioned multiple times in this report, the results could be more accurate. If there would have been more data available, methods would have been more precise. This could have led to the selection of a different method. There are multiple factors leading to limitations with the proposed helicopter fuel consumption method.

One of the main points is the lack of good and extensive data. At multiple stages in the development of the four different methods, gaps in the information available were found.
For example, the relation between power delivered and fuel flow is known by engine manufacturers and possibly by helicopter manufacturers, but was not made available for this project. A Rolls-Royce representative replied near the finalization of the project that the data is proprietary and there might be a possibility to get a non-disclosure agreement[(39)] This would make a missing part of data available and would have improved method 4.

Another point is the lack of data for other phases than cruise. This makes it impossible to base the factors used on clean helicopter data. Now it is based on the limited flight data available from Blue Hawaiian, which makes it difficult to determine on what conditions the difference in fuel burn depend. More information would be welcome to make the factors of method 3 more accurate.

Linked to the lack of data on fuel flow differences in different flight phases, there is also a lack of knowledge about the torque settings in different flight phases, more information on this part could improve the results of method 2.

For the Bell 407 reasonably extensive fuel flow data was available in the flight manual. However, this was not the case for most other helicopters. As a consequence, the model was developed based on the Bell 407 data only. This fact limits the reliability of the model for other helicopters. There could be made a more elaborate comparison between different helicopters, to make the model more reliable. A possibility could be to make the helicopter specific factors depending on speed and altitude. A problem is that the data is not presented in a similar way, which makes comparison more difficult.

The limited possibilities in AEDT with respect to helicopters limit the possibilities for fuel burn models. If AEDT would make use of a performance module for helicopters, like it does for jet airliners, the fuel burn could be calculated by integration. The fuel flow could be calculated at every point in the flight and would not depend on procedural steps, which would lead to better accuracy. It must be noted however that in this case also the available fuel flow data for the helicopters should be very extensive. As this was not available in this project it should be obtained in case of more extensive modeling options in AEDT.

An important fact which leads to uncertainty of the results presented by the model is that it was not possible to verify the results with actual flight data. There was no flight data available at Volpe, nor was there a possibility to obtain extensive flight data. As mentioned in section 3.4, Blue Hawaiian Helicopters has been approached and has been very willing to provide some flight data. However, it became clear that for a good validation, extensive flight recordings where needed which simply could not be provided by Blue Hawaiian Helicopters. Therefore it is recommended to actively obtain the extensive flight recordings needed for a good validation process of the method.

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36. Dr. Marilena Pavel – Helicopter Design – Delft University of Technology, Faculty of Aerospace Engineering

37. Christopher Snyder – Propulsion Systems – NASA

38. Larry Coates – Ex Helicopter pilot – Volpe Center

39. Rege Hall – Manager Helicopter Engines Customer Support – Rolls-Royce

Appendix A1 Introductory project code

A1.1 Loop

RUN_LOOP.BAT

```
:: Loop.bat
:: (c) Alexander Haagsma & Elgar van Veggel
::
:: This file will run a loop until the variable stop is set to 0
(with SQL script in txt file).
:: In the loop the different procedures can be called

@ECHO OFF

call start_SQL_SMS.bat

call call_SQL_script_createdb.bat

::Set loop variable
SET /a stop = 1

::Run loop till variable stop=0
:LOOP

IF %stop%==0 GOTO END

call call_SQL_script_update_flightdb.bat

call Run_AEDT.bat

call Change_CSV_name.bat

call call_SQL_script_retrieve_CSV.bat

call Delete_CSV.bat

call call_SQL_script_delete_FR.bat

call Export_stop.bat

for /f "tokens=*" %%a in ('type stop.txt') do set /a stop = %%a

GOTO LOOP

:END
```

```
call call_SQL_script_results.bat

call close_SQL_SMS.bat

call Delete_TXT.bat
```

To be able to run the loop, a couple of additional batch files have been written:

start_SQL_SMS.BAT

```
:: start_SQL_SMS.bat
:: (c) Alexander Haagsma & Elgar van Veggel
::
:: This file will open SQL Management Studio

@ECHO OFF

::Start SQL Management Studio and wait 6-1=5 seconds to allow for
start-up
START C:\aedt\SQL.lnk
PING -n 6 127.0.0.1 >NUL
```

close_SQL_SMS.BAT

```
:: close_SQL_SMS.bat
:: (c) Alexander Haagsma & Elgar van Veggel
::
:: This file will close SQL Management Studio

@ECHO OFF

::Close SQL Management Studio
TASKKILL /im ssms.exe /f
```

Export_stop.BAT

```
:: Export_stop.bat
:: (c) Kurt Wils & Elgar van Veggel
::
:: This file will run a loop until the variable stop is set to 0
(with SQL script in txt file).
:: In the loop the different procedures can be called

@ECHO OFF

bcp FuelBurnEval.dbo.batch_loop out c:\AEDT\stop.txt -
SVEGGEL8\SQLEXPRESS -T -c
```

Delete_TXT.BAT

```
:: Delete_CSV.bat
:: (c) Alexander Haagsma & Elgar van Veggel
::
:: This file will delete the renamed file so that in the next run of
the loop no double files will occur.

@ECHO OFF

::Delete the renamed file
DEL stop.txt
```

A1.2 Main parts of program

A1.2.1 Block (1)

call_SQL_script_createdb.BAT

```
:: call_SQL_script.bat
:: (c) Alexander Haagsma & Elgar van Veggel
::
:: This file will run the specified SQL script
::
:: Note: Location of SQL Management Studio must be specified
::     SQL Server name must be specified
::     SQL script must be specified

@ECHO OFF

::Run the SQL script and wait 4-1=3 seconds to continue
SQLCMD -E -S VEGGEL8\SQLEXPRESS -ic:\aedt\Create_Insert.sql
PING -n 4 127.0.0.1 >NUL
```

Create_Insert.SQL

```
-- This script creates a db for each aircraft and then inserts the entries
listed below for each flight
-- This also creates a table to write the results into
-- Mind line 83!

-- DB KEY
-- Fleet = Fleet from Flights_Master
-- FlightRecord = FlightRecord from F_M
-- TakeoffAirportCode = first 4 characters of TakeoffAirportCode from F_M
(thus the ICAO code)
-- LandingAirportCode = first 4 characters of LandingAirportCode from F_M
(thus the ICAO code)
-- TakeoffTemperature = TakeoffTemperature from F_M in Fahrenheit
```

```
-- GrossWeightStartTakeoff= GrossWeightStartTakeoff from F_M in metric
tons

USE [FuelBurnEval]
DROP TABLE [757-200]
DROP TABLE [767-300ER]
DROP TABLE [777-300ER]

-------------------------------
-- Create database 757-200
-------------------------------
USE [FuelBurnEval]
GO

SET ANSI_NULLS ON
GO

SET QUOTED_IDENTIFIER ON
GO

CREATE TABLE [dbo].[757-200](
      [Fleet] [nvarchar](255) NULL,
      [FlightRecord] [int] NOT NULL,
      [TakeoffAirportCode] [nvarchar](255) NULL,
      [LandingAirportCode] [nvarchar](255) NULL,
      [TakeoffTemperature] [real] NULL,
      [GrossWeightStartTakeoff] [float] NULL,
--    [RowNumber] [int] NULL,
) ON [PRIMARY]

GO
--------
--INSERT     set db name to AC name and where string to AC name
--------
INSERT INTO FuelBurnEval.dbo.[757-200] (Fleet, FlightRecord,
TakeoffAirportCode, LandingAirportCode, TakeoffTemperature,
GrossWeightStartTakeoff)
SELECT Fleet, FlightRecord, substring(TakeoffAirportCode,1,4),
substring(LandingAirportCode,1,4), (TakeoffTemperature*9/5)+32,
GrossWeightStartTakeoff from FuelBurnEval.dbo.MIT_Flights_Master
WHERE Fleet like '%757-200%' order by FlightRecord

DELETE FROM FuelBurnEval.dbo.[757-200]
WHERE TakeoffTemperature = 32
-- This delete to discard the flights that gave a null value for TO-temp

-------------------------------
-------------------------------
-- Create database 767-300ER
-------------------------------
USE [FuelBurnEval]
GO

SET ANSI_NULLS ON
GO
```

```
SET QUOTED_IDENTIFIER ON
GO

CREATE TABLE [dbo].[767-300ER](
	[Fleet] [nvarchar](255) NULL,
	[FlightRecord] [int] NOT NULL,
	[TakeoffAirportCode] [nvarchar](255) NULL,
	[LandingAirportCode] [nvarchar](255) NULL,
	[TakeoffTemperature] [real] NULL,
	[GrossWeightStartTakeoff] [float] NULL,
--	[RowNumber] [int] NULL,
) ON [PRIMARY]

GO
--------
--INSERT	set db name to AC name and where string to AC name
--------
INSERT INTO FuelBurnEval.dbo.[767-300ER] (Fleet, FlightRecord,
TakeoffAirportCode, LandingAirportCode, TakeoffTemperature,
GrossWeightStartTakeoff)
SELECT Fleet, FlightRecord, substring(TakeoffAirportCode,1,4),
substring(LandingAirportCode,1,4), (TakeoffTemperature*9/5)+32,
GrossWeightStartTakeoff from FuelBurnEval.dbo.MIT_Flights_Master
WHERE Fleet like '%767-300%'

DELETE FROM FuelBurnEval.dbo.[767-300ER]
WHERE TakeoffTemperature = 32



-------------------------------
-------------------------------
-- Create database 777-300ER
-------------------------------
USE [FuelBurnEval]
GO

SET ANSI_NULLS ON
GO

SET QUOTED_IDENTIFIER ON
GO

CREATE TABLE [dbo].[777-300ER](
	[Fleet] [nvarchar](255) NULL,
	[FlightRecord] [int] NOT NULL,
	[TakeoffAirportCode] [nvarchar](255) NULL,
	[LandingAirportCode] [nvarchar](255) NULL,
	[TakeoffTemperature] [real] NULL,
	[GrossWeightStartTakeoff] [float] NULL,
--	[RowNumber] [int] NULL,
) ON [PRIMARY]

GO
--------
--INSERT	set db name to AC name and where string to AC name
```

```
--------
INSERT INTO FuelBurnEval.dbo.[777-300ER] (Fleet, FlightRecord,
TakeoffAirportCode, LandingAirportCode, TakeoffTemperature,
GrossWeightStartTakeoff)
SELECT Fleet, FlightRecord, substring(TakeoffAirportCode,1,4),
substring(LandingAirportCode,1,4), (TakeoffTemperature*9/5)+32,
GrossWeightStartTakeoff from FuelBurnEval.dbo.MIT_Flights_Master
WHERE Fleet like '%777-3%' order by FlightRecord

DELETE FROM FuelBurnEval.dbo.[777-300ER]
WHERE TakeoffTemperature = 32

---------
-- Create results table
---------
USE EVENTRESULTS

DROP TABLE Fuel_Burn_AVG

CREATE TABLE Fuel_Burn_AVG
(FLIGHTRECORD INT,
 Fuel_Burn_Total FLOAT)


-------
-- Create loop ending table
-------
USE FuelBurnEval
DROP TABLE batch_loop

CREATE TABLE batch_loop
      ([loopvalue] [INT],
      )

INSERT INTO batch_loop (loopvalue) VALUES (1)
```

A1.2.2 Block (2)

call_SQL_script_update_flightdb.BAT

```
:: call_SQL_script.bat
:: (c) Alexander Haagsma & Elgar van Veggel
::
:: This file will open SQL Management Studio and will run the
specified SQL script
::
:: Note: Location of SQL Management Studio must be specified
::    SQL Server name must be specified
::     SQL script must be specified

@ECHO OFF

::Run the SQL script and wait 4-1=3 seconds to continue
```

```
SQLCMD -E -S VEGGEL8\SQLEXPRESS -ic:\aedt\update_flightdb_757-
200.sql
PING -n 4 127.0.0.1 >NUL
```

update_flightdb_757-200.SQL

```
-- This script updates the movements_aces, fleet and airport db's with the
data from the last flight record
-- © Kurt Wils & Jef Geudens.
--
-- This file is unique for each aircraft => the input database name
depends on the aircraft type
-- !!! Mind to change the ACCODE and BADA_ID inputs in part 3 and 5 to the
ones of the aircraft that is ran
-----------------------------------
--0 Insert FlightRecord as FlightID
-----------------------------------
USE [FuelBurnEval]
GO

DECLARE @FR_var INT
SELECT
@FR_var = FlightRecord FROM FuelBurnEval.dbo.[757-200]

UPDATE MOVEMENTS_ACES.dbo.FLIGHT
      SET FLIGHT_ID = @FR_var

-----------------------------
--1 Find arrival APT_ID corresponding to the APT_code and insert it into
the flight record
-----------------------------
USE FuelBurnEval
GO

DECLARE @LA_APT_code NVARCHAR(255)
SELECT
@LA_APT_code = LandingAirportCode from dbo.[757-200]

DECLARE @LA_APT_ID INT
SELECT @LA_APT_ID = APT_ID from AIRPORT.dbo.APT_CODE_LU
      WHERE APT_CODE = @LA_APT_code

UPDATE MOVEMENTS_ACES.dbo.FLIGHT
      SET ARR_APT_ID = @LA_APT_ID

-----------------------------
--2 Find takeoff APT_ID corresponding to the APT_code and insert it into
the flight record
-----------------------------
USE FuelBurnEval
GO

DECLARE @TO_APT_code NVARCHAR(255)
SELECT
@TO_APT_code = TakeoffAirportCode from dbo.[757-200]
```

```
DECLARE @TO_APT_ID INT
SELECT @TO_APT_ID = APT_ID from AIRPORT.dbo.APT_CODE_LU
      WHERE APT_CODE = @TO_APT_code

UPDATE MOVEMENTS_ACES.dbo.FLIGHT
      SET DEP_APT_ID = @TO_APT_ID

----------------------------
--3 Insert ACTYPE and ACCODE
----------------------------
UPDATE MOVEMENTS_ACES.dbo.FLIGHT
      SET ACTYPE = 'B752',
            ACCODE = 'B757-2',
            ENG_CODE = '4PW073'

-------------------------------
--4 Find weather station number associated with airport, then insert
TO_temp into All entry of that station
-------------------------------
DECLARE @TO_temp REAL
SELECT @TO_temp = TakeoffTemperature FROM FuelBurnEval.dbo.[757-200]

DECLARE @WTHR_STN INT
SELECT @WTHR_STN = WTHR_STN from AIRPORT.dbo.APT_MAIN
      WHERE APT_ID = @TO_APT_ID

UPDATE AIRPORT.dbo.APT_WTHR_DATA
      SET TEMPERATURE = @TO_temp
      WHERE STN_ID = @WTHR_STN AND WTHR_MONTH = 'ALL'

------------------------------
--5 Set the weight of all profiles of the A/C to the flight specific one
--  Thus it will pick this weight regardless of stagelength
------------------------------
DECLARE @Weight FLOAT
SELECT @Weight = GrossWeightStartTakeoff from FuelBurnEval.dbo.[757-200]

DECLARE @EQUIP_ID INT
SELECT @EQUIP_ID = EQUIP_ID from FLEET.dbo.EQUIPMENT
      WHERE ACCODE = 'B757-2'

DECLARE @ACFT_ID VARCHAR(12)
SELECT @ACFT_ID = ACFT_ID from FLEET.dbo.AIRCOMBO
      WHERE EQUIP_ID = @EQUIP_ID

UPDATE FLEET.dbo.[PROFILE]
      SET WEIGHT = (@Weight*1000*2.20462262)
      WHERE ACFT_ID = @ACFT_ID
```

A1.2.3 Block (3)

Run_AEDT.BAT

```
:: Run_AEDT.bat
:: (c) Alexander Haagsma & Elgar van Veggel
::
:: This file will run AEDT

:: Note: Location of standard directory must be specified

@ECHO OFF

::Change directory and back and run AEDT
cd C:\Program Files\AEDT\FAA_AEE_AEDT_Modules\bin
start /wait FAA.AEE.AEDT.InventoryProcessor.exe 1
cd C:\AEDT
```

A1.2.4 Block (4)

Change_CSV_name.BAT

```
:: Change_CSV_name.bat
:: (c) Alexander Haagsma & Elgar van Veggel
::
:: This file will save the AEDT output CSV file to a map for back-
up. After that it changes the name of
:: the AEDT output CSV file to a fixed name so the results can be
retreived from it.

:: Note: The folder CSV_TEMP should be created

@ECHO OFF

:: Move the file with its original name to the working directory
cd C:\Program Files\AEDT\FAA_AEE_AEDT_Modules\bin
MOVE *.csv "C:\AEDT"
cd C:\AEDT

:: Copy the file with its original name to a backup folder
COPY *.csv "C:\AEDT\CSV_BACKUP"

:: Rename the file to be able to be read
REN *.csv, AEDT_Flight_Result.csv
```

A1.2.5 Block (5)

call_SQL_script_retreive_CSV.BAT

```
:: call_SQL_script.bat
:: (c) Alexander Haagsma & Elgar van Veggel
::
:: This file will open SQL Management Studio and will run the
specified SQL script
::
:: Note: Location of SQL Management Studio must be specified
::     SQL Server name must be specified
::     SQL script must be specified

@ECHO OFF

::Run the SQL script and wait 4-1=3 seconds to continue
SQLCMD -E -S VEGGEL8\SQLEXPRESS -
ic:\aedt\CSV_Fuel_Burn_Extraction.sql
PING -n 4 127.0.0.1 >NUL
```

CSV_Fuel_Burn_Extraction.SQL

```
USE EVENTRESULTS

GO

DROP table Fuel_Burn

CREATE table Fuel_Burn
(NUM  varchar(100), DIST varchar(100),LENGTH varchar(100),TIME
varchar(100),ALT1AFE varchar(1005),ALT2AFE float,ALT1MSL
varchar(100),ALT2MSL varchar(100),V1 varchar(100),V2 varchar(100),DELTAV
varchar(100),FND1 varchar(100),FND2 varchar(100),NOISETHRUST1
varchar(100), NOISETHRUST2 varchar(100),DELTAFND varchar(100), LAT1
varchar(100),LONG1 varchar(100),LAT2 varchar(100),LONG2 varchar(100),X1
varchar(100),Y1 varchar(100),X2 varchar(100),Y2 varchar(100),UNITX
varchar(100),UNITY varchar(100),UNITZ varchar(100),BANKANGLE
varchar(100),FUELFLOW varchar(100),FUELBURN float,WEIGHT varchar(100),TEMP
varchar(100),PRESS varchar(100),MACHNO varchar(100),THETA
varchar(100),DELTA varchar(100),OPMODE varchar(100),EMISS varchar(max))

BULK
INSERT Fuel_Burn
FROM 'c:\AEDT\AEDT_Flight_Result.csv'
WITH (firstrow = 2, FIELDTERMINATOR = ',', ROWTERMINATOR = '\n')

GO

DELETE FROM Fuel_Burn
WHERE ALT2AFE > '3000'
```

```
--At this point, the data is written in the created Fuel_Burn_AVG table,
of which the script is run at the start of execution

DECLARE @flightrecord INT
DECLARE @Fuel_Burn_Total FLOAT

SELECT @flightrecord = Flight_ID FROM MOVEMENTS_ACES.dbo.FLIGHT
SELECT @Fuel_Burn_Total = SUM(FUELBURN) FROM Fuel_Burn

INSERT into Fuel_Burn_AVG
(FLIGHTRECORD, Fuel_Burn_Total)
values (@flightrecord, @Fuel_Burn_Total)
```

A1.2.6 Block (6)

Delete_CSV.BAT

```
:: Delete_CSV.bat
:: (c) Alexander Haagsma & Elgar van Veggel
::
:: This file will delete the renamed file so that in the next run of the loop no double files will occur.

@ECHO OFF

::Delete the renamed file
DEL AEDT_Flight_Result.csv
```

call_SQL_script_delete_FR.BAT

```
:: call_SQL_script.bat
:: (c) Alexander Haagsma & Elgar van Veggel
::
:: This file will run the specified SQL script
::
:: Note: Location of SQL Management Studio must be specified
::     SQL Server name must be specified
::     SQL script must be specified

@ECHO OFF

::Run the SQL script and wait 4-1=3 seconds to continue
SQLCMD -E -S VEGGEL8\SQLEXPRESS -ic:\aedt\delete_FR_757-200.sql
PING -n 4 127.0.0.1 >NUL
```

delete_FR_757-200.SQL

```
-- This is the script that has to be run after AEDT has processed the
flight and before the next flight is processed
-- Change db names to the ones of your aircraft
-------------------------------------------
```

```
-- Delete the flight that has been processed
-------------------------------------------

USE [MOVEMENTS_ACES]
GO

DECLARE @FR_var INT
SELECT
@FR_var = FLIGHT_ID FROM MOVEMENTS_ACES.dbo.FLIGHT

DELETE from FuelBurnEval.dbo.[757-200]
WHERE FlightRecord = @FR_var

------------
-- Adapt loop ending parameter in dbo.batch_loop if specific A/C db is
empty
------------
USE FuelBurnEval

UPDATE batch_loop
      SET loopvalue = (SELECT COUNT(*) FROM [757-200])
```

A1.2.7 Block (7)

call_SQL_script_results.BAT

```
:: call_SQL_script.bat
:: (c) Alexander Haagsma & Elgar van Veggel
::
:: This file will run the specified SQL script
::
:: Note: Location of SQL Management Studio must be specified
::     SQL Server name must be specified
::     SQL script must be specified

@ECHO OFF

::Run the SQL script and wait 4-1=3 seconds to continue
SQLCMD -E -S VEGGEL8\SQLEXPRESS -
ic:\aedt\Results_Fuel_Burn_runonce.sql
PING -n 4 127.0.0.1 >NUL
```

Results_Fuel_Burn_runonce.SQL

```
USE EVENTRESULTS

DROP table Fuel_Burn_Results

CREATE table Fuel_Burn_Results
(NumberOfFlights INT, AverageFuelBurn Float)

DECLARE @numberofentries INT
```

```
DECLARE @totalfuelburn FLOAT

SELECT @numberofentries = Count(FLIGHTRECORD)FROM Fuel_Burn_AVG
SELECT @totalfuelburn = SUM(Fuel_Burn_Total)FROM Fuel_Burn_AVG



INSERT into Fuel_Burn_Results
(NumberOfFlights, AverageFuelBurn)
values (@numberofentries, @totalfuelburn / @numberofentries)
```

Appendix A2 Fuel flow data EC-130 flight manual

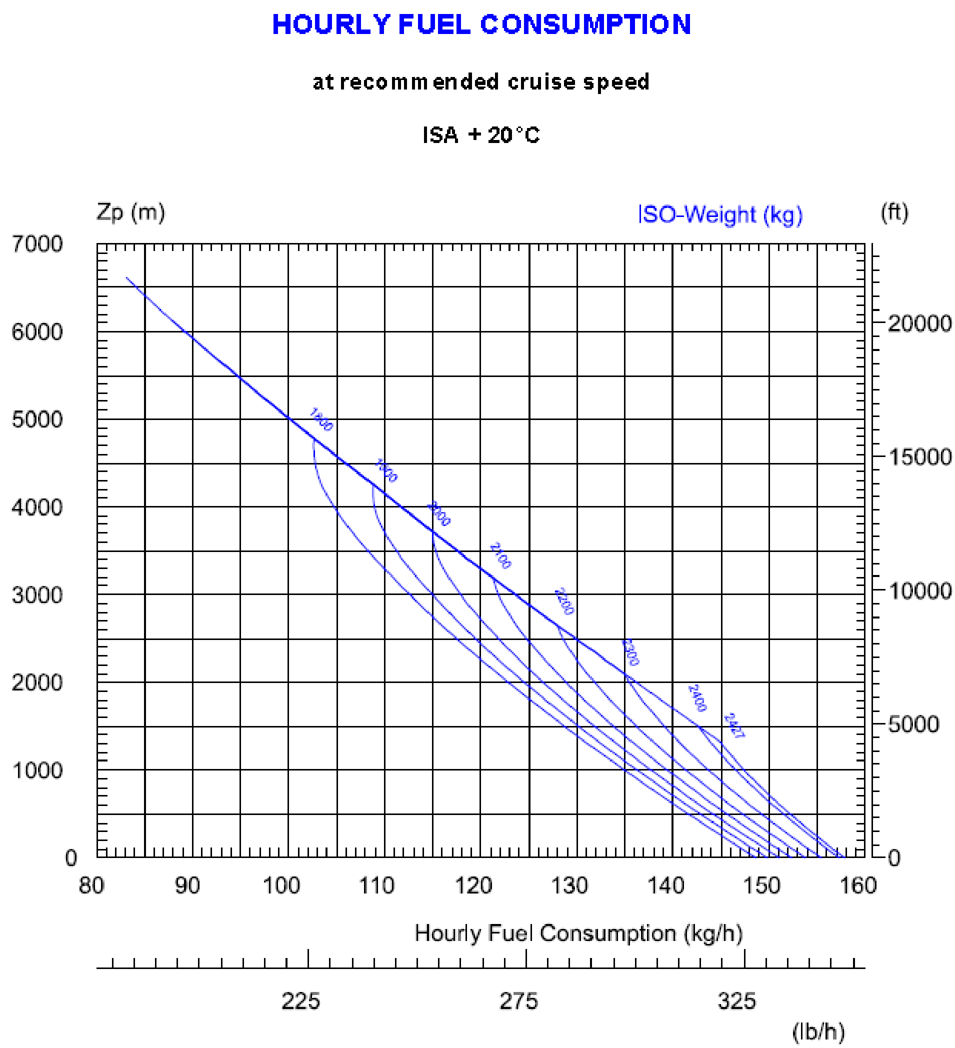
The following performance values and figures refer to an ***EC130 B4***.
Unless otherwise specified, the values and figures refer to a **clean helicopter,** equipped with a **new engine,** at **Sea Level** (SL), in **International Standard Atmosphere** (ISA) and **zero wind** condition.

Note : The following data are extracted from the approved flight manual which is the reference for performance computation.

Performance

Gross Weight	**kg**	**1,800**	**2,000**	**2,200**	**2,300**	**2,400**	**2,427**
	lb	**3,968**	**4,409**	**4,850**	**5,071**	**5,291**	**5,351**
■ Maximum Speed, VNE	**km/hr**	287	287	287	287	287	287
	kts	155	155	155	155	155	155
■ Fast cruise speed (at MCP)	**km/hr**	250	248	244	242	240	240
	kts	135	134	132	131	130	130
■ Recommended cruise speed	**km/hr**	222	222	222	222	222	222
	kts	120	120	120	120	120	120
■ Fuel consumption at fast cruise speed	**kg/hr**	175	175	175	175	175	175
	lb/h	386	386	386	386	386	386
■ Fuel consumption at recommended cruise speed	**kg/hr**	149	151.5	154	155.5	157	157.5
	lb/h	328	334	340	343	346	347
■ Rate-of-climb	**m/sec**	11.6	10.9	10.1	9.6	9.1	9.0
	ft/min	2,290	2,155	1,995	1,905	1,805	1,770
■ Hover ceiling IGE at Take-off power							
• ISA	**m**	5,865	4,920	4,035	3,615	3,210	3,100
	ft	19,255	16,140	13,240	11,865	10,530	10,165
• ISA + 20°C	**m**	5,145	4,175	3,275	2,840	2,420	2,305
	ft	16,880	13,710	10,750	9,320	7,940	7,575
■ Hover ceiling OGE at Take-off power							
• ISA	**m**	5,360	4,400	3,505	3,075	2,650	2,535
	ft	17,590	14,435	11,505	10,090	8,695	8,325
• ISA + 20°C	**m**	4,610	3,630	2,705	2,260	1,830	1,715
	ft	15,130	11,915	8,875	7,415	6,000	5,630
■ Service ceiling (0.5 m/sec., 100 ft/min.)							
• ISA	**m**	>7,010	6,505	5,665	5,265	4,870	4,770
	ft	>23,000	21,345	18,585	17,275	15,980	15,655
• ISA + 20°C	**m**	6,645	5,675	4,755	4,300	3,855	3,735
	ft	21,805	18,625	15,605	14,120	12,655	12,260
■ Range (without reserve, at recommended cruise speed)	**km**	644	635	625	620	615	610
	nm	347	343	337	334	332	329
■ Endurance (without reserve)	**hr : min**	04:07	04:01	03:54	03:51	03:48	03:47

Figure 15: Eurocopter EC 130 performance table[11]



Note : Typical consumption with clean standard aircraft and new engine.

Figure 16: Eurocopter EC 130 hourly fuel consumption at ISA 20C[11]

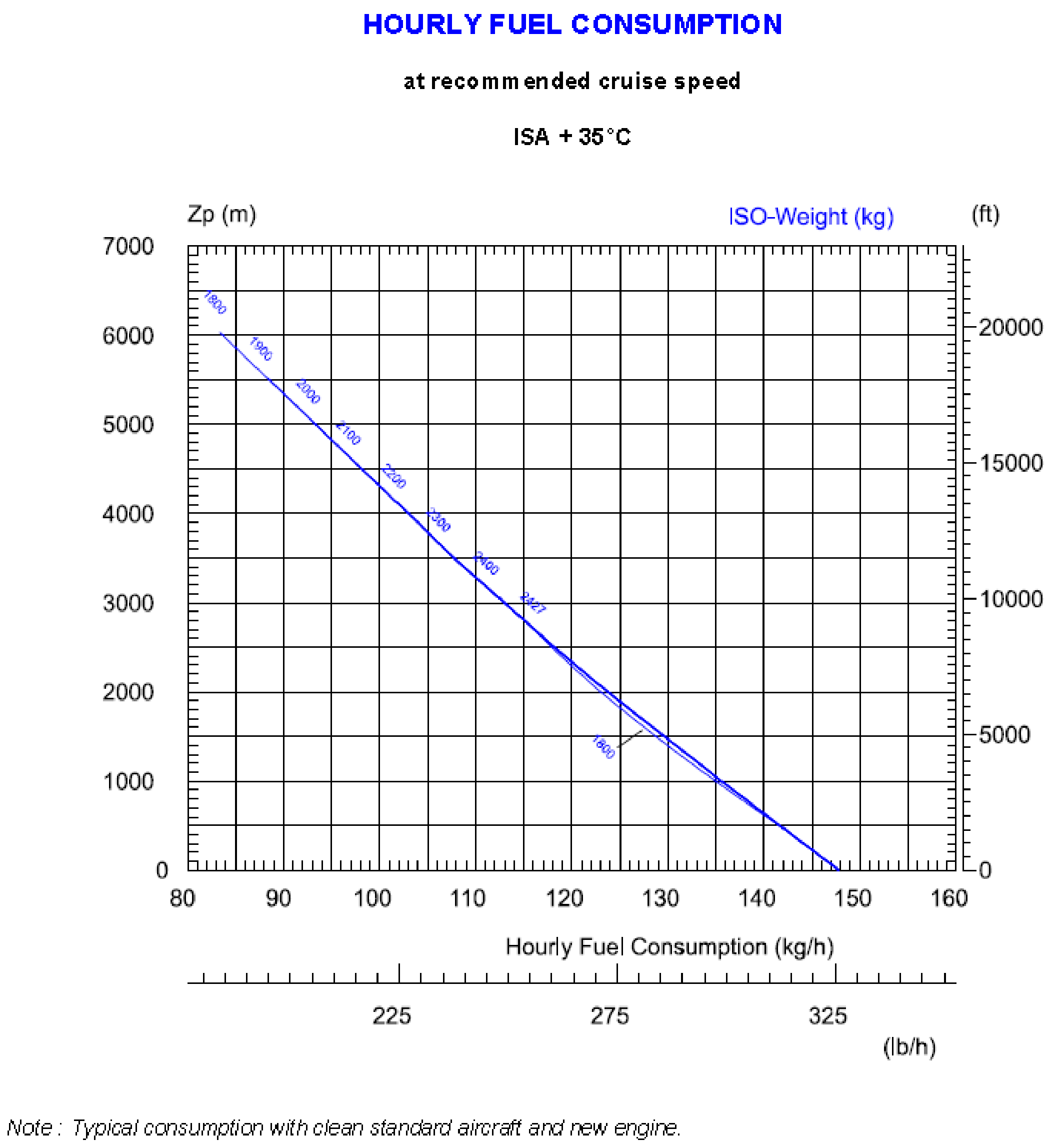


Figure 17: Eurocopter EC 130 hourly fuel consumption at ISA 35C[11]

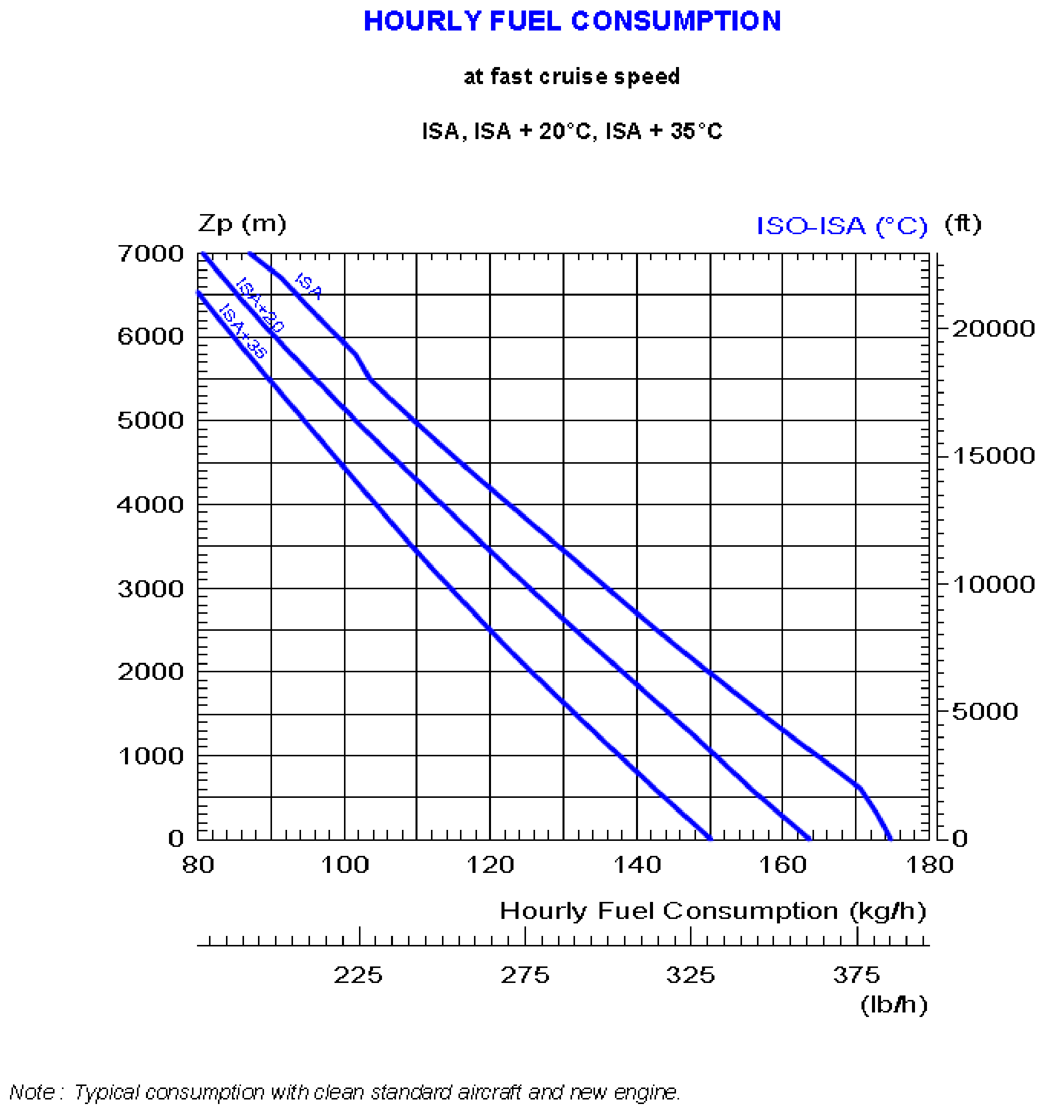


Figure 18: Eurocopter EC 130 hourly fuel consumption at fast cruise speed(11)

Appendix A3 Fuel flow data Bell 407 flight manual

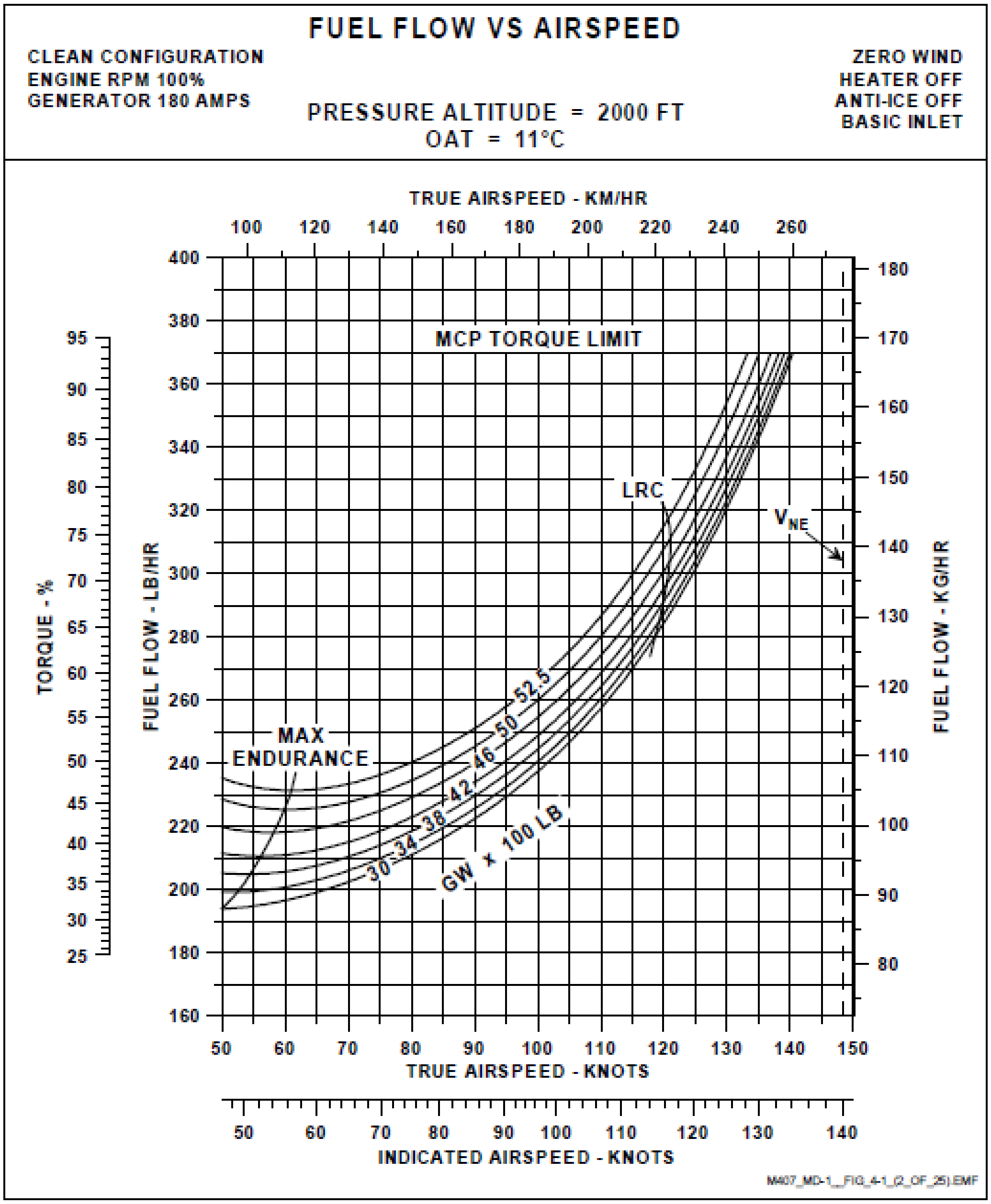


Figure 19: Bell 407 fuel burn for 2000 FT - 11°C[3]

Appendix A3 Fuel flow data Bell 407 flight manual

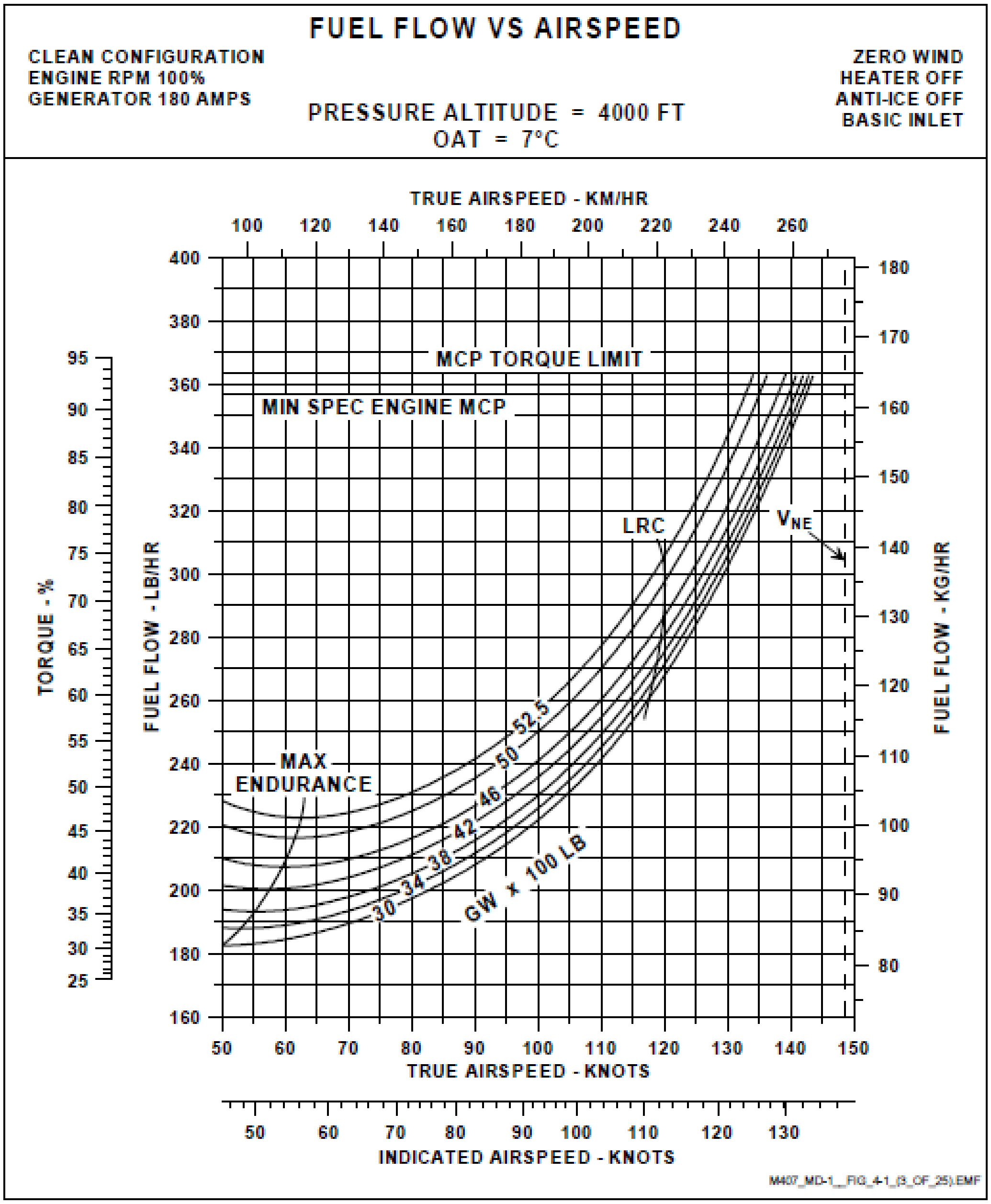


Figure 20: Bell 407 fuel burn for 4000 FT - 7°C(3)

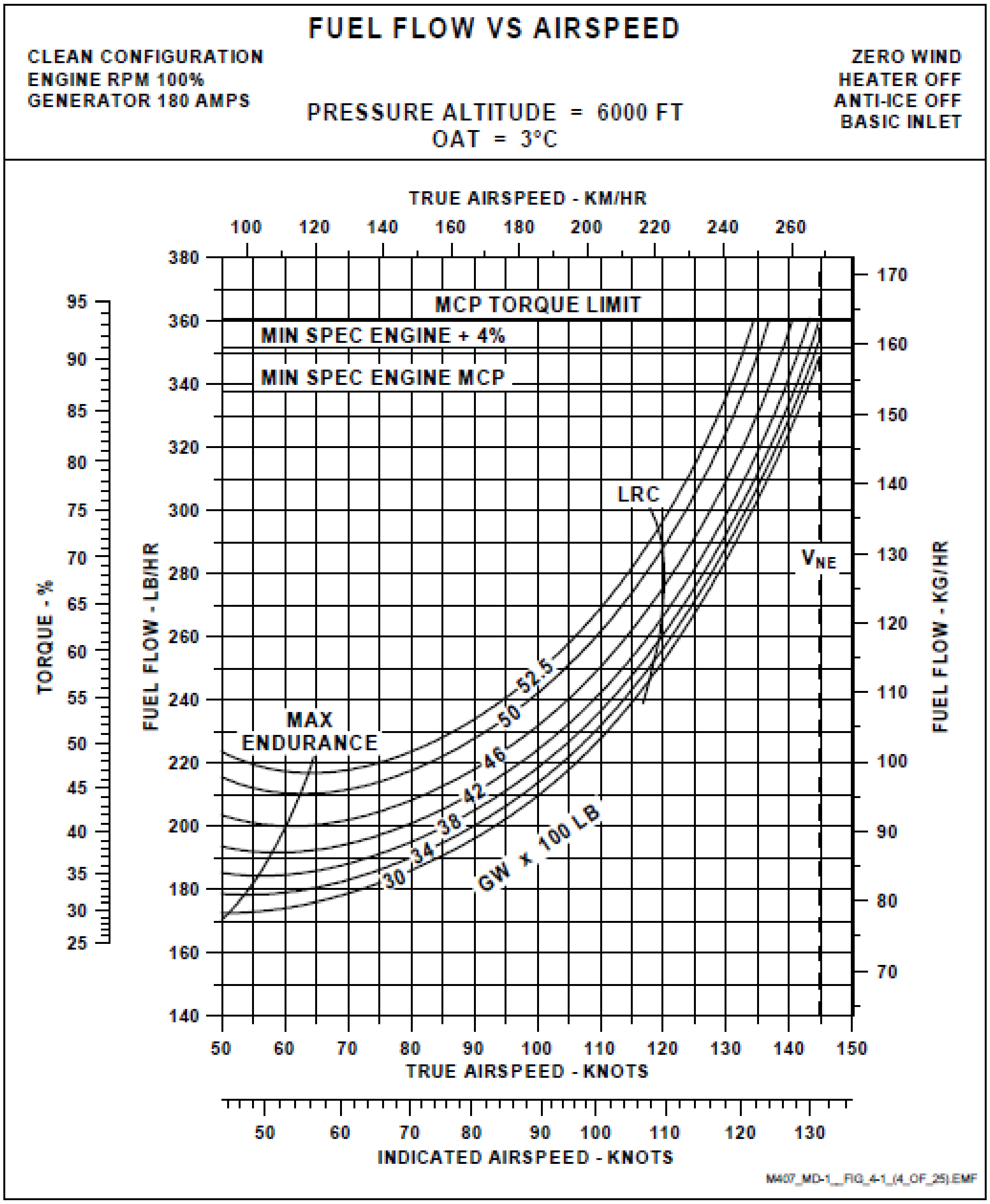


Figure 21: Bell 407 fuel burn for 6000 FT - 3°C(3)

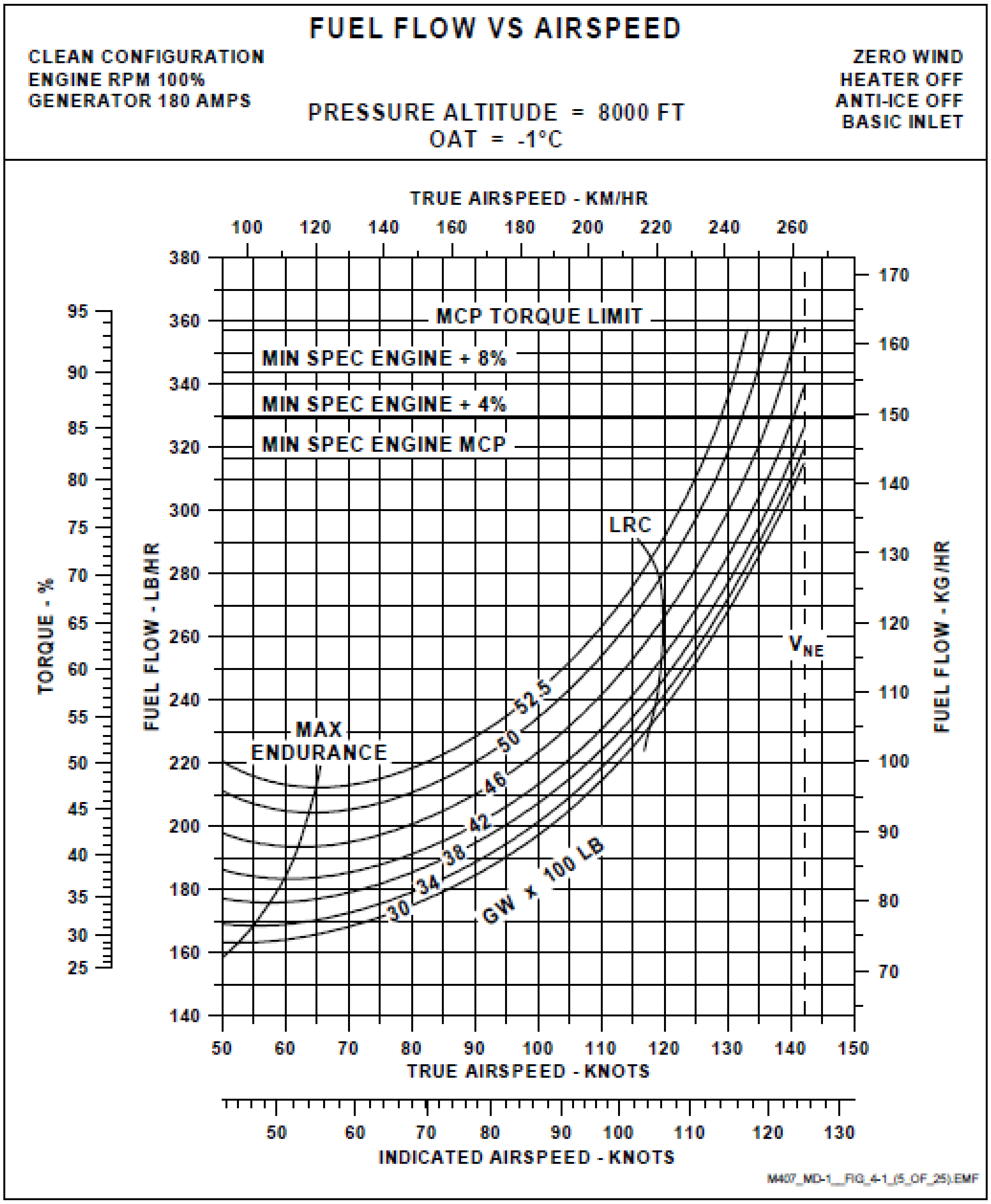


Figure 22: Bell 407 fuel burn for 8000 FT - -1°C(3)

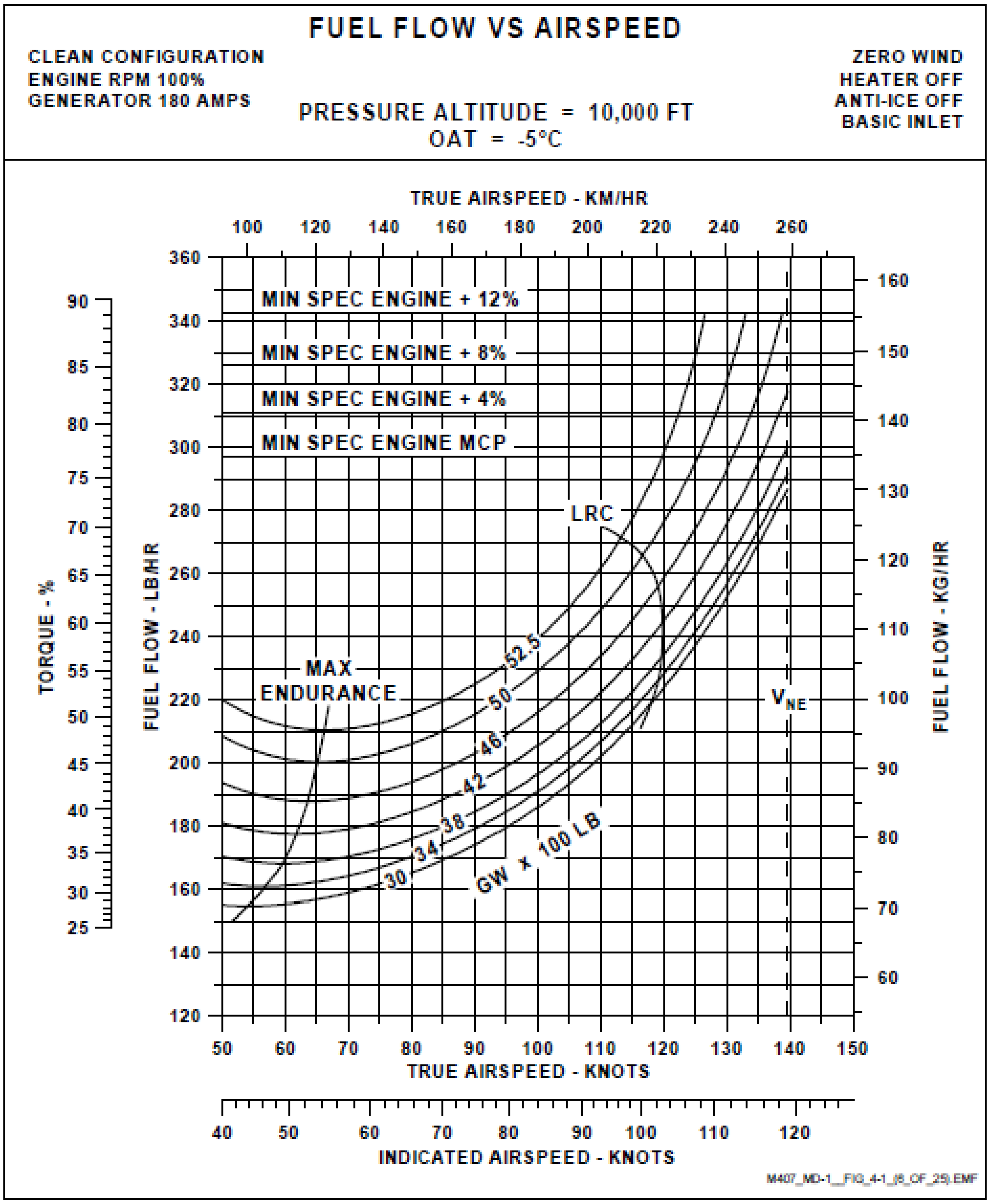


Figure 23: Bell 407 fuel burn for 10000 FT - -5°C(3)

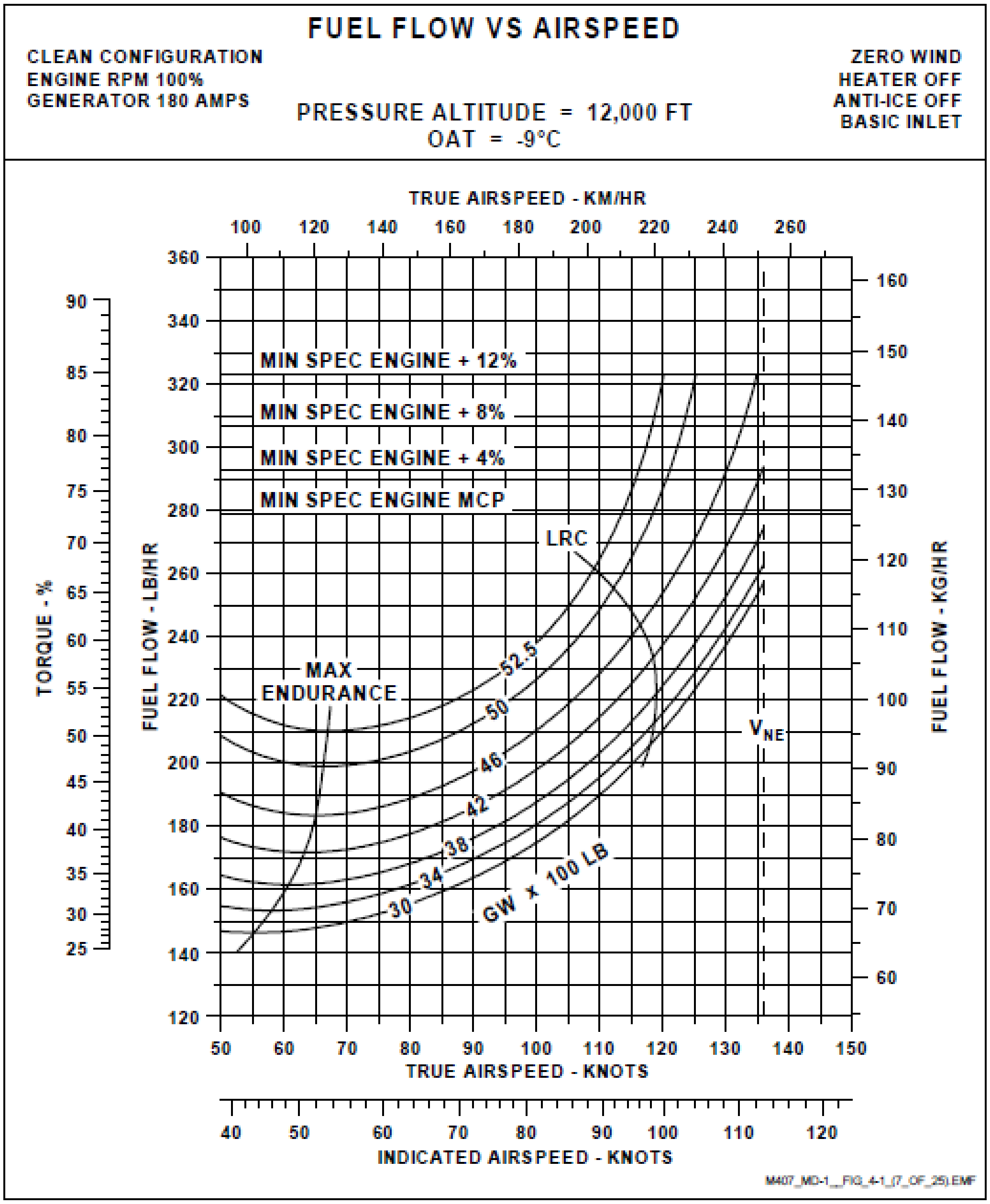


Figure 24: Bell 407 fuel burn for 120000 FT - -9°C(3)

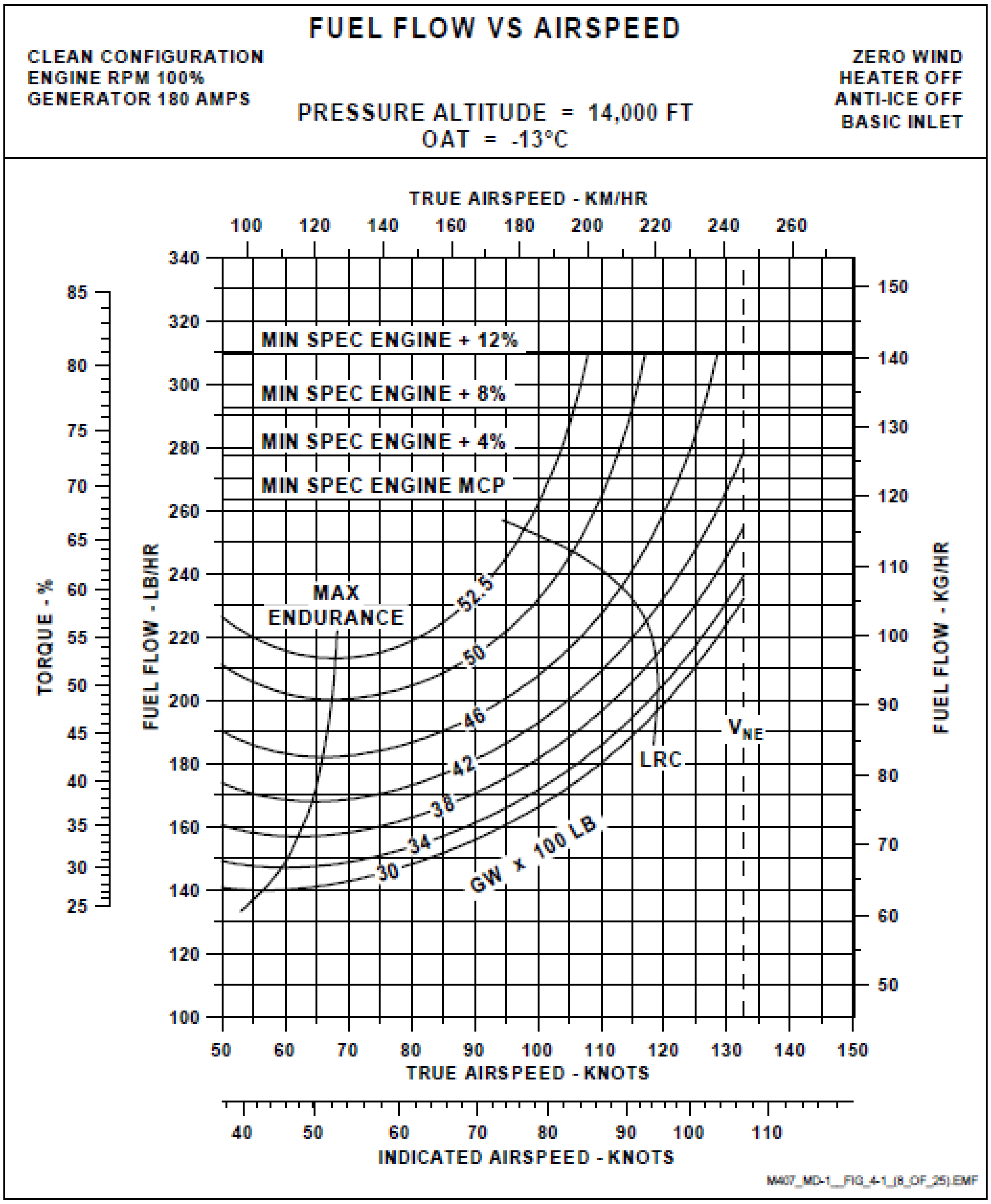


Figure 25: Bell 407 fuel burn for 14000 FT - -13°C(3)

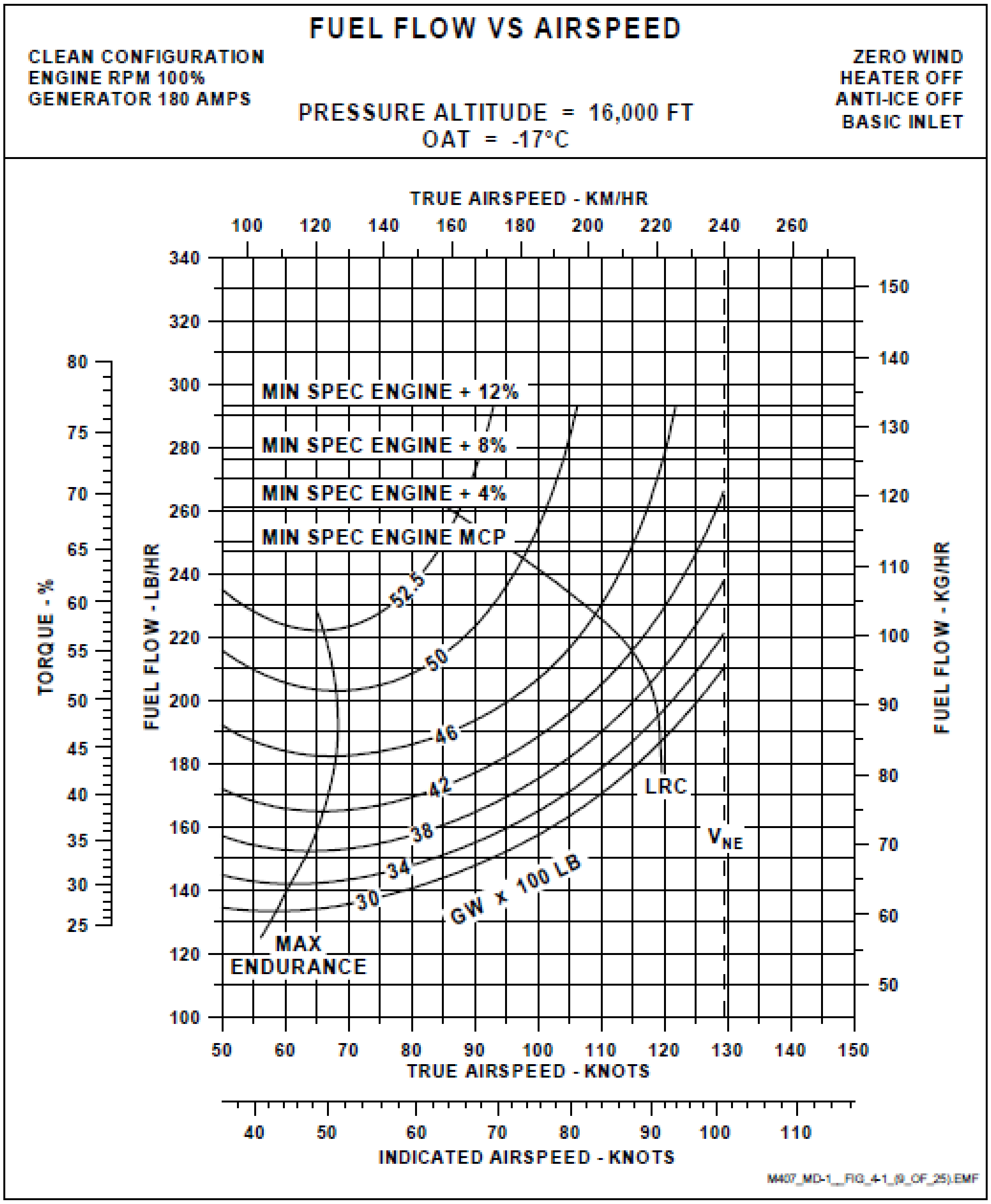


Figure 26: Bell 407 fuel burn for 16000 FT - -17°C(3)

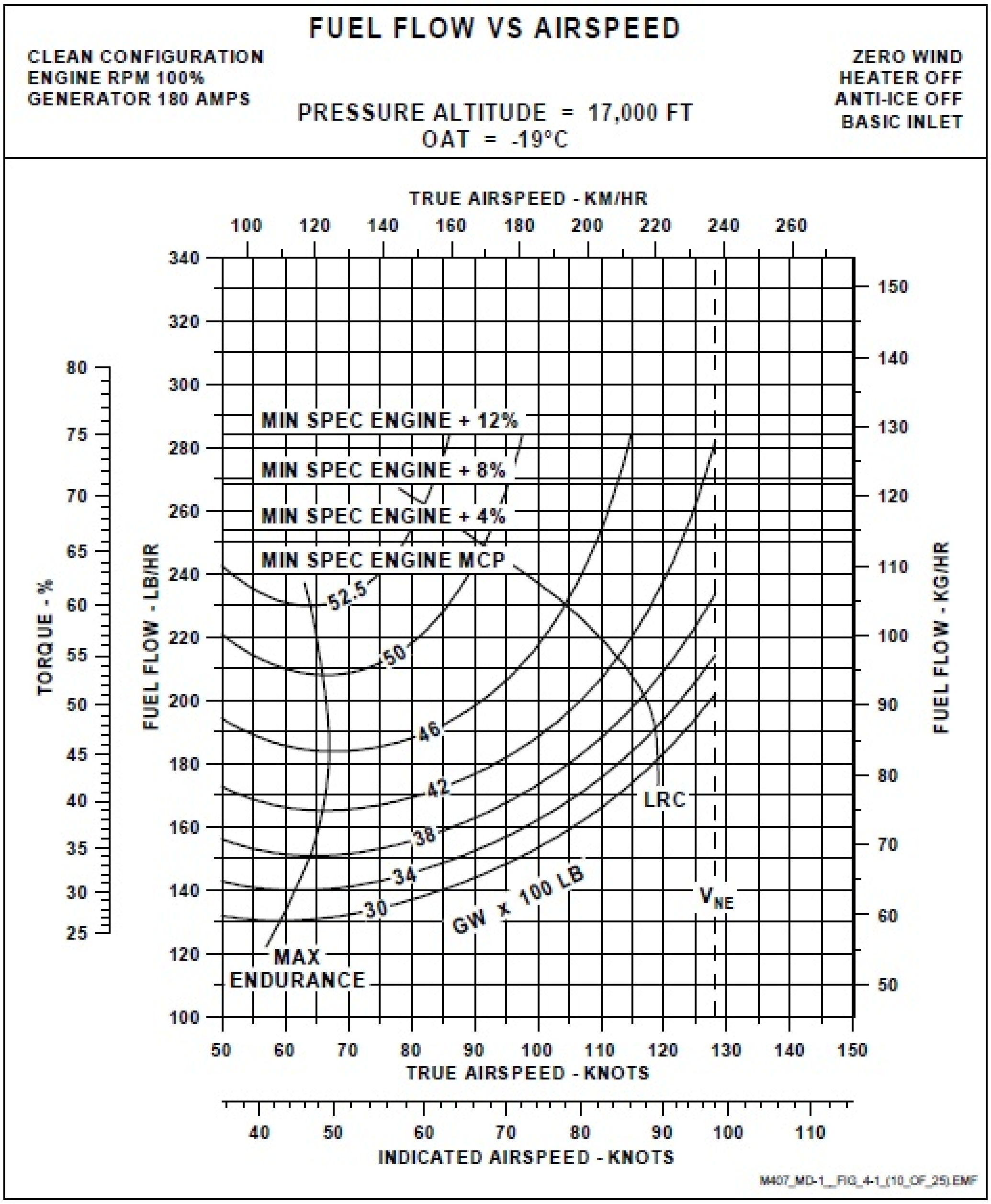


Figure 27: Bell 407 fuel burn for 17000 FT - -19°C(3)

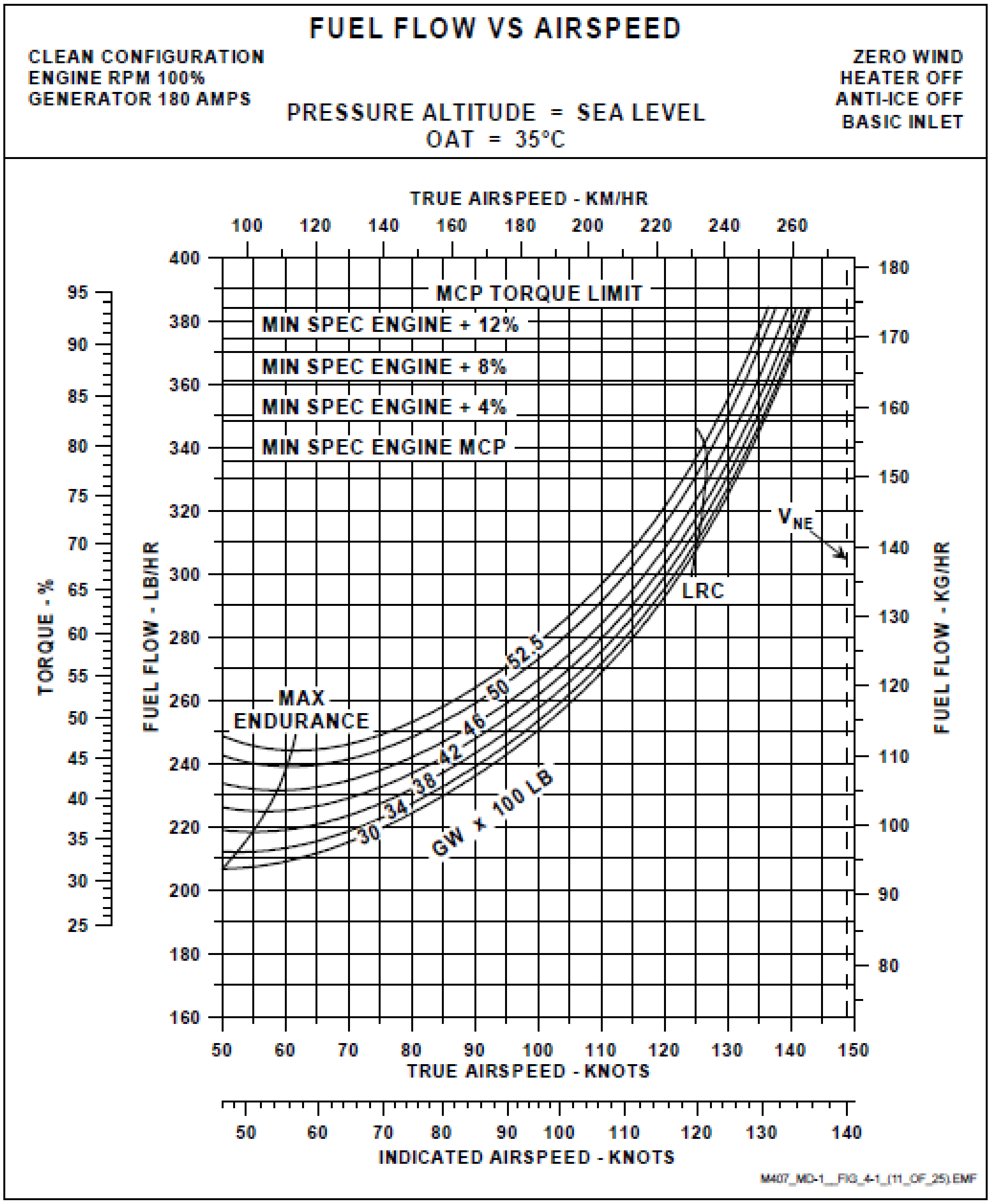


Figure 28: Bell 407 fuel flow for sea level - 35°C(3)

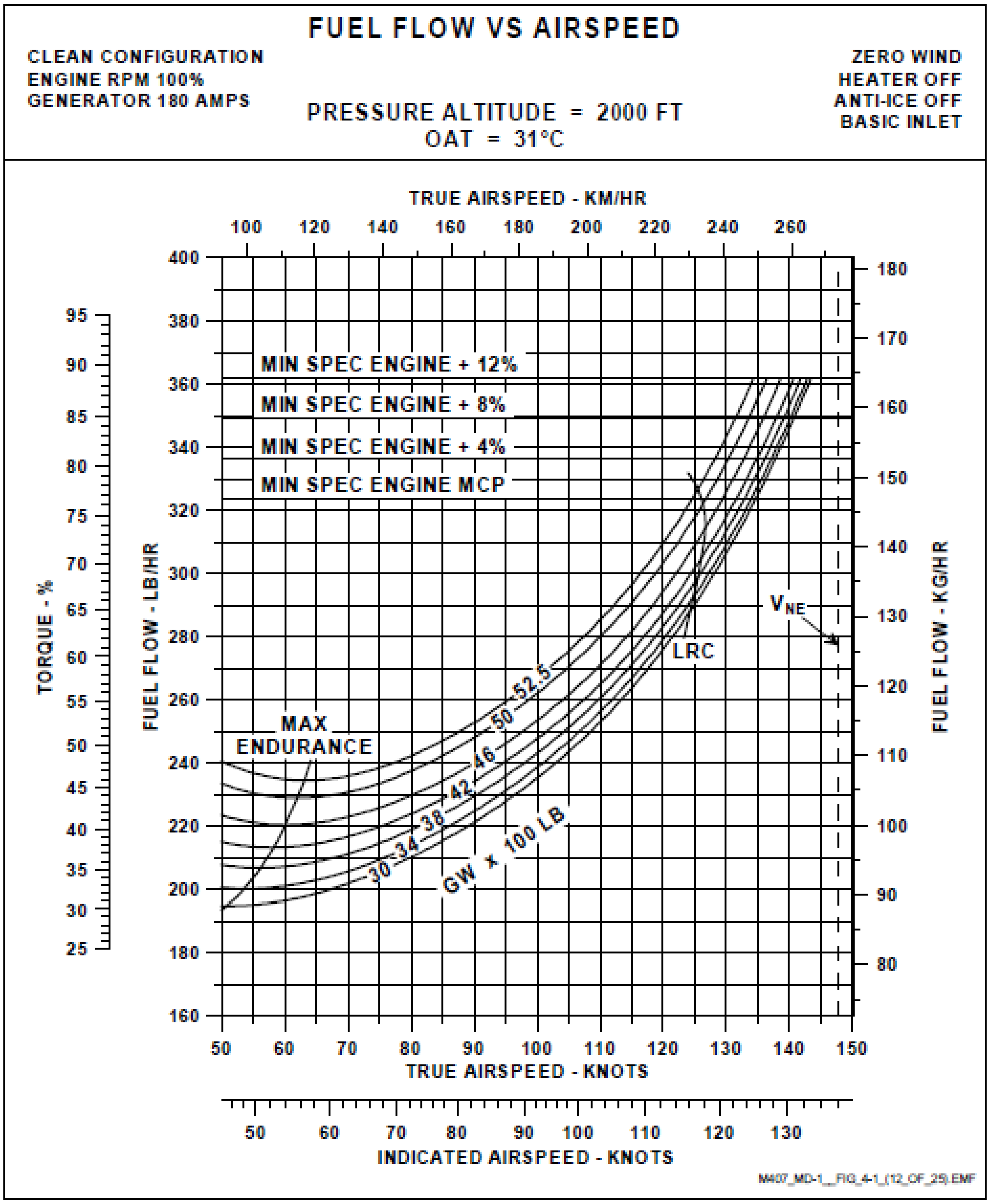


Figure 29: Bell 407 fuel flow for 2000 FT - 31°C(3)

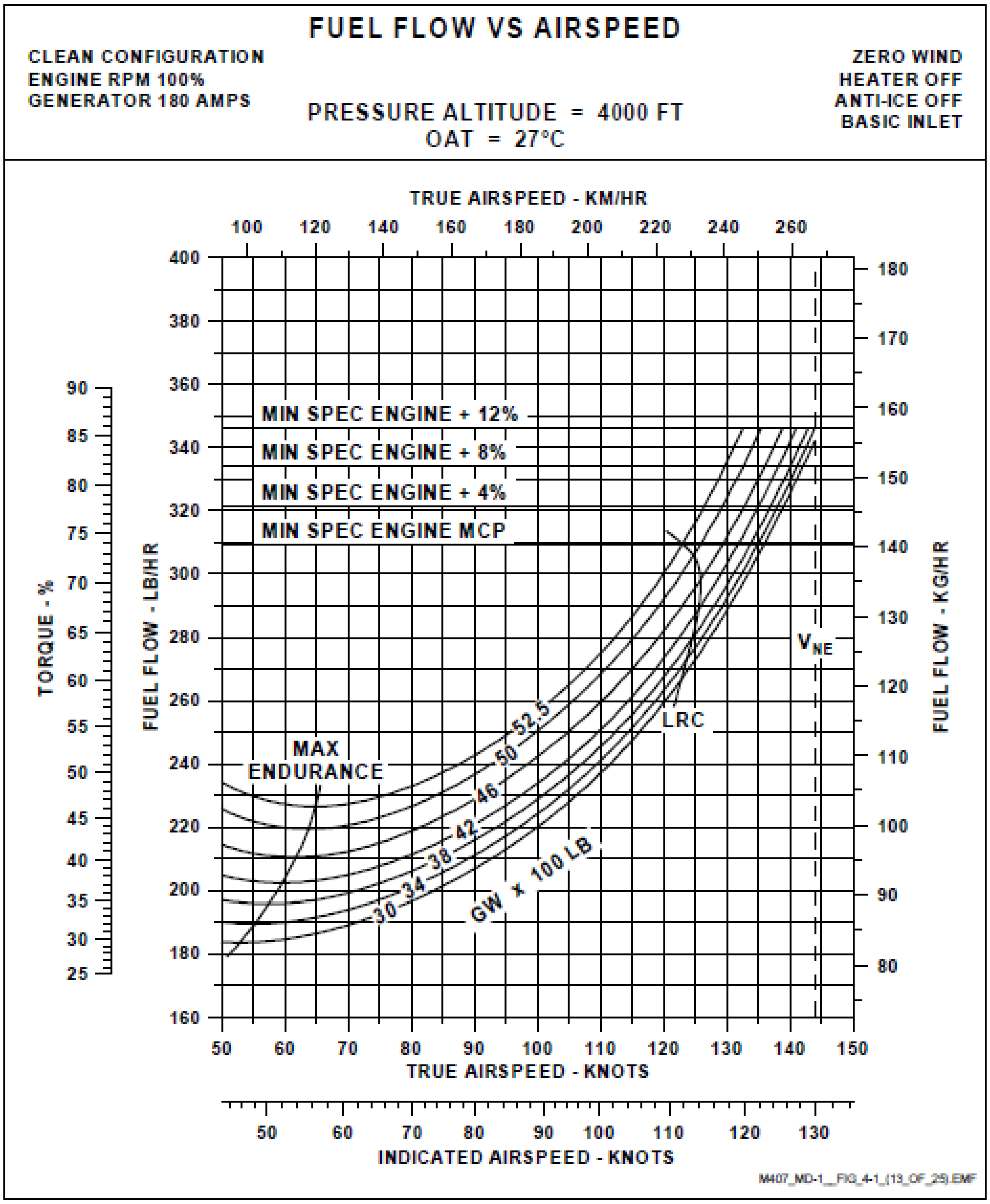


Figure 30: Bell 407 fuel flow for 4000 FT - 27°C(3)

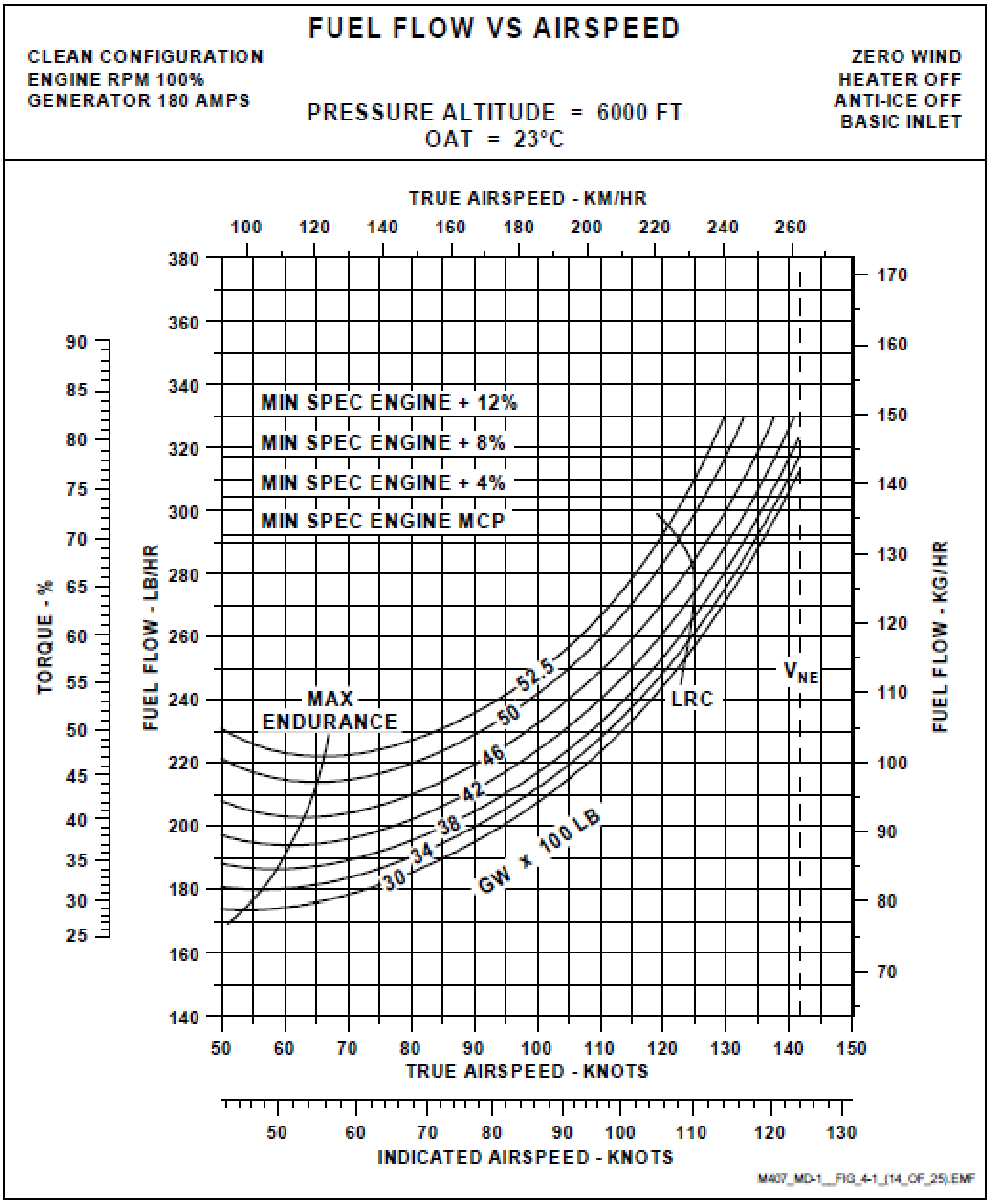


Figure 31: Bell 407 fuel flow for 6000 FT - 23°C(3)

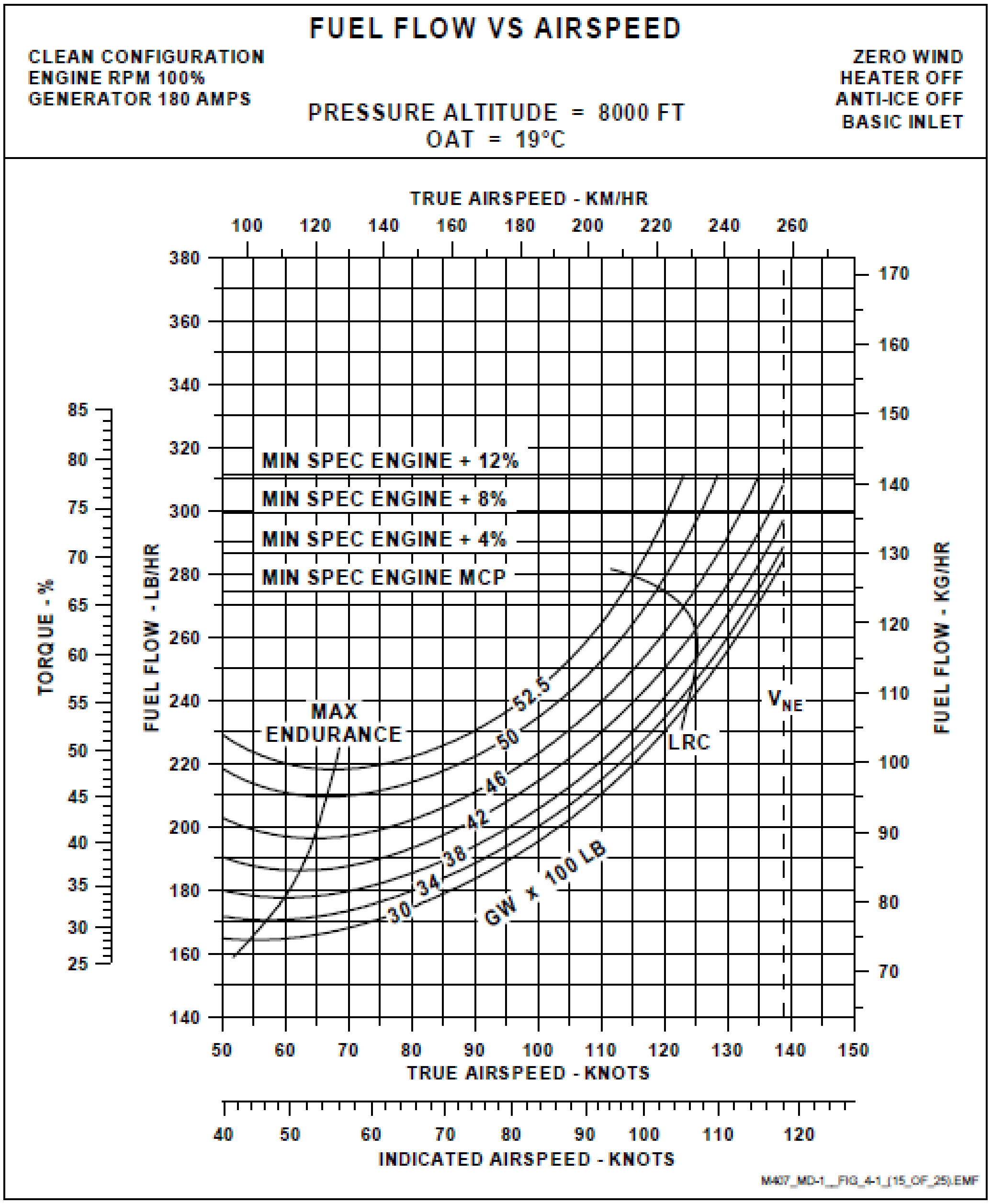


Figure 32: Bell 407 fuel flow for 8000 FT - 19°C(3)

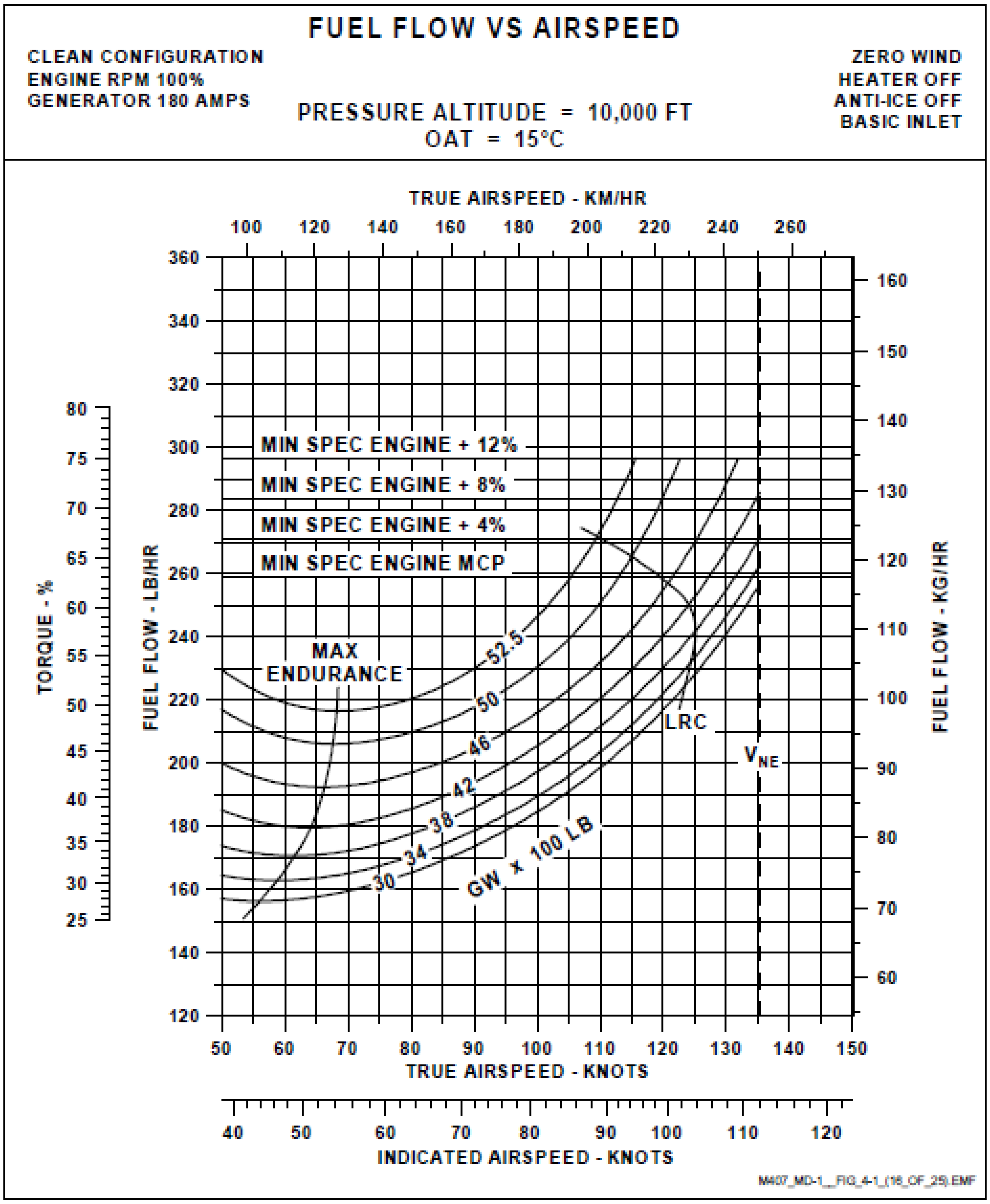


Figure 33: Bell 407 fuel flow for 10,000 FT - 15°C(3)

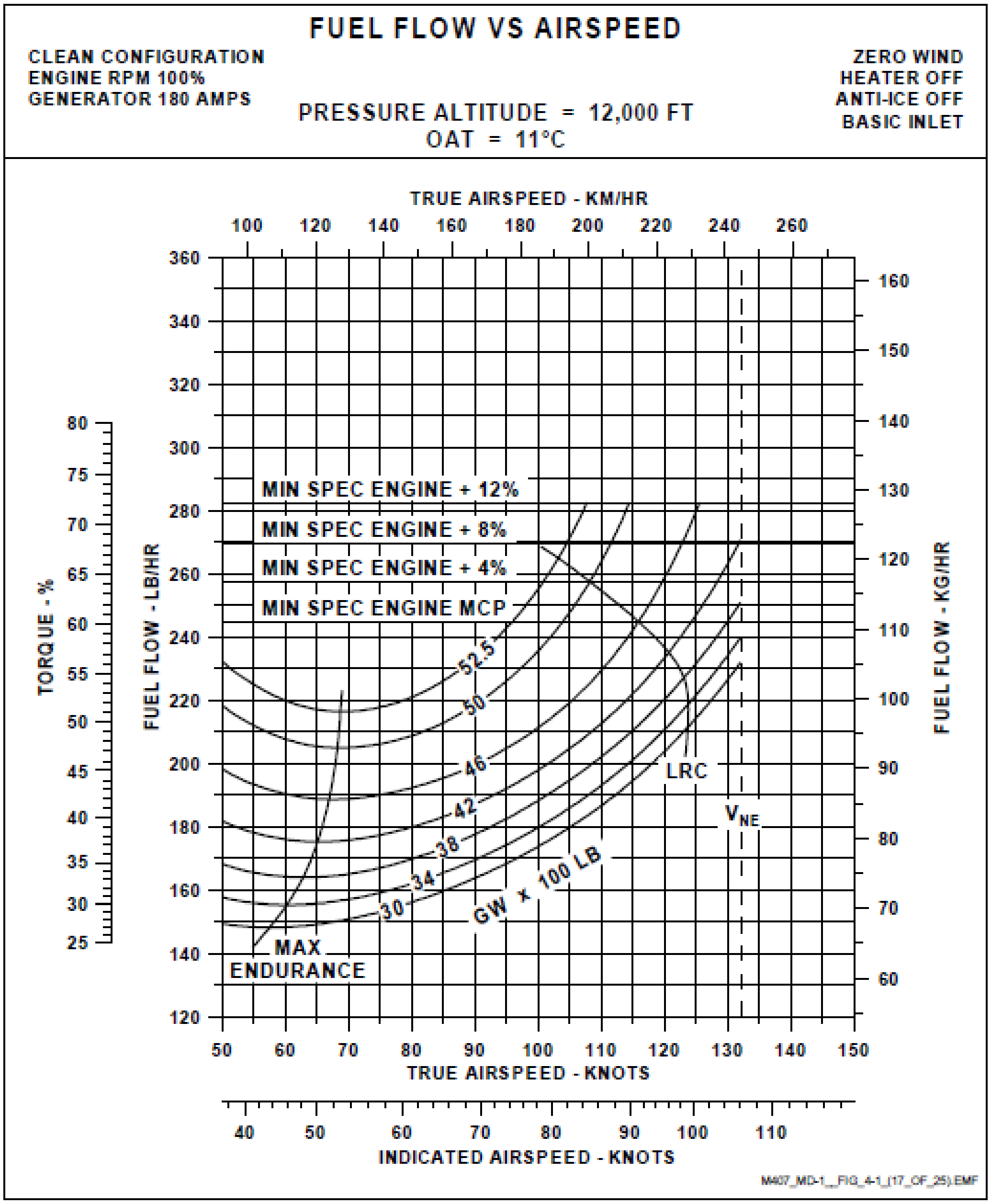


Figure 34: Bell 407 fuel flow for 12,000 FT - 11°C(3)

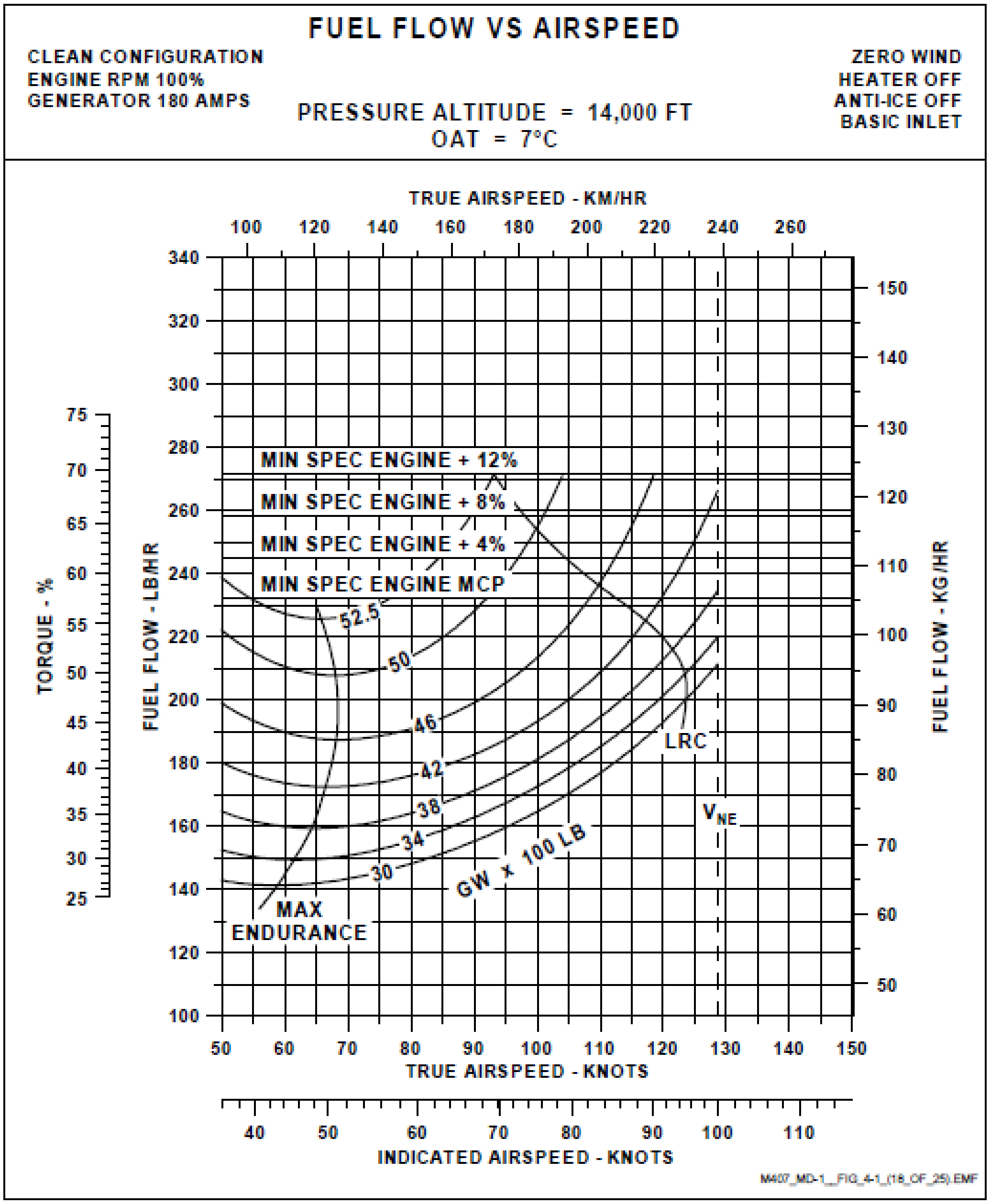


Figure 35: Bell 407 fuel flow for 14,000 FT - 7°C[3]

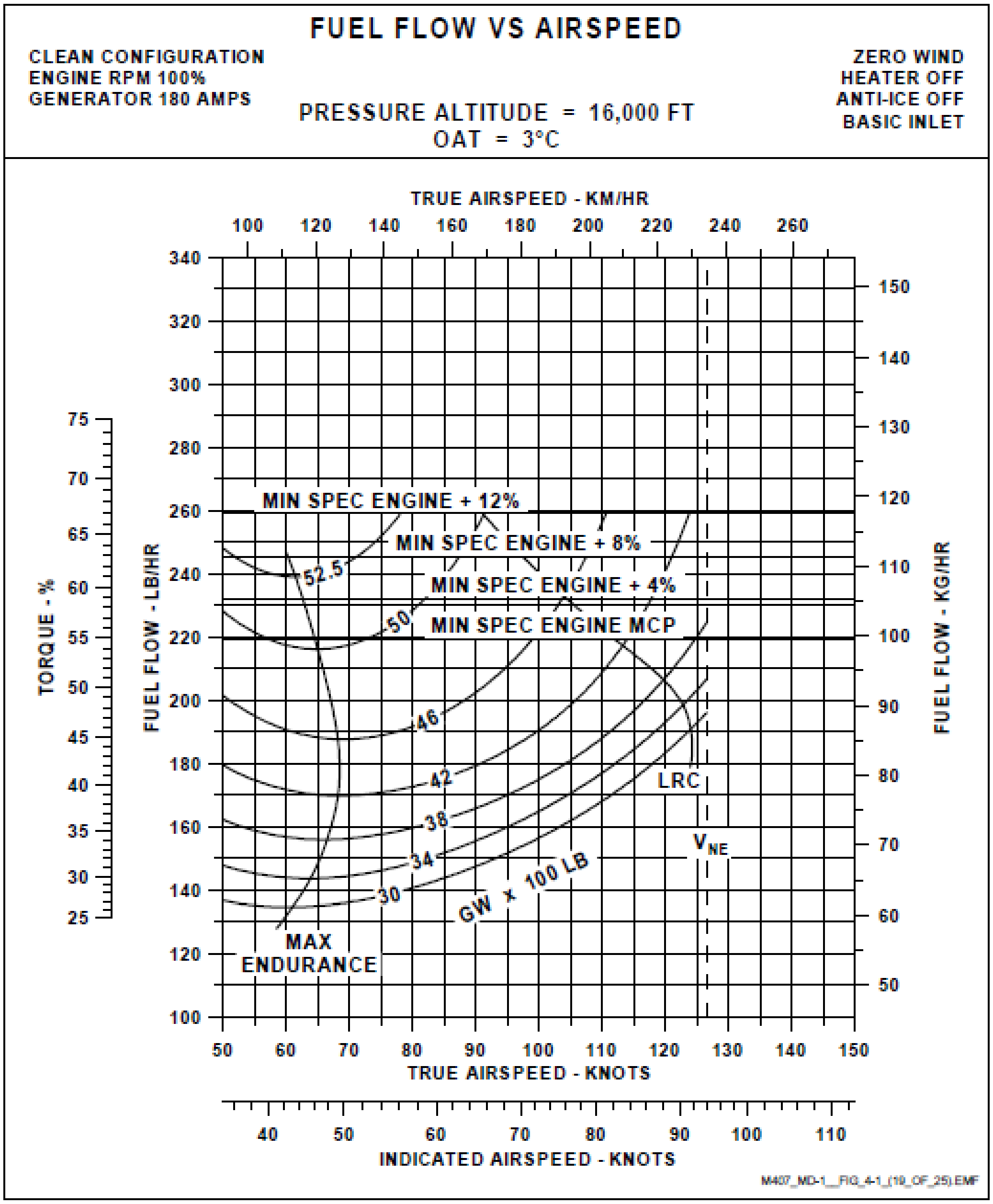


Figure 36: Bell 407 fuel flow for 16,000 FT - 3°C(3)

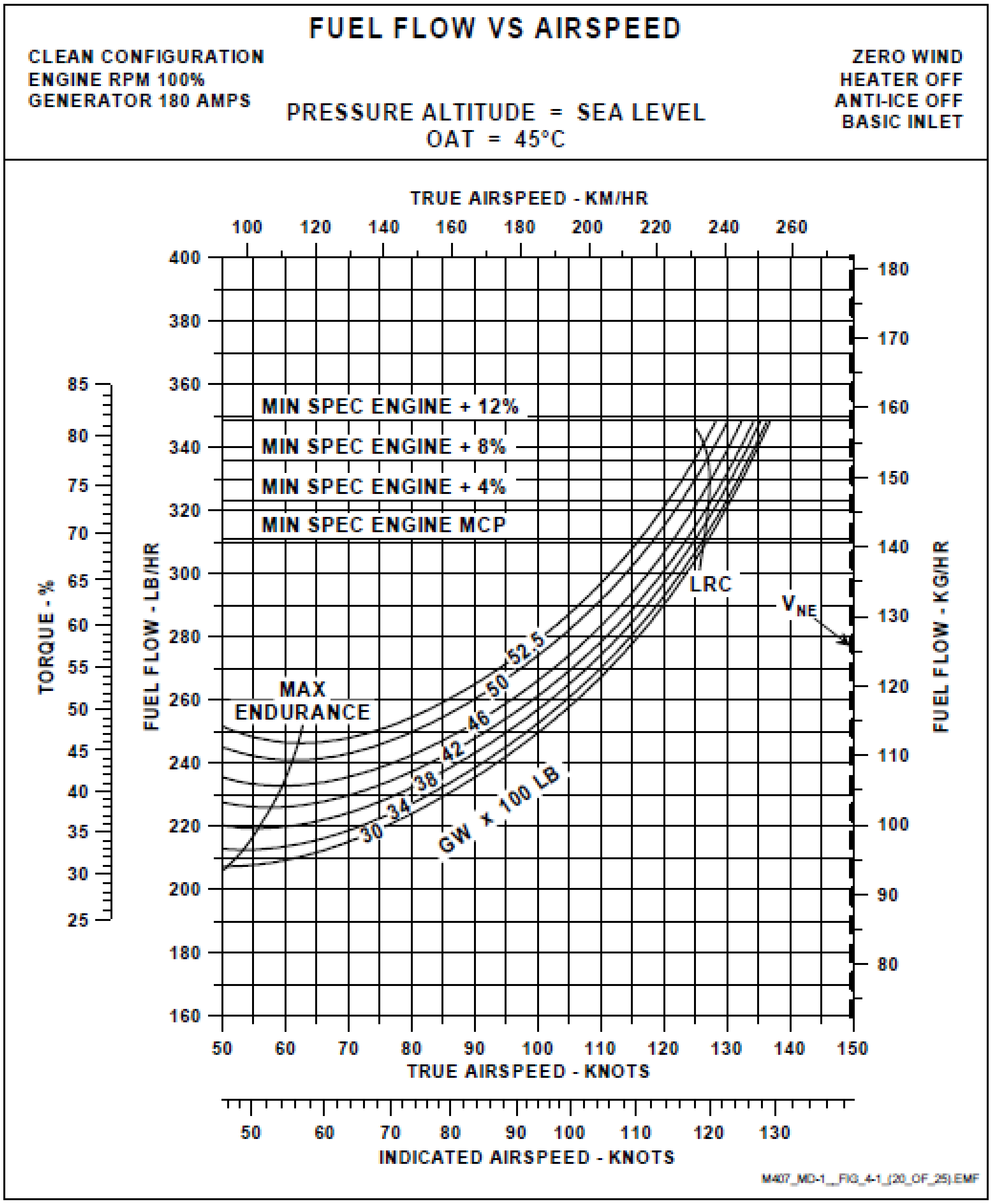


Figure 37: Bell 407 fuel flow for sea level - 45°C(3)

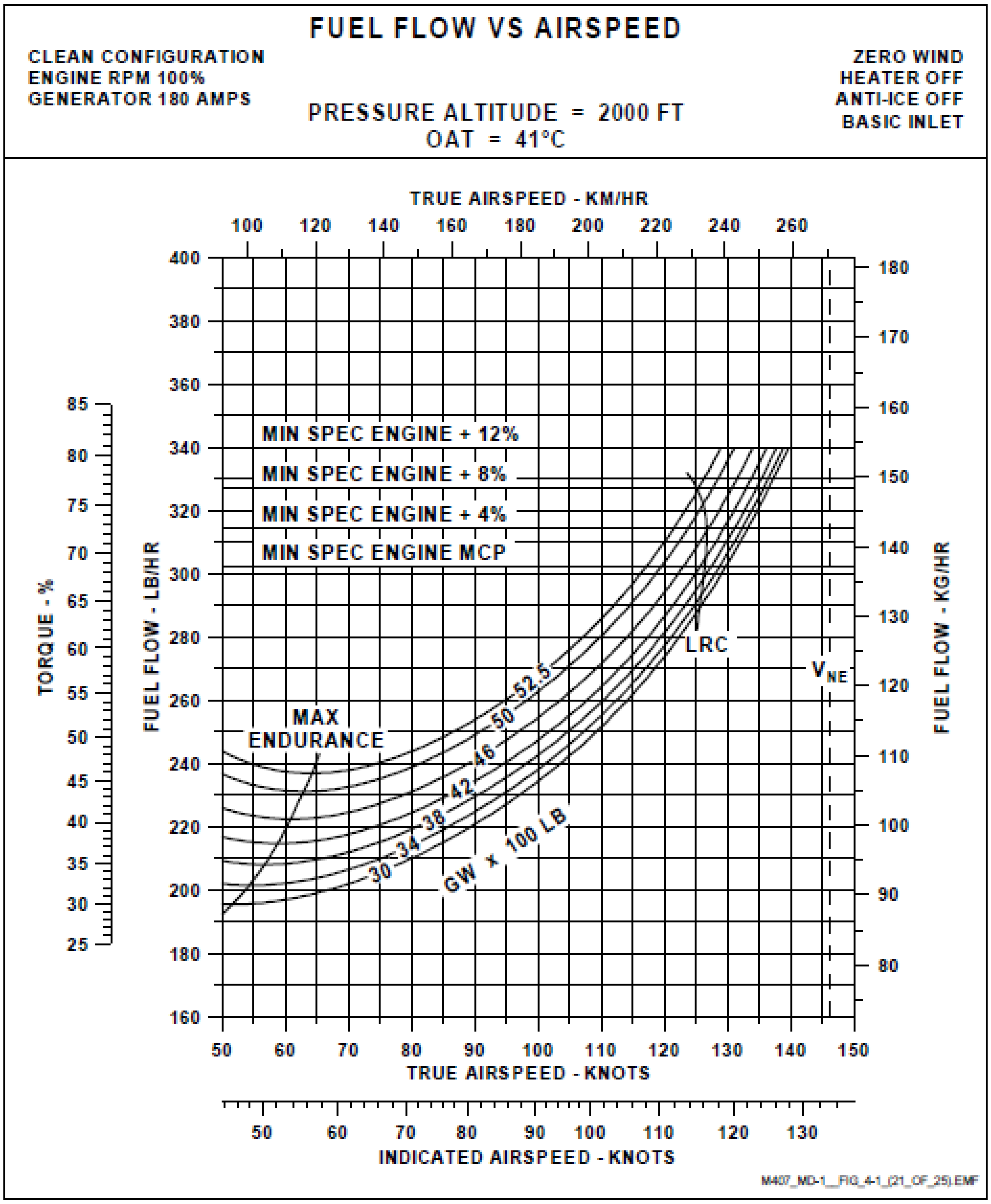


Figure 38: Bell 407 fuel flow for 2000 FT - 41°C(3)

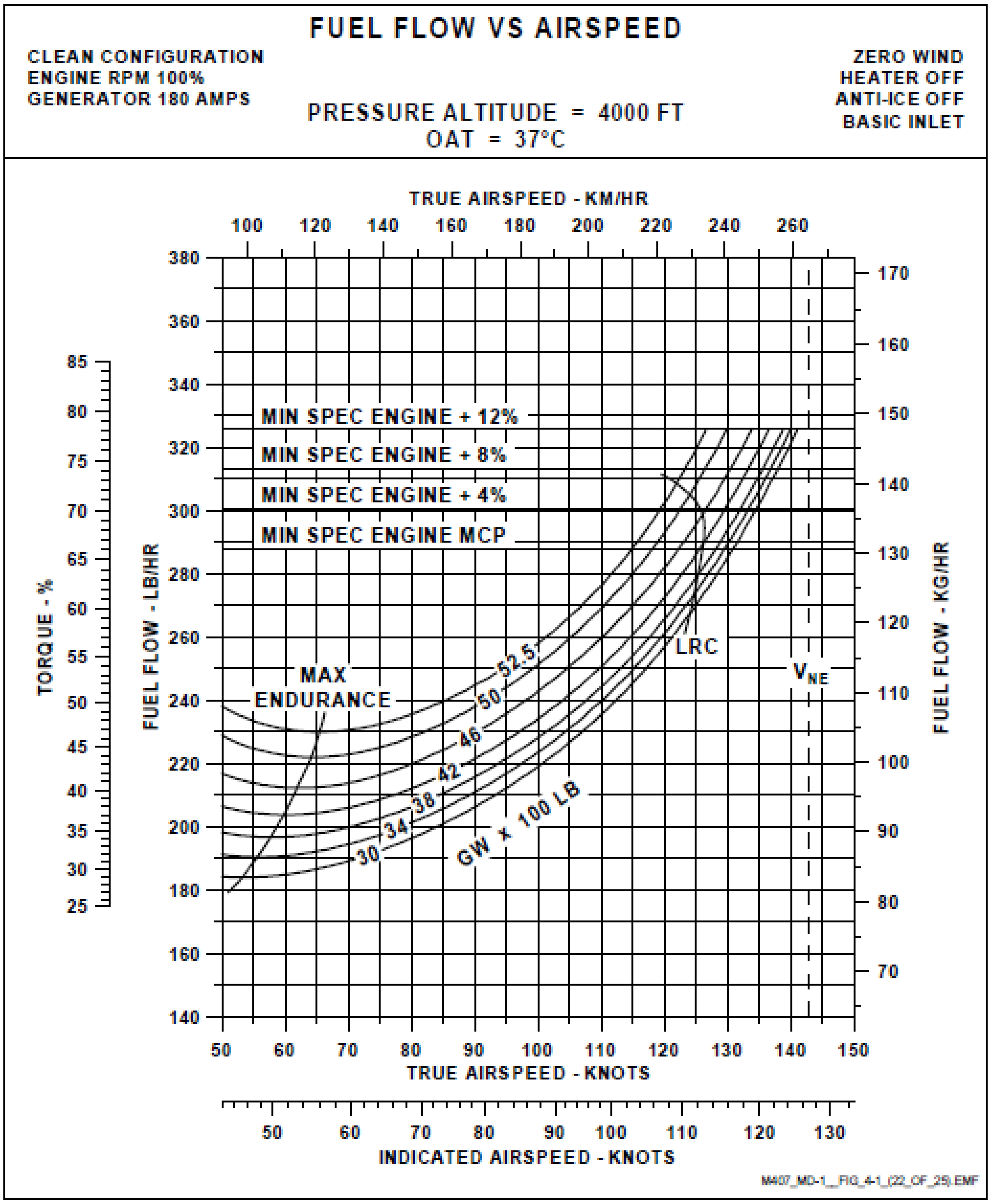


Figure 39: Bell 407 fuel flow 4000 FT - 37°C(3)

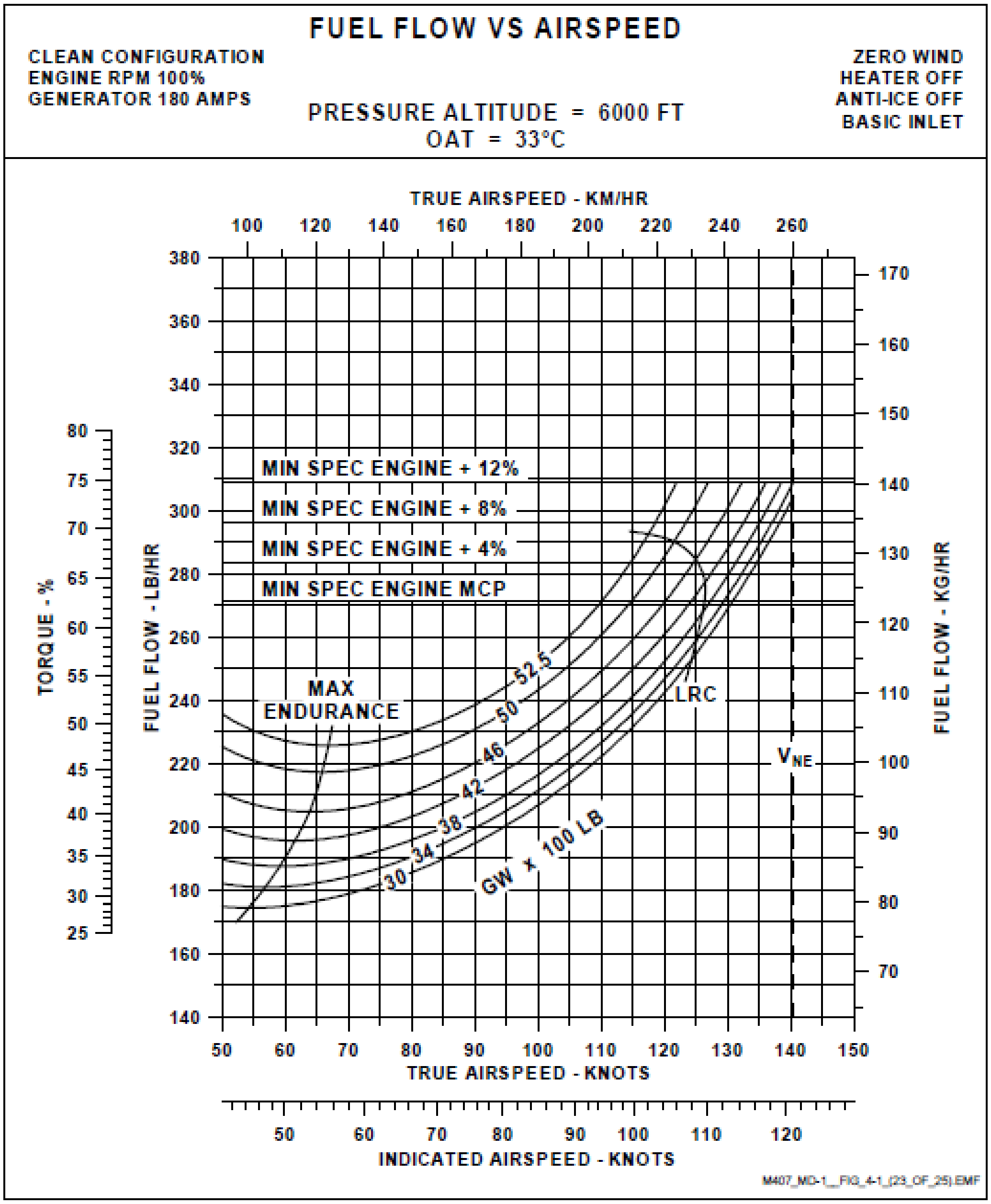


Figure 40: Bell 407 fuel flow for 6000 FT - 33°C(3)

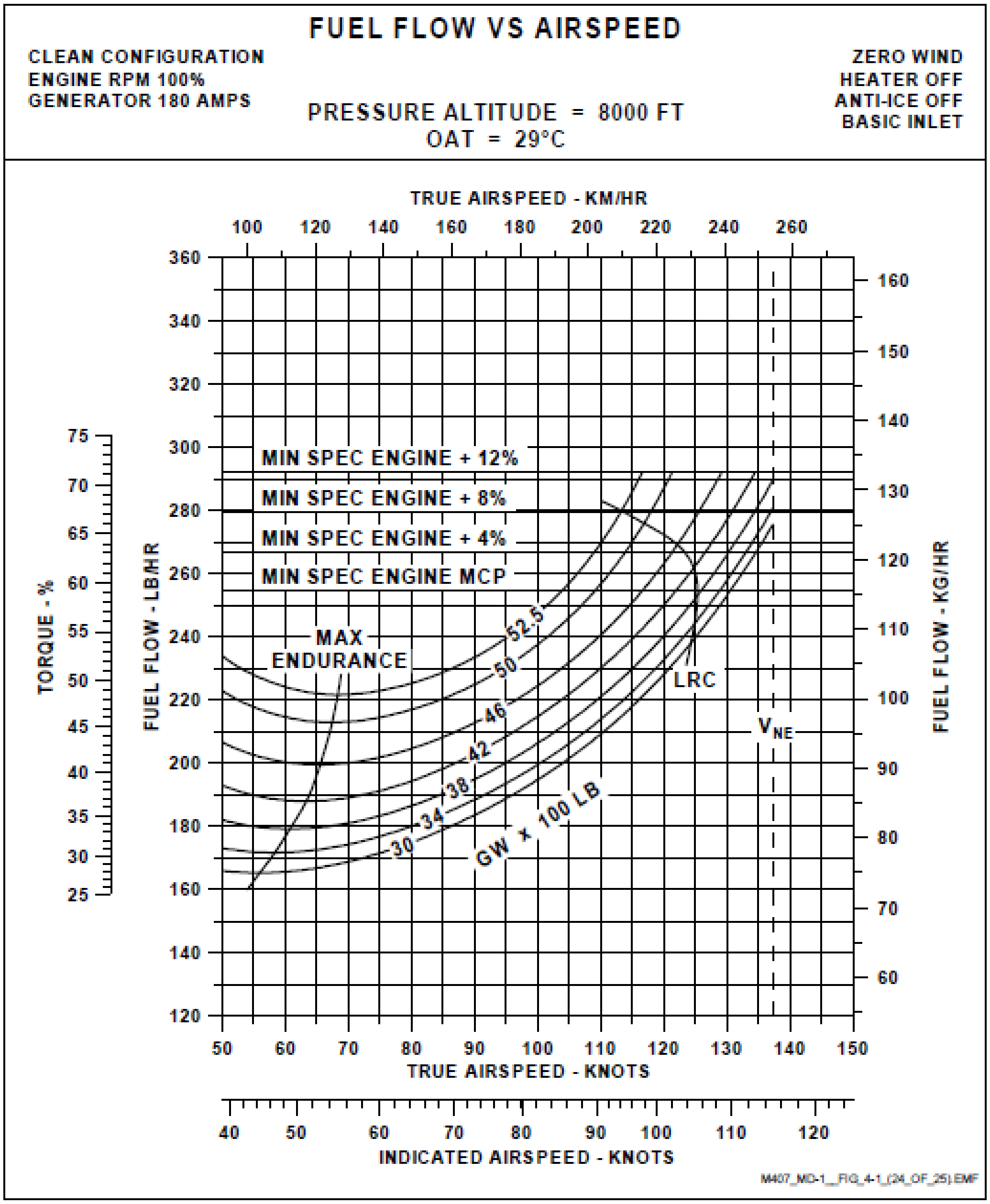


Figure 41: Bell 407 fuel flow for 8000 FT - 29°C(3)

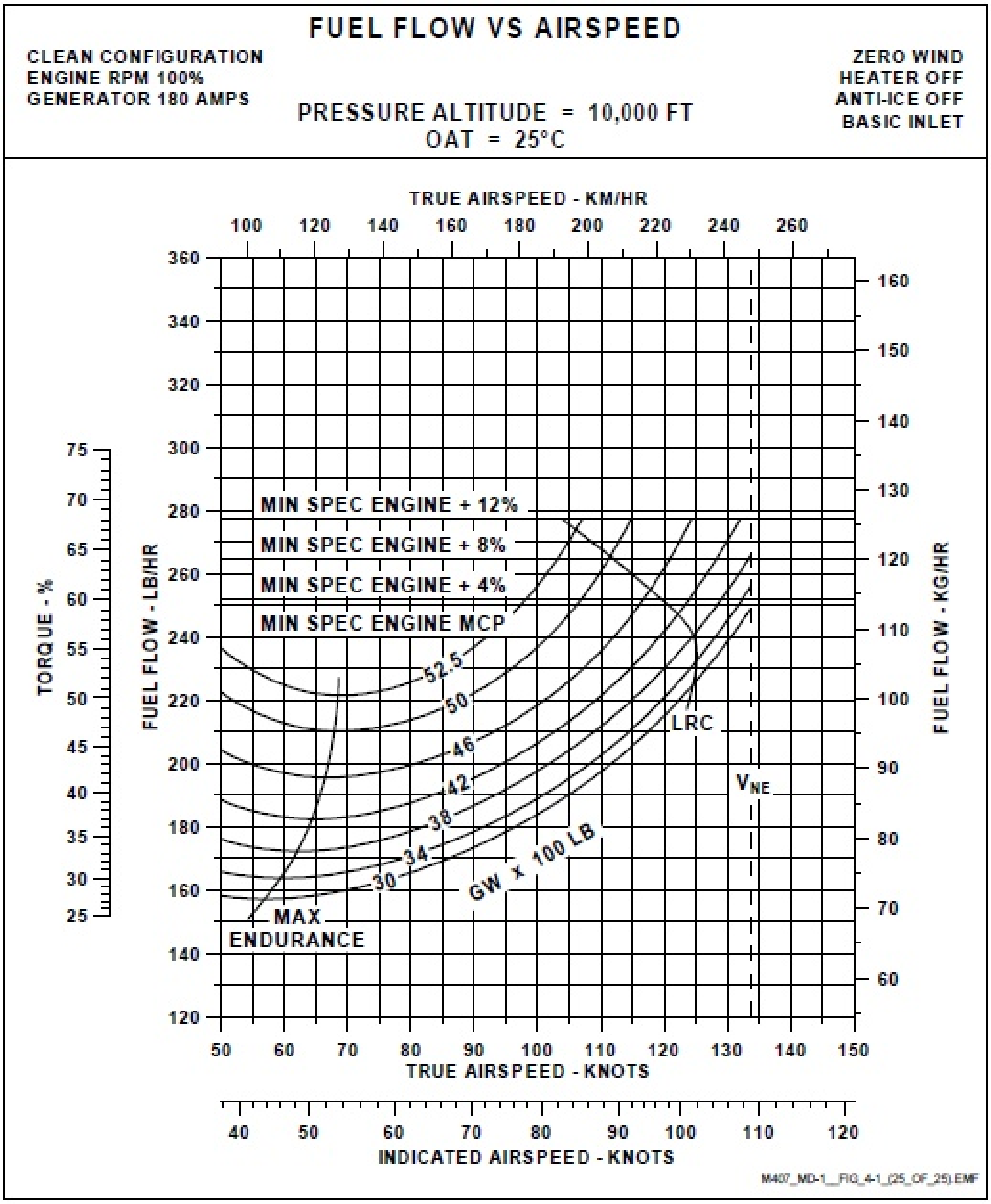


Figure 42: Bell 407 fuel flow for 10,000 FT - 25°C(3)

Appendix A4 Constants k_2 and k_3 for method 2

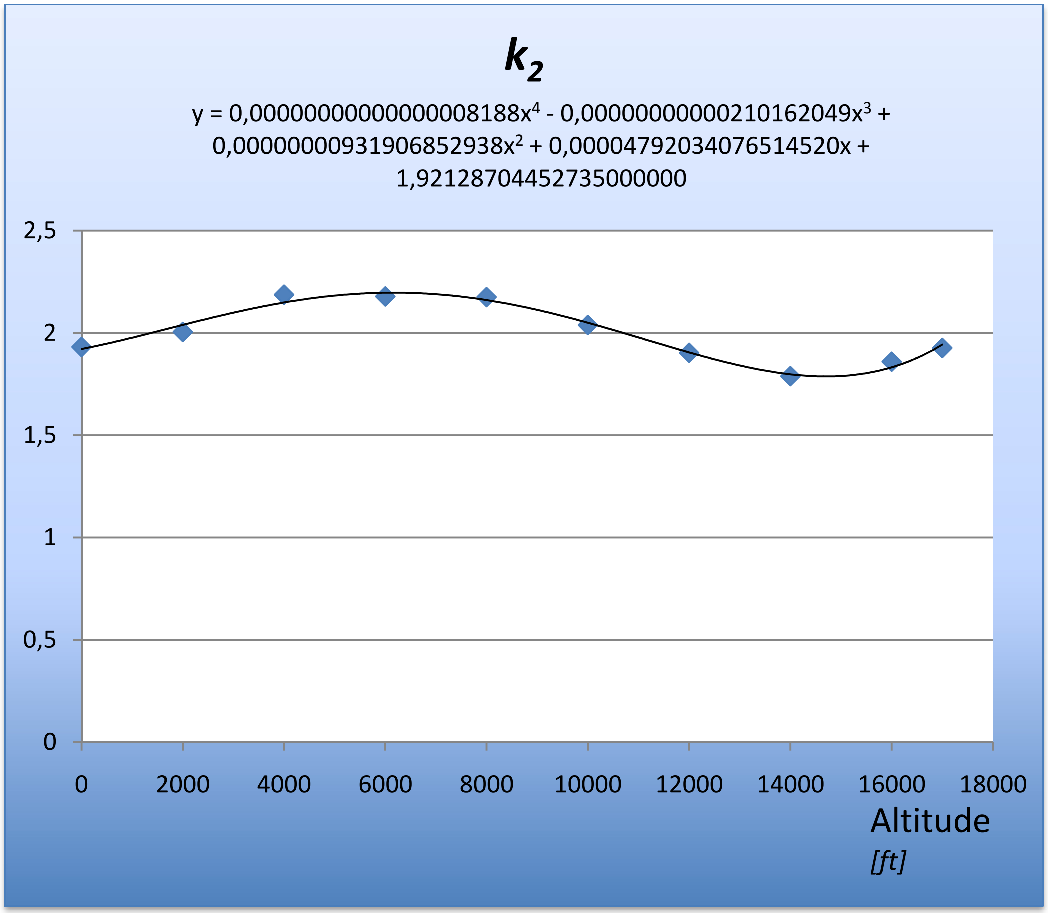


Figure 43: Constant k_2 as function of altitude

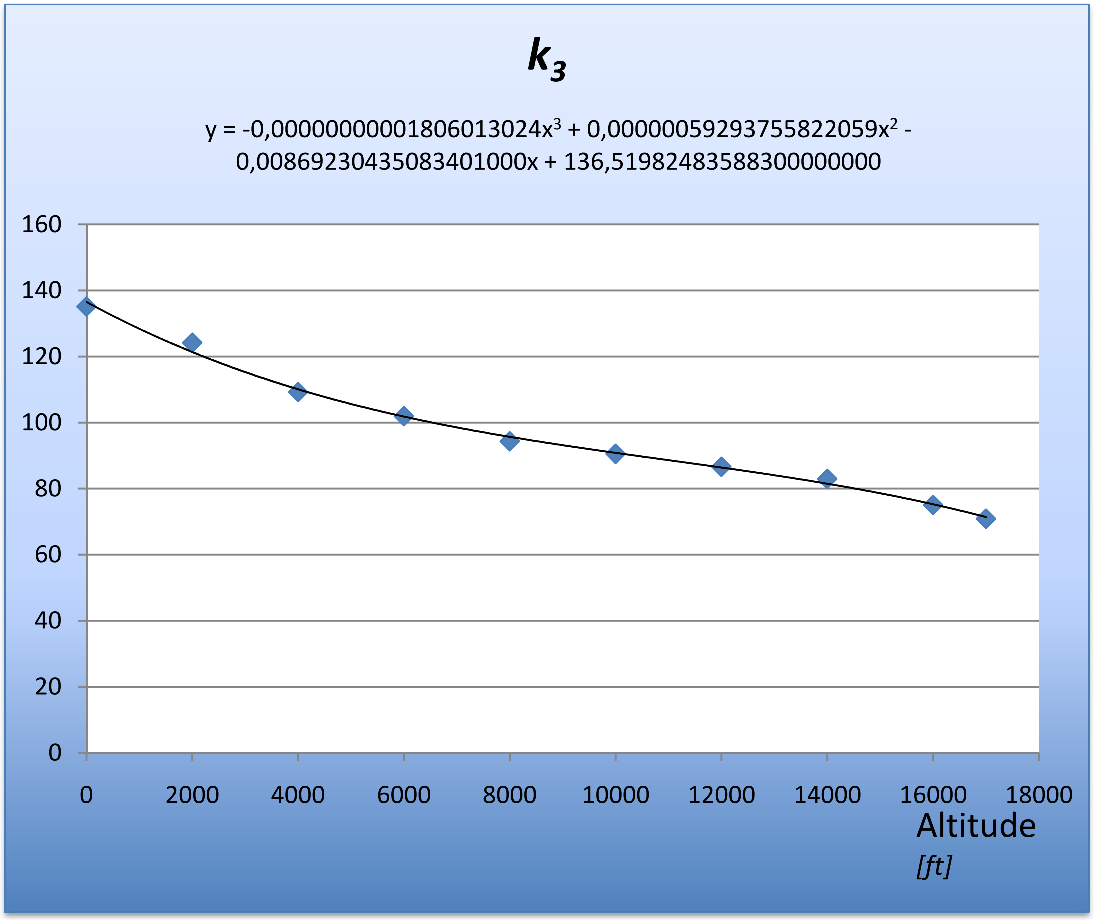


Figure 44: Constant k_3 as function of altitude

Appendix A5 Constants k_2 and k_3 for method 3

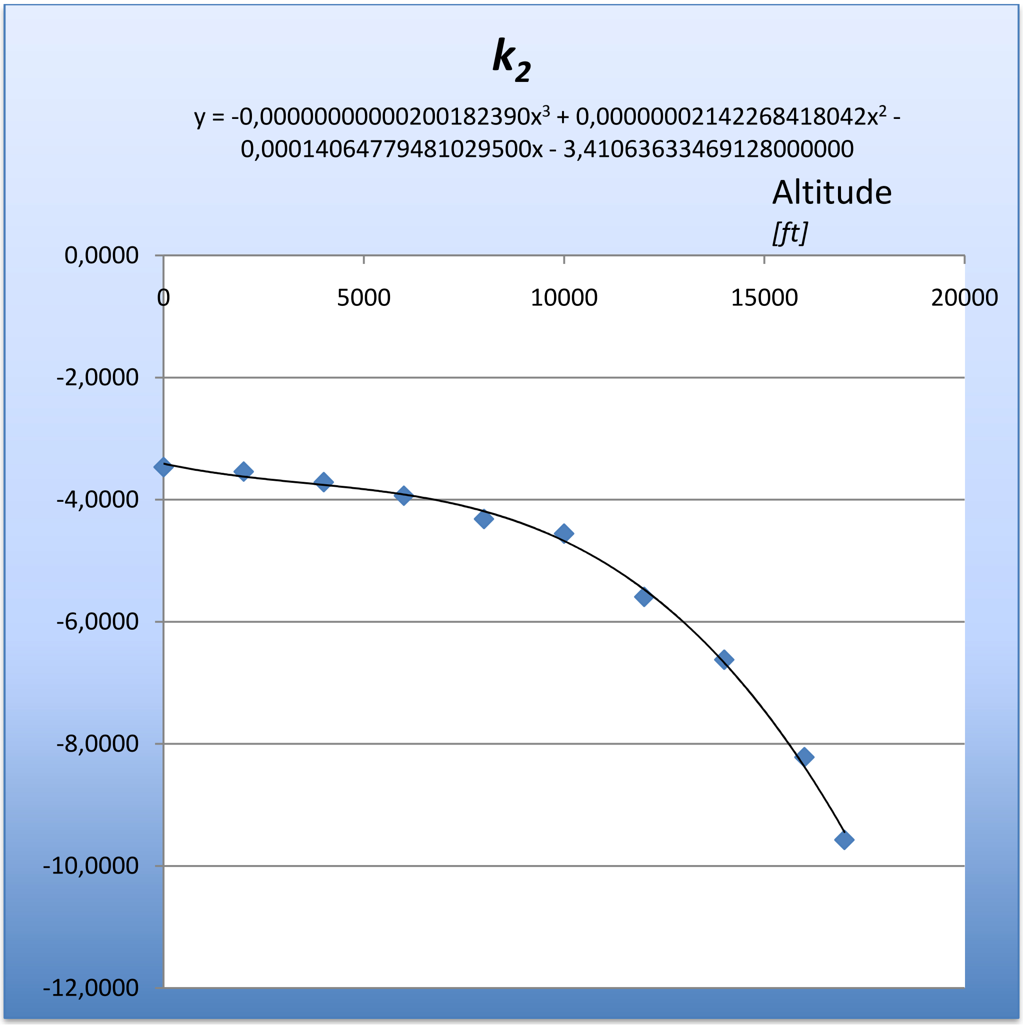


Figure 45: Constant k_2 as function of altitude

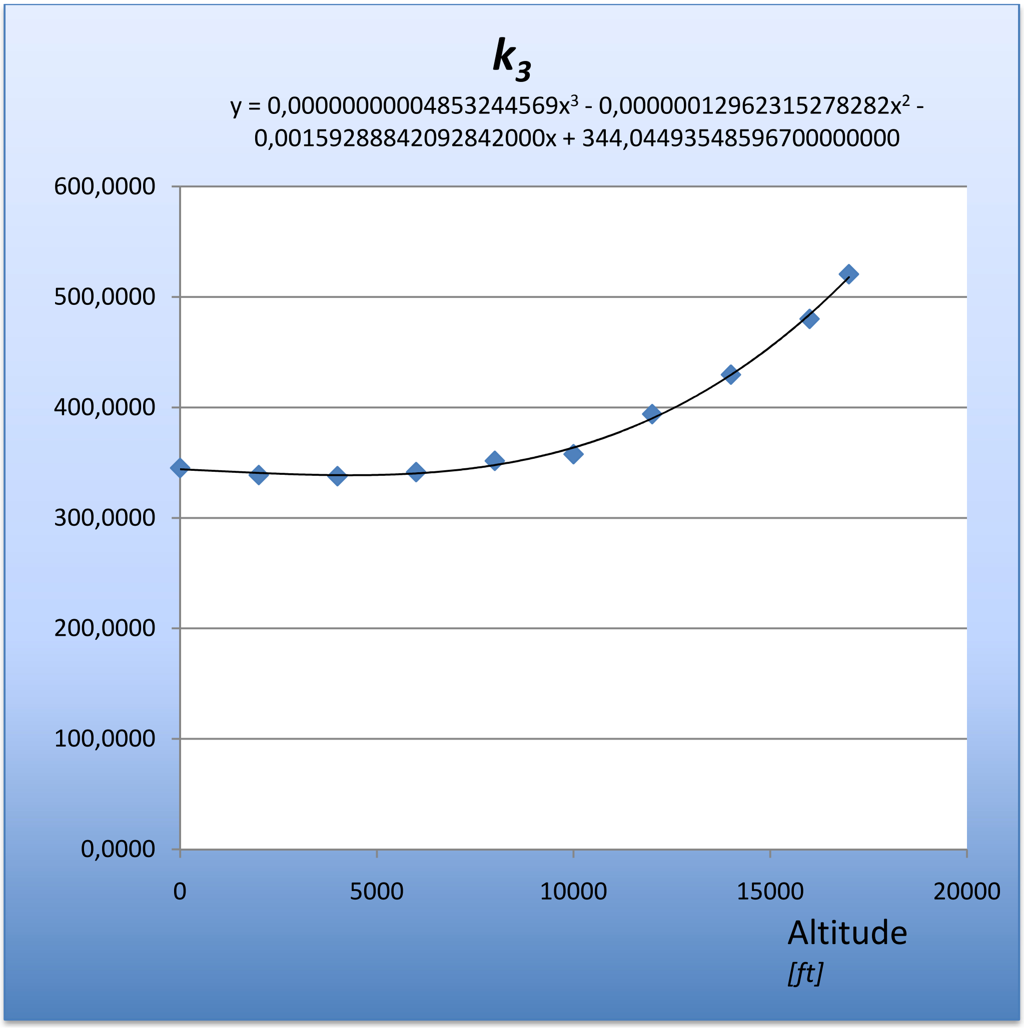


Figure 46: Constant k_3 as function of altitude