**МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ**
**НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ**
**АЕРОКОСМІЧНИЙ ФАКУЛЬТЕТ**
**КАФЕДРА ПІДТРИМАННЯ ЛЬОТНОЇ ПРИДАТНОСТІ ПОВІТРЯНИХ СУДЕН**

**ДОПУСТИТИ ДО ЗАХИСТУ**
Завідувач кафедри
к.т.н., доц.
_______________ О. В. Попов
“____” _______________ 2020 р.

# ДИПЛОМНА РОБОТА
# (ПОЯСНЮВАЛЬНА ЗАПИСКА)

ВИПУСКНИКА ОСВІТНЬОГО СТУПЕНЯ МАГІСТРА

ЗА ОСВІТНЬО-ПРОФЕСІЙНОЮ ПРОГРАМОЮ
«ТЕХНІЧНЕ ОБСЛУГОВУВАННЯ ТА РЕМОНТ ПОВІТРЯНИХ СУДЕН І АВІАДВИГУНІВ»

## Тема: «Методологічні основи підтримання експлуатаційної надійності паливної системи дальномагістрального пасажирського літака з двома турбореактивними двигунами»

**Виконав:** ____________________ О.М. Палагеша

**Керівник:**
Канд. техн. наук, доц. ____________________ О. В. Ругайн

**Консультант з охорони праці:**
Канд. техн. наук, доц . ____________________ О.В. Коновалова

**Консультант з охорони навколишнього середовища:** ____________________ М.М. Радомська
Канд. техн., наук, доц.

**Нормоконтролер** ____________________ Ю.І. Смірнов

**Київ 2020**

# MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

## NATIONAL AVIATION UNIVERSITY

## AIRSPACE FACULTY

## AIRCRAFT AIRWORTHINESS RETAINING DEPARTMENT

**ADMIT TO DEFENCE**
Head of the Department
Ph. D., associate professor
___________ O.V. Popov
«____» __________ 2020

# MASTER DEGREE THESIS

# (EXPLANATORY NOTE)

GRADUATE OF EDUCATIONAL DEGREE "MASTER"

FOR EDUCATIONAL AND PROFESSIONAL PROGRAMS "MAINTENANCE AND REPAIR OF AIRCRAFT AND AIRCRAFT ENGINES»

## Topic: «Methodological bases for maintaining the operational reliability of the fuel system of a long-haul passenger aircraft with two turbojet engines»

**Fulfilled by:** ____________ O.M. Palahesha

**Supervisor:**
Ph.D. in Engineering Science, Assoc. Prof. _____________ O.V. Rugain

**Labour precaution advisor:**
Ph.D. in Engineering Science, Assoc. Prof. _____________ O.V. Konovalova

**Environmental protection advisor:**
Ph.D. in Engineering Science, Assoc. Prof. _____________ M.M. Radomska

**Standards Inspector**
Ph.D. in Engineering Science, Assoc. Prof. ______________ Y.I. Smirnov

**Kyiv 2020**

## NATIONAL AVIATION UNIVERSITY

Educational and Research Aerospace Institute
Aircraft Airworthiness Retaining Department
Educational Degree "Master"
Specialty 272 “Aircraft maintenance”
Educational and professional programs "Maintenance and repair of aircraft and aircraft engines»

**APPROVED BY**

Head of the Department
_____________ O.V. Popov
«____» _____________2020

## Graduation Project Assignment

## Student’s name: *Palahesha Oleksii Mykolayovych*

1. Work theme: “**Methodological bases for maintaining the operational reliability of the fuel system of a long-haul passenger aircraft with two turbojet engines**” approved approved by the Rector’s order of “_02_ ”___10___2020 №_1881/CT.

2. The Graduation Project to be performed between:____ 15.09.2020______and_____17.12.2020_____

3. Initial data for work execution: analysis of the fuel system structure on the example of Boeing-777 and maintenance procedures according to aircraft maintenance manual and Maintenance programme of Ukraine International Airlines, operational statistics of aircraft failures and malfunctions of fuel system during all service life of the airplane, regulatory and design documentation, representation of digital twin technology in the aviation industry and my own example of executing digital twin sensors on Boeing-777 with defined data, operational description, peculiarities, structural features and components, principles of work and mathematical model of the detectors.

4. Content of explanatory note: detailed explanation how to implement new methods for maintaining the operational reliability of the fuel system of a long-haul passenger aircraft with two turbojet engines during maintenance procedures worldwide, to develop measures

how to protect labor and the environment, to decrease the maintenance cost, time and definitely to increase operational reliability and efficiency of the airplane.

5. List of required illustrated material: data and statistics of components or fuel system failure or malfunction during all service life (poster), general overview of digital twin technology (poster), structural scheme of the fuel system of Boeing-777 (poster), example of the digital twin sensor measurement cycle (poster).

6. Calendar plan:

| Stages of Graduation Project Completion | Stages Completion Dates | Remarks |
|---|---|---|
| Task receiving, processing of statistical data, acquaintance with the necessary material, operational documents of the operator, manuals and literature | 14.05.2020 – 15.06.2020 | Done |
| General analysis of composite and fiber optic digital twin sensors | 17.06.2020 – 02.09.2020 | Done |
| Calculation of digital twin sensor measurement cycle | 03.09.2020 – 25.09.2020 | Done |
| Conducting necessary corrections in calculations | 25.09.2020 – 28.09.2020 | Done |
| Implementation of digital twin sensors using due to all regulatory technical documents, maintenance manuals and referring to statistical data on the fuel system failure or malfunction | 29.09.2020 – 07.11.2020 | Done |
| Completion of the explanation note | 08.11.2020 – 10.12.2020 | Done |
| Preliminary report | 14.12.2020 – 17.12.2020 | Done |

7. Advisers on individual sections of the work (Thesis):

| Section | Adviser | Date, Signature | |
|---|---|---|---|
| | | Assignment Delivered | Assignment Accepted |
| Labour precaution | O.V. Konovalova | | |
| Environmental protection | M.M. Radomska | | |

8. Assignment issue date «____» _____________2020.

Supervisor of diploma work ___________ O.V. Rugayn
(signature) (Name, Surname)

Task for execution is given for ___________ O.M. Palahesha
(signature) (Name, Surname)

# ABSTRACT

Explanatory note for diploma work named as “Methodological bases for maintaining the operational reliability of the fuel system of a long-haul passenger aircraft with two turbojet engines”:

00 pages, 00 figures, 00 tables, 00 references

Object of study – is optimal method of maintaining the operational reliability of the fuel system of a long-range aircraft with two turbojet engines and its components.

Subject of study – fuel system of Boeing-777 and it’s maintenance methods.

The purpose of the work – to increase the operational reliability and improve some maintenance procedures of the fuel system of chosen aircraft with the implementation of modern technology.

Research method – analytical processing of all regulatory, technical documents, maintenance manuals, Maintenance programme of the operator and statistical data on fuel system failure or malfunction with reported conclusions from national transportation safety board.

The Practical meaning of diploma work results is determined by evaluating the reliability of Boeing-777 fuel system increase, enhancement of some maintenance procedure and technical operation efficiency rise.

Scientific novelty – the main idea is to propose using of digital twin sensors additionally to aircraft communication addressing and reporting system (ACARS) where it will enhance operational reliability and decrease the maintenance cost of the airplane.

Materials of diploma work are recommended to use during study process and practical activity of design bureau specialists.

**FUEL SYSTEM, COMPONENT RELIABILITY, DIGITAL TWIN TECHNOLOGY, DIGITAL TWIN SENSORS, REGULATORY DOCUMENTS, MAINTENANCE MANUAL, OPERATION EFFICIENCY, ACARS.**

# CONTENTS

# LIST OF ACCEPTED ABBREVIATIONS, SYMBOLS, UNITS, AND TERMS

AC – aircraft;
DTS – digital twin sensor(-s);
DTT – digital twin technology;
ICAO – International Civil Aviation Organization;
MP – Maintenance programme;
SAA – State Aviation Administration;
APU – auxiliary power unit;
ACARS – aircraft communication addressing and reporting system;
MEL – minimum equipment list;
NTSB – National Transportation Safety Board;
NA – not accessible;
AE – adverse event(-s);
ECS – engine control system;
O/J – override/jettison pumps;
FOHE – fuel/oil heat exchanger;
FMU – fuel metering unit;
EICAS – engine indication and crew alerting system;
FMC – flight management computer;
FDR – flight data recorder;
CDU – control display unit;
CVR – cockpit voice recorder;
QAR – quick access recorder;
FQIS – fuel quantity indication system;
ACMF – aircraft condition monitoring function;
EHM – engine health monitoring;
APM – aircraft performance monitoring;

EASA – European Union Aviation Safety Agency;
FAA – Federal Aviation Administration;
AMM – aircraft maintenance manual;
ELMS – electrical load management system;
AI – artificial intelligence;
FBG – fiber bragg grating;
OSA – optical spectrum analyser;
AWG – arrayed waveguide grating;
WDM – wavelength division multiplexing;
EDG – Echelle diffractive grating;
PIC – photonic integrated circuit;
AE – acoustic emission;

$R(t)$ – reliability;
$t$ – continuous operating hours/cycles between diagnostics;
$\varphi(t)$ – constant failure rate;
$e$ – exponential function;
$Q(t)$ – probability of failure;
$S_i$ – possible state of aircraft;
$\eta$ – degree of adverse factors;
$K_\mathrm{d}$ – laboriousness coefficient;
$\lambda(t)$ – failure rate;
$H_\mathrm{y}$ – differential pressure on the seal;
$\mu$ – coefficient of slot seal flow;
$Q$ – fluid leakage;
$T_\mathrm{m}$ – coefficient of variation;
$\mathrm{h}_\mathrm{g}$ – the efficiency of the boos pump.

# INTRODUCTION

The serviceable systems of each wide-range aircraft are an indivisible part of airplane normal operating conditions. The reliability and durability of main elements or separate units is the general task of the maintenance department of any airline or one or another operator. Normally, each modern company or operator has own Maintenance programme (MP), methods, instructions, technologies and procedures which are distinctly approved according to manufacturer's regulatory documents and consequently due to International Civil Aviation Organization (ICAO) or State Aviation Administration (SAA) requirements.

To meet the needs of passengers and cargo transportation without increasing fleet of aircraft required to use modern scientific and technological progress in the field of aviation, to find out new approaches how to maintain the necessary level of profitability and adaptation all present operations  according to rigid rules of aviation industry . This means you need as widely as possible to implement various improvements leading to increased performance, efficiency and safety.

My diploma work is dedicated to studying the fuel system of a long-haul passenger aircraft (AC) with two turbojet engines (on the example of Boeing-777) and investigates new methodological bases to increase the operational reliability of it.

Fuel systems of modern AC are a complex set of interrelated subsystems. A variety of functional and structural connections require appropriate maintenance and defined manufacturer's safety margin during any AC operation. This is achieved by rapid growth of the aviation industry (before the COVID-19 quarantine), technologies, appropriate competition between aircraft manufactures all around the world, including Boeing company and Airbus, eternal wishes of designers to reveal new trends and new solutions in aircraft manufacturing.

The main task of any fuel system in any airplane, starting from general aviation and ending with huge Antonov 225 is to supply jet engines with the necessary quantity of aviation fuel continuously and safely without any malfunction or even failure. Furthermore, the fuel system is designed for placement on aircraft fuel and uninterrupted fuel supply to the aircraft engines, auxiliary power unit (APU). Also on some AC, fuel is used to cool the oil, air conditioning systems, electronic equipment and AC weight balancing, etc.

As well as a working fluid in a variety of automatic devices (control jet nozzle and leaf blades input guiding device). To obtain such level of operational reliability is very complicated task, so manufacturer, operator, and technical personnel have to strictly follow all regulations, maintenance procedures, documents and AC manuals during any types of maintenance works including fuel system. So, it is really important to maintain all elements and aggregates in airworthiness condition. Moreover, the operator has to have relevant and efficient maintenance department. Finally, the problem of new methodological bases for maintaining the operational reliability of the fuel system is very important.

The development of scientific and technological progress in civil aviation sets targets to further improvement of safety and reliability of AC. As was mentioned before the development of scientific and technological progress in civil aviation sets targets for further improvement of safety and reliability of AC. Hence, this development needs involving of new solutions which can propose something new, more practicable or flexible due to tasks of the present day.

All in all, if the operator will be possible to monitor all data, condition and any failures of fuel system and its components continuously via satellites with implementation of digital twin technology (DTT) it will definitely increase operational reliability.

In this diploma I would like to propose the implementation of DTT with digital twin sensors (DTS) on the example of Boeing-777 based on the results of the analysis of reliability of the units of the fuel system, statistical data about their failure, maintenance manuals, technical documentation, procedures, and malfunctions.

Realization of DTT will definitely increase the operational reliability, safety margin and to find out new methodological bases during maintenance works. All in all, it helps to reduce maintenance cost, time, and improve efficiency of the maintenance department of any airline.

# CHAPTER 1: ANALYSIS OF THE RELIABILITY OF THE FUEL SYSTEM OF BOEING-777 AND ITS COMPONENTS

## 1.1 General estimation of operational reliability of the fuel system

The main purpose of carrying out an assessment of the operational reliability of the fuel system is to determine the conformity of their level of reliability with the requirements of airworthiness standards.

Due to the definition of reliability is: “The ability of an apparatus, machine, or system to consistently perform its intended or required function or mission, on demand and without degradation or failure.” To contain the threats and improve the index of operational reliability, actions may be undertaken from the early design phase of the system, to its use phase. The safety assessment of any aircraft and its components is mandatory at the design phase for certification purpose and recommended processes and methods have been given for its achievement. Simply stated, the certification period is aimed to verify the airworthiness condition of AC in complex and fulfilment of safety and operational requirements. Due to the particular complexity of the fuel system it is necessary to consider the components interaction, maintenance procedures and analyze the failure propagation referring on some real accidents reports during the Boeing 777 operation which are directly connected with fuel system malfunction. In addition to this is very important to study how exactly the maintenance of the fuel system is provided according to all regulatory technical documents and highlight all advantages and disadvantages for minimizing any faults or failures.

To cover fuel system operational reliability issues, one has to identify the relevant types of information involved in the aircraft operability. I would like to consider design phase information together with the necessary data during the service. During the aircraft design phase, model-based safety analysis are conducted for the verification of the compliance with safety requirements and the establishment of Master minimum equipment list (MEL). However, for an operational reliability evaluation all the functional conditions that may be required during the different phases of the missions must be taken into account in the model.

So, let us consider some main requirements for the fuel system of Boeing-777:

- fuel system of long-range passenger aircraft has to perform constant fuel supply with the consumption not less than 100% necessary for aircraft engines during any operational settings;
- the fuel has to be delivered to engines under constant pressure and temperature, which are specified in engine certificate;
- each main fuel pump has to provide a normal operating mode during different stages of flight whilst emergency pumps have to be operative and suitable during any malfunction or emergency situation;
- pipelines have to be rigid and properly fixed to avoid any vibration and sustain structural loads from fuel pressure in expected conditions of flight;
- fuel has to freely streamed through the fuel flow meters or cross-feed valves;
- fuel filters have to be available for sump drain and possess quick release units;
- to meet the highest level of fuel flow capacity (including engine operating restrictions);
- to be reliable and properly checked

As we can see in this short list of the main requirements are obligatory for every Boeing-777 in service.

The next step of our reliability assessment will be the real data, reasons and National Transportation Safety Board (NTSB) agency reports of all Boeing-777 accidents which anyhow connected with the fuel system. Nowadays, has produced 1646 units of Boeing-777 in different configurations and producing is still going. Beginning of commercial operation was in 1995, first flight was conducted in 1994. It was first brainchild of the Boeing company with the implementation of new for that time fly-by-wire system.

As of October 2016 only 18 accidents were occurred. Four of them were directly connected with fuel system malfunction. For better understanding of the operational reliability it is also necessary to identify the main aggregates or units of the fuel system that were failed, according to issued NTSB reports to Table 1.1.

Table 1.1 – The main failures and malfunctions of the fuel system and aggregates of the Boeing-777

| Date of incident/origin-destination/operator | Involved aggregate(s) | Reason of failure or malfunction | Type of aircraft/power plant | Methods for eliminating |
|---|---|---|---|---|
| January 17, 2008/ZBAA-EGLL/British Airways | Heat exchanger | Ice crystal formation in pipelines | Boeing 777-236 ER/ Rolls-Royce Trent 895-17 | Heat exchanger was improved |
| 2008/Not accessible (NA)/ British Airways | Engines | Temporary loss of power during flight | Boeing 777/ Rolls-Royce Trent 895-17 | Heat exchanger was improved |
| 2008/N862DA/ Delta Airlines | Engines | Temporary loss of power during flight | Boeing 777/ Rolls-Royce Trent 895-17 | Heat exchanger was improved |
| September 5, 2001/KDEN-EGLL/British Airways | Refueling adapter | Ground fire during refueling | Boeing 777-236/GE-90 | New standards and practices were examined |

Briefly having analyzed all this data, we can see that less than in 25% cases fuel system of Boeing-777 in different modification was the reason of the incident. It tells us that structure and manufacturing have big safety margin, but anyway some cases were experienced and our task is to decrease or even avoid these malfunctions in the future. Now let's try to obtain some calculations with using this data.

Input data :

- Boeing-777 aircraft;
- NTSB reports, statistical data;
- Reliability $R(t)$: probability system still working since start of mission;
- $t$ – continuous operating hours/cycles between diagnostics;
- $\varphi(t)$ – constant failure rate (failures/hr);
- $e$ – exponential function;

The complete mathematical formula of operational reliability of any element or complex system assessment will be looking like:

$$R(t) = e^{-\varphi t} \tag{1.1}$$

$$R(t) = e^{-0.00007 \cdot 1251} = 0.87$$

In this equation, we can see that our reliability value is 0.87 ( a calculation was made on the example of flight from Beijing to London ). Normally, when airline starts to operate new AC the reliability value of system or any element is about 1. We can observe this real tendency shown in failure rate graphics (figure 1.1). Nonetheless, it tells us that Boeing-777 is very reliable and well-designed AC.

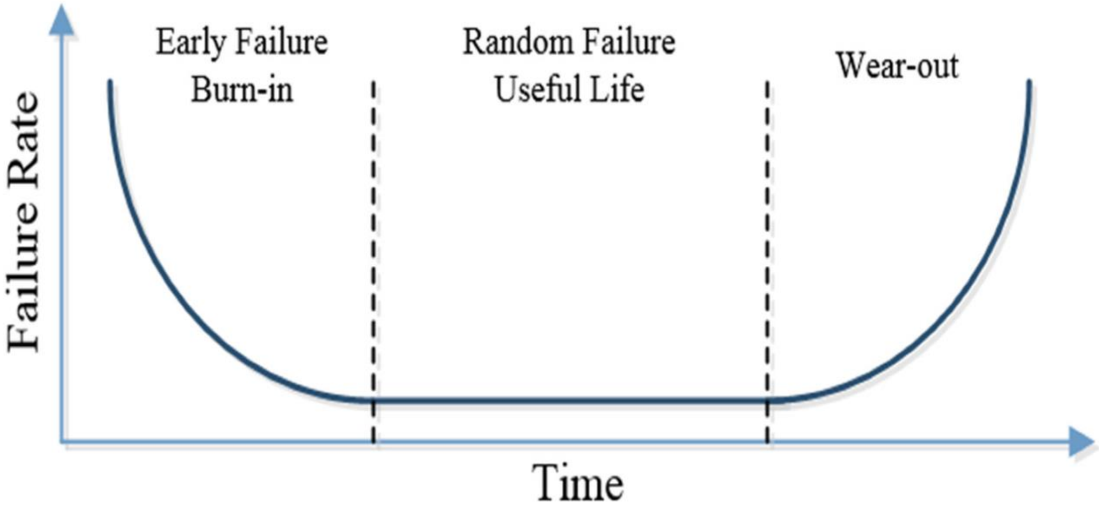


Figure 1.1 – Failure rate graphics of any element and system

However, to finalize the assessment of operational reliability of fuel system and its units of our AC it is necessary to take into account outer conditions which definitely have direct influence to our AC. These conditions we can determine like:

- the probable occurrence of complications of flight conditions ($R_1$) $Q_1 \cdot 10^{-3}$: 2,93; 4,5; 7,9; 4,1;
- the occurrence of a difficult flight situation ($R_2$) $Q_1 \cdot 10^{-4}$: 3,2; 4,84; 7,87; 4,05;
- occurrence of an emergency flight situation ($R_3$) $Q_1 \cdot 10^{-6}$: 3,1; 4,87; 8,1; 3,7.

So, it may be possible to make a first small conclusion that an indicator of operational reliability is the probability of occurrence of a special situation in flight, with the appearance of a specific functional failure taking into account another outer factors. Comparison of calculated probabilities of functional failures that cause the emergence of special flight situations with normalized, allows to evaluate the perfection of the structure and, if necessary, to make a constructive enhancement of the elements or improvements in maintenance procedure.

The fuel system of Boeing-777 consists of tanks, pipelines, aggregates, heat exchangers, fuel meters, cross-feed valves, pumps, fuel nozzles any other devices and provides fuel filling, its placement, feed to the engines, as well as a measurement of the amount and fuel consumption. The basic scheme of the fuel system of the Boeing-777 with its structural components is shown in Figure 1.2.

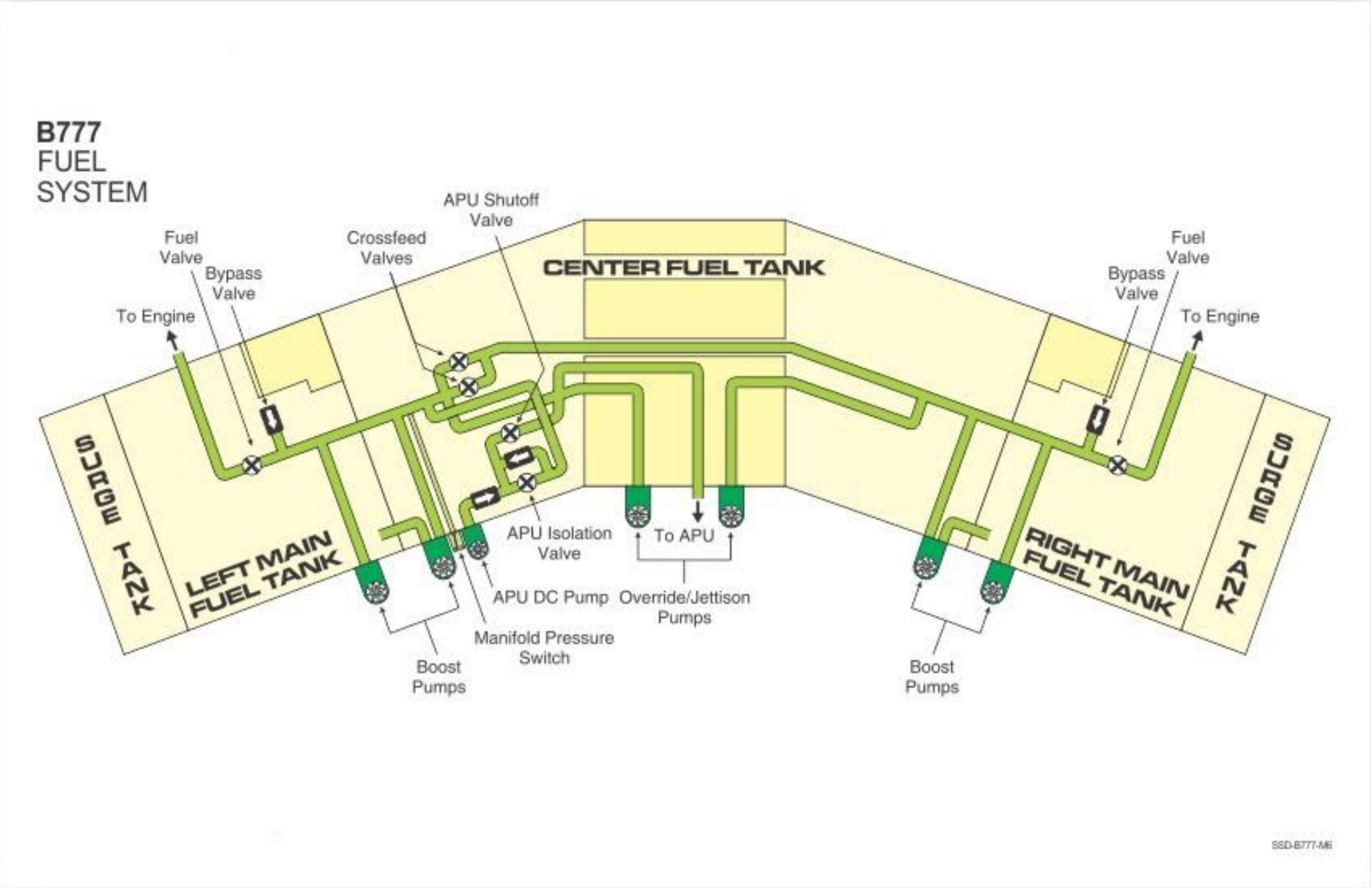


Figure 1.2 – Basic scheme of the fuel system of the Boeing-777

All in all, initial assessment of operational reliability of the fuel system of our AC tells us that Boeing-777 fairly reliable airplane. Nonetheless, in 20% of all 18 cases failures and malfunctions were taken place during all servicing history of this AC on routes. It is necessary to emphasize that despite of modern ACARS already present in the Boeing-777, implementation of DTT and development of new approaches for maintenance procedures are still actual. As a result of the analysis, preliminary conclusions can be drawn about the possibility of changing the periodicity of maintenance of units and even systems, and in some cases, to determine the main directions of operational and theoretical studies for increasing the reliability of products.

### 1.2 Quantitative assessment of the relationship between the disruption of the system's operability and an emergency situation during any phase of flight for the Boeing-777

As was mentioned before any AC is very complex mechanism which has to be reliable as much as it possible and provides the maximum level of operation efficiency, operability with a moderate involving of material resources. It is well known, that on modern AC, many auxiliary and basic systems ensure appropriate functioning of various consumers what is vitally important. Moreover, this functioning has to be very constant despite of many factors which have own negative influence during airplane operation.

Due to ICAO statements and issued materials abnormal situations in flight arise when an aircraft in normal flight mode is exposed to one or more adverse factors. Therefore, such situations have a pronounced random nature. To assess the degree of danger of contingencies, it is convenient to use the Airworthiness Standards governing the list of situations and probability of their occurrence in flight. The degree of danger can be determined from the assumption that during the life of the aircraft each of the four contingencies will give the same level of risk. By combining all contingency situations with their normalized indicators and using this assumption, we can quantitatively determine their degree of danger (risk level) in the form of probabilistic indicators.

In flight, the aircraft is affected by a large number of adverse factors. The evolution of an adverse event (AE) in flight is associated with a combination of several factors that exponentially complicate the situation. So, almost all events in air transport result from exposure of aircraft to AE in flight which have very contributing influence, namely:

- Aviation accidents with human casualties (disaster (D));
- Accidents without casualties (accident (A));
- Serious aviation incidents (there was a real safety risk);
- Aviation incidents (there was a potential safety hazard).

The factors that eventually lead to an accident are related to crew activities human factor, functional efficiency of the aircraft technical factor and environmental conditions environmental factors. Thus, an AE for the most part is a complex event serving as the last element in a chain of sequential events with cause-effect relationships.

Tracing the sequence of adverse event development, we can distinguish from the very beginning the following categories of causes, namely: main, immediate and concomitant. The main one creates a potential opportunity for the emergence of AE in a certain situation. Moreover, immediate and concomitant causes create real conditions for turning such an undesirable opportunity into reality. Thus, the immediate cause is the one that entails AE with a big probability. As was mentioned before, abnormal situations in flight arise when an aircraft in normal flight mode is exposed to one or more unfavourable factors (risk factors) what have unexpected negative influence to the flight . In the Airworthiness Standards, such situations are classified as special situations. Special flight situations are characterized by a combination of aircraft properties or performances and psycho-physiological indicators of crew members when such indicators differ from the normative ones and the flight mode definitely differs from the "regular" one. Simply stated, based on this defined concept during flight, five possible states or conditions of the aircraft can be distinguished. We denote them by $S_i$, where i = 0, 1, 2, 3, 4: Normal ("regular") Flight in the absence of risk factors – $S_0$; Complication of Flight Conditions – $S_1$; Dangerous Situation – $S_2$; Emergency – $S_3$; Catastrophic situation – $S_4$.

- $S_0$ is a "regular" situation when the flight is taking place under the expected operating conditions in the range of recommended flight modes;
- $S_1$ is a Complication of Flight Conditions – a "State of the aircraft in flight" characterized by a slight increase in the psychophysiological load on the crew

or a slight deterioration in the characteristics of stability and controllability or flight characteristics of the aircraft;

- $S_2$ is a Dangerous Situation – a "State of the aircraft in flight" characterized by a marked increase in the psycho-physiological load on the crew or a noticeable deterioration in flight characteristics, stability and controllability, as well as one or more flight parameters exceeding operational limits, but without reaching limiting restrictions and design conditions. A difficult or catastrophic situation in an emergency can be prevented by the timely and correct actions of crew members, including immediate changes to the flight plan, profile and flight mode;
- $S_3$ is an Emergency – a "State of the aircraft in flight" characterized by a significant increase in the psycho-physiological load on the crew, deterioration of flight performance, stability and controllability, and leading to the exceedance of limiting restrictions and design conditions. Prevention of an emergency leading to a catastrophic situation requires high professional skills of crew members;
- $S_4$ is a Catastrophic Situation – a "State of the aircraft in flight" which implies that deaths are almost unavoidable when it occurs.

As can be seen from the formulations, all normalized indicators of special situations are qualitative in nature and can be summarized in Table 1.2.

Table 1.2 – Normalized indicators of special situations in flight when exposed to AE (risk factors)

| Special situation | Signs | | | |
|---|---|---|---|---|
| | Change of psychophysiological load on the crew | Aircraft stability and control deterioration | Output of parameters with certain restrictions | Need to change profile, flight mode or schedule |
| Flight safety complications | Small | Small | – | – |

| | | | | |
|---|---|---|---|---|
| Difficult situation | Influent | Influent | Out of service restrictions output | – |
| Emergency situation | Significant | Significant | Outside of max. calculable limits | +++ |
| Catastrophic situation | Unparalleled | Prevention of human casualties is practically impossible | | |

The Airworthiness Standards also describe the possible frequency of these situations. Depending on the nature of the event under consideration, the following probability values relative to one hour of flight or one flight cycle are used as a quantitative (numerical) representation of the probabilities of occurrence of these situations as recurring situations:

- Repetitive > $10^{-3}$;
- Moderately likely – from $10^{-3}$ to $10^{-5}$;
- Unlikely – from $10^{-5}$ to $10^{-7}$;
- Very small possibility – from $10^{-7}$ to $10^{-9}$;
- Practically impossible – ≤ $10^{-9}$;

The given indicators are widely used in the certification of aviation equipment, investigation of aircraft accidents, as well as in various interpretations in scientific works. When a special situation is taking place, i.e. when there is no corresponding aircraft's reaction to the pilots' actions in their attempts to counteract the effects of the risk factor, one of the above-indicated adverse events occurs: an incident or an accident (figure.1.3).

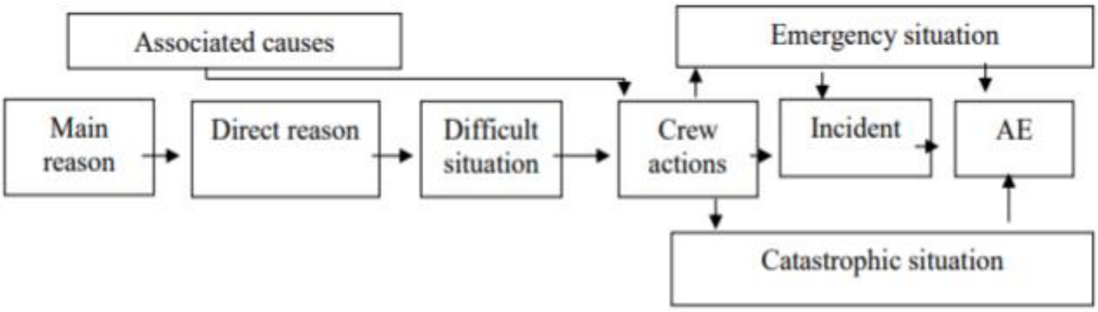


Figure 1.3 – Scheme of causes of the emergency and catastrophic situations

During the flight, the aircraft is exposed to various types of failures, malfunctions and damage disrupt the operation of aircraft systems and assemblies, as well as erroneous actions by the crew or adverse environmental influences. Critical failures are dangerous and can lead to an aviation accident or incident. For the flight crew, the elimination of the effects of such an adverse factors exposure is associated with the performance of complex activities under conditions of high emotional stress and time pressure. These include the failure of ECS (engine control systems), fuel system assemblies and other important aircraft units and systems, wind shear, thunderstorms; gross mistakes by the crew, etc. The degree of danger of such failures can be described by the expression $0 \ll \eta < 1$ (figure 1.4). Such failure can lead to flight mode interference, worsen aircraft stability and manoeuvrability, increase crew emotional stress, etc., but it does not compromise flight safety. The crew successfully deals with the effects of such an failure exposure. In this case, it can be assumed that $0 < \eta \ll 1$. Harmless adverse factors do not lead to dangerous consequences, they only cause minor difficulties in flight. Such a degree of hazard for adverse factor can be taken as $\eta = 0$.

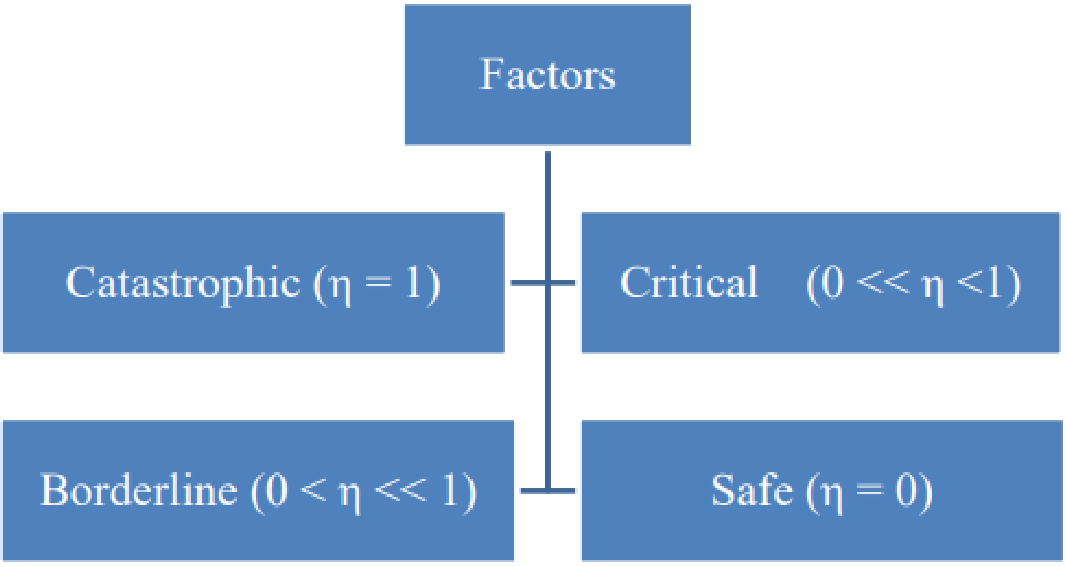


Figure 1.4 – Expression of the degree of adverse factors

The given ranges of hazard variation are rather uncertain and require clarification both in terms of the content of the concept and in terms of the value of the quantity. To resolve this contradiction, we will assume the below statements. Let’s say, logically evaluating the links between specific situations and their frequency, it is possible to formulate them in a different way:

- Catastrophic events, whether aggravated by the action of AE or by a combination thereof, may be attributed to events that are virtually impossible, with a frequency of less than $10^{-9}$;
- Emergencies caused by the same reasons can be attributed to near-unlikely events with a frequency of $10^{-7}$÷$10^{-9}$;
- Dangerous situations caused by the same reasons can be attributed to unlikely events – their frequency is $10^{-7}$÷$10^{-5}$;
- Complication of flight conditions due to moderately probable and frequent events – the frequency is $10^{-5}$÷$10^{-3}$.

Using the above-formulated frequency of occurrence of different hazardous situations, we will determine the probabilities of non-prevention of different special situations from the assumption that a certain aircraft during its service gives the same degree of risk for each of the four special situations. Assuming that a certain in-service aircraft fleet gives the same degree of risk for each of the four special situations, the unobserved value of the probability of adverse factors effect elimination can be determined based on the following example: since the probability of a catastrophic situation occurring within one flight hour (one flight) is defined as the day-night level of $10^{-9}$, while in special situations the probability of occurrence of complex flight conditions is $10^{-3}$, which results in the probability of elimination the value, that is, the probability that the situation will not turn into a catastrophic one, must be greater than or equal to $10^{-6}$And if the effect of the adverse factor leads immediately to an emergency situation, the frequency of which is set to $10^{-7}$, the normalized value, that is, the probability that the situation does not go catastrophic, must be greater than or equal to $10^{-2}$, and so on. Then, for each of the four possible situations, the degree of hazard and the nature of the hazard can be written down as follows:

- Catastrophic situation: $\eta = 1$;
- Emergency situation: $10^{-2} < \eta < 1$;
- Dangerous situation: $10^{-4} < \eta < 10^{-2}$;
- Complication of flight situation $10^{-6} < \eta < 10^{-4}$.

From the above it follows that the comparison of the gradation of special situations by consequence severity (non-elimination of consequences) with the gradation of special situation occurrence frequency is one of the guiding principles for assessing both the aircraft and flight safety. The full relationship between specific situations, their consequences, incidence and degree of danger are based on the above judgments.

In this regard, we need a constructive improvement of the fuel system, with the implementation of modern solutions aimed at improving the operational reliability. Simply stated, to reduce the possibility of AC getting into a dangerous situation through the failure or malfunction of the fuel system or its unit and aggregates.

### 1.3 Evaluating the reliability of the Boeing-777 fuel system components which have been already failed during all history of commercial operation

In this part of my diploma project I would like to analyze the reliability of fuel system components which were involved during accidents for all history, of all Boeing-777 commercial operations on routes and demonstrate vital conclusions from the NTSB and SAA official reports. Let's say, that this assessment will help a lot to highlight the most problematic spots and definitely helps us efficiently implement DTT on this aircraft.

Well, the fuel on the Boeing 777 is stored in three fuel tanks: a centre tank, a left main tank and a right main tank (see

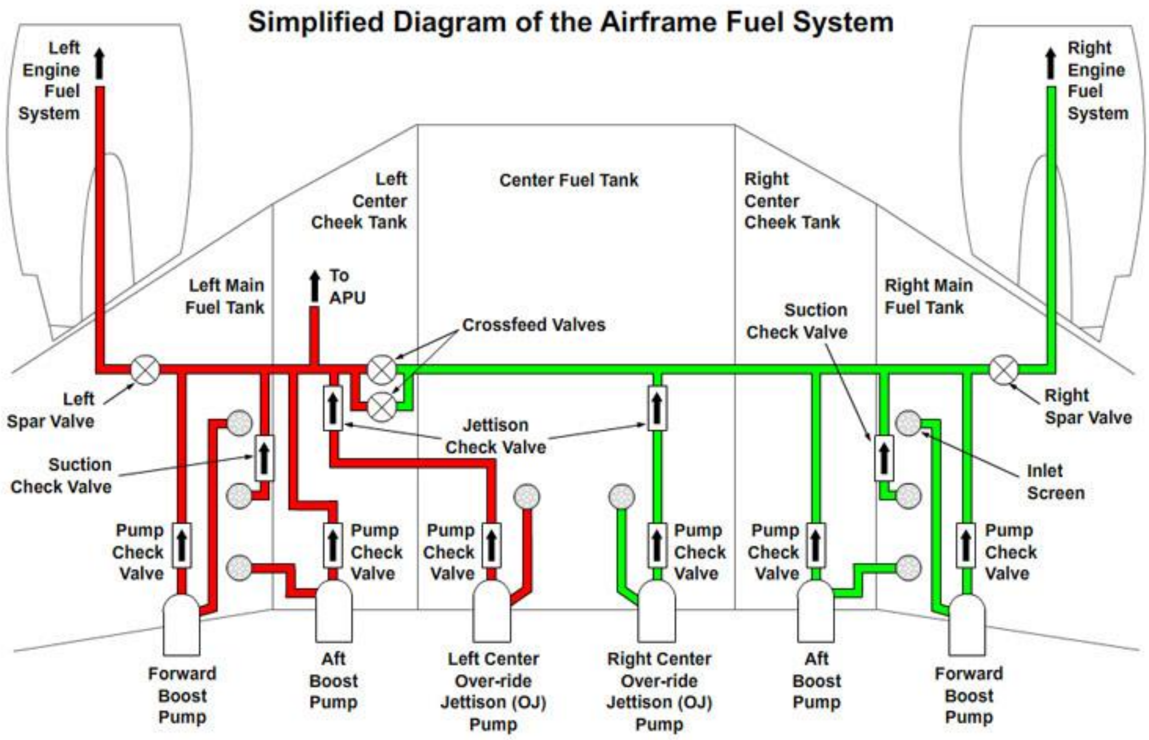


figure 1.5). The centre tank contains two override / jettison (O/J) pumps and each main fuel tank contains two boost pumps, identified as forward and aft. Each of the pump inlets is protected by a ¼ inch mesh screen and the pumps are equipped with a check valve fitted in the discharge port, to prevent fuel in the fuel feed manifold flowing back through the pump. A pressure switch, mounted between the pump's impeller and check valve, monitors the fuel pressure and triggers an advisory warning in the flight deck if the pressure rise across the pump drops below a value, of between 4 and 7 psi.

Figure 1.5 – Simplified diagram of the airframe fuel system

The fuel feed manifold runs across the aircraft and connects to the engine fuel feed lines. The manifold is split between the left and right system by two cross-feed valves, identified as forward and aft. When these valves are closed, and the centre tank is the source of the fuel, the left O/J feeds the left engine and the right O/J feeds the right engine. The fuel from the left and right main tanks supply their respective engines during main tank feed. Spar valves in the fuel manifold provide a means of shutting off the fuel supply to the engines.

To prevent large amounts of 'free water' building up in the fuel tanks, the aircraft is fitted with a water scavenge system that uses jet pumps operated by motive flow from the OJ and boost pumps. The aircraft is equipped with a centre tank fuel scavenge system, which increases the amount of useable fuel in this tank. The system uses jet pumps, provided with motive flow from the boost pumps, to draw fuel from the lowest part of the centre tank and feed it into both main fuel tanks. A float valve mounted in the centre tank turns on the motive flow when the centre tank contents are below 15,800 kg.

Float valves mounted in each of the main fuel tanks prevent fuel scavenge when the contents of these tanks are above 12,500 kg. Each tank is vented to atmosphere through channels in the roof of the fuel tanks, which are connected to surge tanks mounted outboard of each of the main tanks. The surge tanks are vented to atmosphere through a flame arrestor and a scoop mounted on the lower surface of each wing. If fuel is loaded into the centre tank, the normal operation is to select all O/J and boost pumps on at the start of the flight.

As the O/Js operate at a higher delivery pressure than the boost pumps the centre tank will empty first. The airframe fuel system supplies fuel to the low pressure engine-driven pump, which forms part of the main engine pump. This raises the fuel pressure (and fuel temperature slightly) and pumps the fuel through a Fuel/Oil Heat Exchanger (FOHE) – figure 1.6. The FOHE serves the dual purpose of cooling the engine oil and raising the temperature of the fuel so that ice does not affect the downstream components, including the low pressure pump filter and the Fuel Metering Unit (FMU). The FOHE is a hybrid cross-flow / counter-flow design and it includes a matrix of fine tubes. The fuel enters the top of the FOHE and passes through the tubes; the hot oil enters the FOHE main body and passes around the fuel tubes.

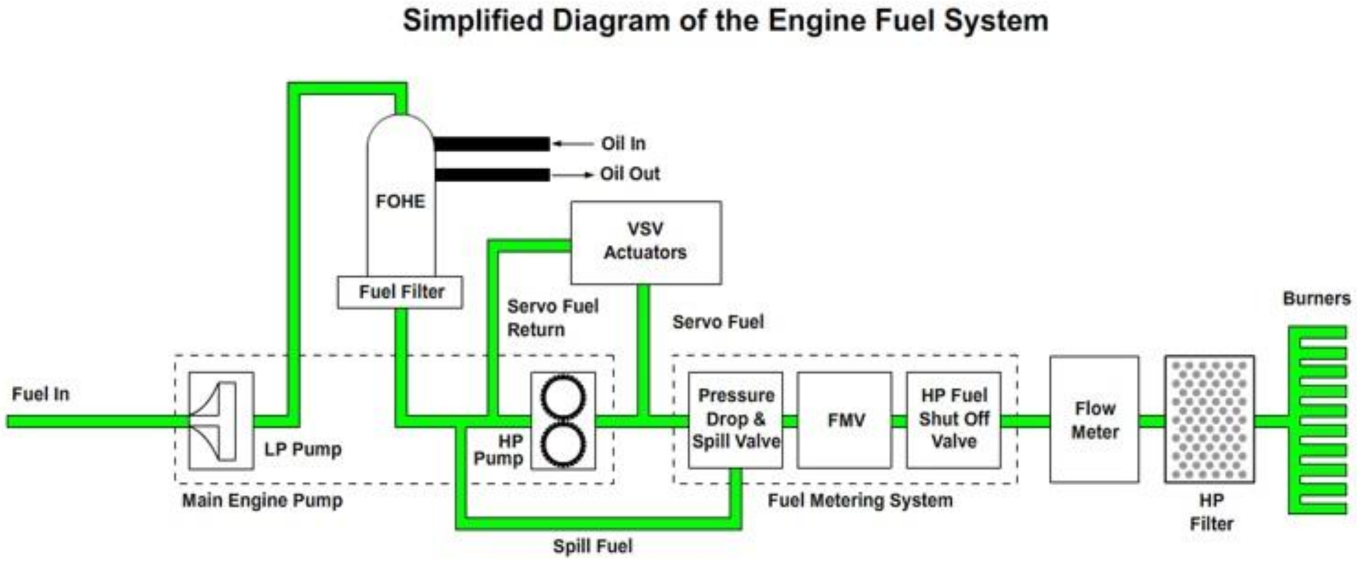


Figure 1.6 – Simplified diagram of the engine fuel system

The temperature of the fuel after it has passed through the FOHE is considerably above its entry temperature. The FOHE filtering matrix consists of over 1,000 small tubes (figure 1.7) that are crimped at various locations along their length to improve thermal transfer efficiency. The crimps at the inlet of the tubes are to a slightly smaller diameter than the remainder of the crimps to prevent small debris becoming lodged in the matrix. The tubes protrude by approximately 4 mm from the matrix top plate, which separates the fuel from the oil, and therefore extend into the fuel in the inlet chamber.

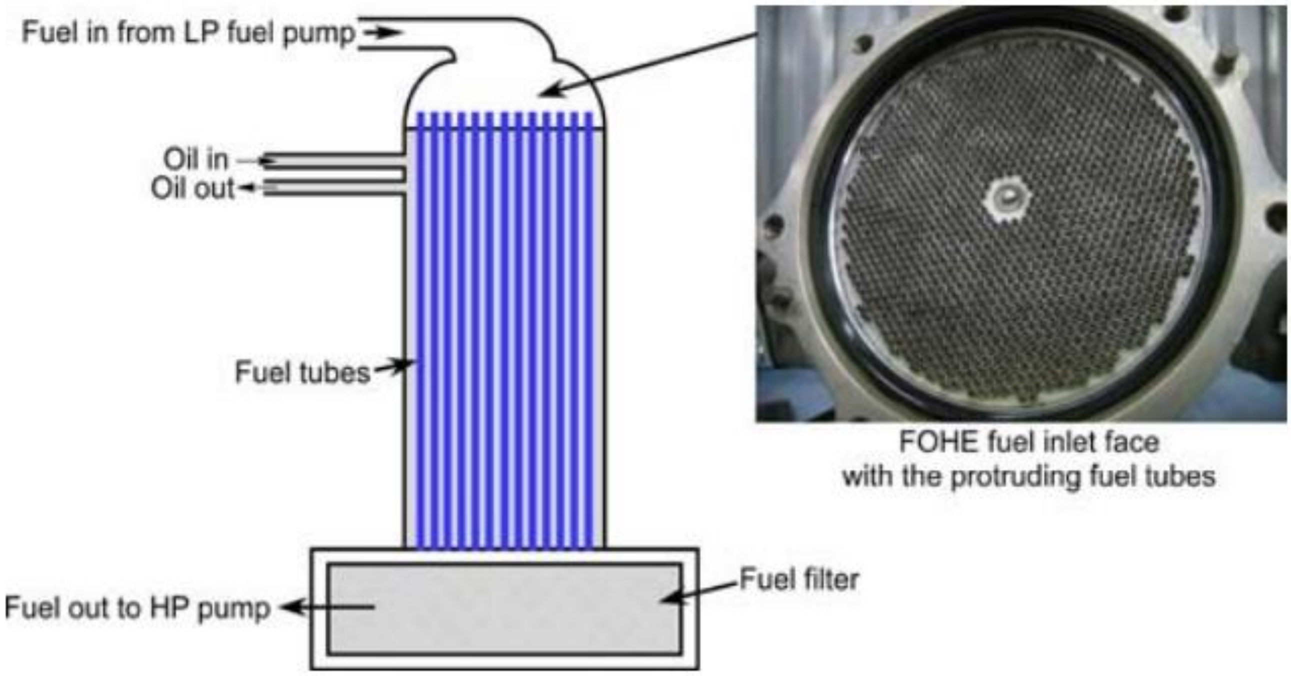


Figure 1.7 – Fuel/Oil heat exchanger of Boeing 777

In the event that the oil becomes too viscous during engine start in cold conditions, the FOHE incorporates an oil pressure relief valve to bypass oil away from part of the matrix to reduce the time taken to heat the oil to operating temperatures. Under certain conditions the fuel flow may not be sufficient to keep the oil temperature within limits and therefore cooling is augmented by an Air Oil Heat Exchanger, controlled by the ECS. The low pressure filter is mounted directly below and downstream of the FOHE. After the low pressure filter, the fuel travels to the high pressure pump of the main engine pumps where its pressure is again raised, to the values needed for injection through the fuel spray nozzles in the combustion chamber.

The main engine pump comprises a centrifugal low pressure stage and a gear-type high pressure stage (figure 1.8). Both stages are housed in a single unit, although low pressure fuel is passed to the FOHE/low pressure filter unit before being fed back to the high pressure stage.

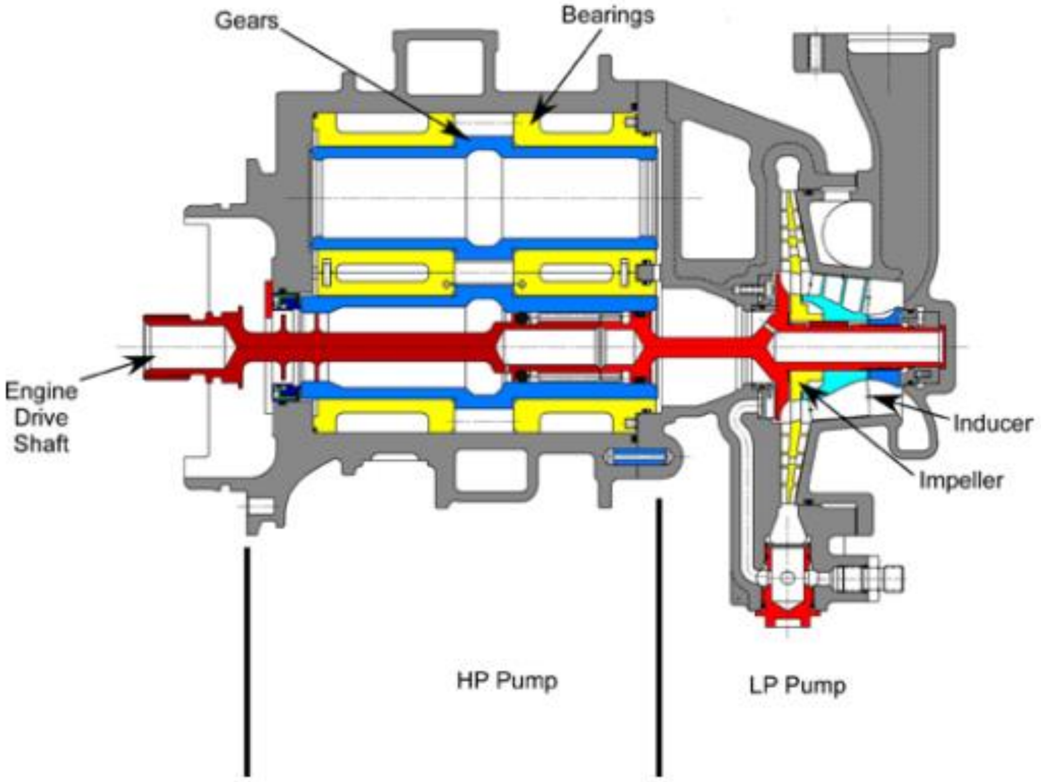


Figure 1.8 – Main engine pump structural elements

The pump is driven from the high pressure spool of the engine through the accessory gearbox. There are four phosphor-bronze plain bearings which mount the two gears of the high pressure stage and these are coated with a dry-film lubricant, although the fuel itself is the primary lubricant. The high pressure fuel is ported into the FMU. The FMU contains a fuel metering valve, which regulates the fuel flow to match a thrust demand and is commanded from the ECS. The FMU is attached to the main engine pump case but is a separate unit. The fuel from the FMU is routed to the burners via a flowmeter and a coarse high pressure strainer.

The fuel temperature indication system has a temperature probe located between ribs 9 and 10 in the left main tank. The probe is situated approximately 12.6 inches above the lower wing skin and is located 40 inches outboard of the aft boost pump inlet. The fuel in the left wing tank can be slightly colder than the right wing tank. This is because the right fuel tank contains two hydraulic fluid/fuel heat exchangers, which are used to cool the hydraulic fluid, whereas the left wing has only one.

Fuel temperature is displayed in white on the primary engine indication and alerting system (EICAS). The EICAS low temperature warning trigger automatically defaults to the freezing limit of Jet A, unless another temperature, such as the freezing point of Jet A-1, has been set in the Flight Management Computer (FMC) Control Display Unit (CDU). Once the fuel temperature reaches 3°C above the fuel freezing temperature (-37°C for Jet A and -44°C for Jet A-1) the fuel temperature indication turns amber and the fuel temp low advisory message is displayed on the EICAS.

On long flights the temperature of the fuel in the main wing tanks will tend towards the temperature of the boundary layer around the wing, which can be up to 3°C lower than total air temperature. Whilst the cheek tanks of the centre tank are situated in the wings, and are affected by aerodynamic cooling, the majority of the centre tank fuel is sandwiched between the cabin and the air conditioning packs. Hence the fuel in the centre tank is considerably warmer than the fuel in the main tanks.

The aircraft manufacturer had previously undertaken tests on a B777-200, which has the same wing fuel system as the B777-200ER, to determine the effectiveness of the fuel temperature probe. During the test three racks of thermocouples, mounted vertically in the tank, were fitted along the span of the left main fuel tank. The test established that there is a temperature gradient along the wing span with the coldest fuel inboard and the warmest fuel outboard. This gradient occurs because the wing surface to fuel volume ratio results in the fuel in the outer sections of the wing cooling at a greater rate than the fuel in the inboard sections of the wing. However, a consequence of the wing dihedral and flexing in flight is that the cold fuel migrates towards the inboard sections of the wing. A comparison of the test data with the actual fuel probe temperatures revealed that there is a close correlation between the temperature of the fuel measured by the probe and that measured by the rack of thermocouples mounted adjacent to the probe. Engine control is performed by a digital electronic engine control unit. Its primary function is to control operation of the FMU, based on power demands from the thrust levers and from information, including speeds, temperatures and pressures, received from sensors on the engine.

So, briefly understand the operational mission of the main elements of the system we can see that in general the fuel system and its components are very reliable integral mechanism. Let’s say, that main problem spot of the Boeing-777 in different modifications was the FOHE in combination with engine type Rolls-Royce Trent 895-17. After all incidents where FOHE was involved main problematic places of this aggregate were eliminated and improvements done in next engine generations models what have been installed on Boeing-777. Moreover, I would like to represent official reports of the real data recordings which were taken after NTSB investigations for better understanding the causes of failures or other contributing factors and how is provided the monitoring process of the fuel system condition and its components.

In accordance with regulatory requirements, the aircraft is equipped with a 25-hour duration Flight Data Recorder (FDR) and a 120 minute Cockpit Voice Recorder (CVR). The aircraft is also tooled up with a Quick Access Recorder (QAR). A comprehensive range of parameters (on the example of flight from Beijing to Heathrow airport) was available from the FDR and QAR, with just over 1,400 parameters recorded. Salient parameters from the FDR and QAR includes (figure 1.9):

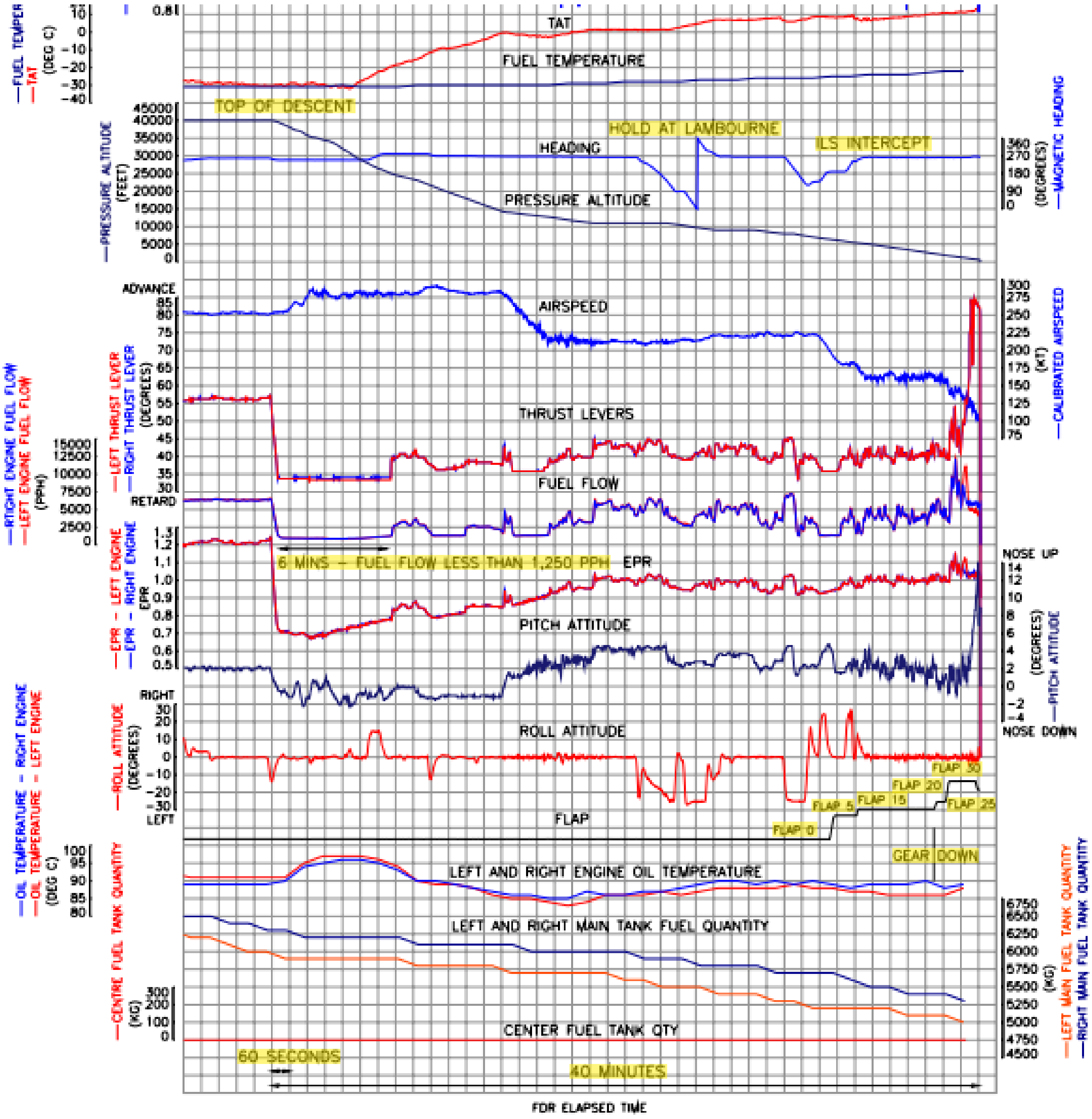
- Fuel temperature within the left main fuel tank (recorded by the FDR at a rate of once every 64 seconds and by the QAR at a rate of once every four seconds). The temperature is recorded by both FDR and QAR with a resolution of 1°C (flight from Beijing to Heathrow airport);
- Fuel flow delivery to both engines (recorded by both the FDR and QAR at a rate of once every second) during any operational phase of the aircraft. A smoothing filter is applied to the parameter prior to recording. Unless specified, all fuel flows are referenced in their filtered state;
- Demanded and selected fuel metering valve position for both engines (recorded by the QAR once per second);
- Spar valve positions (is recorded by the FDR once per second);

- Fuel pump low pressure warnings from all six pumps; two centre fuel tank O/J fuel pumps and the left and right main fuel tank forward and aft boost pumps (each low pressure warning recorded by the FDR once every four seconds);
- Left and right engine fuel cutoff valves (recorded by the FDR once per second);
- Fuel quantity within the centre, left main and right main fuel tanks (recorded by the FDR at a rate of once every 64 seconds and by the QAR once every four seconds);
- Fuel Quantity Indication System (FQIS) water detection system. Three detectors, one in the centre fuel tank and one in each of the left and right main fuel tanks (indications recorded by the FDR once every 64 seconds);
- Left and right engine oil pressure and oil temperature (recorded by the FDR at a rate of once every 64 seconds and by the QAR once every two seconds).

Brief description of what happened during the approach of the Boeing 777 (flight from Beijing to Heathrow airport in 2008) from NTSB and British air accidents investigation branch official reports – «Following the reduction in thrust, the autopilot attempted to maintain the aircraft on the glideslope. As the airspeed started to decay the autopilot compensated by commanding a progressively nose-high pitch attitude. By about 240 ft the airspeed had reduced to 115 kt, at which point there was a master caution aural warning, indicative of the ‘airspeed low’ warning. This speed was now some 20 kt below the target approach speed, at which time the commander selected flap 25. At 200 ft, airspeed had reached 108 kt and the stick shaker started to activate as the aircraft neared the stall. Shortly afterwards the co-pilot made a nose-down pitch control input which reduced the aircraft pitch attitude and automatically disconnected the autopilot. At this time the commander made a ‘MAYDAY’ call. The aircraft remained near to the stall and three seconds later it impacted the ground at a descent rate of about 1,400 fpm (~25 ft/s) and a recorded peak normal load of 2.9g; the time was 1242:09 hrs. The aircraft bounced and then slid along the ground, during which time the FDR and CVR records ceased due to a loss of electrical power».

Figure 1.9 – Salient parameters of Boeing- 777 FDR on the example of flight from Beijing to Heathrow airport operated by British Airways

Boeing-777 is also equipped with an Aircraft Condition Monitoring Function (ACMF) system. The ACMF is a centralised system designed for the purpose of providing



Engine Health Monitoring (EHM) and Aircraft Performance Monitoring (APM). It also records flight data onto a QAR, which is widely used for flight data monitoring, incident investigation and maintenance purposes. FDR certification requirements do not apply to QAR and ACMF type systems. The QAR is not required to be accident protected and there is no requirement governing the use of buffering or the recording of certain parameters. Unlike the FDR system, the ACMF may also be readily modified by the operator to suit its operational requirements. The ACMF uses buffers so that analysis may be performed on data that occurred both before and after an event has been detected. This feature is commonly used within the EHM and APM functions. The aircraft manufacturer also used a similar feature within the QAR start logic, where data was recorded with a time offset so that engine pre-start information could be captured.

As a result of investigations and laboratory testings (flight from Beijing to London Heathrow) commission established that, under certain conditions, it was possible to partially block the FOHE and restrict the fuel flow to the engine HP fuel pump. These restrictions were achieved by injecting water directly into the boost pump inlet, leading to a high water concentration1 in the fuel. As the water moved through the fuel system it formed ice crystals, which subsequently blocked the ends of a majority of the tubes in the FOHE matrix. It was established that under certain circumstances 25 ml of water, when introduced into the fuel flow in this manner, could form sufficient ice to restrict the fuel flow through the FOHE.

However, this restriction could always be cleared by reducing the fuel flow, which changed the equilibrium between the cold fuel and hot oil in the heat exchanger, such that the ice melted on the inlet face of the FOHE sufficient to restore the original fuel flow. Variation of the FOHE oil temperature made a small difference to the amount of water required to restrict the FOHE, whereas variations in fuel temperature and fuel flow had a larger affect. It was concluded that it was not possible to restrict the fuel flow through the FOHE when the temperature of the fuel in the main tank was above -15°C (at a fuel flow of 6,000 pph) and -10°C (at a fuel flow of 12,000 pph). Moreover, when restricted, the fuel flow never dropped below that required by the engine for operation at flight idle.

The accident flight’s minimum fuel temperature of -34°C was identified as being unusual, although testing has shown that most ice accumulates on the inside of fuel feed pipes at temperatures between -5°C and -20°C. The rate that ice accumulates will reduce as the temperature drops further toward the minimum experienced in flight. Therefore, the minimum fuel temperature experienced on the accident flight is not considered a causal factor, however it did contribute to the low fuel temperature of -22°C on approach.

The accident flight had operated for over eight hours in the cruise, at an average fuel flow of about 7,000 pph. During the same period, fuel temperatures had remained below -20°C and, due to the use of the mode for the step climbs, fuel flows had not exceeded 8,897 pph. Testing has shown that at similar temperatures and flow rates, ice can be formed within the fuel feed pipes. Testing has also demonstrated that ice may be released from the fuel feed pipes at higher levels of fuel flow, similar to those attained during the final stages of the approach when the maximum fuel flow reached 12,288 pph.

Analysis of 175,000 flights identified that the accident flight was unique among 35,000 Rolls-Royce powered flights in having a combination of the lowest cruise fuel flow, combined with the highest fuel flow during approach while at the lowest temperature on approach. Just two flights from 142,000 Pratt and Whitney powered aircraft flights had these features. However, analysis of the N862DA (Delta Airlines case in 2008) incident and subsequent data mining identified that this flight was not unique with respect to its combination of fuel temperature and fuel flows, although only a relatively small percentage (0.3%) of flights shared the same features.

It is not fully understood why other Rolls-Royce powered Boeing 777 flights that had similar features to the Beijing/Heathrow accident flight, and perhaps more so the N862DA incident flight, did not experience similar fuel restrictions. Testing does offer some explanation, with the observation of ‘randomness’ in the formation of ice, indicative that there may also be a variance in the quantity of ice generated during similar flights. Similarly, differences between the Heathrow accident flight and N862DA incident flight, with one experiencing a more rapid onset and the other a more progressive restriction, indicate that factors other than flow rate and temperature may affect the release of ice from within fuel feed pipes. The properties of ice generated within an aircraft, rather than a laboratory environment, may also have different characteristics.

Although other flights having similar levels of fuel restriction to Heathrow flight and N862DA were not discovered, it cannot be ruled out that other aircraft experienced a lower level of fuel flow restriction that went undetected. A search of previous ECS Control Loop 17 occurrences, and an fuel metering valve position algorithm, did not identify any flights that had suffered a ‘gross’ mismatch in commanded and actual fuel flow. However, when the incident flight of N862DA was analyzed, the fuel metering valve position and expected fuel flow algorithm did not detect a mismatch until several minutes after the restriction had first started to occur. The ECS control loop 17 also activated some minutes later. Testing has shown that ice on the inlet face of the FOHE will clear when the commanded fuel flow is reduced to idle thrust.

All in all, after all revealed information and testing have shown that ice generated within a fuel system may restrict the flow of fuel to the engine such that commanded thrust cannot be achieved. There are a number of other scenarios in which commanded thrust may not result in the appropriate delivery of fuel to the engine. However, there is no current requirement to record parameters which control the delivery of fuel to the engines, such as the position of the fuel metering valve. On Beijing to London Boeing-777, the FDR did record the loop in control, although this parameter does not reflect the dynamic nature of the fuel metering valve nor its immediate position. In this accident (and the incident to N862DA), the availability of the fuel metering valve positional information was invaluable in being able to determine that the engine control system was functioning correctly and that a fuel restriction had occurred, but there is no requirement that this be recorded on the crash-protected FDR. The required FDR parameters for commercial air transport aircraft are provided in ICAO Annex 6 Part 1. This Annex is currently subject to amendment to include a wider range of recorded information than is currently prescribed. This enhanced list of FDR parameters has already been adopted and implemented by the FAA but not yet by EASA. As well as ‘power on each engine’, the proposed change to the Annex details a number of examples of ‘additional engine parameters’ to be recorded, including ‘fuel cutoff lever position’. For future fuel-flow related investigations it is important that the operational position of the engine fuel metering devices be known. Thus it would be appropriate that this information be required by regulation to be recorded by a FDR. The QAR is recognised, by accident investigators and aircraft manufacturers, as providing a valuable source of additional information. Unlike the FDR there is no legislative requirement governing the buffering of data prior to recording. On many occasions, buffering has not been an issue, although during this accident, had the fuel restriction occurred just a few seconds later, the accompanying fuel metering valve data from the QAR would not have been available. By means of a software update to the ACMF, by the operator, the degree of data buffering of QAR data on its Boeing 777 aircraft has been greatly reduced. Other Boeing 777 operators have not implemented these changes.

Finally, due to analysis of all issued official NTSB reports and investigation data it is possible to highlight the main factors which have contributed to the fuel system malfunction:

- Accreted ice from within the fuel system released, causing a restriction to the engine fuel flow at the face of the FOHE, on both of the engines;
- Ice had formed within the fuel system, from water that occurred naturally in the fuel, whilst the aircraft operated with low fuel flows over a long period and the localised fuel temperatures were in an area described as the ‘sticky range’;
- The FOHE, although compliant with the applicable certification requirements, was shown to be susceptible to restriction when presented with soft ice in a high concentration, with a fuel temperature that is below -10°C and a fuel flow above flight idle;
- Certification requirements, with which the aircraft and engine fuel systems had to comply, did not take account of this phenomenon as the risk was unrecognised at that time.

# CONCLUSION TO PART 1

To maintain operational reliability is very complex and vital problem, so using of DTT will be an advantage. Nevertheless of rapidly developing in different technologies and already present design solutions in aircraft manufacturing this approach with implementation of digital model will bring us many useful and practicable during aircraft servicing.

As a result of the analysis of the operating conditions of the fuel system of the Boeing-777, the requirements for it, as well as statistical information on its failures and malfunctions, it was concluded that the fuel system is one of the most important AC systems on which the safety of the AC depends. Therefore, it is necessary to monitor the condition of fuel system units and assemblies, to timely detect and prevent their failures and malfunctions, thereby maintaining the operational reliability of the fuel system at a high level. In addition, constructive, organizational and technological measures are needed to improve the operational reliability of the AC's fuel system.

From the very beginning of the analysis of faults in the fuel system of the Boeing-777 in different modifications it can be seen that the malfunction of the FOHE is common and repetitive. However, it is also necessary to take into account other outer factors and human factor as well. As a result FOHE was later changed and modified by producer. Nonetheless, it will be vital necessary to keep the high level of operational reliability of the fuel system in the future to minimize or even avoid such situation. All in all, Boeing-777 has fairly good instruments of monitoring the fuel system condition, but implementation of DTT without doubt will definitely help to improve reliability and tracking of any faults in the future. Methods and means for this implementation will be reproduced during following chapters.

# CHAPTER 2

# IMPROVEMENTS ON THE FUEL SYSTEM AND IMPLEMENTATION OF DTT ON BOEING-777

## 2.1 Brief description of the DTT and how it works

Nowadays it is clearly understandable that issues regarding safety and reliability are critical for the aviation industry. For providing a high level of quality and reliability it's obligatory to produce quality products and have effective means for maintaining the operabilty of all systems and structural units of produced aircraft. Unfortunately, any failure or malfunction can lead to fatal incidents and financial reparations for the involved operator of the AC. However, it is not only the task of the AC manufacturer. For maintaining of high operational reliability value really important have qualified maintenance personnel as well as effective MP according to operator requirements accepted by SAA.

Despite of the modern fleet, more durable turbofan engines and innovations in maintenance techniques, recent research has shown maintenance spending stable continues to increase. In fact, airlines now spend more money on maintenance than on fuel or crew. Nowadays, the need to cut maintenance, repair and overhaul costs is a pressing and important issue for airlines all around the world. Indeed, maintenance is one of the major contributors to aircraft operating costs. Flight delays and cancellations from unplanned maintenance cost airlines billions of dollars every year — not to mention the distinctly impact on customer satisfaction. Because of this, the minimization of operating costs and optimization of operational availability continue to be top priorities for airlines. For this, actual problem and have analyzed the main problematic spots of Boeing-777, I would like to propose an innovative DTT as when in use, will help airlines achieve these aims and without doubt increase operational reliability of fuel system.

Let's briefly look through for the principal scheme of DTT (figure 2.1) and how it works. With the help of DTS which will be installed on the aircraft by the producer, digital twin refers to a digital replica of a real physical system (in our case fuel system), which can display how the engine is running, conditions of the system, any faults or malfunctions to maintenance department of the operator and the manufacturer whilst our aircraft is still in the air during any phase of flight.

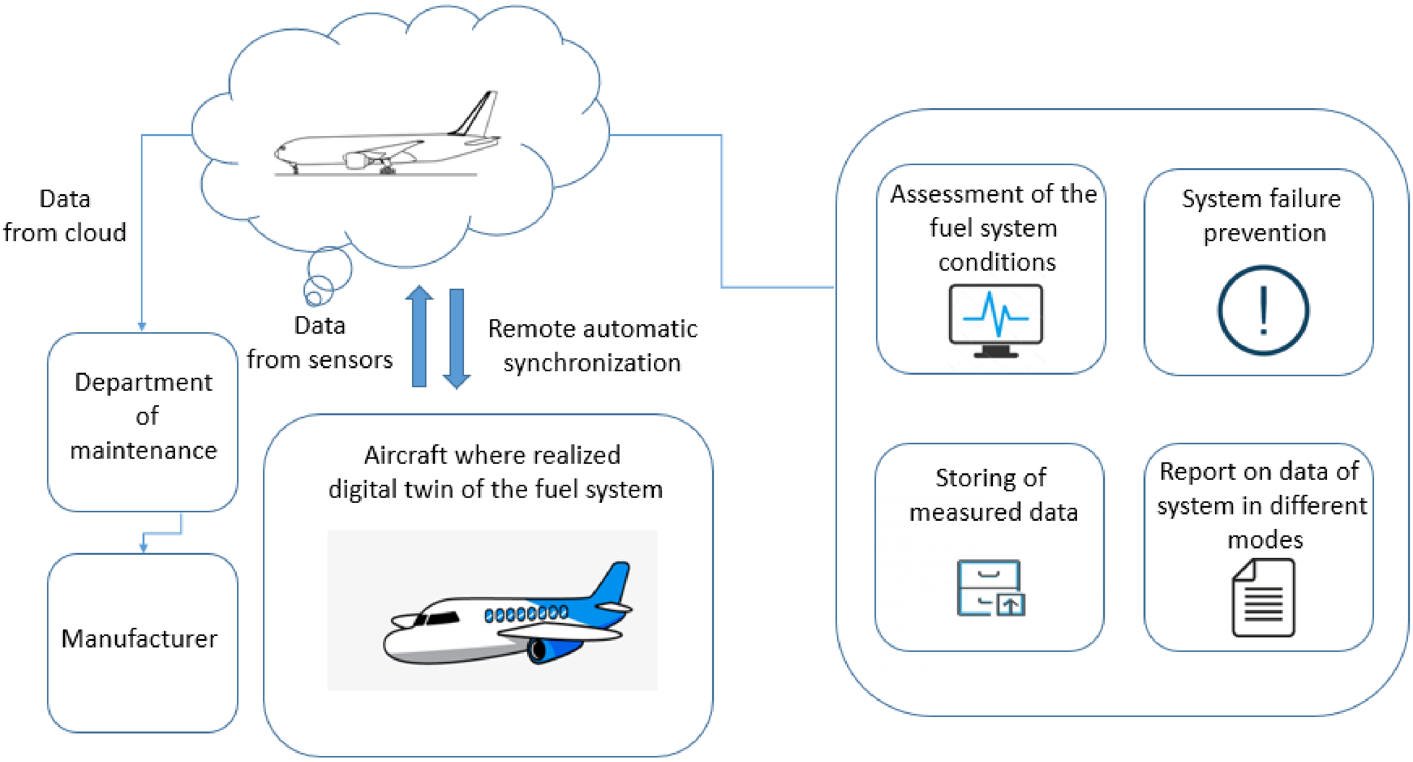


Figure 2.1 – Overview of the DTT and principles of its work

To bring it real, at design stage producer should make an artificial model of the Boeing-777 fuel system with thousands of data points specific to each unit and aggregate. These are then used to build a digital model of the real physical system that monitors parts and unit assemblies in real-time, providing essential information throughout the fuel system lifecycle, such as fuel temperature, pressure and other parameters. By implementing DTT and creating a virtual model of the system, manufacturer and operator of the AC can receive early warnings, predictions or even a plan of action by simulating "what-if" scenarios based on weather, other outer factors, performance, operations and other variables, helping keep aircraft in service for longer thereby reducing the cost index of maintenance part. Simply stated, DTT is a new approach for AC maintenance tasks. Furthermore, it is a good addition for the already present ACARS system on modern airplanes including the Boeing-777 family. If we take into account some statistical data it's suggested that predictive analytics and constant monitoring can optimize maintenance planning and operability by reducing the need for routine maintenance. By triggering maintenance when needed − helping for airline to increase fleet availability by up to 35% and reduce labor costs by 10%. Nevertheless, one of the main probable problems will face manufacturer, is that the storage and analysis of a huge amount of data can lead to overload of data storing systems especially if we are talking about monitoring of all parameters in real time. Meanwhile, the next generation of cloud solutions and improvements in software will solve this problem, which covers all areas from predictive maintenance to analysis of operational performance during any phase of flight. New cloud solutions are a vital instrument for global development of DTT, especially when it concerns about planned and unscheduled maintenance of the airplane. In our time, such approach will not only improve the operational reliability of fuel system, but all data which obtain producer will be possible to improve component quality or design of released AC.

Previously airlines have been concerned about the amount of physical hardware they might need to adopt new technologies, but the transformation into mobile environment using tablets or devices and eliminating the cost of purchasing and managing on premise technology is proving to be more convenient and attractive. Exactly adopting of DTT will help for the maintenance department of any operator to receive all real data from the aircraft fuel system or other structural aggregate simply on their mobile phones or on the tablets via special software which has to be developed by the manufacturer.

As I have mentioned before digital twin is a digital model of a real physical aircraft system that transfer the information about internal processes and condition of a real system components under the influence of interference and the environment. An important feature of the DTT is that the information from the sensors of a real device operating parallel is used to assign input influences to it. Operation is possible both online and offline. Moreover, it is possible to compare the detectors information of the digital twin model with the sensors of a real device, identifying deviations and their causes. The DTT is one of the modern tools that allows you to simulate various options for complete and partial failures, the operation of structural elements, taking into account their modes of operation, environmental influences and varying degrees of wear of any aggregates at any time.

Historically, the aviation industry is at the forefront of innovation – many researchers confirmed that this field leads to the take-up of new technologies for digital transformation to overcome some of the industry's greatest challenges. It helps to fly more fuel efficiently, regularly, and what is not less important – safely. Airlines and worldwide well-known aircraft manufacturer companies like Airbus Group, a Boeing company etc. are constantly looking for new improvements in operational processes and although some technologies or approaches. Regarding that fact that many of them may be at the beginning of their lifespan the aviation world is fully aware of the benefits what they will bring. Moreover, when the quantity of air travelers (at least before Covid-19 pandemic) is rapidly growing and demand for new AC constantly rising (figure 2.2).

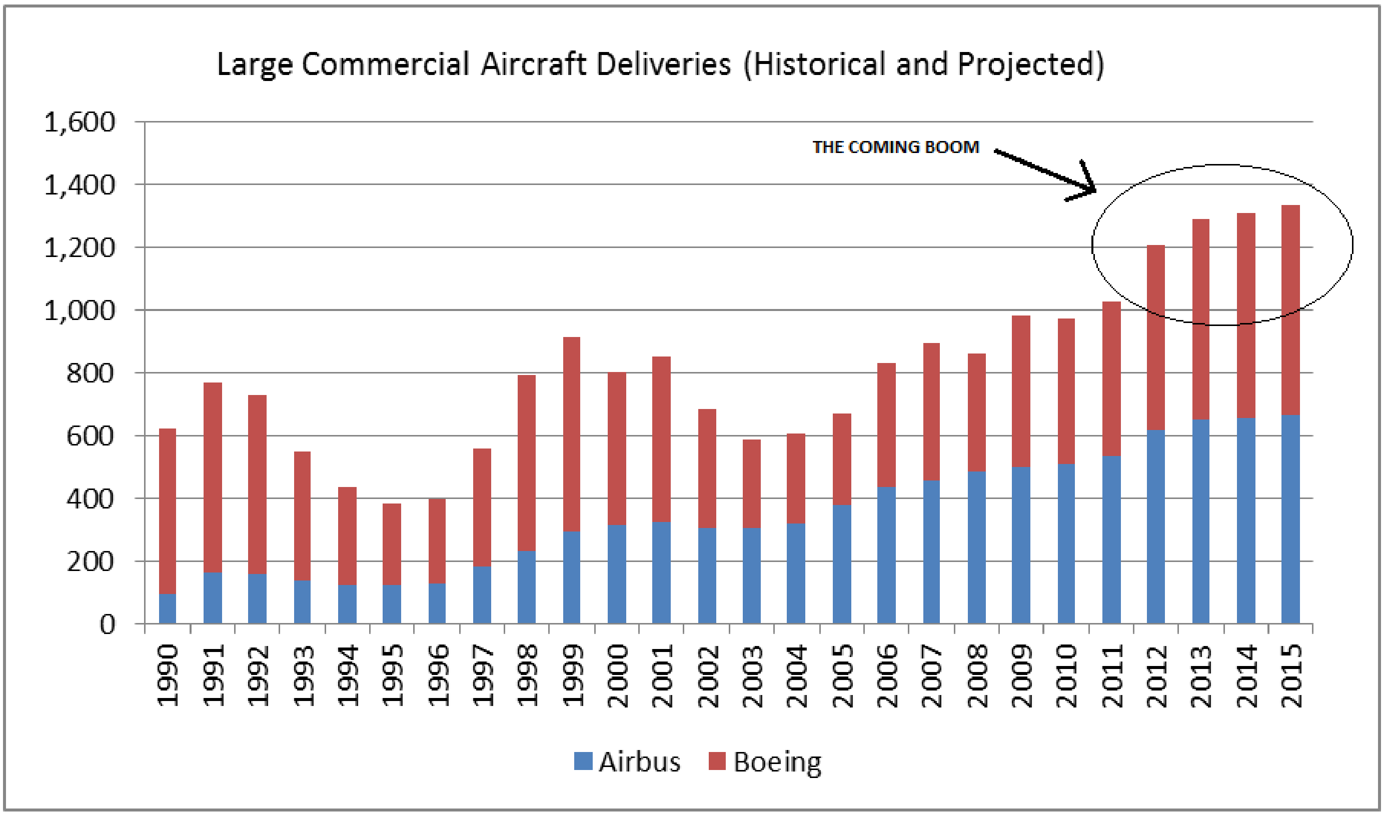


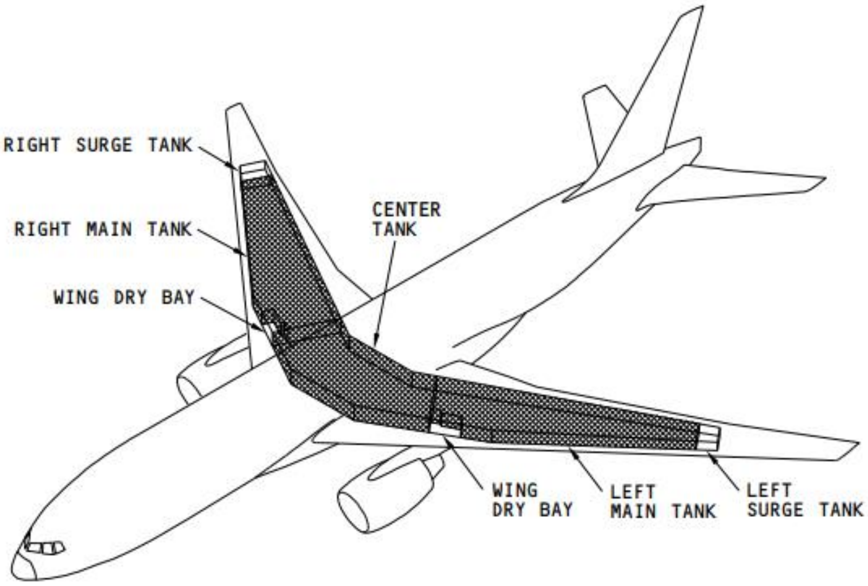
Figure 2.2 – Statistical graph of aircraft deliveries from 1990 till 2015

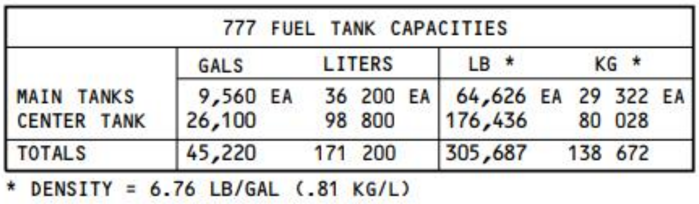
## 2.2 Detailed illustration of Boeing-777 fuel system structure and its main components

For better understanding of how and where it will be possible to install new DTS it is probably evident that operator and manufacturer should evaluate the structural components and structure of fuel system referring to information aircraft maintenance manual (AMM) and other vital tutorials. In addition to this, some conclusions have to be taken from previous incidents what had happened due to failure/malfunction of fuel system or its elements. Furthermore, it is important for analyzing of the vulnerable spots in the fuel system structure to improve its reliability. Putting it simply, fuel system of any AC is designed to accommodate the fuel and feed it to the engines and APU during any phase of flight. The fuel system comprises such subsystems, namely:

- Fuel storage;
- Pressure refuel;
- Engine fuel feed;
- APU fuel feed;
- Defuel;
- Jettison;
- Fuel indicating.

According to AMM, Boeing-777 has 3 main tanks (left/right/center) with a total capacity of 171 200 liters where all fuel is accommodated (figure 2.3) including all unusable fuel .





777 FUEL TANK CAPACITIES

| | GALS | LITERS | LB * | KG * |
|---|---|---|---|---|
| MAIN TANKS | 9,560 EA | 36 200 EA | 64,626 EA | 29 322 EA |
| CENTER TANK | 26,100 | 98 800 | 176,436 | 80 028 |
| TOTALS | 45,220 | 171 200 | 305,687 | 138 672 |

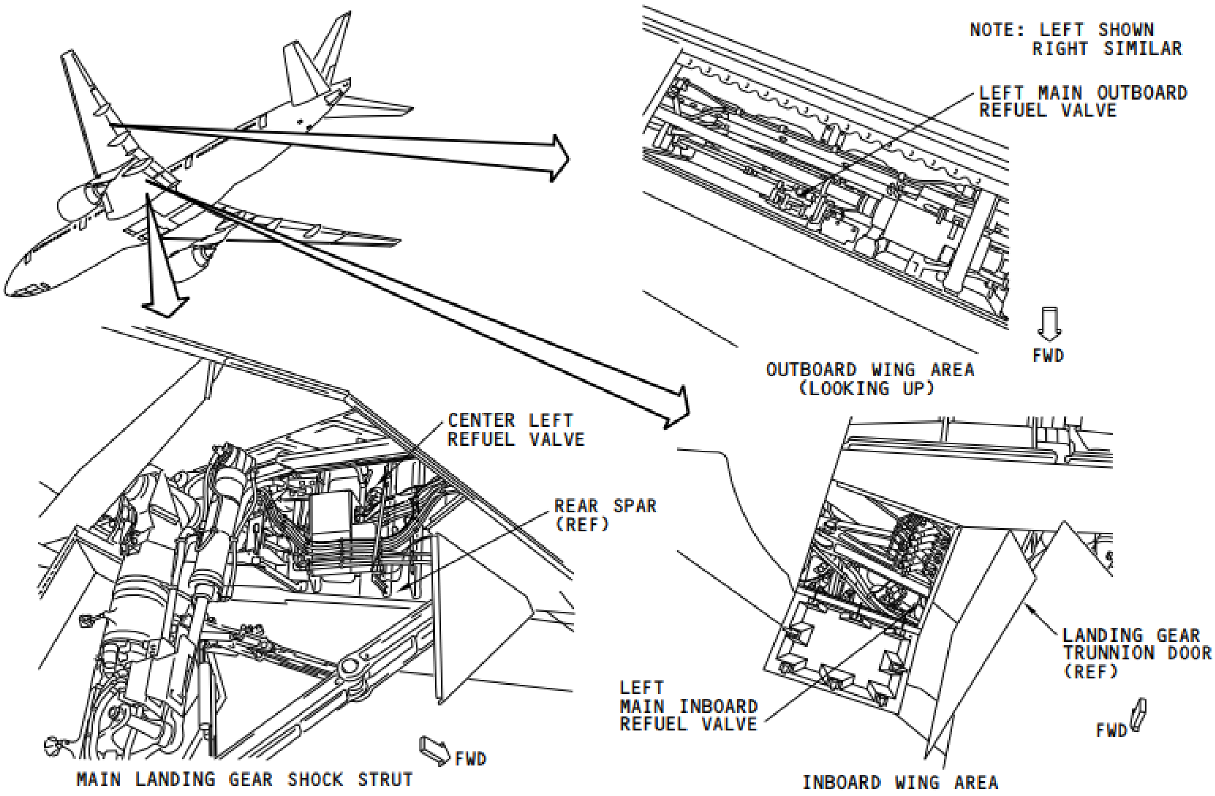
* DENSITY = 6.76 LB/GAL (.81 KG/L)

Figure 2.3 – Boeing-777 fuel tanks locations and capacity

Wing ribs divide the fuel tanks into bays, and reduce the movement of fuel during airplane maneuvers. Access doors and cutouts are entrances into the airplane fuel tanks for inspection or component repair. The center tank is in the center wing section and in the inboard wing box of the left and right wings. The left main tank is in the wing box of the left wing. The right main tank is in the wing box of the right wing. An adjacent surge tank is outboard of each main tank. The wing dry bays are above each engine strut.

The pressure refuel system transfers fuel from the refuel adapters to the airplane tanks. It is possible to operate the pressure refuel system with the integrated refuel panel on the left wing. The fuel quantity processor unit and the electrical load management system control the system.

There are two refuel valves in each fuel tank (figure 2.4). In the left main fuel tank, the inboard refuel valve actuator is outboard of the main landing gear shock strut. The outboard refuel valve is between the fairings of the outboard flap. The refuel valve actuators are in similar locations in the right main fuel tank. In the center tank, the left refuel valve actuator is on the rear spar, inboard of the main landing gear shock strut. The right refuel



valve actuator is in a similar location in the right side of the center tank.

Figure 2.4 – Pressure refuel components locations

Engine fuel feed − supplies fuel to the engines from the tanks. The engine fuel feed system uses these components to supply fuel to the engines: fuel pumps, fuel pump pressure switches, crossfeed valves, spar valves. The normal procedure for engine fuel feed operation is to supply fuel from the center tank first. When the center tank is empty, you supply fuel from the main tanks. If you open a crossfeed valve, you can feed an engine from the opposite main tank to correct a fuel imbalance between the main tanks. The engines can also use suction feed from a main tank. The engine fuel feed system uses power from the Electrical Load Management System (ELMS) and the engine fuel spar valve battery. The engine fuel feed system has four boost pumps (figure 2.5). The left forward boost pump receives 115v ac power from two sources: the ground service bus or the left transfer bus. The boost pump control switch controls power to the pump. A light on the switch shows when there is low pressure at the pump outlet. Two pumps are for each main tank. They attach to the rear spar of each wing. The forward boost pumps are outboard of each main landing gear shock strut. The aft boost pumps are inboard of each main landing gear shock strut. The aft boost pump has a shield that protects it. Also the engine fuel feed system has two fuel spar valves. The spar valve actuators attach to the rear spar of each wing, outboard of the forward boost pumps.

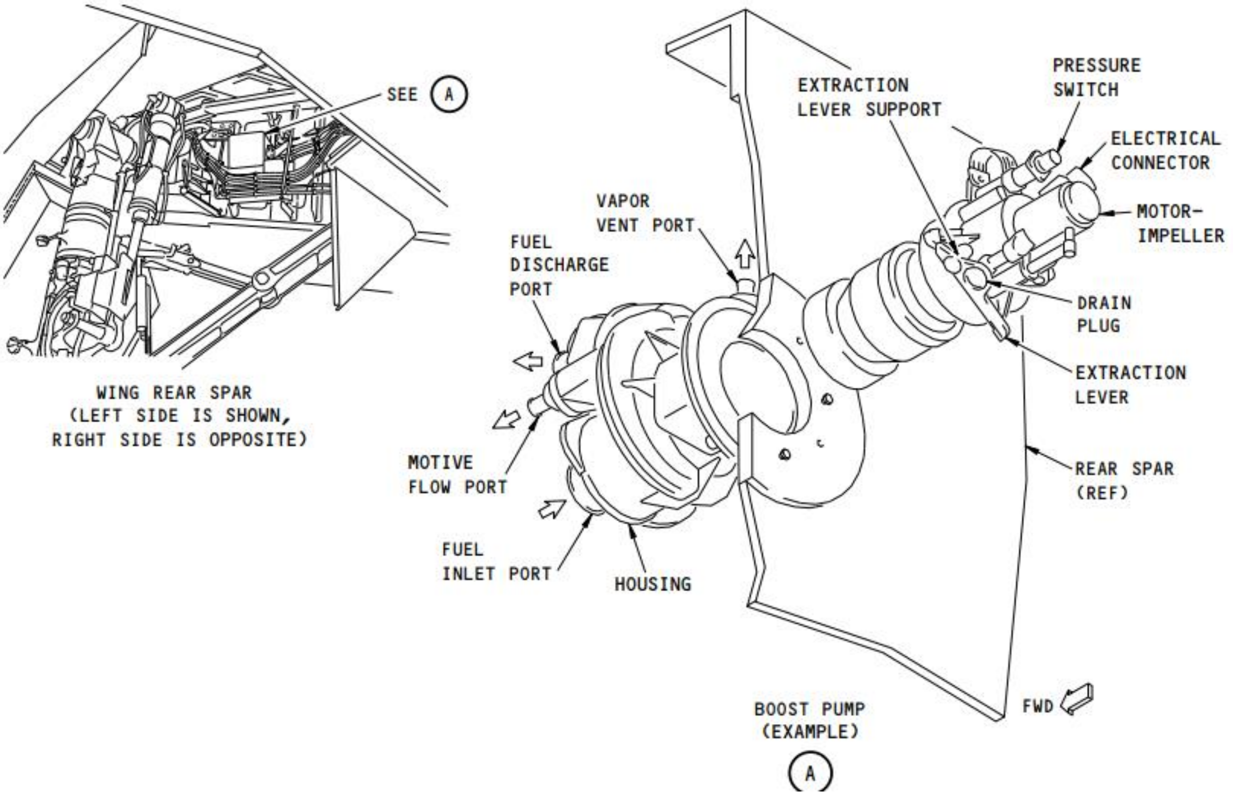


Figure 2.5 – Structural components of boost pump (example)

The APU fuel feed system supplies fuel to the APU during APU operation. The ELMS supplies power to the APU dc fuel pump and APU fuel shutoff valve. The pump operates automatically when the APU selector is in the ON position and there is no pressure in the left engine feed manifold. When there is pressure in the left engine feed manifold, the pump does not operate. The APU fuel feed system can supply fuel to the left engine in the air when there is no pressure in the left engine feed manifold and the left engine is not operating. The ELMS opens the APU isolation valve and turns on the APU dc fuel pump to permit this. The APU fuel feed system has these components (figure 2.6):

- APU DC fuel pump;
- APU isolation valve;
- APU fuel shutoff valve;
- APU isolation check valve.

The ELMS automatically controls the APU dc fuel pump and the APU isolation valve. When you start the APU on the ground and ac power is not available, the ELMS starts the APU dc fuel pump. During flight, if there is an engine flameout, the ELMS can start the APU dc fuel pump and open the APU isolation valve. This lets the dc fuel pump supply fuel to the left engine when the ac boost pumps do not operate.

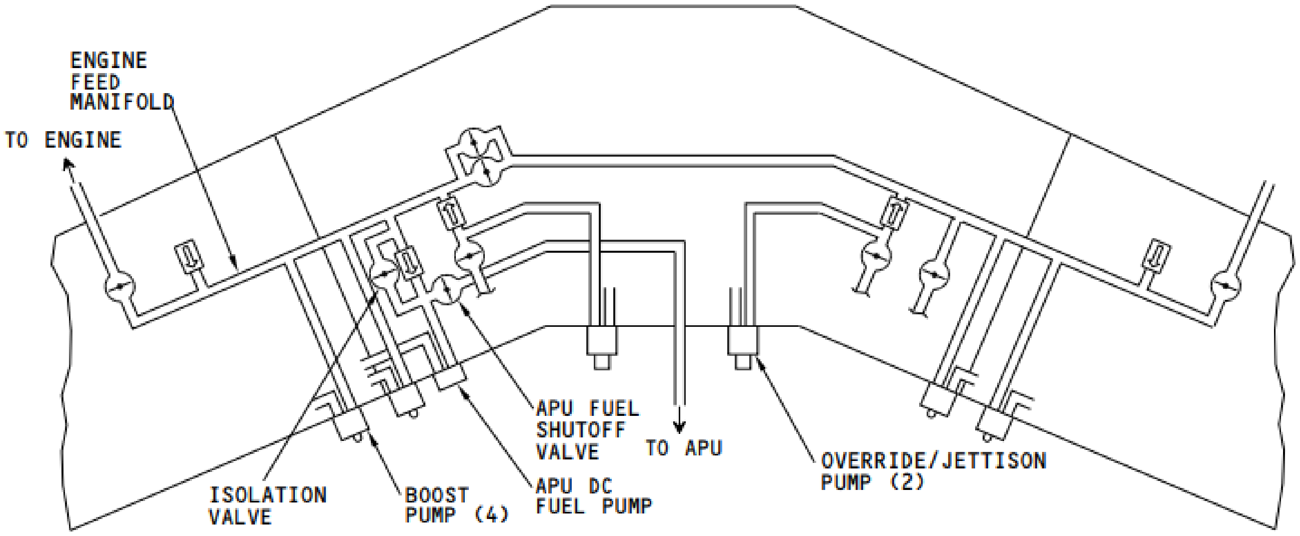


Figure 2.6 – The APU fuel feed system components location

The defuel system moves fuel from the airplane tanks to refuel station. It also moves fuel from one airplane tank into another (tank-to-tank transfer). In general, there are two ways to get fuel out of the tanks: to use the airplane fuel pumps (pressure-defuel) or use ground pumps (suction-defuel). The defuel valve connects the engine feed manifold to the refuel/jettison manifold. The defuel valve is a motor-actuated valve. The valve body is in tubing in the right side of the center tank. The tubing connects to the right engine feed manifold and the refuel/jettison manifold. The valve actuator is on the right rear spar.

The fuel jettison system dumps fuel overboard to reduce the landing weight. It is possible to operate the jettison system from the fuel panel on the overhead panel inside the cockpit. The ELMS controls the fuel jettison system. There are two override/jettison pumps in the center tank and one fuel jettison pump in each main tank. Each pump has a pressure switch that sends a signal through the ELMS. The jettison system has these components:

- Override/jettison pumps;
- Jettison pumps;
- Jettison isolation valves;
- Isolation check valves;
- Refuel/jettison manifold;
- Jettison nozzle valves.

There are two override/jettison pumps in the center tank. They are in the left and right wheel wells on the rear spar. Fuel jettison pumps are in each main tank. They are on the rear spar forward of the flaperons. There is one fuel jettison isolation valve in each section of the center tank. The valve actuators are on the rear spar just outboard from the fuselage. These are the same kind of valve as the other motor-actuated valves in the fuel system. There is a jettison isolation check valve in each section of the center tank. The valve prevents fuel jettison by the left and right main tank fuel boost pump. The jettison pumps supply fuel from the main tank to the refuel/jettison manifold during fuel jettison. The jettison pumps can supply fuel at a pressure of 36 psi and a flow rate of 70,000 pounds (31750 kg) per hour. Each pump assembly has a motor-impeller and a housing.

Fuel indicating − measures fuel quantity in the tanks, fuel temperature, senses fuel pump outlet pressure, controls refuel operations, shows when there is water in the tanks with the help of special aggregates. These are the fuel quantity indicating system components: tank units, densitometers, water detectors, fuel temperature sensor, wiring harnesses, fuel quantity processor unit.

These are a set of different sensors present in the fuel tanks (figure 2.7):

- Tank units (60);
- Densitometers (3);
- Water detectors (3);
- Temperature sensor.

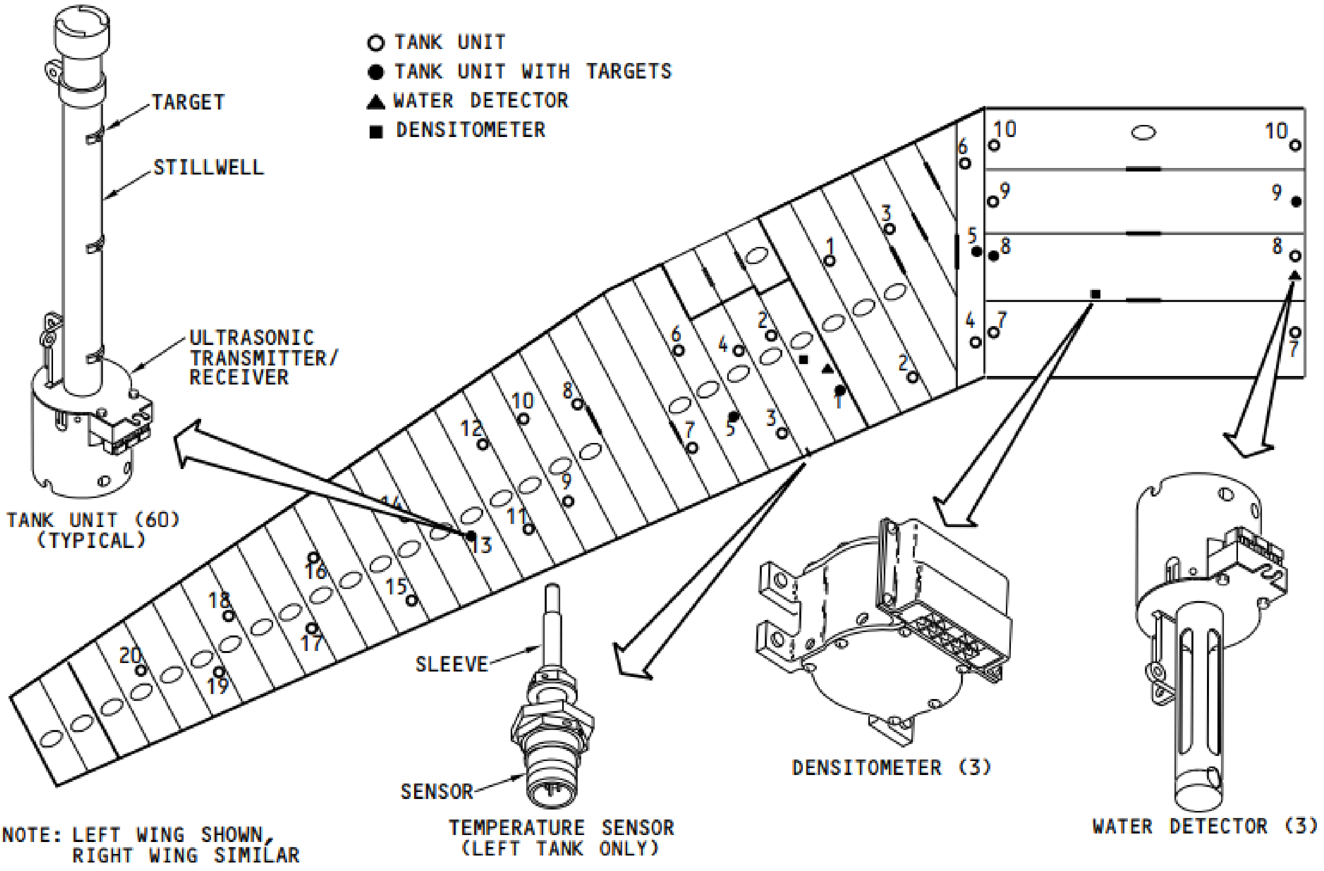


Figure 2.6 – Fuel tank sensors types and their location

The EICAS display shows total fuel quantity and fuel temperature in the lower right corner of the EICAS display. The fuel synoptic display shows individual tank quantities and the total fuel quantity. It also shows the fuel temperature and the minimum fuel temperature. The minimum temperature is 3°C more than the freeze temperature.

As we can see the fuel system of Boeing-777 is a complex unit with a sophisticated set of structural components where each aggregate has a determined purpose and responsibility for its own functions. However, almost all principal units and parts are the same as other models of airplanes. All in all, the aircraft fuel system is a vitally important mechanism where failure/malfunction of which can lead to unpredictable results.

## 2.3 Brief description of the DTS and its principles of operation

For understanding how exactly this sensor will be implemented on AC it is necessary to evaluate which exact data will be monitored and get as much as possible technical data of the DTS. As a fuel system is a complex system, we need an enhanced digital twin model (according to digital twin classification) from the manufacturer whilst the mounting of a set DTS.

Analytics for predicting failures and maintaining automated, live, up-to-date asset health scores usually requires data from multiple modalities. The modalities of DTS may include:

- Parametric data ( temperature, pressure);
- Spectral sensors (raman spectroscopy);
- Image Sensors ( infrared imaging, visible light cameras);
- Free text data (manufacturer comments from service records or other forms of communication);
- Structured database tables (Maintenance databases).

As we can see, the DTS is able to handle data from multiple modalities in a seamless and most efficient way, delivering best-in-class performance using the latest techniques. Representations used to combine information from different modalities and provide new information not possible from each individual source.

For example, the condition assessment of a jettison isolation valve may use sensor data on flow, input pressure, output pressure along with data from an infra-red sensor inspection equipment and also needs to take into account all the text input from maintenance records. The problem is similar for predicting the failure of key components in a boost pump or the rest components of the fuel system. Advanced DTS technologies for fuel system and its aggregates health monitoring can help identify issues at a different stage of a problem developing fuel system health monitoring uses magnetic sensing technologies to monitor fuel flow inside the pipelines and between the connection to boost pumps as they are subjected to outer loads and uses new technology to estimate vibrations and resonance in real-time to provide estimates of individual pipeline health. In addition, this approach can be used to improve boost pump health monitoring, FOHE condition, fuel quality, temperature, etc. Nonetheless, the major problem is that aviation fuel is a liquid, and the presence of water is an indivisible part of this substance. It is very important to monitor not only the quantity of water inside the fuel but also the operation conditions of elements that providing heating, delivering, and feeding engines.

Analyzing all mentioned before it will be logically to emphasize the main advantages of DTS (figure 2.7) :

- Gives more precise information that already present sensors about temperature variations and outer aerodynamic loads during different operating modes of the engines;
- Availability to measure a big quantity of physical parameters under certain extreme conditions;
- Low level of malfunction and high operational reliability;
- The light mass of the whole sensor gives us relatively low weight loss;
- Small dimensions give us convenient methods of mounting onto the pipeline and we do not need to globally change the system;
- Very high level of durability and wearability;
- Better understanding of operating conditions and capabilities, resulting in improved system safety and lower application of resources;
- Possibility of modernization;

- Low maintenance cost.

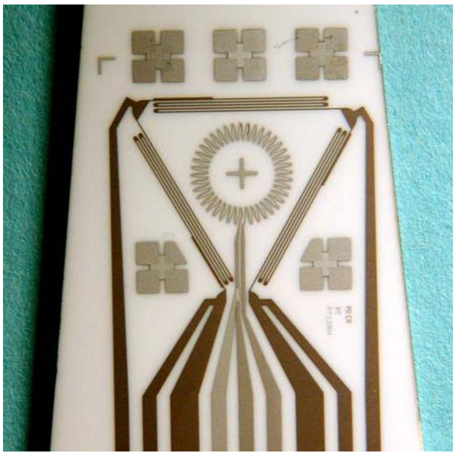


Figure 2.7 – Sample of one of the types DTS

In fact, the entire sensor is a microscopic product, enclosed in a triangle of approximately 1.5 cm on the 50 μm side. Moreover, this sensor possible to apply in different fields of human activity and industry. For simple example implementation of the DTS in engine component testing, the sensor can provide minimally intrusive performance for advanced engines, materials, and components in extreme, high-temperature environments, propulsion system validation, and experimental verification of computational models.

## 2.4 Calculation of DTS reliability

The operating time for failure of the DTS , obtained on the basis of the collection and analysis of statistical data during testing and from working cycles already mounted on other systems, is:

$t_i$ = {0,57; 0,82; 0,93; 1,08; 1,21; 2,22; 3,80; 4,14; 6,72; 8,0}, $m = 10$;

Estimated coefficient of variation of data $v = 0,4$;

Limit relative error $d = 0,15$;

Trust probability $q = 0,85$;

Number of degrees of freedom $K = 1$.

The law of distribution of the DTS operating time for failure - Weibull, the law of distribution of elimination time of the DTS - normal.

We calculate the actual value of the coefficient of variation and the limiting relative error:

$$T_m = \frac{\sum_{i=1}^{m} t_i}{m} \tag{2.1}$$

$$T_m = \frac{(1,77+2,02+3,63+5,08+7,21+10,22+12,80+14,14+16,72+18,0)}{10} = 9,159$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{m} \left(t_{\mathrm{i}} - T_m\right)^2}{m-1}} \tag{2.2}$$

$$\sigma = \sqrt{\frac{(1,77-9,159)^2 + (2,02-9,159)^2 + (3,63-9,159)^2 + (5,08-9,159)^2 +}{10-1}}$$

$$\frac{+(7,21-9,159)^2 + (10,22-9,159)^2 + (12,80-9,159)^2 + (14,14-9,159)^2 +}{}$$

$$\frac{+(16,72-9,159)^2 + (18,0-9,159}{} = 6,065$$

$$\nu = \frac{\sigma}{T_m} \tag{2.3}$$

$$\nu = \frac{6,065}{9,159} = 0,662$$

$$d = max\left\{\frac{T_m - T_{mi}}{T_m}; \frac{T_{ma} - T_m}{T_m}\right\} \tag{2.4}$$

$$d = max\left\{\frac{9,159-1,77}{9,159}; \frac{18-9,159}{9,159}\right\} = max\{0,807;\ 0,965\} = 0,965$$

Since the coefficient of variation $\nu$ = 0,662 less than the specified (0,7), and $d_{\max}$ = 0,965 > 0,2, then we accept the final value of the test volume $N$ = 40.

Taking into account the fact that there are six DTS on the airplane, the number of observed AC should be at least 20.

Estimate of the Weibull distribution parameters

To estimate the parameters of the Weibull distribution $a$ and $b$, we use the method of successive approximations:

$$A = \frac{\sum_{i=1}^{m} \ln t_i}{m} \tag{2.5}$$

$$A = \frac{\ln(1,77) + \ln(2,02) + \ln(3,63) + \ln(5,08) + \ln(7,21) + \ln(10,22) + \ln(12,80) +}{10}$$

$$\frac{+\ln(14,14) + \ln(16,72) + \ln(18,0)}{} = \frac{19,394}{10} = 1,939$$

The initial approximation of the parameter *b*:

$$b_0 = \frac{m+1}{(A - \ln t_i)\cdot(0,23\cdot m + 3,71)} \tag{2.6}$$

$$b_0 = \frac{10+1}{(1,939 - \ln(1,77))\cdot(0,23\cdot 10 + 3,71)} = 1,338$$

On $k+1$ step we compute the approximation $b_{k+1}$:

$$b_{k+1} = \left( \frac{\sum_{i=1}^{m} t_i^{b_k} \ln t_i + (N-m)\cdot t_m^{b_k} \cdot \ln t_m}{\sum_{i=1}^{m} t_i^{b_k} + (N-m)\cdot t_m^{b_k}} - A \right)^{-1} \tag{2.7}$$

Process of calculation $b_k$ is carried out until condition is satisfied:

$$\left| \frac{b_{k+1} - b_k}{b_k} \right| < 0,001 \tag{2.8}$$

$$b_1 = \left( \frac{\sum_{i=1}^{10} t_i^{1,338} \ln t_i + 30\cdot 18^{1,338} \ln 18}{\sum_{i=1}^{10} t_i^{1,338} + 30\cdot 18^{1,338}} - 1,939 \right)^{-1} = \left( \frac{533,616 + 4146,003}{211,651 + 1434,418} - 1,939 \right)^{-1} = 1,106$$

$$\left| \frac{1,106 - 1,338}{1,338} \right| = 0,173 > 0,001$$

$$b_2 = \left( \frac{\sum_{i=1}^{10} t_i^{1,106} \ln t_i + 30\cdot 18^{1,106} \ln 18}{\sum_{i=1}^{10} t_i^{1,106} + 30\cdot 18^{1,106}} - 1,939 \right)^{-1} =$$

$$= \left( \frac{292,245 + 2120,344}{118,704 + 733,589} - 1,939 \right)^{-1} = 1,121$$

$$\left| \frac{1,121 - 1,106}{1,106} \right| = 0,014 > 0,001$$

$$b_3 = \left( \frac{\sum\limits_{i=1}^{10} t_i^{1,121} \ln t_i + 30 \cdot 18^{1,121} \ln 18}{\sum\limits_{i=1}^{10} t_i^{1,121} + 30 \cdot 18^{1,121}} - 1,939 \right)^{-1} =$$

$$= \left( \frac{303,772 + 2214,295}{123,173 + 766,093} - 1,939 \right)^{-1} = 1,120$$

$$\left| \frac{1,120 - 1,121}{1,121} \right| = 0,00089 < 0,001$$

Using the method of successive approximations, we determined $b_3 = 1,120$.

$$a = \frac{\left( \sum\limits_{i=1}^{m} t_i^b + (N-m) \cdot t_m^b \right)^{\frac{1}{b}}}{m} \tag{2.9}$$

$$a = \frac{\left( \sum\limits_{i=1}^{10} t_i^{1,120} + 30 \cdot 18^{1,120} \right)^{\frac{1}{1,120}}}{10} = 42,852$$

Thus, the Weibull distribution parameters:

$a = 42,852$

$b = 1,120$

Evaluation of reliability indicators
Assessment of reliability indicators of the integral section:

a) mean time between failures

$$\overline{T} = a \cdot \Gamma \left( 1 + \frac{1}{b} \right) \tag{2.10}$$

$$\overline{T} = 42,852 \cdot \Gamma \left( 1 + \frac{1}{1,120} \right) = 42,852 \cdot 0,96177 = 42,214$$

b) probability of failure-free operation

$$P(t) = e^{-\left( \frac{t}{a} \right)^b} \tag{2.11}$$

$$P(t) = e^{-\left( \frac{9,159}{42,852} \right)^{1,12}} = 0,837$$

c) probability of failure

$$q(t) = 1 - P(t) \tag{2.12}$$

$$q\left(t\right)=1-0,837=0,163$$

d) failure rate

$$\lambda\left(t\right)=\frac{b}{a}\cdot\left(\frac{t}{a}\right)^{b-1} \qquad (2.13)$$

$$\lambda\left(t\right)=\frac{1,120}{42,852}\cdot\left(\frac{9,159}{42,852}\right)^{1,12-1}=0,022$$

In order to collect data on the reliability of the DTS, a surveillance plan is chosen, involving unlimited monitoring of 60 DTS (20 AC).

According to the data obtained during the implementation of the observation plan, it is determined that the time between failures of the DTS has a Weibull distribution with parameters:

$a$ = 42,852

$b$ = 1,120

The obtained values of the distribution parameters allowed us to estimate the probability of failure of the sensors and the mean time between failures:

$\overline{T}=42,214$

$q(t)=$ 0,163

Thus it can be seen that the failures of the DTS occur periodically, most often the electrical part fails. Therefore, it is necessary to develop a procedure for replacing the sensor, which allows reducing the labor capacity and the time of servicing the fuel system of the Boeing-777 in different modifications.

### 2.5 Calculation of the efficiency of the fuel system with installed DTS and with implementation of DTT.

Calculation of leakage in the slot seals in a boost pumps of the impeller.

$D_{\text{y}}=95\text{mm}$ - packing diameter;

Radial gap in the slot: $\delta=10^{-3}D_{\text{y}}=10^{-3}\cdot 95=0,095\text{mm}$, but $\delta$ should not be less than 0,2 mm [13], therefore we take $\delta = 0{,}2\mathrm{mm}$;

Calculation of leakage:

$$Q_{\mathrm{y}} = \mathrm{m p}\, D_{\mathrm{y}}\, \mathrm{d} \sqrt{2gH_{\mathrm{y}}} \tag{2.14}$$

where:

$H_{\mathrm{y}}$ - differential pressure on the seal;

$\mu$ - coefficient of slot seal flow;

$$H_y \approx \left( H_T - \frac{V_{2u}^2}{2g} \right) - \frac{U_2^2 - U_y^2}{8g} = H_T - \frac{V_{2u}^2}{2g} - \frac{U_2^2}{8g}\left( 1 - \frac{D_y^2}{D_2^2} \right), \tag{2.15}$$

where $H_T = \dfrac{H}{\eta_\Gamma}$;

$\mathrm{V}_{2\mathrm{u}}$ - circumferential component of the absolute flow velocity at the outlet of the impeller, if $\mathrm{V}_{1\mathrm{u}} = 0$: $V_{2u} = \dfrac{gH_T}{U_2}$;

$U_2 = \mathrm{w}\dfrac{D_2}{2}$ and $U_{\mathrm{y}} = \mathrm{w}\dfrac{D_{\mathrm{y}}}{2}$ - portable velocities at corresponding radii;

$\mathrm{h}_{\mathrm{g}}$ - The efficiency of the boost pump can be determined from the empirical formula of Lomakin [14]:

$$1-\ \mathrm{h}_{\mathrm{g}} = \frac{0{,}42}{(lg\,\mathrm{D}_0 -\ 0{,}172)^2} = 0{,}19\, \text{Ю}\, \mathrm{h}_{\mathrm{g}} = 0{,}855;$$

$$U_2 = 303{,}5 \cdot \frac{0{,}2}{2} = 30{,}35 m/s; \quad U_y = 303{,}5 \cdot \frac{0{,}095}{2} = 14{,}42 m/s;$$

$$H_T = \frac{50}{0{,}855} = 58{,}5m, \text{ whence} V_{2u} = \frac{9{,}81 \cdot 58{,}5}{30{,}35} = 18{,}9 m/s;$$

$$H_y = 58{,}5 - \frac{18{,}9^2}{2 \cdot 9{,}81} - \frac{30{,}35^2}{8 \cdot 9{,}81}\left( 1 - \frac{95^2}{200^2} \right) = 31{,}2m;$$

$$\mu = \frac{1}{\sqrt{\zeta_{\text{in}} + \lambda_{\text{sl}} \frac{C}{2\delta} + \zeta_{\text{out}}}} = \frac{1}{\sqrt{(1,3 \div 1,35) + \lambda_{\text{sl}} \frac{C}{2\delta}}},$$

(2.16)

Where C - clearance length, $C = 8\text{mm}$;

$\lambda_{\text{sl}}$ – coefficient of frictional resistance in a slot;

$$\lambda_{\text{sl}} = \lambda \sqrt{1 + \frac{1}{4\left(1 + 1,3\sqrt{\lambda}\right)^2} \left(\frac{U_{\text{y}}}{V_0}\right)^2}\text{, or } \lambda_{\text{sl}} \approx \lambda \sqrt{1 + \left(\frac{V_{\text{u}}}{V_0}\right)^2};$$

$$V_{\text{u}} \approx \frac{U_{\text{y}}}{2} = \frac{14,42}{2} = 7,21\text{m/s};$$

$V_0 = \mu\sqrt{2gH_{\text{y}}}$ - flow velocity in the gap;

In the first approximation we take $\mu = 0,6$, then:

$$V_0 = 0,6\sqrt{2 \cdot 9,81 \cdot 31,2} = 14,8 m/s;$$

$\lambda$ - coefficient of friction resistance for pipelines, we take in accordance with the Reynolds number:

$$Re = \frac{2\delta\sqrt{V_0^2 + V_{\text{u}}^2}}{\nu} = \frac{2 \cdot 0,0002\sqrt{14,8^2 + 7,21^2}}{1,5 \cdot 10^{-6}} = 4390,1, \quad \text{then:}$$

$$\lambda = \frac{75}{Re} = \frac{75}{4390,1} = 0,017; \quad \text{then } \lambda_{sl} = 0,017\sqrt{1 + \left(\frac{7,21}{14,8}\right)^2} = 0,019;$$

$$\mu = \frac{1}{\sqrt{1,33 + 0,019\frac{8}{2 \cdot 0,2}}} = 0,76;$$

In the second approximation:

$$V_0 = 0,76\sqrt{2 \cdot 9,81 \cdot 31,2} = 18,8 m/s;$$

$$Re = \frac{2\delta\sqrt{V_0^2 + V_u^2}}{\nu} = \frac{2 \cdot 0,0002\sqrt{18,8^2 + 7,21^2}}{1,5 \cdot 10^{-6}} = 5369,4;$$

$$\lambda = \frac{75}{Re} = \frac{75}{5369,4} = 0,014; \qquad \lambda_{\text{sl}} = 0,014\sqrt{1 + \left(\frac{7,21}{18,8}\right)^2} = 0,015;$$

$$\mu = \frac{1}{\sqrt{1,33 + 0,015\frac{8}{2\cdot 0,2}}} = 0,79\,;$$

In the third approximation:

$$V_0 = 0,79\sqrt{2\cdot 9,81\cdot 31,2} = 19,5m/s\,;$$

$$\mathrm{Re} = \frac{2\delta\sqrt{V_0^2 + V_u^2}}{\nu} = \frac{2\cdot 0,0002\sqrt{19,5^2 + 7,21^2}}{1,5\cdot 10^{-6}} = 5544,1\,,$$

$$\lambda = \frac{75}{Re} = \frac{75}{5544,1} = 0,0135\,; \qquad \lambda_{\mathrm{sl}} = 0,0135\sqrt{1 + \left(\frac{7,21}{19,5}\right)^2} = 0,014\,;$$

$$\mu = \frac{1}{\sqrt{1,33 + 0,014\frac{8}{2\cdot 0,2}}} = 0,788\,; \quad => \quad \mu = 0,79\,, \quad \text{whence}$$

$$Q_y = 0,79\cdot 3,14\cdot 0,095\cdot 0,0002\sqrt{2\cdot 9,81\cdot 31,2} = 1,17\cdot 10^{-3}\,.$$

For sealing between stages:

$$Q_{y2} = \mu\pi D_{y2}\delta\sqrt{2gH_{y2}}\,,$$

where: $H_{y2} = \frac{gH_T}{2U_2^2} + \frac{U_2^2}{8g}\left(1 - \frac{D_{y2}^2}{D_2^2}\right);$

$$D_{y2} = 42,6\mathrm{mm} \Rightarrow H_{y2} = \frac{9,81\cdot 58,5}{2\cdot 30,35^2} + \frac{30,35^2}{8\cdot 9,81}\left(1 - \frac{42,6^2}{200^2}\right) = 11,52\,\mathrm{m}\,;$$

$C = 15,7\mathrm{mm};\ \delta = 0,3\mathrm{mm};$

$$V_u \approx \frac{U_y}{2} = \frac{\omega D_{y2}}{2}\cdot\frac{1}{2} = \frac{303,5\cdot 42,6\cdot 10^{-3}}{2}\cdot\frac{1}{2} = 3,23m/s\,;$$

$$\mu = \frac{1}{\sqrt{(1,3\div 1,35) + \lambda_{\mathrm{sl}}\frac{C}{2\delta}}}\,; \qquad \lambda_{\mathrm{sl}} \approx \lambda\sqrt{1 + \left(\frac{V_{\mathrm{u}}}{V_0}\right)^2}\,; \qquad V_0 = \mathrm{m}\sqrt{2\,gH_{\mathrm{y}}}\,;$$

In the first approximation we take $\mu = 0,6$, then:

$$V_0 = 0,6\sqrt{2\cdot 9,81\cdot 11,52} = 9,02m/s\,;$$

$$Re=\frac{2\cdot 0,0003\sqrt{9,02^2+3,23^2}}{1,5\cdot 10^{-6}}=3832,3;$$

$$\lambda=\frac{75}{3832,3}=0,02; \qquad \lambda_{sl}=0,02\sqrt{1+\left(\frac{3,23}{9,02}\right)^2}=0,017;$$

$$\mu=\frac{1}{\sqrt{1,33+0,017\frac{15,7}{2\cdot 0,3}}}=0,75;$$

In the second approximation:

$$V_0=0,75\sqrt{2\cdot 9,81\cdot 11,52}=11,27m/s;$$

$$Re=\frac{2\cdot 0,0003\sqrt{11,27^2+3,23^2}}{1,5\cdot 10^{-6}}=4689,5;$$

$$\lambda=\frac{75}{4689,5}=0,016; \qquad \lambda_{sl}=0,016\sqrt{1+\left(\frac{3,23}{11,27}\right)^2}=0,017;$$

$$\mu=\frac{1}{\sqrt{1,33+0,017\frac{15,7}{2\cdot 0,3}}}=0,75;$$

$\mu=0,75$, whence $Q_y=0,75\cdot 3,14\cdot 0,0426\cdot 0,0003\sqrt{2\cdot 9,81\cdot 11,52}=0,45\cdot 10^{-3}$.

$$\eta_{0cm}=\frac{Q}{Q+q_{ym}}=\frac{0,0167}{0,0167+1,17\cdot 10^{-3}+0,45\cdot 10^{-3}}=0,94\ \%;$$

According to obtained results, efficiency of fuel system operation is much greater than the generally accepted operational efficiency without implementation of DTT and mounted DTS: $\eta$=0,9 %.

### 2.6 Increasing operational efficiency and reliability of the fuel system due to installation of DTS and involvement of DTT on Boeing-777

In general, DTT in the aviation industry is already doing their job. For example, digital twins of equipment and predictive analytics reduce fleer downtime by up to 12% increasing the efficiency of the fuel system, when designing digital twins, they reduce the time spent on the process by up to 30%, and the rate of personnel training using digital twin technology increases by 50%. As a result, airlines using modern innovative technologies are adapting to faster conditions that increase the efficiency and effectiveness of funds that directly affect their competitiveness.

DTS for advanced aeronautical and aerospace research applications must be capable of operating in environments where stress and temperature gradients and aerodynamic factors are high, or sensors must be kept to a minimum. The multifunctional thin-film sensor, developed at NASA's Glenn Research Center, integrates into smart sensor designs for sensors that measure:

- the magnitude and direction of deformation stress;
- heat flow;
- surface temperature;
- speed and direction of flow.

The entire sensor is a microscopic product, enclosed in a triangle with an area of approximately 1.5 cm on the side with a thickness of 50 μm. Designed for applications, material systems and engine component testing, the sensor can provide minimally intrusive performance for advanced engines, materials and components in hostile, high-temperature environments, propulsion system validation, and experimental verification of computational models.

DTT system allows for:

- automatic detection and correction of drift in the Digital Twin;
- adaptation to changing conditions, both locally (for the asset) and globally (for all assets);
- highest performance levels when predicting future observations of the fuel system condition has a unique ability to build and update models using Artificial Intelligence that searches through model libraries to identify the best performing models.

This method uses a Genetic algorithm-based evolutionary search algorithm that searches through various Classification, Regression, Clustering, and Physics-based models to identify the best new models or model parameters that match closely with the performance of the physical assets. In addition, transfer learning and active learning techniques are applied where domain knowledge and human guidance is required during the model updating process. This approach allows for rapid model development and continuous model updates so the Digital Twin maintains perennial correspondence to the physical asset.

## CONCLUSION TO PART 2

As it is shown the implementation of DTT will play a very important role in the lifecycle of the aircraft fuel system and in servicing works. But the realization of this technology needs enough investments and innovative cloud infrastructure. So, that’s where DTT really comes up and proves that it is capable to improve maintenance and diagnostic processes in the modern aviation field especially in the decreasing of the maintenance cost, conveniently in control of all parameters remotely at any time, even from mobile devices, improvement of fault earlier detection and statistical reports which help to construct an appropriate servicing program of the fuel system. It also can increase mission reliability, extend the duration of life-limited components, and of course increase maintenance quality, without compromising any safety or reliability issues.

A digital twin monitoring system would immediately have a beneficial impact on safety as well as cost savings for airplane operators. First and foremost, having an accurate and reliable digital twin system will better ensure the safety of the aircraft. The system of sensors can be placed in the most remote and hard to inspect areas of the fuel system providing detailed information in fully automatic comparison with artificial analog with the help of wireless connection. The DTT will show the possibility of eventual failure, even when the aircraft is in the air.

Analysis of the standard maintenance procedures on the example of Boeing-777 was made. We considered most frequent failures, typical servicing works with units of fuel system. The obtained results demonstrate that fuel system failures are occurring relatively often in case of huge necessity of human resource and non-opportunity of remote prediction of any system faults in different flight modes. So the implementation of the DTT is highly recommended. This system will allow monitoring and predicting failures before they can lead to unexpected results which in some cases can cause catastrophic situation.

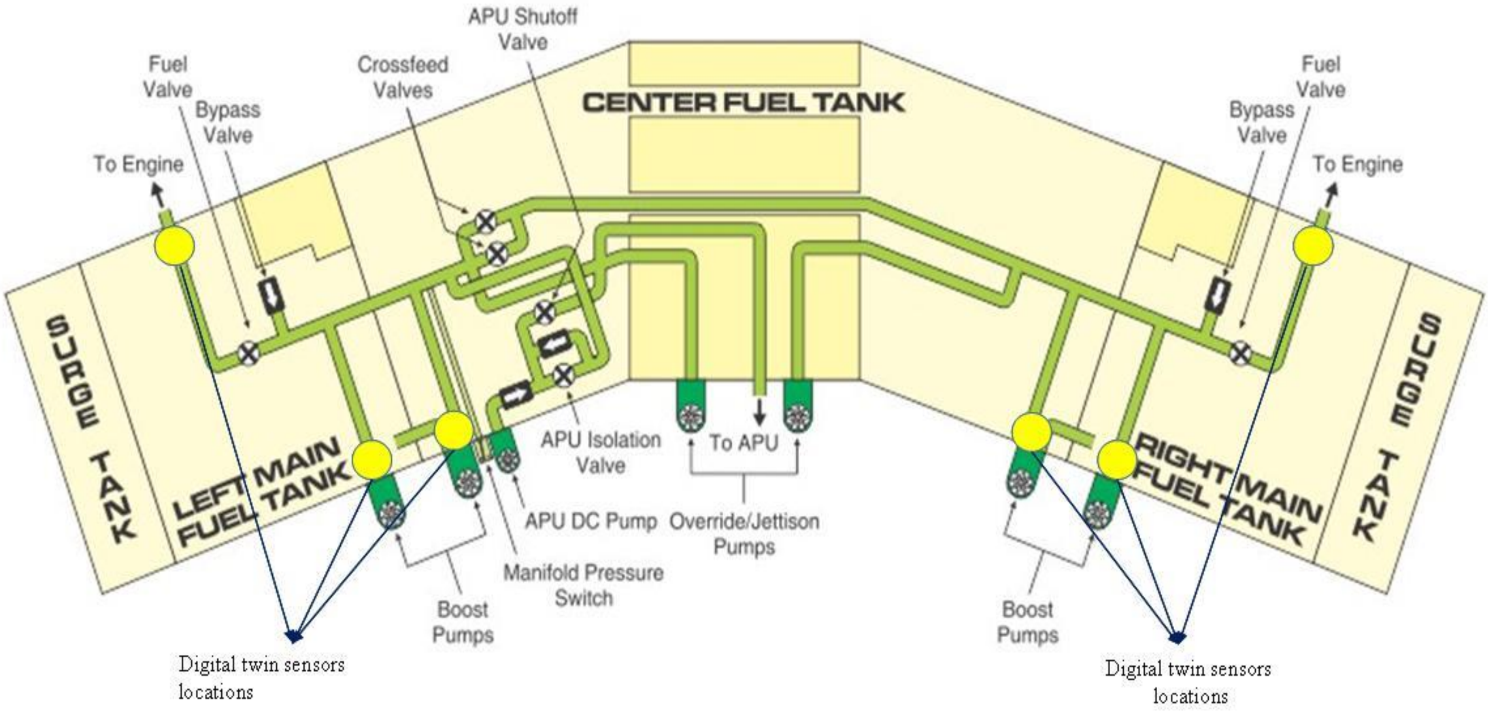
# CHAPTER 3

## ANALYSIS AND OPTIMIZATION OF THE DTT DESIGN

### 3.1. Possible locations of DTS

The constantly expanding variety of different sensors including DTS demonstrates difficulties in resolving the contradiction between the requirements of the economy and reliability. With the increase of the load for sensors during any phase of flight and

Scheme of the fuel system with location of digital twin sensors



accomplished calculations of failure rate, it will be logically demonstrating the possible design of DTS likely locations in fuel system structure (figure 3.1).

Figure 3.1 – Scheme of the fuel system with location of DTS

Thus, the proposed places of location of the DTS aimed at eliminating the shortcomings of existing problems and increasing operability of the fuel system will increase its level of operational reliability. The DTS takes into account not only a large number of factors but also the relationship between them. Therefore, it is excellent for the complex system in the process even if we are talking about the operation at high altitudes. Moreover, the DTT leverages advances in Artificial Intelligence (AI) in several ways that make it scalable for future challenges and growth:

- new AI technology is addressing the massive amounts of unstructured data that enterprises must deal with in the lifecycle of a part and asset. It is estimated that 80% of all data will continue to be unstructured, and AI enables machines to read and understand diverse data, connecting to common and shared semantics, and finding mistakes and quality issues that can be automatically correctly;
- semi-automation is provided by AI and integration of complex tasks like configuring models and analytics, and understanding error progation through systems of models.

Airlines and operators who understand how analytics and data can help them finally control their operations, financial decisions and maintenance works to a level not yet seen understand the competitive and business growth advantages of the Digital Twin.

### 3.2 Material and structural components of DTS

Fiber Bragg grating (FBG), which is an in-fiber component, consists of a periodic modulation of the index of refraction along the fiber core, as shown in figure 3.2, FBG functions like a filter when a broad-band light is transmitted into the fiber core, reflecting light at a single wavelength, l , and a single wavelength is filtered in the transmitted light spectrum.

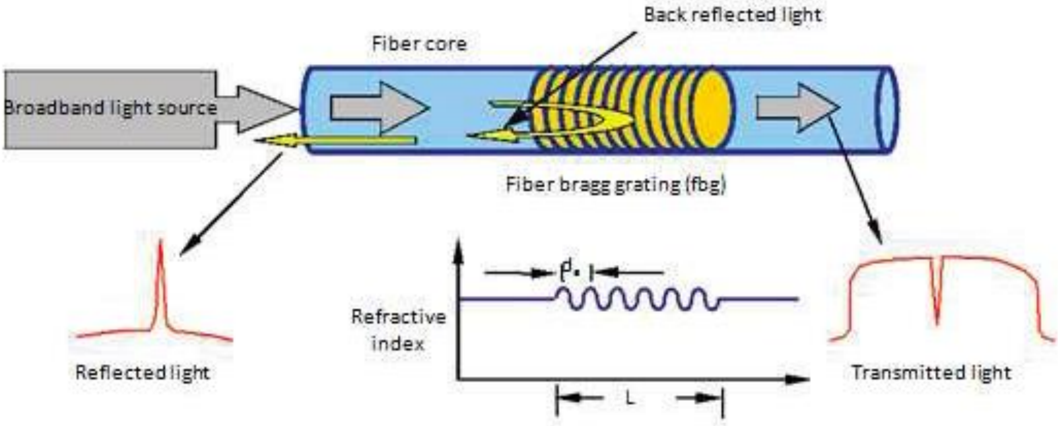


Figure 3.2 — Schematic diagram of Fiber Bragg Gratings

When there is a force exerted on the FBG, it will compress or expand, thus the grating spectral response is changed.

In order to be able to use a network of FBG sensors in a wide range of situations, the preferred choice would be a system with a scan rate variable in the required range. The scan rate should also be related to the high number of sensors that is usually required for high-spatially-resolved structural monitoring. Furthermore, in order to comply with aerospace requirements, the interrogation system should be light, small, low-power consuming and immune to electromagnetic interference.

The interrogation systems that have been developed to date are usually suitable for different measurement frequency ranges. The simplest available FBG interrogator is the conventional optical spectrum analyser, which is however cumbersome, costly and offers only low speed scanning. Below 1 kHz, it is possible to use tunable Fabry-Perot filters to realise wavelength sweeping by means of mechanical moving parts. For measurements from 1 kHz to 20 kHz, a combination of a CCD array and a diffractive grating has proved effective. Instead between 20 and 500 kHz, primarily three methods have been reported in the literature: the use of a laser diode with output wavelength centred in the middle of spectrum; a Fabry-Perot filter with a broadened and fixed spectrum; and an arrayed waveguide grating (AWG) with fixed spectrum. Of these, the concepts of laser diode and arrayed waveguide grating are the most reliable. If the laser diode is replaced by a tunable laser source, it becomes possible to operate the interrogator in the wavelength-sweeping mode for the measurement of strains due to operational loads. However, it is not feasible to operate the system simultaneously in the two modes. Instead, an AWG, the core device used for wavelength division multiplexing (WDM) in optical communication systems, can be used to overcome this problem; it has already been used successfully for the interrogation of FBG sensors. Unlike systems based on a laser diode or a tunable laser source, the AWG-based system can achieve both high resolution and broad range, thus enabling both high speed and accurate monitoring of quasi-static strains. In addition, this type of system is lightweight and can be miniaturised.

Recently, was developed a wavelength interrogation system based on an Echelle diffractive grating (EDG), which deploys planar light wave circuits technology offering the same functionality as an AWG. The interrogation system based on EDG is capable of achieving a wavelength resolution of less than 1 pm with a measurement accuracy of ±10 pm and a scan rate of 300 kHz. Both low and high scan rate are provided, by using dedicated channels. In the "sweeping mode", the transmission wavelength of the EDG channel is tuned by adjusting the EDG chip temperature allowing load monitoring, while in the "parked mode" the transmission wavelength of all EDG channels is fixed and can be used for damage detection.

Besides universities and research centers, a number of companies have also been developing novel interrogation systems, which in some cases are already available on the market. In particular, three novel solutions have been proposed recently by industry. A lightweight, high-speed and self-powered fibre optic sensor system based on the use of monolithic photonic integrated circuit (PIC) microchip technology in order to integrate and miniaturise the optical and optoelectronic components; reportedly the system is capable of measuring static and dynamic data over a range of ±4000 $\mu\varepsilon$, at sampling frequencies of up to 500 kHz, therefore being suitable for the real time detection of operating load, fatigue and damages. Parallel processing interrogator that allows massive multiplexing of a high number of FBG sensors sampled at high rates. Groups of up to 16 sensors can be sampled simultaneously up to 1 MHz on a single fibre with the capability of switching between multiple fibres in the kHz range. Also in this case, the solution allows for smart composite sensing applications ranging from low-frequency load monitoring applications to ultra-high frequency acoustic emission (AE) monitoring and Lamb-wave based damage detection. In recent years, NASA and the company 4DSP LLC have collaborated on the design of a commercially available, quasi-distributed, fibre-optic-based system for gathering large amounts of data from massive multiplexing of FBG sensors at a high sampling rate with 1 με resolution this instrument uses a tunable laser source and a Michelson interferometer to interrogate up to 64 separate sensors arrays, each comprising up to 2000 sensors located along a fibre cable with a length of up to approximately 24 m. The interrogation algorithm can support a 100 Hz sweep capability, making the system suitable for highly spatially resolved measurements of the aircraft structural shapes.

Finally, it is worth mentioning a recent strategy for FBG sensor interrogation that addresses the lack of robustness associated with multiplexing FBG sensors in one or more fibre arrays.

In order to overcome this lack of redundancy, Wild developed a sensing architecture called Distributed Optical Fibre Smart in which a large number of Smart Transducer Interface Modules are positioned at the nodes of an all-fibre sensor network for the simultaneous distribution of sensing, power and communication.

While structural health monitoring using fiber Bragg sensors is promising and has been used successfully in several applications, there are still some challenges and questions that need to be resolved before implementation of such a system would be possible. Fiber sensors need to be proven to be durable and reliable for the life and operating conditions of the structure, especially where the fibers are embedded in the structure and cannot be replaced. Similarly for sensors bonded on the outside of the structure, that bond must be durable for the life of the structure in order for the system to function properly.

There are numerous benefits to use fiber Bragg sensors as a structural health monitoring system. The fibers are light, small, and geometrically flexible allowing them to fit into tight spaces without interfering with the structure. Fiber Braggs are immune to electromagnetic interference, radio frequency interference, radiation, corrosion, and can be safely used in high temperature and explosive environments. Fiber Bragg sensors can be used without changing the conductivity of the parent material, which is important for lightning strike considerations. With multiplexing, a single fiber can measure hundreds of points with sub millimeter resolution**.** The sensors have a high bandwidth, can measure multiple parameters simultaneously, have a low signal to noise ratio, and show little deterioration over time. Fiber sensors have the capability of being bonded externally to structure or embedded within the material.

## CONCLUSION TO PART 3

In the 3rd part it was expected that implementing of the structural health monitoring system is highly important. Also the layout of the sensors and the network system were proposed. There are a lot of benefits of such technology. First of all it allows to perform constant monitoring of the state of the structure. Secondly it can determine the damage or crack propagation at its very first stages which allows to perform repair works very quickly without letting the damage to spread further. Also such network allows quick access diagnostics for regular technicians as well as extended mode for certified engineeres to perform deeper investigation of the damage and crack propagation.

Fiber Bragg sensors were choosen as the most optimal variant due to their simple principle of work, ability to work in both directions, compression and extension and also their resistance to numerous harmful factors. The most suitable for FBG sensor location is joining area between composite body shell and underframe, because this is the most stressed parts of the fuselage. This technology is relatively new on the market but it constantly growing and developing. We considered the structure of FBG sensor, it’s operation features.

The direct cost benefits from implementing such system are obvious. An online system would reduce (and ideally eliminate) the need for time based inspections, so the labor and man-hours associated with visual and nondestructive inspection and disassembly/reassembly can be eliminated. An additional direct cost associated with current commercial aviation practices is the removal and replacement of undamaged or slightly damaged parts prior to the end of their useful life. Indirect cost benefits from an online structural health monitoring system are also varied. The greatest, benefit is that the airplane structure can be used to its full lifetime, which, by necessity, is longer than the current design lifetime. Transport airplanes could continue to fly for as long as it is economical, knowing that the life of the plane will be determined by the actual performance of the structure.

# CHAPTER 4

# LABOUR PRECAUTION

## 4.1 Factors with adverse contributing effect that are in place for the operation and repair of the Boeing-777 AC fuel system

First of all, requirements for maintenance of the fuel system of the AC must be observed in accordance with the rules of «Actions of safety features at working places during maintenance procedures» (ССБТ. ГОСТ 12.0.230.2-2015). There are some set of operational hazards which can occur during maintenance of the AC fuel system:

- increased of dust and gas contamination in the service area;
- harmful products of engine exhaust gases and liquids with hazardous content from vessels and AC pipelines what experience pressure loads;
- non-regulated noise, vibrations;
- dimmed lightning places where maintenance procedures conducting;
- decreased or even increased values of temperatures of any AC, material surfaces and different tools;

- self-driven machinery, vehicles of special demands and purposes for other vehicles;
- edges with sharp angles with different roughness;
- insufficient delivery of natural light;
- developing of shock wave (explosion, vapors from flammable fluids);
- highly positioned AC parts with complicated access to them;
- high level of static electricity;
- presence of hazardous chemical components that are residuals or the main part in percentage of fuel and lubricants;
- real danger for inadvertently slip (due to icing, humidification at high level of the surfaces of AC, ladders and coverings of parking places);
- tools and materials for maintenance of AC which can fall and damage structural parts of the aircraft likely stabilizer, fuselage frame and when at height conducting the maintenance using mechanized lifts;
- any part of the constructions (production tools and equipment, side staircases or simple stairs).

In fact, there are many hazardous contributing factors at any producing or repairing organization. So, it is necessary to evaluate all negative moments before involving of any labour precaution actions. If an employee field of work out of the airport buildings, the noise level should not exceed 50 dB. Furthermore, workers who zone o responsibility located in the production area of the airport, including on-site parking of AC, the apron, and the noise level should not exceed 85 dB according to the "Safety Rules for Maintenance and Maintenance of Aviation Equipment":

- humidity increasing about 70 %;
- level of humidity reduction to 30 %;
- workplaces new location at a height of 1 m relative to the ground surface (for servicing engines, fuel caissons etc.).

### 4.2 Technological measures aimed to reduce the level of exposure to hazardous and harmful production factors during operating the fuel system of an AC

In this part I would like to overview technological measures what are proposed to reduce the hazardous and harmful production factors arising from various forms of maintenance of the AC system.

Simply stated that can be different variations of this problem but to attain some level of exposure to hazardous and harmful production factors reduction it is necessary to use useful methodological bases. Hygienic standards in the parameters of the microclimate in the working area are given in Interstate standard due to ГОСТ 12.0.230.2-2015 («General sanitary and hygienic requirements for the air of the working area»). Working area should extend at least for up to 2 m above the floor or ground, where all maintenance procedures were planned to conducted. Permanent jobs is considered, that job when we can make an assessment more than half of whole time, or more than 2 hours continuously. Additionally, these restrictions haven’t to be hesitated because with increasing of some incapacitation increases effectiveness of committed works. Working in different places n different time arrangements, then it's all think of permanent jobs.

Finally, to prevent or reduce the impact of hazardous and harmful production some actions have to be provided and the following activities have been developed:

- briefing conducting for drivers special transport with basic traffic rules and access to the AC;
- the speed of movement of special vehicles and self-propelled vehicles in the parking areas and on the platform should be no more than 20 km / h. At the entrance to the serviced AC, before reaching it - 10 m the driver is obliged to stop the car and start the approach at a speed of no more than 5 km / h under the direction of the official currently responsible for the AC;
- for the maneuvering of special vehicles there are one-way gates with a width of 3.5 m;
- to reduce the dustiness of the working area in the open area, it is envisaged to use special machines that clean the soil with a strong stream of water, in enclosed spaces, the use of natural and forced ventilation;

- on the platform, in the hangar there are sources of artificial lighting;
- portable electric lamps with a voltage of 28 V;
- when working on caissons-tanks, portable explosion-proof lamps with a voltage of 28 V;
- for the removal of static electricity in the hangar and in the parking lot of the AC installed wells, for grounding AC;
- in order to reduce the influence of noise from running engines, when it is necessary to check the tightness of the fuel system, it is envisaged to use anti-noise headphones;
- in order to reduce toxic fumes of fuel (the maximum permissible concentration is 300 $mg/m^3$), when working in fuel tanks, mandatory use of personal protective equipment of respiratory organs;
- in works related to open fuel volumes, special silicate ointments are used to protect open parts of the body;
- when working on high-lying parts of the power plant, tools and equipment are located on the staircases in the sorts, so that they do not fall and injure maintenance personnel;
- for eliminating of the increased pollution, stands are periodically cleaned of dirt, ice, snow, and also the using of specially designed footwear is obligatory;
- system of ventilation of the AC hangar uses the circulation of warm dry air in the winter and cold in the summer.

Main idea is to create a healthy environment in the maintenance zones of the fuel system, fresh air enters to the working area.

### 4.3 Calculation of ventilation of the hangar when servicing the Boeing-777

Hangars are used to service the fuel conditioning system. Since the fuel is less harmful to human health, the evaporator should be equipped with ventilation.

The amount of fresh air required to dilute harmful emissions to an acceptable concentration is calculated using the formula: $Q = 3600 \cdot \mu \cdot A \cdot \sqrt{\frac{2 \cdot g}{\gamma_{н}}} \cdot H$ [m$^3$/hour], (4.1)

where $\mu$ = 1 - Supply air flow coefficient for rectangular opening;

$A$ – area of supply air holes, m$^2$;

$g$ = 10,81 – acceleration of gravity, m/c$^2$;

$\gamma_{н}$ = 9,25 – specific gravity of air, N/m$^3$;

$H$ - thermal head, Pa.

To obtain some measurements data of the area of the supply holes we should determine the overall space of the hangar.

Hangar area is determined like digit based on the geometric dimensions of the AC

- Length of AC L = 51 m;
- Wingspan Lк = 34 m.

Distance between AC to the wall of the hangar should be at least - 6 m for special vehicle corridors and stairs. The distance between the extreme points of the wings must be at least - 10 m.

Area according to data of intake openings:

$$A = 2 \cdot 2 \cdot 25 = 100 \text{ (m}^2\text{)}.$$

Obtained area:

$$S = a \cdot b \text{ (m}^2\text{)}, \quad (4.2)$$

$$S = 80 \cdot 90 = 7200 \text{(m}^2\text{)}.$$

Sizing holes dimensions $2 \times 2м$; Number of holes 29.

The thermal head is generated in the chamber due to the difference in the specific weight of the air at the bottom and at the top of the room.

$$H = h \cdot (\gamma_H - \gamma_{в})[\text{Pa}], \qquad (4.3)$$

Where $h$ - height between the centers of the fence and the outlet, m;

$\gamma_{н}$, $\gamma_{в}$ - specific gravity of air inside and outside the room, N/m$^3$.

$\gamma_{н} = 12,25\ N/m^3$,

$\gamma_{в} = 12,23\ N/m^3$,

$h = 25\ m.$

Then the heat head:

$$H = 25 \cdot (12,25 - 12,23),$$

$$H = 0,5(\text{Pa}).$$

$$Q = 3600 \cdot 1 \cdot 100 \cdot \sqrt{\frac{2.9,8}{12,25} \cdot 0,5}\ ,$$

$$Q = 250452\ \left(\text{m}^3/\text{h}\right).$$

Having obtained the required pressure and efficiency of the fan, we chose the fan. with the following features:

$H = 0,5\ Pa,$

$\eta = 0,55\%,$

$Q = 250452\ m^3/h.$

Selection of the fan motor.

Statistical power of the electric motor is represented by the formula:

$$N = \frac{\text{H} \times \text{Q} \times \text{B}}{3600 \times 102 \times h}\ [\text{kW}], \qquad (4.4)$$

where $B$ = 3,1 - coefficient of power.

$$N = \frac{0,5 \cdot 240452 \cdot 3,1}{3400 \cdot 122 \cdot 0,55} = 8,7$$

Optimizing features of the fan blades to the corresponding motor with rated power with a safety margin about 5 %:

$$N \quad = 8,7$$

It gives us a such conclusion that calculated ventilation parameters of the determined hangar ensures that maintenance personnel are performing safely in maintenance of the two of Boeing-777 AC fuel systems.

### 4.4 Fire and explosive safety in the working area of AC maintenance

All issues closely connected with an explosive safety of civil aviation enterprises is carried out in accordance with suitable documentation and resolutions on fire protection of enterprises, organizations and institutions of civil aviation. Moreover, maintaining of high level of explosive safety is the main task of any operator of organization providing scheduled maintenance.

Putting it simply, it describes that the main provisions for the organization of fire prevention work, service and training of fire units at the enterprises of the SAA, as well as duties of officials to ensure fire safety at the facilities and all buildings of the civil aviation enterprises. According to the "Instruction of the Safety Rules for Maintenance and Current Repair of Aviation Equipment", when servicing the fuel system to the occurrence of a fire or explosion, the following factors:

- it is necessary to exclude the influence on the operating jets of the liquid under pressure, when the fuel system of the engine is spilled to prevent fuel spillage on the engine parts and the AC parking stand;
- hot structural components fuel ingression, electrical wiring;
- ignition sources with spilled fuel;
- disruption of metallization to remove electrical discharge during refueling;
- sparks from impact and friction, when the instrument falls;
- rigid violation of fire safety requirements (smoking at not designated for this purpose places, availability of open fire sources).

The following activities in my diploma program were developed:

- in order to prevent fire and fight it in maintenance areas, a fire protection panel is installed with the main means of protection and fire fighting;

- carbon dioxide, powder fire extinguishers, shovels, hooks, fire extinguishers, sand containers;
- in the hangar there are both portable and stationary fire protection methods.
- AC input into the hangar is performed no earlier than - 20 minutes after the engine has stopped;
- the whole AC in the hangar is installed in such a way that one of the AC can be freely withdrawn;
- when AC is introduced into the hangar for a day or more, the fuel from the tank will merge and the tank will be filled with inert gas;
- in the place where there is an increased fire hazard, use a hand foam fire extinguisher, for example.
- Personnel protection features from the fire hazard against it in the areas where maintenance is provided, fire protection panels are installed.

Dangerous, for firefighting and vulnerable for explosive safety are:

- airplane fuel tanks;
- general power plant compartments;
- technical compartments including aft and rear parts;
- panels of AC generators;
- compartments for luggage hold;
- hot Air Pipeline Laying Area.

According to the "Instruction of labor safety rules for maintenance and current repair of aviation equipment" the fire safety of the is provided by the fire protection system. Prevention of fire is achieved:

- technological processes automatization and hazards risks avoiding connected with work combustible substances using of fireproof materials for cabin crew and passenger cabin equipment;

- pressurized compartments including ambient air probably gives cooling of both the engine parts and the aggregates inside of them, comprising the possibility of removing and minimizing the quantity from fuel vapors;
- involvement of electrical equipment concerned with the main task of fire and explosion risks in accordance with the requirements of the "Rules for the installation of electrical installations».
- fire protection provides: compartments for luggage hold, the use of fire extinguishing means and appropriate types of fire equipment tools, application of automatic fire alarm and fire extinguishing systems.

### 4.5 Instruction for the implementation of the rules for maintenance of labor protection

To ensure the safety of people working with AC, the following rules must be observed:

- persons without access to the working areas where risks of fire and explosive are high with a list of task cards work are prohibited;
- the parking brakes of Boeing-777 should not be released even after works finishing. AC is obligatory to equip with reliable grounding devices;
- all AC distance in one row between other AC must meet the requirements of airport and the operator;
- it is forbidden to ignore safety measures during operation of the AC and overheat or somehow damage the electrical components, units and ignore overheating indication if it was triggered;
- all maintenance procedures in areas of increased fire hazard, it is obligatory to have with you a spark-free instrument;
- aerodrome territory must be fire protected as much as possible, especially in the areas of AC par stands, protected from debris, oiled rags, dry grass and other combustible substances and materials;
- after removing the equipment and units, the plug-in connectors must be closed with plugs, and the open ends of the electrical wires must be insulated;

- the state of the ATC electrical network should be checked at least twice a year;
- work on painting, washing and engine washing is necessary on-site only for this purpose;
- before adding AC oil, it is necessary to remove static electricity from the filler neck;
- when filling up the fuel in the open, it is forbidden to drain the landing fuel;
- integrity of psi fire extinguishers must be in operational condition and stored in the designated area.

During maintenance of substations in open areas and in places it is strictly forbidden:

- smoking and the use of open fire is closer than - 25 meters from substations and other fire hazardous areas;
- work beginning and initiating without checking AC grounding, availability and serviceability of fire extinguishing methods;
- it accepts AC of special vehicles without fire, grounding and sparking methods;
- defective electric heating and lighting equipment are used;
- carry out painting, washing and engine washing in places without equipment;
- within - 3 hours after the end of the colorful work with the appearance of a spark;
- when launching the AC engine in front of the leaked fuel;
- store containers with combustible materials, solder, incinerator and grass at a distance from the AC and the manufacturing plant closer to the rule;
- when the AC is filled with fuel, repairs and checks are performed on the radio and electrical equipment as a whole, on-board network, battery replacement, AC engine heating, connection of electrical power sources;
- storage in sheds, docks, flammable and combustible liquids, flames, oxygen tanks, oiled rags, motor vehicles;
- wash and clean household equipment, parts and AC parts with flammable materials;

- drain the oily products on soil or in unsuitable containers;
- when working indoors, electric wires are laid on the route of transporting the internal horn.

Practical usage of fire extinguishing equipment for purposes not related to fire fighting. In the event of a fire, it is necessary to report this to the duty officer of the airline fire department, shop manager, shift supervisor, and conduct an independent fire extinguishing schedule.

# CONCLUSION TO PART 4

Based on the analysis of hazardous and harmful production factors during maintenance of the AC fuel system, measures have been developed to improve the safety of long-range maintenance and operation of the Boeing-777 AC.

One of the important moments in improving the efficiency of aviation is the development of the competence of aviation personnel, the development and implementation of modern maintenance and repair programs and new technologies for the operation of the Air Force, which require the development of new approaches. , rules and safety standards.

# CHAPTER 5 ENVIRONMENTAL PROTECTION

## 5.1 Boeing-777 fuel system operation danger analysis

Today, environmental protection is one of the most important problems for humanity. The general objective of environmental protection is effective measures aimed at maintaining the cleanliness of the environment in human settlements and improving the efficient use of natural resources. In civil aviation operational companies, the main area of action to reduce environmental impact is as follows:

- total reduction of emissions of untreated sewage and harmful emissions in the territory of aerodromes;
- reduction of air pollution by harmful substances from AC power plants and ground vehicles;
- exclude the annoying effect of aviation and other industrial noise;
- protection from the impact of electric fields, waste disposal of the activities of airlines.

Harmful combustion products for aviation fuels in AC and special vehicle engines include carbon monoxide, non-combustible carbon, nitrogen and sulfur oxides, soot and soot. To prevent soil contamination during fuel system maintenance, tanks have been placed in the AC parking areas to collect fuel sludge and special pallets to prevent fuel flow when changing fuel system configurations. In AC's periodic maintenance, the sewer lines are equipped with a basin for tanks, where together with the fuel, chemical liquids, the precipitate is emptied, washed from the surface of the site. Strict enforcement of rules on storage, transport and use of fuels and lubricants can prevent heavy carbon fractions, nitrogen dioxide, hydrogen sulphide from entering the atmosphere and groundwater. The collection of spent fuel in special containers and their subsequent treatment enables the rational use of the country's natural resources. With the development of the third-generation Boeing 777X, Boeing worked with General Electric to provide a 2% improvement in fuel efficiency for the 777-300ERs in production. General Electric improved the fan module and high pressure compressor stage 1 bushing in the GE-90-115 turbo air blower. GE stated that these improvements, the most important of which is based on work to develop the 787, will reduce fuel combustion by 0.5%. Boeing’s wing changes were meant to deliver the rest. Boeing said every 1% improvement in 777-300ER fuel combustion means the ability to fly an additional 75 nmi (139 km; 86 mi) with the same fuel load or add ten passengers or 2,400 lb (1,100 kg). cargo for a "restricted" flight.

## 5.2 The negative impact of air transport on the environment

According annually issued articles from ICAO aviation industry overall impact on environmental pollution is relatively small. However, the dynamics of growth in air transportation in the world, accompanied by an increase in the number of AC, requires the most serious attitude to the issue related to environmental protection.

The negative impact of aviation transport on the environment can be divided into two large groups :

- substance chemical factors:
- frequently emissions issues concerned with harmful substances of AC engines and their influence on the atmosphere, prevents the penetration of ultraviolet radiation;
- availability on the territory of the aviation organization of a huge fuel oil storage facilities, wash grounds, which retain oil products, chemical solutions, mineral oils.
- factors of physical impact in the airport zone:
- jet engines noise;
- electromagnetic flashes of ground-based air traffic control systems.

## 5.3 AC as a source of environmental pollution

The projected growth of air traffic in the world limited harmful emissions from AC motors. ICAO has developed stricter standards for AC motor emissions in this regard.

Gases for gas turbine engines contain the following main components that pollute the atmosphere: carbon monoxide, hydrocarbons (methane, acetylene, ethane, ethylene, propane, benzene, toluene, etc.), nitrogen oxides, aldehydes (formaldehyde, acrolin, acetic acid, etc.). (visible smoky steam behind the engine nozzle), benzo-pyrene.

When the turbocharged engine and propeller engine are running for one minute, 2-4 mg of carcinogens, mainly benzypyrene, are released into the atmosphere.

Atmospheric emissions from AC motors in accordance with ICAO standards are not permitted and should be excluded when designing new AC motors and AC motors. It has been found that carbohydrates in airports due to the release of sewers account for almost 20% of air pollution.

The quantitative characteristic of emissions of harmful substances from an AC motor is the Mi / Ne emission index, which shows how many grams of a substance are released into the air when 1 kg of fuel is burned.

This parameter describes "engine malfunction".

In it:

$M_i$ - mass in grams of the ejected i-th harmful substance (ingredient) after some certain time of engine operation;

$N_e$ - takeoff thrust.

The ICAO standards on the emission control parameter for the public day are as follows[22]:

$M_{CO} / Ne$ = 0,56 g / kW;

$M_{CxHy} / Ne$ = 0,2 g / kW;

$M_{NOx} / Ne$ = 0,8 g / kW.

## 5.4 Requirements of Ukrainian laws to ensure environmental safety

Part VII "Environmental Security" of the Declaration on the Sovereignty of the State of Ukraine declares that Ukraine has the right to prohibit the construction or suspension of enterprises, establishments, plants and establishments that pose a threat to environmental safety. Ukraine cares about the environmental safety of its citizens.

The Law on Economic Independence of Ukraine mentions these main objectives of economic independence, security achievements, and the creation of healthy and safe living and working conditions. The Law on Enterprises of Ukraine stipulates that all enterprises are obliged to take environmental measures in a timely manner. Companies are responsible for maintaining requirements and standards for nature conservation, the rational use of natural resources and restoration.

Finally, the Ukrainian Environmental Protection Law defines the basic principles of environmental protection behalf of SAA:

- priority of environmental safety requirements, mandatory compliance with environmental standards, norms and restrictions on the use of natural resources
- ensuring an environmentally safe environment for human life and health;
- greening materials production on the basis of a comprehensive solution to environmental issues.

Among other measures, environmental expertise guarantees citizens' environmental rights. In Ukraine, governmental, civil and some other environmental assessments are planned, which must be carried out in legislation, investment, administration and economic activities that may affect the environment.

The purpose of an environmental impact assessment is to:

- identification of the environmental hazards of economic and other activities that may directly affect the state of the natural environment in the future;
- ensuring that projects comply with legal requirements;
- assessment of the completeness and validity of the anticipated conservation measures.

The positive conclusions of the environmental impact assessment are the reasons for opening funding for the plant's development project. Without this, the creation of programs and projects is prohibited. Expert units of the Ministry of Environment and Nuclear Safety of Ukraine or specially established committees carry out the state's ecological expertise. Relevant administrations, other institutions and organizations will be invited to participate in this work. The conclusions of the state environmental review, after approval by the ministry, are mandatory for implementation.

Public environmental assessment is carried out by independent expert groups at the initiative of public organizations and by local authorities at their own expense. This study is independent of state environmental expertise.

Therefore, environmental expertise, on the other hand, is a measure to combat and prevent damage to the natural environment even before actual pollution. On the other hand, this study will enable companies to be classified according to the degree of environmental risk and to develop measures and ways to minimize the negative consequences of their activities.

In current companies, greening of production is achieved by creating ecological passports. The ultimate goal of an environmental certificate is to reduce the harmful environmental impact of companies.

## 5.5 Environmental hazard of the operation of the Boeing-777 and its systems

At present, the environmental issues of AC use are more acute than ever. Not surprisingly, the consequences of human technological advances are so obvious that they are difficult to overlook. By conquering the skies, we have forgotten our impact on nature and the environment. Of course, air contact is not the most polluting activity in the human environment.

Consequences of almost all human environmental activities. However, because habitats are directly related to the environment, it is not all that people who pollute the environment are poisoning themselves. Therefore, our task is not only to develop new alternatives, but also the environment.

AC emits toxic gases from airport belts and airport engines. Gas turbine engine exhaust components include the following main components: carbon monoxide, hydrocarbons (methane CH4, acetylene C2H2, ethane C2H6, ethylene C2H4, propane C3H8, benzene C6H6, toluene C6H5CH3, etc.), nitric oxide, alkaline oxide, aldehyde, aldehyde CH2 = CH = CHB, acetaldehyde (CH3CH, etc.), sulfur oxides, soot (smoke lamps visible behind engine nozzles), benzopyrene.

Running a turbojet or turbocharged engine for 1 minute releases 2-4 mg of carcinogens into the atmosphere, mainly benzopyrene. ICAO regulations do not allow the release of draining fuels into the AC atmosphere, so they should be excluded during the design of new AC motors and variables.

The quantitative emission characteristic of AE is an emission index, which shows how many grams of a substance are released into the air when 1 kg of fuel is burned.

The content of carbon monoxide and hydrocarbons in the AE emissions is determined from the complete combustion of the fuel. In these modes, maximum combustion of unburned fuel is observed because the combustion completeness of the fuel is minimal for the small temperature and air pressure in the combustion chamber. In addition, the low gas mode degrades the fuel injection, thereby degrading the completeness of combustion. In low gas mode, NO emissions will be minimal, engine takeoff mode will be maximized, and the combustion chamber temperature will be maximum.

The noise situation of the airline and the surrounding area is determined by many sources of noise, the main of which are AC power plants and special vehicles for airport services for various purposes. In the territory of most airlines and in the territory of the airline, the noise created by the aviation facilities is predominant, and the reduction affects the interests of a large number of people.

The main source of engine noise is the fan.

The main components of propeller noise are rotational noise and spiral.

Advances in science and technology have created an artificial electromagnetic field, the source of which is the transmitters of radar, radio navigation, and broadcasting stations. The amount of electromagnetic radiation emitted by these devices exceeds the natural area several times and affects human health.

Medical and biological studies have shown that the degree of exposure to heavy electromagnetic fields depends on the frequency range, radiation intensity, nature, and duration of exposure.

The nervous system is the most vulnerable to electromagnetic fields and its changes have been observed. The changes are characterized by conditioned reflex function disorders, electroencephalogram transitions, and pathomorphological disorders of the brain and spinal cord. Electromagnetic fields radio frequencies directly affect the structure of the anterior lobe and interstitial brain, the nature of some biomechanical changes that cause conditioned reflex function, and the course of neural processes. Changes in the nervous system affect the functioning of the cardiovascular, endocrine and other systems. The effect of electromagnetic fields  causes cataracts in the eye - blurring the lens..

The economic activities of airlines are related to AC services and contribute to the deterioration of environmental conditions.

As a result of such operations in apron areas, parking lots, as well as hangars and large airports, up to 40 tons of hydrocarbons, solar, organic and mineral oil washing chemicals and phenols enter the soil per hour. The cause of such effects on the soil is the loss of fuel and lubricants during AC charging. However, not only does the soil spill flammable lubricants, it is also damaged by air.

The number of losses should be reduced to minimize damage to the soil and atmosphere.

### 5.6 Calculation of the control parameter for the emission of the GE-90 engine for compliance with ICAO emission requirements

The concentration of CO and CXNY in the flue gas of an AC engine depends on the characteristics of its combustion chamber (the value of the combustion coefficient), the engine. The maximum amount of fuel combustion in the engine takes place in the design mode - takeoff (maximum thrust mode of the engine).

In this mode, modern engines burn almost completely, which is not possible in practice. In all other modes, the value is low, ie the combustion completeness is low, the engine emits incomplete combustion products (CO and CXNY and others) into the atmosphere, and air pollution increases.

The concentration of NOX in the flue gas of an AC engine depends on the temperature of the mixture in the combustion chamber (the higher the NOX is formed) and the higher the maximum (up to 2500-3000 K) take-off mode and the longer the mixture resides in the combustion chamber. NOX), which occurs at low aircraft speeds.

Maximum NOX emissions occur during engine takeoff mode and related modes, AC start-up, and flight altitude recruitment. It is clear that engine emissions in the airport area depend on its mode of operation and the duration of operation in this mode. Along the airport area, we will understand a space that is 100 m high and the aerodrome is limited in size.

The engines of modern airliners operate in the airport zone in such modes and such a duration of operation (table 5.1).

Table 5.1 Typical cycle of engine operation

| Name of the engine operating mode | Relative thrust, $\overline{Ne}$ | Duration of the regime, *t,* min |
|---|---|---|
| The regime of small gas when taxiing before takeoff | 0,07 | 18 |
| Takeoff mode | 1 | 0,7 |
| The climb mode (1000 m) | 0,85 – 0,98 | 4.7 |
| Approach Mode | 0,3 – 0,42 | 5 |
| The regime of low gas during taxiing after landing | 0,05 | 9 |

$$\bar{R} = \frac{R}{Ne}, \tag{5.1}$$

where $R$ – thrust of the engine in a given mode;

$N_e$ - thrust of the engine on takeoff (maximum thrust).

The table shows the average statistical parameters ($\bar{R}$ and $t$) for large airports in the world.

As the table shows, the longest lasting and most dangerous to the environment is the small gas regime. In modern AC motors, the thrust value in this mode is 3-9 percent of the maximum value of Ne, and this mode is used before takeoff and after landing, as well as during engine warm-up. above. The duration of the taxi regime depends on the size of the airport, the flight, the time of the next day, the intensity of the flight and the weather.

During the certification process, determine the actual emission index appropriate to the engine operating mode and find the control parameters of the test engine $\frac{M_i}{R_0}$ set by the ICAO standard. This parameter determines the "degree of damage" of the engine.

$$\frac{M_i}{R_0} = \left[\frac{g}{\kappa N}[]\right], \tag{5.2}$$

where $M_i$ – mass in grams of the ejected i-th harmful substance (ingredient) after some certain time of engine operation;

$R_0$ – takeoff thrust of the engine in the kilonewtons.

In these cases, the emissions of the AC motors will not be the same during the flight along the airport area and route, as the engines operate in fundamentally different modes. In this regard, pollution in the airport area is "more harmful" ( approximately 0.6 - 0.8 on the route). In addition, many are local pollution of the air surface layer of the airport area, which is more concentrated and more stable than the general pollution of the upper troposphere of the flight route. Moreover, for these reasons, pollution in the airport area is becoming more harmful.

Therefore, the calculation of the emission of AC engines in the airport zone is more important, and we will give it more attention than the calculation during the flight along the route.

"Degree of harmfulness" of each AC engine is characterized, as mentioned above, by its emission control parameters for various ingredients -$\frac{M_i}{Ne}$. The task of calculating engine emissions is to determine the mass of each ingredient thrown out of the engine after a certain time of its operation - $M_i$ (as $Ne$ - engine thrust on the takeoff mode - the value known from the documentation, in particular from the form of the engine).

We will calculate the quantities $\mathrm{M}_i$ for the airport zone (from the above considerations), that is, $M_i = M_{iA}$ on those modes and for that period of time of its operation, while the AC is in this zone with operating engines.

An AC in the airport zone is less than a flight runway that consists of the following stages:

- Start and warm up of the engines;

- Taxiing for executive launch;
- Takeoff;
- Climb - 1000 m;
- Descend - 1000 m;
- Mileage;
- Taxiing till the engine stop.

However, at these stages, AC motors operate in different modes. Therefore, for ease of calculation, the AC strip is divided into ground stages and take-off and landing stages.

I.e $M_{\text{ian}}=M_{\text{ig}}+M_{\text{it-l}}$ .

Ground stages - this is the start of engines, their warm-up, taxiing the AC before take-off and after landing.

The main features of these operations (in order to calculate engine emissions) are the low gas mode and time that AC motors operate in the same mode - these are the longest operations in the airport area. This situation simplifies the calculation.

$M_{ig}=K_{ig}\cdot G_{\text{fg}}$, $K_{\text{ig}}$ - the release factor of the i-th ingredient in terrestrial operations

$G_{\text{fg}}$ - mass of fuel spent by the engine of the AC for ground operations of the runway, kg.

$G_{\text{fg}}=C_{\text{sp.lg}}\cdot R_{\text{lg}}\cdot t_{\text{lg}}$,

where $C_{sp.lg}$ – Specific fuel consumption during engine operation at the LG mode, kg/H·h;

$R_{\text{lg}}$ – thrust of the engine in the LG mode, H;

$T_{\text{lg}}$ – engine run time low rpm mode, hours;

$M_{\text{i-to}}$ - total emission of i-th harmful substances during take-off operations, kg.

Takeoff landing operations is takeoff, climbing – 1000 m, descending from height – 1000 m and landing.

In this case, to calculate the emission of AC engines that is in the air, the emission characteristic is the mass emission rate $W_i$ (kg subs. / h), which shows how much of a given harmful substance is released in this mode of engine operation per unit time.

Mass emissions of AC during take-off and landing operations:

$M_{ito} = W_{i1} \cdot T_{1to} + W_{i2} \cdot T_{2to} + W_{i3} \cdot T_{3to}$ ,

where $T_{1,2,3\ to}$ - The operating time of the engine, respectively, during take-off, when climbing - 1000 m and with a decrease from the height - 1000 m, h;

$W_{i1,2,3}$ - mass emission rate of i-th ingredient under suitable engine operation modes respectively at takeoff, climb - 1000 m and descend - 1000 kg / h.

Data for calculation of emission control parameters of GE-90 engines of Boeing-777 AC by ingredients CO, $C_xH_y$, $NO_x$ is given in tables 5.2 through 5.4.

Table 5.2 – GE-90 engine running time in operating modes

| Name of the engine operating mode | Thrust, $\overline{N}$e | Duration of the regime *t*, minutes |
|---|---|---|
| Running, warming up, taxiing | 0,07 | 2 |
| End of Table 5.2. | | |
| Takeoff | 1 | 0,7 |
| Set of the height of 1000 m | 0,85 | 2,2 |
| Approach for landing | 0,3 | 4 |
| Taxiing after landing | 0,07 | 6 |

Table − 5.3 Standard emission data for engine emissions GE-90

| Harmful substances | CO | $C_xH_y$ | $NO_x$ |
|---|---|---|---|
| Kin, (kg subs. / kg of fuel) for the engine GE-90 | 0,035 | 0,015 | 0,005 |

Table − 5.4 Table of the mass emission rate of the ingredient under the appropriate engine operating conditions

| Mass emission rate, kg sub. / h | Engine operating mode | | |
|---|---|---|---|
| | Takeoff | Cruising | Nominal |
| WCO | 2,65 | 2,4 | 2,4 |
| WCH | 0,5 | 0,55 | 0,5 |

| Mass emission rate,<br>kg sub. / h | Engine operating mode | | |
|---|---|---|---|
| | Takeoff | Cruising | Nominal |
| WNO | 3,5 | 2 | 2,5 |

Engine specifications:

$N_e = 2500$ h.p. = 1850 kW; $N_{cr} = 1300$ kW; $C_{\text{sp.lg}} = 0{,}025$ кg / kW·h

From table 5.2:

$T_{\text{og}} = 2$ min = 0,367 (h) ;

$T_{1\text{fl}} = 0{,}7$ min = 0,0117 (h);

$T_{2\text{fl}} = 2{,}2$ min = 0,0367 (h);

$T_{3\text{fl}} = 4$ min = 0,067 (h);

Then $G_{fg} = 0{,}069 \cdot 378 \cdot 0{,}033 = 0{,}86$(kg).

Determine the mass of each ingredient that thrown out by the engine when working on the ground:

$M_{CO} = 0{,}035 \cdot 0{,}86 = 0{,}03$ (kg);

$M_{CH} = 0{,}015 \cdot 0{,}86 = 0{,}013$ (kg);

$M_{NO} = 0{,}005 \cdot 0{,}86 = 0{,}0043$ (kg);

$M_{COto} = 2{,}65 \cdot 0{,}01 + 2{,}4 \cdot 0{,}0367 + 2{,}4 \cdot 0{,}1 = 0{,}35$ (kg);

$M_{CHto} = 0{,}5 \cdot 0{,}01 + 0{,}55 \cdot 0{,}0367 + 0{,}5 \cdot 0{,}1 = 0{,}075$ (kg);

$M_{NOto} = 3{,}5 \cdot 0{,}01 + 2 \cdot 0{,}0367 + 2{,}5 \cdot 0{,}1 = 0{,}358$ (kg).

Calculating mass emission in the terminal area:

$M_{CO} = 0{,}03 + 0{,}35 = 0{,}38$ (kg);

$M_{CH} = 0{,}013 + 0{,}075 = 0{,}088$ (kg);

$M_{NO} = 0{,}0043 + 0{,}358 = 0{,}362$ (kg).

ICAO standards on the emission control parameter for AC engines are currently:

$M_{CO}/Ne = 0{,}56$ g / kW; $M_{CH}/Ne = 0{,}2$ g / kW; $M_{NO}/Ne = 0{,}8$ g / kW;

$M_{CO}/Ne = 380/1850 = 0{,}23 < 0{,}56$ g / kW;

$M_{CH}/Ne = 88/1850 = 0{,}08 < 0{,}2$ g / kW;

$M_{NO}/Ne = 362/1850 = 0{,}2 < 0{,}8$ g / kW.

According to the values obtained, it follows that the engine emission does not exceed the established ICAO norms.

## CONCLUSION TO PART 5

Therefore, AC motors meet ICAO standards for all parameters. Due to the growing impact of the artificial environment, its protection is the most pressing and multifaceted issue. In recent years, environmental issues have become more and more important. It is gradually becoming a global issue, and it is becoming more and more acute.

The reasons for this situation are various anthropogenic factors. It's like a population explosion and rapid urbanization. The enormous impact on the environment is caused by human factors: waste disposal, pollution of reservoirs and forests, increasing the load on farmland - this is human work. Reducing fuel consumption and CO2 emissions has become a priority in the development of aviation technology, thanks to a number of innovations and developments in recent years. At present, data on the efficiency and cost of basic technology engines, transmission and alternating current show that industrial development in the next 10-15 years will lead to a 20-30% reduction in fuel consumption and CO2 emissions..

The controlled emission parameters of carbon monoxide CO, a mixture of hydrocarbon compounds CxNx, and nitrogen oxide NOx are within the ICAO standard limits, and their values are very small compared to the limit values. Based on the above, it can be concluded that the engine meets the ICAO emission standards..

# GENERAL CONCLUSIONS

1. The analysis of the operational characteristics of the Boeing 777 fuel system shows that the fuel system must be reliable, meet the highest requirements for production and maintenance. Analyzed statistical data on Boeing-777 fuel system failures and malfunctions. The main cause of the error is a malfunction of the pump.

2. The installation of a labyrinth seal instead of a lip seal offers a creative way to increase operational capability. The use of labyrinth seals reduces fuel pump service failure and economic costs.

3. The labyrinth seal of the rotating shaft provides non-contact sealing by controlling the fluid flow by centrifugal motion and by creating a controlled fluid vortex. At higher speeds, the centrifugal motion pushes the fluid away from any part of the body. Similarly, if the labyrinth chamber is designed correctly, the liquid from the main chamber is wrapped around the labyrinth chamber and moved in a spiral motion. This prevents it from escaping and removes other liquids.

4. This design of the sealing part allows to reduce the flow when the geometric size and shape of the labyrinth head sealing part changes during the transition to higher pressure, which greatly affects the rotor consumption and axial displacement;

Slope compaction against the spine creates low pressure in the last gap, and compacted slope compression creates low pressure in the last chamber;

The circular ribs on the vertical axis and the expansion of the chamber increase the gas flow path inside the chamber, creating a lower velocity in the chamber, reducing the pressure in the last gap, and creating a minimum groove from the labyrinth seal.

5. Damage to the maze seal of the centrifugal fan has a significant impact not only on power consumption but also on the production level. Improving abrasion-resistant seals is important not only to improve current efficiency and capacity, but also to keep them at a more critical level. Head and efficiency are reduced during damaged maze seals [15]. The performance curve is shifted down and to the left, reducing compressor capacity and limiting pump output.

6. Based on the analysis of hazardous and noxious industrial factors occurring during the maintenance of the AC fuel system, measures have been developed to improve the safety during maintenance and operation, in addition to short-term maintenance of the Boeing-777 AC. .

7. AC-mounted engines comply with ICAO standards for all parameters. Due to the growing impact of the artificial environment, its protection is the most pressing and multifaceted issue. In recent years, environmental issues have become more and more important. It is gradually becoming a global issue, and it is becoming more and more acute.

8. Most people agree that lip seals need to be removed regularly for unknown reasons, but engineers should always look at the picture. It is known that all applications for the use of lip seals are already over, but new options have emerged for users who know the reliability and energy. Unfortunately, the lip seal does not meet the expectations of most intermediate pump users. It makes no difference that the lipstick is in the cassette configuration.

# REFERENCES

1. TE Munns and RM Kent, ‘Structural Health monitoring degradation mechanism and system requirements’, 19th proc. of Digital Avionics Systems Conf. DASC, Philadelphia, USA, 2000.

2. PM Pawar and R Ganguli, ‘Helicopter rotor health monitoring – a review’, Proceedings of IMechE Vol. 221 Part G: J. Aerospace Engineering, 2007.

3. ‘A Review of Structural Health Monitoring Literature: 1996-2001’, Los Alamos National Laboratory Report, LA-13976-MS, 2003.

4. C Boller and M Buderath, ‘Fatigue in aero structures—where structural health monitoring can contribute to complex subject’, Phil. Trans. R. Soc. A, Vol 365, pp 561–587, 2007.

5. E Taylor, ‘Structural monitoring system, keeping aircraft out of the hangar’, Australian aviation, July 2008.

6. H Stehmeier and H Speckmann, ‘Comparative Vacuum Monitoring (CVM) Monitoring of fatigue cracking in aircraft structures’, 2nd European Workshop on Structural Health Monitoring, Munich/Germany, July 7 - 9, 2004.

7. RD Finlayson et al, ‘Health Monitoring of Aerospace Structures with Acoustic Emission and Acousto-Ultrasonics’, 15th conf. of WCNDT, Rome, 2000.

8. H Pfeiffer and M Wevers, ‘Aircraft Integrated Structural Health Assessment – Structural Health Monitoring and its implementation within the European project AISHA’, EU Project Meeting on Aircraft Integrated Structural Health Assessment (AISHA), Leuven, Belgium, June 2007.

9. VK Varadan and VV Varadan, ‘Wireless Remotely Readable and Programmable Microsensors and MEMS for Health Monitoring of Aircraft Structures’, in ”Structural Health Monitoring”, pp. 96–105, CRC Press, 1999.

10. UIA AMM.pdf

Turboprop engines and especially engines of An-140 are known to be one of the most expensive elements as in operating, as well as in maintenance and repair

%

Figure 1.3 – Failures distribution

Let us consider fuel system as a compound of subsystems and distinguish the unit which need

Table 1.6 – Statistics of fuel system subsystems failures o for the operation period

| Year<br>Subsystem | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Overall | Overall, % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel drainage | 0 | 0 | 1 | 2 | 2 | 2 | 0 | 0 | 0 | 0 | 1 | 2 | 1 | 0 | 11 | 22,9 |
| Refueling | 0 | 0 | 1 | 0 | 1 | 3 | 1 | 0 | 1 | 2 | 1 | 0 | 1 | 0 | 11 | 22,9 |
| Feeding | 0 | 0 | 2 | 1 | 2 | 1 | 2 | 0 | 1 | 1 | 2 | 2 | 1 | 2 | 17 | 35,4 |
| Fuel consumption | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 1 | 0 | 3 | 1 | 0 | 0 | 0 | 9 | 18,8 |
| Overall | 0 | 0 | 4 | 3 | 6 | 7 | 5 | 1 | 2 | 6 | 5 | 4 | 3 | 2 | 48 | 100,0 |