



# AEROSPACE INFORMATION REPORT

**AIR7975™****REV. A**Issued 2019-12  
Revised 2026-06

Superseding AIR7975

**(R) Aircraft Fuel System Design Guidelines**

## RATIONALE

This document has been revised to include:

- References to new relevant SAE documents issued since the last revision of this document
- Changes in issues of referenced documents
- Updates to terminology and definition of general terms
- Additional detail on fuel types for military aircraft and fuel additives
- Clarifications to various subsections
- Additional information on surge pressures
- Additional information on the measurement of fuel temperature
- Corrections to various formulae

## FOREWORD

This document is intended to give an overview of the major steps and considerations in designing a fuel system. It is primarily focused around large commercial aircraft, though much of the guidance would be applicable to military aircraft, smaller aircraft, and rotorcraft. It discusses the design at a system/aircraft level and is not intended as a design manual for individual system components.

SAE Executive Standards Committee Rules provide that: "This report is published by SAE to advance the state of technical and engineering sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user."

SAE reviews each technical report at least every five years at which time it may be revised, reaffirmed, stabilized, or cancelled. SAE invites your written comments and suggestions.

Copyright © 2026 SAE International

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, or used for text and data mining, AI training, or similar technologies, without the prior written permission of SAE.

**TO PLACE A DOCUMENT ORDER:** Tel: 1-877-606-7323 (U.S. and Canada only)  
Tel: 1-724-776-4970 (outside U.S. and Canada)  
Fax: 724-776-0790  
Email: [CustomerService@sae.org](mailto:CustomerService@sae.org)  
<http://www.sae.org>

**SAE WEB ADDRESS:**

Full document details: **SAE AIR7975A**

For more information on this standard, visit  
<https://www.sae.org/standards/content/AIR7975A/>

Documents

Standard, visit Sharing Hub

## TABLE OF CONTENTS

|       |                                                                                 |    |
|-------|---------------------------------------------------------------------------------|----|
| 1.    | SCOPE.....                                                                      | 5  |
| 1.1   | Purpose .....                                                                   | 5  |
| 2.    | REFERENCES.....                                                                 | 5  |
| 2.1   | Applicable Documents .....                                                      | 5  |
| 2.1.1 | SAE Publications.....                                                           | 5  |
| 2.1.2 | ASTM Publications.....                                                          | 6  |
| 2.1.3 | United Kingdom Ministry of Defence (UK MOD) Publications .....                  | 6  |
| 2.1.4 | U.S. Government Publications.....                                               | 7  |
| 2.1.5 | EASA Publications .....                                                         | 7  |
| 2.1.6 | FAA Publications .....                                                          | 7  |
| 2.1.7 | Coordinating Research Council (CRC) Publications .....                          | 8  |
| 2.1.8 | IEC Publications.....                                                           | 8  |
| 2.1.9 | Other Publications.....                                                         | 8  |
| 2.2   | Related Publications .....                                                      | 8  |
| 2.2.1 | FAA Publications.....                                                           | 8  |
| 2.2.2 | Other Publications.....                                                         | 8  |
| 2.3   | Acronyms .....                                                                  | 8  |
| 2.4   | Symbols .....                                                                   | 10 |
| 2.5   | Definitions .....                                                               | 10 |
| 2.6   | Units and Formulae.....                                                         | 12 |
| 3.    | OVERVIEW OF FUEL SYSTEM DESIGN.....                                             | 12 |
| 3.1   | Fuel System Requirements.....                                                   | 14 |
| 3.2   | Aviation Fuel .....                                                             | 16 |
| 3.2.1 | Fuel Types .....                                                                | 16 |
| 3.2.2 | Additives.....                                                                  | 16 |
| 4.    | FUEL STORAGE .....                                                              | 16 |
| 4.1   | Tank Boundaries .....                                                           | 18 |
| 4.1.1 | Uncontained Engine Rotor Failure (UERF).....                                    | 18 |
| 4.1.2 | Engine Feed Tanks.....                                                          | 19 |
| 4.1.3 | Surge Tanks.....                                                                | 20 |
| 4.1.4 | Additional Wing/Center Tanks .....                                              | 21 |
| 4.1.5 | Auxiliary Cargo Tanks/Additional Center Tanks (ACTs)/Other Fuselage Tanks ..... | 22 |
| 4.1.6 | Tail Tanks and Center of Gravity Considerations .....                           | 22 |
| 4.1.7 | Expansion Space .....                                                           | 23 |
| 4.1.8 | Dry Bays.....                                                                   | 23 |
| 4.2   | Structural Considerations/Tank Pressures .....                                  | 23 |
| 4.2.1 | Pressure on the Tank Floor .....                                                | 23 |
| 4.2.2 | Pressure on a Tank Wall.....                                                    | 24 |
| 4.2.3 | Crashworthiness .....                                                           | 25 |
| 4.3   | Tank Volumes .....                                                              | 25 |
| 4.4   | Venting .....                                                                   | 27 |
| 4.4.1 | Vent System Design.....                                                         | 27 |
| 4.4.2 | Vent System Sizing.....                                                         | 29 |
| 4.5   | Water Removal .....                                                             | 42 |
| 4.5.1 | Water Scavenge.....                                                             | 42 |
| 4.5.2 | Water Drain .....                                                               | 43 |
| 4.5.3 | Icing Considerations.....                                                       | 43 |
| 4.6   | Fuel Pipes and Fittings.....                                                    | 44 |
| 5.    | ENGINE AND APU FEED.....                                                        | 44 |
| 5.1   | Engine Feed.....                                                                | 44 |
| 5.1.1 | Pump Location .....                                                             | 47 |
| 5.1.2 | Cross-Feed .....                                                                | 47 |
| 5.1.3 | Engine Interface, Boosted Operation.....                                        | 50 |



|            |                                                                                                   |    |
|------------|---------------------------------------------------------------------------------------------------|----|
| 5.1.4      | Engine Interface, Unboosted - Suction (Gravity) Feed .....                                        | 51 |
| 5.1.5      | Engine Interface Surge Pressure .....                                                             | 52 |
| 5.2        | APU Feed.....                                                                                     | 52 |
| 6.         | TRANSFER AND OVERRIDE .....                                                                       | 53 |
| 6.1        | Override System Considerations .....                                                              | 54 |
| 6.2        | Transfer System Considerations.....                                                               | 55 |
| 7.         | REFUEL AND DEFUEL .....                                                                           | 55 |
| 7.1        | Refuel .....                                                                                      | 55 |
| 7.1.1      | Refueling Interfaces .....                                                                        | 55 |
| 7.1.2      | Automatic Refuel.....                                                                             | 56 |
| 7.1.3      | Manual Refuel .....                                                                               | 56 |
| 7.1.4      | Refuel System Design.....                                                                         | 56 |
| 7.1.5      | Refuel System Sizing .....                                                                        | 57 |
| 7.1.6      | Surge Pressure Considerations .....                                                               | 58 |
| 7.1.7      | Electrostatic Buildup During Refueling.....                                                       | 61 |
| 7.2        | Defuel .....                                                                                      | 63 |
| 8.         | JETTISON .....                                                                                    | 63 |
| 8.1        | Jettison Sizing .....                                                                             | 64 |
| 9.         | FUEL QUANTITY INDICATION AND FUEL MANAGEMENT .....                                                | 64 |
| 9.1        | Fuel Quantity Indication .....                                                                    | 64 |
| 9.1.1      | Calculation of Fuel Quantity.....                                                                 | 64 |
| 9.1.2      | Measurement of Fuel Temperature .....                                                             | 66 |
| 9.1.3      | Calculation of Aircraft Gross Weight and Center of Gravity.....                                   | 67 |
| 9.2        | Fuel Management .....                                                                             | 67 |
| 9.2.1      | Considerations for Positioning of Level Sensors .....                                             | 68 |
| 9.2.2      | Fuel Transfer and Control of Center of Gravity.....                                               | 69 |
| 9.2.3      | Weight and Balance Considerations.....                                                            | 69 |
| 10.        | OTHER CONSIDERATIONS .....                                                                        | 69 |
| 10.1       | Segregation of Electrical Wiring .....                                                            | 69 |
| 10.2       | Segregation of Electrical Buses .....                                                             | 70 |
| 10.3       | Intrinsic Safety.....                                                                             | 70 |
| 11.        | NOTES .....                                                                                       | 71 |
| 11.1       | Revision Indicator.....                                                                           | 71 |
| APPENDIX A | Basic Fluid Mechanics for Fuel Systems .....                                                      | 72 |
| Figure 1   | Overview of a fuel system .....                                                                   | 14 |
| Figure 2   | Independent self-contained tanks .....                                                            | 17 |
| Figure 3   | Integrated fuel tank .....                                                                        | 17 |
| Figure 4   | UERF spread angles.....                                                                           | 18 |
| Figure 5   | Protected fuel volume .....                                                                       | 19 |
| Figure 6   | Plan view showing surge tank.....                                                                 | 20 |
| Figure 7   | Side view showing surge tank.....                                                                 | 21 |
| Figure 8   | Effect of fuel in outboard tanks .....                                                            | 21 |
| Figure 9   | Fuel movement under acceleration.....                                                             | 24 |
| Figure 10  | Fuel volume definitions .....                                                                     | 26 |
| Figure 11  | Vent system arrangement on swept winged aircraft.....                                             | 29 |
| Figure 12  | Flow rate versus altitude during descent to maintain ambient pressure (from NAVAIR 06-5-504)..... | 31 |
| Figure 13  | Altitude versus airflow during descent (refer to NAVAIR 06-5-504) .....                           | 32 |
| Figure 14  | NACA inlet area against altitude (from NAVAIR 06-5-504) .....                                     | 33 |
| Figure 15  | Vent inlet cross-sectional area against velocity (from NAVAIR 06-5-504) .....                     | 33 |
| Figure 16  | Pressure ratio versus altitude at different airspeeds (from NAVAIR 06-5-504) .....                | 33 |

|           |                                                                                             |    |
|-----------|---------------------------------------------------------------------------------------------|----|
| Figure 17 | Allowable pressure recovery (from NAVAIR 06-5-504) .....                                    | 34 |
| Figure 18 | Airflow versus altitude, per NAVAIR 06-5-504 .....                                          | 35 |
| Figure 19 | Example one tank system for vent sizing calculation .....                                   | 36 |
| Figure 20 | Pressure drop for non-adiabatic airflow in a constant area duct (from NAVAIR 06-5-504)..... | 37 |
| Figure 21 | Pressure and fuel volume versus time during refueling (from NAVAIR 06-5-504) .....          | 38 |
| Figure 22 | Pressure and flow during refueling (from NAVAIR 06-5-504).....                              | 39 |
| Figure 23 | Altitude versus time during aircraft climb (from NAVAIR 06-5-504) .....                     | 41 |
| Figure 24 | Tank pressure and vent tube pressure drop versus flow rate (from NAVAIR 06-5-504).....      | 41 |
| Figure 25 | Engine feed arrangement of pumps and shutoff valve (SOV) .....                              | 46 |
| Figure 26 | Engine feed system schematic .....                                                          | 46 |
| Figure 27 | Collector cell arrangement .....                                                            | 49 |
| Figure 28 | Suction feed system.....                                                                    | 51 |
| Figure 29 | Pressure and flow available at engine inlet (from NAVAIR 06-5-504).....                     | 51 |
| Figure 30 | Override pump characteristics (based on NAVAIR 06-5-504).....                               | 54 |
| Figure 31 | Pressure available and pressure drop versus flow (from NAVAIR 06-5-504) .....               | 57 |
| Figure 32 | Electrostatic discharge .....                                                               | 62 |
| Figure 33 | Typical height-volume curve (from NAVAIR 06-5-504).....                                     | 66 |
| Figure 34 | Level sensor positioning.....                                                               | 68 |
| Table 1   | Fuel flow under different conditions .....                                                  | 48 |

## 1. SCOPE

This document describes the major design drivers and considerations when designing a fuel system for a large commercial aircraft. While not intended as a design manual for individual system components, it does refer out to other SAE specifications where more detail on specific components and subsystems is given. It does include examples of a number of calculations associated with sizing of fuel systems, based on those given in NAVAIR 06-5-504, as well as an appendix summarizing basic fluid mechanical equations that are key for fuel system design. It is acknowledged that most of these calculations would today be performed by modeling tools rather than by hand, but it is considered important for the designer to understand the principles.

Some details specific to military aircraft are included, but it is intended that later issues of this document will include appendices that give specific considerations for military aircraft, smaller commercial aircraft, and rotorcraft. Features unique to these types of vehicle are generally not included in this issue.

### 1.1 Purpose

This document is intended to give fuel system designers a better understanding of the overall design process and the elements that need to be considered when designing an airframe fuel system and an appreciation of the concepts and equations that drive the configuration and sizing of a system.

## 2. REFERENCES

### 2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

#### 2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 1-877-606-7323 (U.S. and Canada only) or 1-724-776-4970 (outside U.S. and Canada), [www.sae.org](http://www.sae.org).

|         |                                                                                            |
|---------|--------------------------------------------------------------------------------------------|
| AIR790  | Considerations on Ice Formation in Aircraft and Engine Fuel Systems                        |
| AIR1326 | Aircraft Fuel System Vapor-Liquid Ratio Parameter                                          |
| AIR1615 | Thesaurus for Fuel System Components                                                       |
| AIR1660 | Fuel Level Control Valves and Systems                                                      |
| AIR1662 | Minimization of Electrostatic Hazards in Aircraft Fuel Systems                             |
| AIR4170 | Reticulated Polyurethane Foam Explosion Suppression Material for Fuel Systems and Dry Bays |
| AIR4783 | Glossary of Terms - Aircraft Ground Refueling and Defueling                                |
| AIR5128 | Electrical Bonding of Aircraft Fuel Systems                                                |
| AIR5691 | Guidance for the Design and Installation of Fuel Quantity Indicating Systems (FQIS)        |
| AIR5774 | Composite Fuel Tanks, Fuel System Design Considerations                                    |
| AIR6148 | Synthetic Jet Fuels from Non-Petroleum Feed Stocks                                         |
| AIR6325 | Fuel Level Point Sensing                                                                   |

|         |                                                                                                                                |
|---------|--------------------------------------------------------------------------------------------------------------------------------|
| AIR7484 | Guidance on the Impact of Fuel Properties on Fuel System Design and Operation                                                  |
| ARP594  | Fuel Pump Thermal Safety Design                                                                                                |
| ARP1401 | Aircraft Fuel System and Component Icing Test                                                                                  |
| ARP1665 | Definition of Pressure Surge Test and Measurement Methods for Receiver Aircraft                                                |
| ARP4028 | Aircraft/Engine Fuel Pump Two Phase (Slugging Flow) Inlet Performance Test and Evaluation                                      |
| ARP5412 | Aircraft Lightning Environment and Related Test Waveforms                                                                      |
| ARP5414 | Aircraft Lightning Zone                                                                                                        |
| ARP5416 | Aircraft Lightning Test Methods                                                                                                |
| ARP5776 | Aircraft Flame Arrestor Installation Guidelines and Test Methods                                                               |
| ARP5794 | Centrifugal Aircraft Fuel Pump Requirements, Design and Testing, Aerospace Standard                                            |
| ARP6078 | Aircraft Fuel Tank Inerting Systems                                                                                            |
| ARP6385 | Aircraft Fuel Pump Mechanical and Electrical Safety Design                                                                     |
| ARP8615 | Fuel System Components: General Specification For                                                                              |
| AS5751  | Design and Operating Requirements of the Onboard Aircraft Refueling System and Associated Ground Refueling Equipment Interface |
| AS18802 | Fuel and Oil Lines, Aircraft, Installation of                                                                                  |

#### 2.1.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, [www.astm.org](http://www.astm.org).

|            |                                                                                                                    |
|------------|--------------------------------------------------------------------------------------------------------------------|
| ASTM D286  | Method of Test for Autogenous Ignition Temperature of Petroleum Products (withdrawn in 1966)                       |
| ASTM D1655 | Standard Specification for Aviation Turbine Fuels                                                                  |
| ASTM D2155 | Standard Test Method for Determination of Fire Resistance of Aircraft Hydraulic Fluids by Autoignition Temperature |
| ASTM D4054 | Standard Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives                                  |
| ASTM D4865 | Standard Guide for Generation and Dissipation of Static Electricity in Petroleum Fuel Systems                      |
| ASTM D7566 | Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons                               |

#### 2.1.3 United Kingdom Ministry of Defence (UK MOD) Publications

Available from Ministry of Defence - UK, UK Defence Standardization, Kentigern House, Room 1138, 65 Brown Street, Glasgow G2 8EX, UK, <https://sts.defencegateway.mod.uk>.

DEF STAN 91-091 Turbine Fuel, Aviation Kerosene Type, Jet A-1

#### 2.1.4 U.S. Government Publications

Copies of these documents are available online at <https://quicksearch.dla.mil>.

|               |                                                                                  |
|---------------|----------------------------------------------------------------------------------|
| MIL-A-25896   | Adapter, Pressure Fuel Servicing, Aircraft, Nominal 2.5 Inch Diameter            |
| MIL-DTL-5624  | Turbine Fuel, Aviation, Grade JP-5 (NATO F-44)                                   |
| MIL-DTL-83133 | Turbine Fuel, Aviation, Kerosene Type, JP-8 (NATO F-34) and NATO F-35            |
| MIL-F-17874   | Fuel Systems, Aircraft, Installation and Test of                                 |
| JSSG-2009     | Department Of Defense Joint Services Specification Guide: Air Vehicle Subsystems |

#### 2.1.5 EASA Publications

Available from European Union Aviation Safety Agency, Konrad-Adenauer-Ufer 3, D-50668 Cologne, Germany, Tel: +49 221 8999 000, [www.easa.europa.eu](http://www.easa.europa.eu).

|                   |                                                                                                                                                        |
|-------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|
| AMC 20.128A       | Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor Failure                               |
| AMC 25.905(d)     | Release of Propeller Debris                                                                                                                            |
| AMC 25.981        | Ignition Precautions                                                                                                                                   |
| AMC 25.1305(a)(2) | Fuel Indication System(s)                                                                                                                              |
| AMC 25.1315       | Negative Accelerations                                                                                                                                 |
| CS-25             | Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes (this document is based on Amendment 28, unless otherwise stated) |

#### 2.1.6 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue SW, Washington, DC 20591, Tel: 866-835-5322, [www.faa.gov](http://www.faa.gov).

|                |                                                                                                                                                      |
|----------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| 14 CFR Part 25 | Code of Federal Regulation, Airworthiness Standards: Transport Category Airplanes (this document is based on Amendment 152, unless otherwise stated) |
| AC 20-119      | Fuel Drain Valves                                                                                                                                    |
| AC 20-128A     | Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor Failure                             |
| AC 25-7C       | Flight Test Guide for Certification of Transport Category Airplanes                                                                                  |
| AC 25-11B      | Electronic Flight Displays                                                                                                                           |
| AC 25.1309-1B  | System Design and Analysis                                                                                                                           |
| AC 25.954-1    | Transport Airplane Fuel System Lightning Protection                                                                                                  |
| AC 25.975-1    | Fuel Vent Fire Protection                                                                                                                            |
| AC 25.981-1D   | Fuel Tank Ignition Source Prevention Guidelines                                                                                                      |

AC 25.981-2A Fuel Tank Flammability Reduction Means

AC 25.994-1 Design Considerations to Protect Fuel Systems During a Wheels-up Landing

Federal Aviation Administration Joint Aircraft System/Component Code Table and Definitions, updated Oct. 27, 2008

#### 2.1.7 Coordinating Research Council (CRC) Publications

Available from Coordinating Research Council, 1 Concourse Parkway, Suite 800, Atlanta, GA 30328, Tel: 678-795-0506, [www.crcao.org](http://www.crcao.org).

CRC Report No. 647 CRC Aviation Committee - World Fuel Sampling

CRC Report No. 663 Handbook of Aviation Fuel Properties

NAVAIR 06-5-504 Aviation Handbook - Fuel and Fuel Systems, May 1967

#### 2.1.8 IEC Publications

Available from IEC Secretariat, 3 rue de Varembe, PO Box 131, CH-1211 Geneva 20, Switzerland, Tel: +41 22 919 0211, [www.iec.ch](http://www.iec.ch).

IEC 60079 Electrical Apparatus for Explosive Gas Atmospheres: 3rd Edition

#### 2.1.9 Other Publications

Civil Aeronautics Board. (1966). Aircraft accident report, United Airlines Flight 227 (Report No. 1-0032).

#### 2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

##### 2.2.1 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue SW, Washington, DC 20591, Tel: 866-835-5322, [www.faa.gov](http://www.faa.gov).

AC 20-24D Approval of Propulsion Fuels, Additives, and Lubricating Oils

AC 25-8 Auxiliary Fuel System Installations

##### 2.2.2 Other Publications

Langton, R., Clark, C., Hewitt, M. and Richards, L. (2009). *Aircraft fuel systems*. Wiley-Blackwell.

#### 2.3 Acronyms

AC Advisory Circular

ACT Auxiliary Center Tank or Auxiliary Cargo Tank

AIR Aerospace Information Report

APU Auxiliary Power Unit

ARP Aerospace Recommended Practice

|        |                                                                            |
|--------|----------------------------------------------------------------------------|
| ASTM   | ASTM International (previously American Society for Testing and Materials) |
| ATA    | Air Transport Association                                                  |
| CFR    | Code of Federal Regulations                                                |
| CG     | Center of Gravity                                                          |
| CS     | Certification Specification                                                |
| EMI    | Electromagnetic Interference                                               |
| FAA    | Federal Aviation Administration                                            |
| FOD    | Foreign Object Debris                                                      |
| FQI    | Fuel Quantity Indication                                                   |
| FQIS   | Fuel Quantity Indicating System                                            |
| HIRF   | High Intensity Radiated Field                                              |
| kg     | Kilogram                                                                   |
| kV     | Kilovolt                                                                   |
| LP     | Low Pressure                                                               |
| m      | Meter                                                                      |
| MAC    | Mean Aircraft Chord                                                        |
| MOD    | Ministry of Defence (UK)                                                   |
| NEA    | Nitrogen Enriched Air                                                      |
| OBIGGs | Onboard Inert Gas Generating System                                        |
| Pa     | Pascal                                                                     |
| psi    | Pounds per Square Inch                                                     |
| REACH  | Registration, Evaluation, Authorization, and Restriction of Chemicals      |
| rms    | Root/Mean Square                                                           |
| s      | Second                                                                     |
| SOV    | Shutoff Valve                                                              |
| TVP    | True Vapor Pressure                                                        |
| UERF   | Uncontained Engine Rotor Failure                                           |
| ZFWCG  | Zero Fuel Weight Center of Gravity                                         |

## 2.4 Symbols

Symbols used within equations will be defined local to the equation, but common items are given below.

|   |                                  |
|---|----------------------------------|
| g | Gravity (9.81 m/s <sup>2</sup> ) |
| ρ | Density (kg/m <sup>3</sup> )     |
| Y | Specific Weight (ρ*g)            |

## 2.5 Definitions

**AUTOIGNITION TEMPERATURE:** The minimum temperature at which an optimized flammable vapor and air mixture will spontaneously ignite when heated to a uniform temperature in a normal atmosphere without an external source of ignition, such as a flame or spark.

**AVAILABILITY:** Probability of the system having the ability to perform its function with or without failures present.

**CELL:** Subdivision of a fuel tank, where there is restricted flow to/from the cell and the rest of the tank.

**ELECTRICAL BONDING:** The joining of conductive parts to form an electrically conductive path that assures electrical continuity and the capacity to safely conduct current between the conductive parts.

**ELECTROSTATIC DISSIPATION:** Reduction of any charge buildup on any fluid, structure, or equipment.

**ELECTROMAGNETIC INTERFERENCE (EMI):** Any emitted, radiated, conducted, or induced voltage that degrades, obstructs, or repeatedly interrupts the desired performance of electronic equipment.

**EXPANSION SPACE (in context of fuel tanks):** The portion of the ullage that is available for thermal expansion of the fuel prior to fuel spilling overboard

**FAIL-SAFE DESIGN (general):** A system or component that mitigates or prevents unsafe consequences of failure. Fail-safe design can be considered in the context of fuel system design for items where the failure position is considered the safest option; for example, the engine isolation valve (shutoff valve) typically should not fail to the closed position in flight.

**FAIL-SAFE DESIGN (in the context of ignition risk):** 14 CFR § 25.981 paragraph a(3) defines a fail-safe design as "Demonstrating that an ignition source could not result from each single failure, from each single failure in combination with each latent failure condition not shown to be extremely remote, and from all combinations of failures not shown to be extremely improbable." Within the context of 14 CFR/CS § 25.1309, an extremely improbable event (catastrophic) must have a probability of less than 10<sup>-9</sup> per flight hour. Within the context of 14 CFR/CS § 25.1309, an extremely remote event (hazardous/severe major) must have a probability of less than 10<sup>-7</sup> per flight hour.

**HIGH INTENSITY RADIATED FIELD (HIRF):** Expected aircraft radiated field environment resulting from exposure to radio frequency (RF) energy of a strength sufficient to adversely affect either a living organism or the performance of a device subjected to it. An example of devices generating such a field are RADAR transmitters.

**IGNITION SOURCE:** A source of sufficient energy to initiate combustion of fuel vapor, such as within the fuel tank ullage space.

**INTEGRITY:** The integrity of a system is the probability of that system displaying data or performing an operation that may appear correct to the users of the system but in actual fact is in error or inappropriate, without the system indicating that there is a fault (i.e., the error is caused by an undetected and/or unindicated failure).

**INTRINSICALLY SAFE:** Any instrument, equipment, or wiring that is incapable of releasing sufficient electrical, thermal, or light energy under normal operating or anticipated failure conditions to cause ignition of a specific hazardous atmosphere mixture in the most easily ignited concentration. Refer to AC 25.981-1D for a comprehensive review of energy sources and acceptable energy magnitudes. Refer to AC 25.954-1 for review of lightning threats. More details regarding intrinsically safe design can be found in IEC 60079.

**LATENT FAILURE:** A failure whose presence may not be readily apparent to the flight crew or maintenance personnel.

**LIGHTNING INDIRECT EFFECTS:** Electrical transients in aircraft fuel system circuitry/wiring/plumbing that occur when energy from a direct strike to the aircraft is coupled into equipment wiring or other structure and plumbing. These transients are coupled through electromagnetic field penetration into the aircraft interior or through structural IR voltage rises due to the lightning current flow on the aircraft. Refer to AC 25.954-1.

**LIGHTNING STRIKE ZONES:** Aircraft surface areas and structures classified according to the possibility of lightning attachment, dwell time, and current conduction. Refer to ARP5414. Note that ARP5412 gives details of the lightning environment associated with this zoning, and ARP5416 provides test methods (Section 7 is particularly relevant to fuel systems).

**NORMAL OPERATION:** The operating condition of a component in the absence of faults and threats.

**OUTGASSING:** Release of air dissolved from within the fuel, typically during climb. This causes spontaneous generation of air bubbles within the fuel.

**SAFETY:** Ability of a system to operate in normal, abnormal, and failed modes with an acceptable level of hazard.

**SURGE:** Increase in pressure due to a change in condition in the system when fuel is flowing, such as a valve closure, or when fuel starts to flow, such as a valve opening

**SURGE TANK:** Also called vent tank. A tank, usually located as the most outboard tank in a wing or tail plane. This tank is designed to be normally dry and provide the interface to the vent outlet/NACA while ensuring that any fuel that floods into the vent system during fast taxi turns does not leave the aircraft tank system.

**RELIABILITY:** Ability of a system to operate with the required integrity and safety without failure/repair.

**TRIBO-ELECTRIC CHARGING:** The tribo-electric effect (also known as tribo-electric charging) is a type of contact electrification in which certain materials become electrically charged after they come into frictional contact with a different material. Flow of fuel against structure, pipes, or components can cause this charging of the fuel and the item it is flowing over.

**ULLAGE:** Space above the fuel surface within an aircraft fuel tank (i.e., space between the fuel surface and upper tank surface) filled with a mixture of air and fuel vapor.

**NOTE:** Due to structural and vent configuration, typically not all of the ullage is available for fuel expansion.

**UNSAFE SYSTEM OPERATING CONDITION:** Operating condition in which the airplane is operating one failure away from a catastrophic failure condition (including fuel tank ignition or over pressure) that is greater than extremely remote.

Terminology associated with ground refueling systems and activities is given in AIR4783.

Terminology associated with fuel system components is given in AIR1615.

## 2.6 Units and Formulae

All the formulae in this document are derived from those in NAVAIR-06-5-504, although they have been converted to SI units and errors have been corrected when found. SI units are used throughout this document, except where it is common industry practice to use other units; for example, unless within an equation, altitude is referred to in feet, and pump and refuel pressures are referred to in psi. The conversion between SI units and imperial units for common parameters are given below:

Length: 1 meter (m) = 3.28 feet = 39.37 inches

Volume: 1 m<sup>3</sup> = 1000 liters (L) = 264.17205 U.S. gallons

Mass: 1 kilogram (kg) = 2.205 pounds

Pressure: 1 Pascal (Pa) = 0.00014504 pound per square inch (psi)

Force: 1 Newton (N) = 0.224808942 pound-force (lbf)

Temperature: X°C = (F-32) \* 5/9 °F (so 0 °C = 32 °F, 100 °C = 212 °F)

## 3. OVERVIEW OF FUEL SYSTEM DESIGN

In the context of this document, the airframe fuel system is considered to encompass all elements associated with provision and storage of fuel to the engine and APU contained within the airframe, ending at the engine feed pipe shutoff valves (referred to as the SOV) which control fuel flow to the pylon and any other interface components (such as shutoff valves or check valves) which control the fuel flow to/from the pylon. Other functions, often grouped with fuel systems, such as inerting/flammability reduction, will not be included in this document. Further detail about inerting system design can be found in ARP6078. Details of explosion suppressant foam, which is sometimes used as a means of flammability reduction, can be found in AIR4170.

The airframe fuel system provides a number of basic functions:

- Storage of fuel, including maintenance of the tanks at a suitable pressure (venting)
- Provision of fuel to the engines and APU
- Provision of fuel to subsystems for thermal management
- Transfer of fuel between tanks and management of those transfers (if required)
- Refueling and defueling
- Jettison (if required for safety or economic reasons)
- Provision of fuel quantity data, fuel temperature, warnings, advisories, maintenance data, etc., to the flight crew and maintenance crew (i.e., fuel measurement and management), including display and control interfaces

The ATA chapter breakdown is as follows (refer to FAA Joint Aircraft System/Component Code Table and Definitions):

|       |                                 |
|-------|---------------------------------|
| 28-00 | Aircraft Fuel System            |
| 28-10 | Fuel Storage                    |
| 28-20 | Aircraft Fuel Distrib. System   |
| 28-21 | Aircraft Fuel Filter/Strainer   |
| 28-22 | Fuel Boost Pump                 |
| 28-23 | Fuel Selector/Shutoff Valve     |
| 28-24 | Fuel Transfer Valve             |
| 28-30 | Fuel Dump System                |
| 28-40 | Aircraft Fuel Indicating System |
| 28-41 | Fuel Quantity Indicator         |
| 28-42 | Fuel Quantity Sensor            |
| 28-43 | Fuel Temperature Indicator      |
| 28-44 | Fuel Pressure Indicator         |
| 28-97 | Fuel System Wiring              |

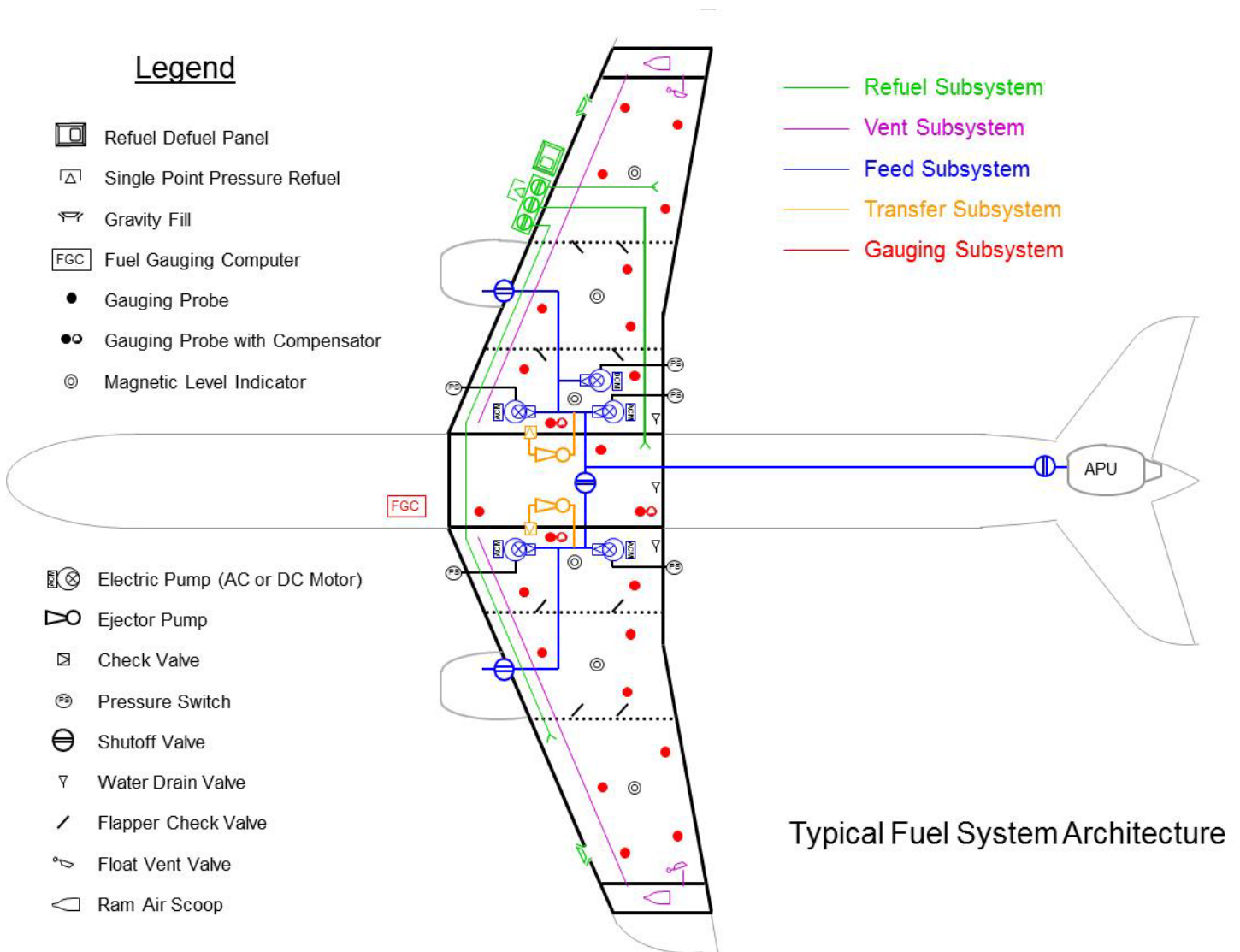


**Figure 1 - Overview of a fuel system**

### 3.1 Fuel System Requirements

In essence, fuel system requirements are relatively simple and can result in a simple system, but other considerations in a modern, large (more integrated) commercial and military aircraft often drive increased complexity. Elements that must be considered when designing a fuel system fall broadly into three areas:

a. Aircraft level requirements, for example:

- Number and location of engines
- Mission length/range (i.e., fuel mass required)
- Pressure/flow to the engine
- Operational altitude range
- Operational temperature
- Required refueling time

- Center of gravity requirements
  - Availability/dispatchability
  - ETOPs requirements
  - Subsystem integration for thermal management requirements
  - Diagnostic and fault tolerance requirements
- b. Knowledge based on previous experience, often embedded within the 14 CFR/CS requirements for commercial aircraft and associated ACs/AMCs, MIL-F-17874, and JSSG-2009 App E and F for military aircraft:
- Water buildup and the need for ways to remove it (scavenge, water drain, etc.); refer to 14 CFR/CS §25.971
  - Static charge buildup; refer to 14 CFR/CS §25.899
  - Surge pressures; refer to 14 CFR/CS §25.979(d)
  - Installation principles (movement and deformation of pipes, wire chafing, etc.); refer to 14 CFR/CS § 25.993
  - Fuel tank ignition risk; refer to 14 CFR/CS §25.981(a) and AC 25.981-1D
  - Fuel tank flammability reduction; refer to 14 CFR/CS §25.981(d) and AC 25.981-2A
  - Fuel system lightning protection; refer to 14 CFR/CS §25.954
- c. Other constraints:
- Regulation/airworthiness authorities; other 14 CFR/CS requirements, local regulation, etc.
  - Other legal requirements such as REACh, emission requirements, noise regulation, etc.
  - Airframe limitations such as tank pressures, structural fatigue, etc.
  - Fuel properties
  - Material properties

By taking all these elements into account, a basic fuel system architecture can be determined. The basic architecture should be tested against safety and reliability requirements to ensure that it has sufficient levels of redundancy and that all catastrophic and hazardous failure conditions have been addressed. Typically, a Failure Modes Effects and Criticality Analysis (FMECA) document is produced to document critical failure modes and derive monitoring and diagnostic requirements. These are, in turn, used to define the necessary fuel system related advisories, cautions, and warnings to safely operate the aircraft.

Once the fuel system architecture is established, then requirements for individual components can be developed. All components should be designed with material and design considerations for the intended operating environment and conditions, including temperature, pressure, humidity, vibration, and acoustics. Specific guidance regarding fuel system component qualification can be found in ARP8615 and will not be discussed further in this document.

## 3.2 Aviation Fuel

### 3.2.1 Fuel Types

Jet fuel itself will not be discussed in detail in this document, but this paragraph gives a high-level summary of what fuels are typically used.

Most commercial aircraft operate using Jet-A or Jet-A1 fuel, as defined in ASTM D1655 or DEF-STAN-91-091, although many countries have their own fuel specification. Further details about the fuel properties that impact fuel system design can be found in AIR7484.

Both ASTM D1655 and DEF-STAN-91-091 allow the use of certain synthetic components as well as traditional crude derived fuels. The approved synthetic components are given in ASTM D7566. These have been approved following a process described in ASTM D4054. Further details about such fuels and their properties, which may impact fuel system design, will be included in AIR6148.

Other major fuels used in commercial aviation include Russian TS-1 and Chinese No. 3 Jet.

Military aircraft generally can operate on the above commercial fuels but have their own specifications and fuel type designations, specifically MIL-DTL-5624 (JP-5), MIL-DTL-83133 (JP-8).

Commercial and military fuel types are very similar. Specifically, JP-8 is very similar to Jet A1, with the only difference being the presence or absence of fuel additives. JP-8, Jet-A1, and Jet-A all require a flash point of 100 °F, whereas JP-5 requires a flash point of 140 °F (the higher flash point is for safety concerns when operating aboard air-capable ships).

### 3.2.2 Additives

All fuel specifications control the definition and presence of additives in bulk fuel. Commercial specifications allow for the presence of additives but generally do not require additives. Military specifications require certain additives.

Generally, there are four basic additives:

- FSII - Fuel System Icing Inhibitor - prevents freezing of water dissolved in the fuel
- CI/LI - Corrosion Inhibitor/Lubrication Improver - as its name implies
- SDA - Static Dissipater Additive - prevents adverse development and storage of electrostatic charges in fuel
- AO - Antioxidant - prevents oxidation of fuel in long-term storage

## 4. FUEL STORAGE

Fuel tanks are either independent self-contained units that are installed inside the aircraft or they can be integrated into the aircraft structure. If integrated into the aircraft structure, then the tank walls will be whatever material the aircraft is constructed from. Historically, aluminum was most common; however, for military aircraft and some modern, large commercial aircraft, composites are becoming more common for weight and strength reasons. Specific design considerations for composite tanks are given in AIR5774.

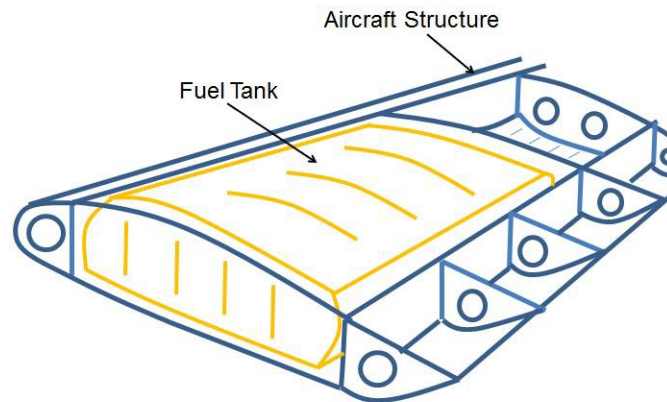


**Figure 2 - Independent self-contained tanks**

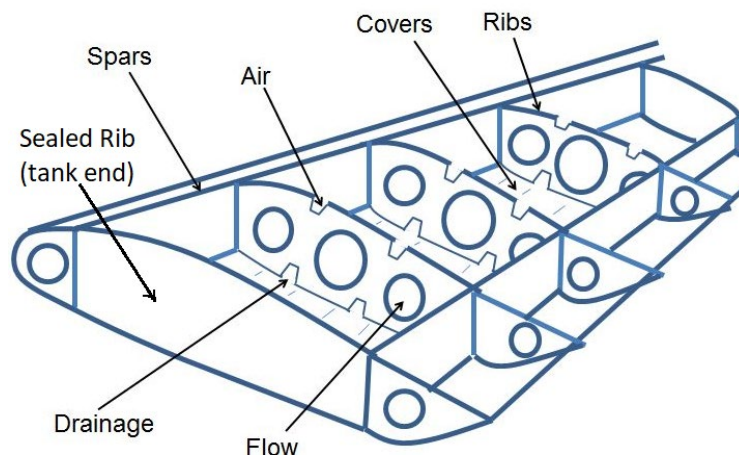


**Figure 3 - Integrated fuel tank**

Fuel tanks can be installed in any location where integrity after a crash (specifically wheels up landing) can be demonstrated. Typical locations for fuel tanks are within the wings, the center wing box, tail, or any convenient location in the fuselage.

For integrated wing tanks, the upper and lower covers of the wings, along with the front and rear spars, form the tank walls. The tank structure terminates at a point usually inboard of the wing tip so that any vent outlet is not within the zone 1 lightning zone (refer to ARP5414).

If more fuel is required, other than that contained within the wings, then a center tank is often installed in the fuselage, between the two wings. Additionally, the horizontal stabilizer on the tail may also be used as a fuel tank. Note that use of the horizontal stabilizer as a fuel tank can have significant impact on the center of gravity of the aircraft.

If more fuel is required for the aircraft to achieve the desired range, then ACTs (auxiliary cargo tanks/additional center tanks) may be added. Usually, these are cargo pallet-shaped tanks, which can be installed and removed as required.

Other areas within the aircraft can be used for tanks, dependent on aircraft design and range requirements.

One of the starting points for the design of the fuel system is knowledge of the mission range/profile which determines the volume/mass of fuel that the aircraft needs to carry in order to complete the mission.

## 4.1 Tank Boundaries

### 4.1.1 Uncontained Engine Rotor Failure (UERF)

One consideration for setting the tank boundaries is minimizing the impact of an uncontained rotor burst (uncontained engine rotor failure [UERF]). 14 CFR/CS §25.903(d) requires that design precautions are taken to minimize the hazards to the aircraft in the event of engine rotor failure. The quantity of fuel remaining following a UERF event should be maximized.

AC 20-128A can be interpreted as follows for fragment size and energy and spread angle considerations (see Figure 4):

- 0 to 3 degrees spread angle: one-third disk considered to be infinite energy
- 3 to 5 degrees spread angle: one-third disk finite energy or intermediate fragment
- 5 to 15 degrees spread angle: small fragments, protection is given by primary structure

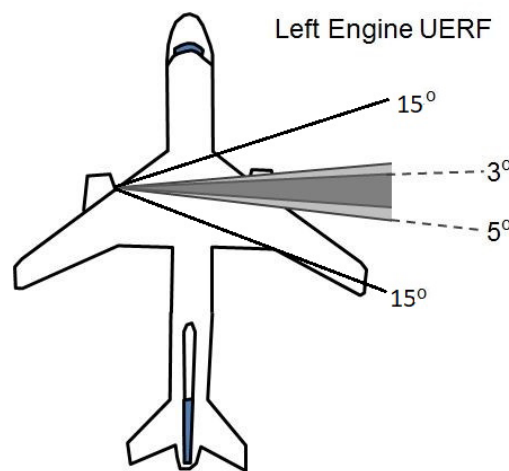


**Figure 4 - UERF spread angles**

Further details are given in AC 20-128A, which details the one-third fragment size and the consideration for infinite energy, as well as the analysis which should be performed. EASA AMC 20.128A also includes dry bay considerations, and other factors which should be considered. There are similar considerations for aircraft with propellers; AMC 25.905(d) states that "... precautions should be taken within an impact zone defined by the region between the surfaces generated by lines passing through the center of the propeller hub making angles of at least 5 degrees forward and aft of the plane of rotation of each propeller."

Although in principle this means that additional structure could be used to provide protection for the 3 to 5 degrees case, this is difficult to justify and the 5 degrees case is usually the design driver (a manufacturer can choose to demonstrate compliance in other ways, but this requires sufficient evidence to justify any alternate approach). In terms of fuel tank boundaries, AC 20-128A states that "any fuel reserves should be isolatable, such that damage from a disc fragment will not result in loss of fuel required to complete the flight or a safe diversion." In practice, this drives the position of fuel tank boundaries for a twin engine aircraft so that an uncontained rotor burst in one engine will not disrupt the fuel flow to the other engine (i.e., will not pierce the tank feeding that other engine). If the boundary is beyond the 5 degrees spread angle from each rotor plane in the engine, then it is considered that a rotor burst in one engine will not puncture the tank feeding the opposite/other engine(s) and so fuel feed to the remaining engine(s) can continue following a UERF event.

For fan blades specifically, a spread of 15 degrees for fragments sized by a maximum dimension determined by the blade tip with one-third the blade airfoil height. When considering the energy, the mass should be assumed to be one-third of the airfoil, including any part span shroud, with the center of gravity assumed to lie at the center of the fragment, and the transitional energy is calculated based on the velocity of the center of gravity (neglecting rotational energy).

Tank boundaries should be set (see Figure 5) to maximize the protected volume of fuel. For example, if all the fuel from both wings and the center tank could be lost, then this would probably be unacceptable to the certification authorities.

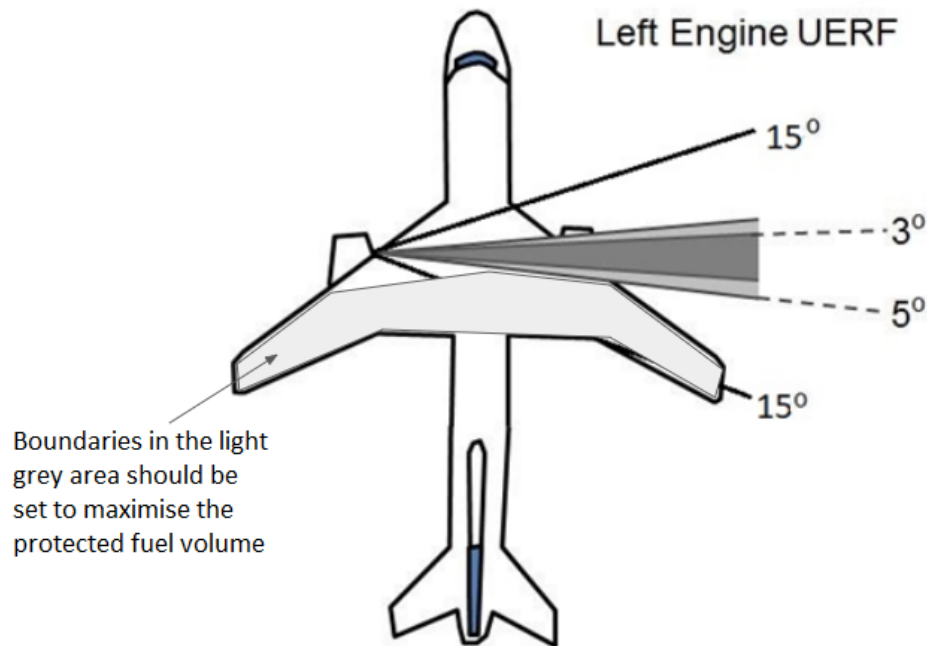


**Figure 5 - Protected fuel volume**

AC 20-128A also requires that any flammable liquid (i.e., fuel) shutoff valve controlling fuel supply to the engine must be able to be operated following an uncontained rotor failure, which means that redundant control, and segregation of control wiring, must be implemented in order to ensure that control is still possible, even if the fragment cuts the wire on one route.

#### 4.1.2 Engine Feed Tanks

The initial driver for both the number of tanks and the tank boundaries is the number and position of the aircraft engines.

14 CFR/CS §25.953 leads to a requirement that each engine is fed from a separate tank. 14 CFR/CS §25.953(a) states that each fuel system must meet the requirements of 14 CFR/CS §25.903 by:

- a. Allowing the supply of fuel to each engine through a system independent of each part of the system supplying fuel to any other engine.

In addition, 14 CFR/CS §25.903(b) implies segregation, with requirements that state:

- b. Engine Isolation: The power plants must be arranged and isolated from each other to allow operation, in at least one configuration, so that the failure or malfunction of any engine, or of any system that can affect the engine, will not:
  1. Prevent the continued safe operation of the remaining engines
  2. Require immediate action by any crewmember for continued safe operation

Interpreting this in terms of the fuel system means that a separate engine feed tank is required for each engine so that if one tank has an issue (e.g., contaminated fuel, blockage, etc.), then this does not prevent fuel being available to feed to the other engines. This means that for a two-engine aircraft, a minimum of two tanks is required, and for a four-engine aircraft, a minimum of four tanks is required. For structural reasons, these tanks are usually located in the wings for large commercial aircraft (there is less stress on the wing root if the bulk of the fuel is stored on the wings throughout the flight); see [4.1.4.1](#).

EASA AMC 20-128A also includes dry bay considerations and other factors that should be considered.

#### 4.1.3 Surge Tanks

These can also be called vent tanks. The surge tank is associated with a group of tanks and acts as a last barrier before air or fuel exits the aircraft. Most aircraft have what is called an open vent system, i.e., the tanks are vented to atmosphere, allowing the free flow of air between the outside atmosphere and the inside of the tank system. Under certain fuel loads and maneuver combinations, it is possible for fuel to flow into the vent system, and so it is possible for the fuel to flow overboard through the vent outlet. There should be no fuel spill during normal operations of the aircraft; therefore, it is necessary to provide a tank to collect the fuel that might flow through the vent system when the tanks are full, during typical ground maneuvers such as fast taxi turns, and typical air maneuvers. Surge tanks are typically located at the highest point in the wing, which means usually in the wing tip for the majority of aircraft with a dihedral wing (and tail plane tip if there is a tank in the tail plane). Surge tanks are typically sized for the volume of fuel that might travel through the vent system if the aircraft is fully loaded with fuel, during four fast taxi turns and a takeoff. Under these conditions, there must be no spillage of fuel.

A consideration is the return of any fuel collected in the surge tank to the engine feed tanks. This could be as simple as having a “clack” valve or “flapper” valve located at the bottom of the surge tank in the boundary between the surge tank and the fuel tank adjacent to it. This valve will open to allow flow of fuel from the surge tank when the fuel in the adjacent fuel tank is at a level below the valve but will remain closed, preventing flow of fuel from the fuel tank to the surge tank, under the pressure exerted by the fuel, if there is fuel at a level above it in the fuel tank. The valve is basically a hinged door, which will be held closed when the pressure on the opening side is greater than the pressure on the other side.

If the tank arrangement is such that fuel cannot flow from the surge tank back into an adjacent tank by gravity, then it will be necessary to provide another suitable transfer means, such as siphoning via the vent tubes, or transfer using a jet pump. A typical arrangement for siphoning is shown in Figures 6 and 7.

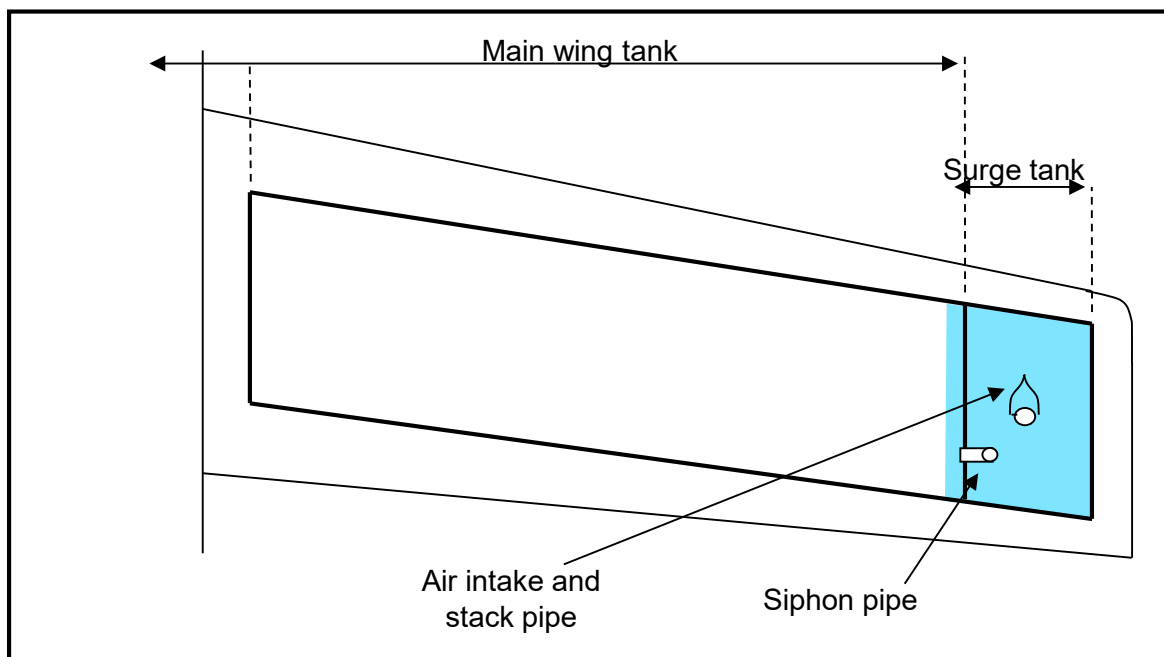


**Figure 6 - Plan view showing surge tank**

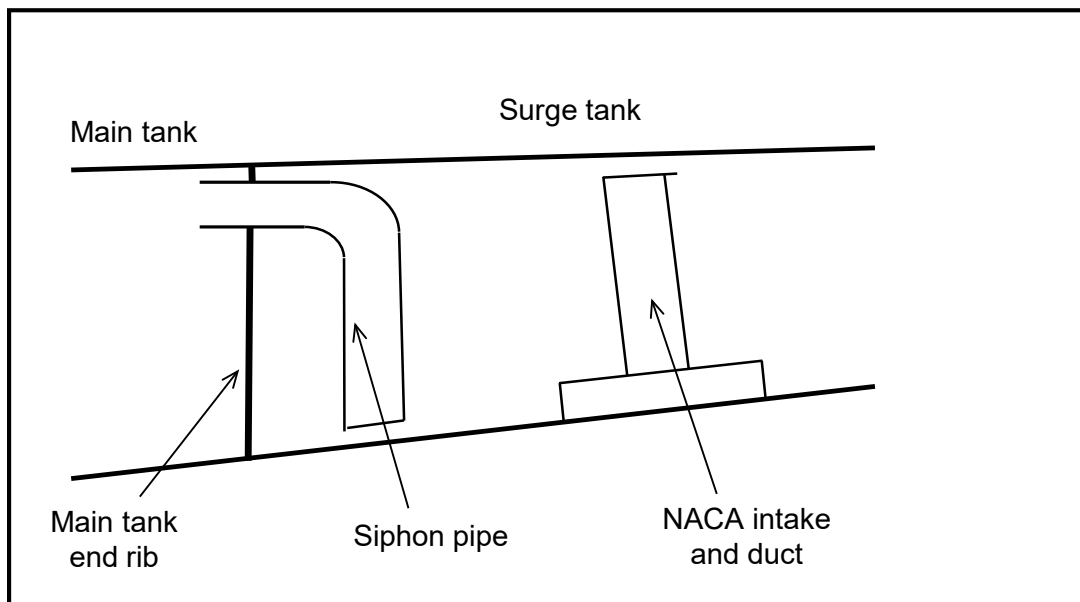


**Figure 7 - Side view showing surge tank**

#### 4.1.4 Additional Wing/Center Tanks

If additional fuel is required in order to meet the mission requirements of the aircraft, once the engine feed and surge tanks have been determined, then any remaining space in the wings and fuselage section between the wings can be used for additional tanks. There may be further considerations in the placement of these tanks, and the fuel weight may be used to provide wing bending relief to reduce the fatigue loading on the wing root.

Fuel stored in these additional tanks can either be fed directly to the engine or transferred into the engine feed tanks.

##### 4.1.4.1 Wing Bending Relief/Wing Tip Tanks

When an aircraft is being refueled, as the fuel load increases, the wing gradually “droops,” or bends downward, under gravity. When the aircraft takes off, the lifting effect of the airflow across the wing means that the wing flexes upward, with increasing upward bending toward the tip of the wing. If the fuel can be kept outboard for as long as possible during a flight, then the upward bending effect will be minimized. Depending on the aircraft and the wing configuration (i.e., how flexible the wing is), this can provide significant benefit in reducing structural weight, as less bending means less fatigue. This means a lighter structure can be used. Some aircraft are configured to have outer tanks that are kept full until almost the end of the flight, providing the maximum possible wing bending relief.

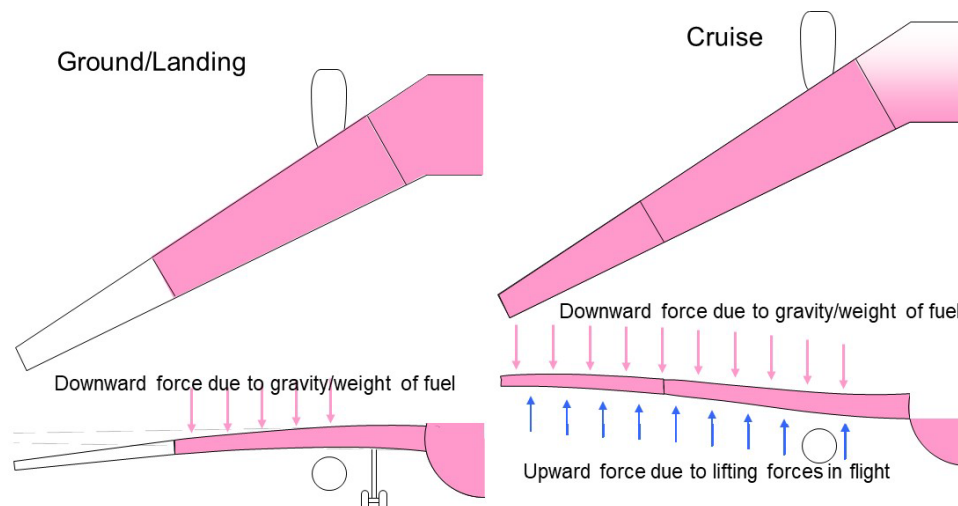


**Figure 8 - Effect of fuel in outboard tanks**

If this option is implemented, there are other fuel system considerations:

- a. The fuel in the outboard tanks potentially becomes critical toward the end of flight; therefore, there must be a better than  $10^{-9}$  probability that failures will not prevent the fuel being accessible when required. This means that multiple means of accessing the fuel and moving it to an engine feed tank are required.
- b. Tanks in the extremities of the aircraft, especially if these are very thin tanks, are likely to get very cold during long flights and possibly reach the point where the fuel starts to freeze. Action needs to be taken before this temperature is reached to ensure the fuel is still accessible; therefore, the temperature will need to be monitored and an alert raised in the cockpit if the fuel temperature approaches the specified fuel freeze point.
- c. Tanks in the wing tips impact center of gravity. Since the wings sweep toward the back of the plane on most aircraft, maintaining fuel outboard in the wing keeps the center of gravity further toward the back of the aircraft (often desirable).

#### 4.1.5 Auxiliary Cargo Tanks/Additional Center Tanks (ACTs)/Other Fuselage Tanks

If more fuel is needed, then additional center tanks or auxiliary cargo tanks (ACTs) can be added. These are usually palletized tanks, which fit within the cargo area of the aircraft. On many aircraft, which have the facilities for these tanks being added, the tanks can be added or removed as needed for the missions the aircraft is flying.

In addition, depending on aircraft configuration, tanks can be located within the aft fuselage or external to the fuselage (i.e., structurally and aerodynamically part of the fuselage; sometimes referred to as “conformal tanks”). Such solutions are often found in midrange regional jets or in business jets.

#### 4.1.6 Tail Tanks and Center of Gravity Considerations

If a tank is added in the horizontal or vertical stabilizer of the aircraft, this is often called a trim tank. It can be added to give additional range, or it can be added to provide some influence on the center of gravity, bringing it more toward the rear of the aircraft, which, with some aircraft configurations, leads to efficiency improvements (i.e., reduced fuel burn in cruise). Various considerations drive the criticality of the installation and therefore the complexity:

- a. How close to the center of gravity limit does the trim tank fuel bring the aircraft under various fuel loads and flight/ground conditions? (This may mean that the tank cannot be fully loaded on the ground but requires transfer of fuel after takeoff, or it may put other restrictions on the loading of the aircraft for cargo, etc.)
- b. How will the fuel be used during the flight: will it be brought forward as soon as there is sufficient space in the center/wing tanks, or will as much fuel as possible be left in the tank until near the end of the flight? This may also drive the need to monitor the temperature of the fuel; see discussion in [4.1.4](#) about fuel temperature and tanks in the extremities of the aircraft. If the fuel is left in the tank until near the end of the flight, then the transfer potentially becomes critical; thus, there may need to be a better than  $10^{-9}$  probability that failures will not prevent the fuel being accessible when required. This drives the need for multiple pumps/valves.

The pipe from the main tank system to the trim tank usually passes through the pressurized zone, so it must be double walled, shrouded, and with a shroud drain to ensure there is no leakage into the passenger compartment. If the shroud drain outlet is in an area which might be subjected to lightning attachment, then a flame arrestor may be needed at the outlet. Consideration must be given to crashworthiness characteristics of the pipe routing (refer to 14 CFR/CS §25.993) The flexibility of the connection must account for fuselage break points, and any effects where structure may cut through the pipe in a guillotine or slashing effect under crash landing conditions must be evaluated. It is common to include two pumps or pumping devices in the tail tank to ensure the fuel can be pumped forward, even under failure conditions. Similarly, it is typical to include two valves so the tank can be refueled, even under failure conditions.

A vent/surge tank will also be needed within the tail associated with this tank.

#### 4.1.7 Expansion Space

In sizing the tanking system, 14 CFR/CS §25.969 also requires that there must be an expansion space of at least 2% of tank capacity. In case of tanks filled to volumetric shutoff, this allows a change in temperature of 25 °C from completion of refuel until the engines start burning fuel, before the expansion space is filled, assuming a typical expansion of Jet A/Jet A-1 fuel at 0.8%/10 °C (0.45%/10 °F). Land-based military aircraft typically require 3% expansion space for temperature variation. Ship-based military aircraft typically require 5% expansion space (from JSSG) for fuel temperature variation and sloshing due to ship movement.

#### 4.1.8 Dry Bays

Sometimes it is necessary to partition off a part of the tank and maintain this as a dry section, known as a “dry bay.” One of the primary reasons for this is driven by 14 CFR/CS §25.967, which states “no engine nacelle skin immediately behind a major air outlet from the engine compartment may act as the wall of an integral tank.” By adding a dry bay over any such air outlets, the direct contact with a fuel tank is removed.

The possibility of fuel leaking into an engine after an uncontained engine rotor burst may also drive the need for a dry bay. AC 20-128, paragraph 8(a)(4)(i) states “protection from the effects of fuel leakage should be provided for any fuel tanks located above an engine or APU and within the one-third disc and intermediate fragment impact areas. Dry bays or shielding are acceptable means. The dry bay should be sized based on analysis of possible fragment trajectories through the fuel tank wall and the subsequent fuel leakage from the damaged fuel tank so that fuel will not migrate to an engine, APU, or other ignition source during either in flight or ground operation.”

### 4.2 Structural Considerations/Tank Pressures

#### 4.2.1 Pressure on the Tank Floor

The structural design of the tank must take into account the pressures exerted by the fuel. Refer to 14 CFR/CS §25.963(a) and (d)(1). In a static condition, the pressure on the bottom of a fuel tank depends on the height of fuel above the tank floor. In simple terms:

$$P_f = \rho \cdot h \cdot g \quad (\text{Eq. 1})$$

where:

$P_f$  = pressure on the tank floor (Pa)

$\rho$  = density (kg/m<sup>3</sup>)

$h$  = height of fuel (m)

$g$  = gravity (m/s<sup>2</sup>)

Therefore, as the tank is exposed to increases in apparent gravity or acceleration, the pressure on the bottom of the tank increases in direct proportion to the increasing  $g$  load.

#### 4.2.2 Pressure on a Tank Wall

The pressure on the tank wall at a depth,  $d$ , will be proportional to that depth, assuming a constant,  $g$ , and will increase according to the relationship:

$$P_w = \rho \cdot d \cdot g \quad (\text{Eq. 2})$$

where:

$P_w$  = pressure on the tank wall (Pa)

$\rho$  = density ( $\text{kg/m}^3$ )

$d$  = depth in fuel (measured from fuel surface) (m)

$g$  = gravity ( $\text{m/s}^2$ )

The shape of the wall has no influence on the pressure at a given level.

##### 4.2.2.1 Accelerated Liquids in Equilibrium

If a tank with fluid in it is given a constant or uniform acceleration, the fluid comes to rest relative to the container as shown in Figure 9.

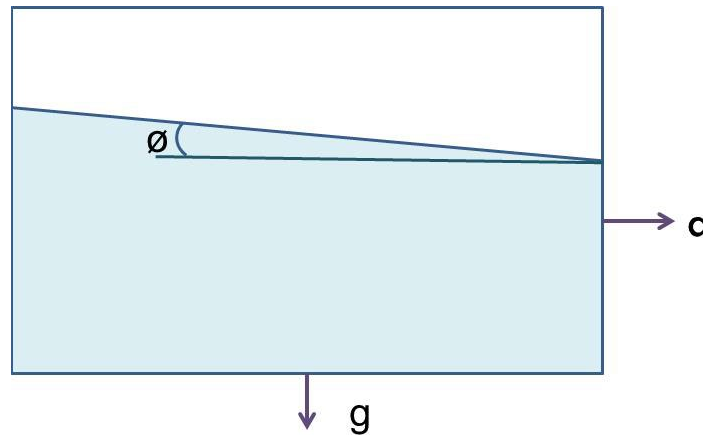


**Figure 9 - Fuel movement under acceleration**

The resultant force acting on the wetted surface of the tank is perpendicular to the free surface of the liquid and may be calculated from:

$$\text{Resultant acceleration} = \sqrt{a^2 + g^2} = \text{resultant gravity} \quad (\text{Eq. 3})$$

where:

$a$  = acceleration ( $\text{m/s}^2$ )

$g$  = gravity ( $\text{m/s}^2$ )

The surface of the liquid is inclined to the horizontal at an angle  $\theta$  such that:

$$\theta = \tan^{-1} \frac{a}{g} \quad (\text{Eq. 4})$$

This is particularly important for gauging systems, where the relative angle of the fuel surface to that when the tank is horizontal can impact the accuracy, if not accounted for.

14 CFR/CS §25.963 gives specifics of the hydrostatic pressures that the tank must be able to withstand without rupture.

#### 4.2.3 Crashworthiness

In considering the design of the fuel tank structure, thought must be given to the effects of fuel movement, particularly in crash scenarios. An emergency landing situation can generate 9 g forward inertial forces (refer to 14 CFR/CS §25.561(3)). Specific crash cases and requirements are given in 14 CFR/CS §25.963. Movement of fuel can cause additional force on the spar. In order to prevent this exceeding design thresholds, baffle ribs or semi-sealed ribs may be introduced into the tank, which limit the movement of the fuel, allowing only part of the tank fuel load to impact the spar under a crash condition. Baffle ribs can also be used to reduce fuel sloshing in large tanks.

#### 4.3 Tank Volumes

Although the maximum volume of fuel required is driven by the length of mission the aircraft is expected to fly, there are other considerations that also have to be accounted for when sizing the tanks:

- a. 14 CFR/CS §25.969 requires there be 2% expansion space; this can include the surge tank space as well as the ullage space in each tank.
- b. 14 CFR/CS §25.959 requires that the unusable fuel quantity be established as the point at which an engine first malfunctions (due to fuel starvation). Fuel less than this quantity cannot be included in calculation of the fuel available for a mission.
- c. 14 CFR/CS §25.971 requires that each tank must have a sump. See Figure 10; the sump is within the volume represented by (5) + (6) with an effective capacity, in normal ground attitudes, of not less than the greater of 0.1% of tank capacity or 0.25 L (0.066 gallon).

The calculation of usable fuel volume also depends on the location of the vent openings (i.e., the fuel below the vent opening in normal attitudes is considered) and the pump pickups (i.e., the fuel is not usable if the pump cannot extract it from the tank). The various references for different key volumes are depicted in Figure 10.

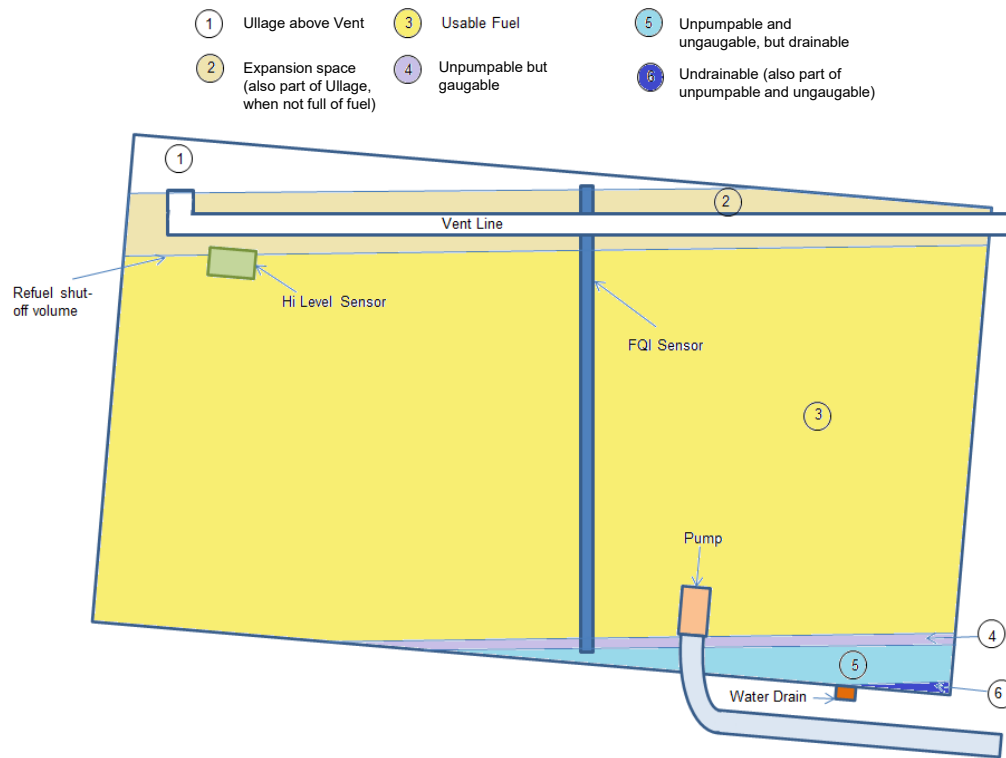


**Figure 10 - Fuel volume definitions**

From Figure 10:

- (1) represents part of the ullage space that will never contain fuel: A volume above the vent tube entrance or vent interconnect opening that cannot be filled with fuel (and therefore not available as expansion space). This volume is kept to a minimum, consistent with good vent tube entrance design and structural considerations with vent interconnect design.
- (2) represents part of the ullage space that can be filled with fuel: The volume between the high level shutoff for refuel and the vent entrance. This is to allow for fuel expansion due to temperature increase after completion of refuel. Refuel overshoot (i.e., fuel flowing after high level indication is reached) potentially could encroach into this space, but this is a failure condition (normally, refuel must terminate at a point that leaves the ullage space reserved for expansion empty of fuel).
- (3) represents the volume of fuel available to the engine from normal full tank level (high level shutoff) to the lowest point at which the pump can effectively pump fuel.
- (4) + (5) + (6) represent a volume of fuel that is unpumpable (unusable) for engine feed or transfer cases depending on the specific use of the associated tank. This is the point at which the pump first starts pumping air. Note that the sum of fuel volumes (4) and (5) is the drainable sump. This volume of fuel can be drained from the aircraft, if necessary, via the water drains/sump drains at the bottom on the tank until volume (6) is reached. During pressure defuel, the pumps can pump beyond the “unpumpable” limit, as the fact that air is entrained in the fuel does not matter in defuel. Note that this unusable fuel must be included in the zero fuel weight of the aircraft.
- (5) + (6) represent the volume of fuel that sits below the FQI sensor and is therefore physically ungaugable. Note, though, the FQI display in the cockpit will read zero when the unpumpable volume is reached (refer to 14 CFR/CS §25.1337).
- (6) represents the volume of fuel that cannot be drained from the aircraft by use of normal drains (this is trapped fuel).

An accurate volume can be quite difficult to determine, although made much easier through the use of 3D modeling tools, such as CATIA, and must take account of variation due to manufacturing tolerances and any displaced volume due to equipment, plumbing, and structural elements (ribs, etc.) submerged in the fuel.

The shape of a tank will impact the quantities involved. The ideal situation is to minimize unusable quantities (while still maintaining the minimum sump volume required by 14 CFR/CS §25.971), but large, flat tanks (e.g., center tanks without much curve on the bottom surface) can end up with relatively large unusable quantities due to a thin layer of fuel distributed over the bottom of the tank

#### 4.4 Venting

This section is specifically for open vent systems.

Vent systems without direct communication between different surge tanks can be used to prevent NEA “washing” by crosswinds on the ground or in flight when an inerting system is included in the design.

Tanks can be pressurized (for example, to transfer fuel by pressurization or to decrease the size of an inerting system). A (normally) closed vent system is one in which there are valves that control the airflow in and out of the fuel tanks and is one example of a pressurized system. Closed vent systems may be incorporated to help manage the inert status of fuel tank ullages and reduce the amount of Nitrogen Enriched Air (NEA) required for Onboard Inert Gas Generating Systems (OBIGGS). The specific considerations for pressurized tanks are not discussed here but will be discussed in a future issue within an appendix for military aircraft specifically, as pressurized vent systems are more commonly found on these aircraft. The specific considerations for rotorcraft with bladder tanks are not discussed here but will be included in a future issue within an appendix for rotorcraft.

##### 4.4.1 Vent System Design

14 CFR/CS §25.975 requires that a venting system must be provided that ensures that the difference in pressure between the inside of the fuel tank and the outside of the fuel tank is maintained at acceptable levels during normal flight operation, maximum rate of ascent and descent, and refuel/defuel. It further requires that the airspace of tanks with interconnected outlets must be interconnected.

When designing the vent system, consideration must be given to where the inlets into the vent system are located. The vent inlets are located in the ullage space at the top of the tank, but under different attitudes the exact location of the air bubble at the top of the tank will move. The pipe arrangement for the vent must also ensure that fuel siphoning from the tanks to the surge tank does not occur (refer to 14 CFR/CS §25.975(2)).

On low-speed aircraft with straight (unswept) wings and plenty of dihedral angle, the airspace above the fuel will always be located at the outboard end of the wings and will extend inboard as fuel is consumed. Venting the wing is then a simple matter of creating a surge tank at the wingtip and connecting the wing tank with the surge tank via a penetration (above the maximum fuel level) in the sealed boundary rib between them. It is then only necessary to ensure that there are sufficient gaps at the tops of all the other ribs to allow each bay to “breathe” with its neighbor. This allows air to pass from the root all the way out to the wingtip.

However, on aircraft with swept wings and those with minimal dihedral (or anhedral) angle, other considerations come into play. On flat winged aircraft, the airspace is not positively located at the root or the tip but can “wander about” depending on the forces acting on the fuel mass. On swept wing aircraft, the inertia forces acting on the fuel during takeoff and climb drive the fuel backward and outboard within each of the wing tanks, so the airspace tends to move inboard to the root during these flight phases. At other times, however, the airspace is located in the outer wings.

Ultimately, regardless of the aircraft type or tank configuration, the vent system configuration should ensure that fuel spillage is prevented during all (ground and flight) operations.

On these aircraft, provision must be made to ensure this moving airspace always communicates with the surge tank and air intake located at the wingtip. This is achieved by fitting dedicated vent pipes from the root out to the surge tank with inlets in each tank along the way. These inlets are often fitted with float valves which prevent fuel entering the vent tube, but which allow air passage when the inlets are not submerged in fuel. This prevents fuel flooding into the vent tube during refueling. Note that there is still usually one open (no float valve) vent pipe in the tank so that failure of the float valve does not cause an over-pressurization of the tank. On some aircraft, the vent pipes are formed using the existing structure by fitting closed “top-hat” or box section stringers along the underside of the top skin which carry the air between the root and the tip of the wing, as this reduces the weight of the vent system.

The sizing of the surge tank has already been discussed in [4.1.3](#). The vent pipes all terminate in the surge tank, and this must contain an opening to the outside atmosphere to allow the flow of air to/from the tanks. 14 CFR §25.975(7) requires that the vent system must prevent explosions caused by the propagation of flames from outside the fuel tank for a minimum of 2 minutes and 30 seconds (this is to allow evacuation following a crash). This drives the need for a flame arrestor to be fitted to the outlet to outside atmosphere from the surge tank. This device prevents the propagation of any flame. Note that when sizing/designing the flame arrestor, consideration must also be given to the effect of icing. Further details about flame arrestors can be found in ARP5776.

The surge tank connection to the outside atmosphere is via a NACA duct. This is designed to minimize the amount of ice or moisture allowed to accumulate in the scoop port, or pass into the wing, and to minimize drag. It also provides some pressure recovery, meaning that the tanks are at a slightly higher pressure than the surrounding atmosphere (typically less than 1.5 psi). This pressure recovery is important to improve engine feed pump performance and minimize air evolution from the fuel.

Since it is possible, under failure conditions, for the vent system or flame arrestor to become blocked, potentially leading to over-pressurization of the tank and structural damage to the aircraft, a secondary means of pressure relief may be fitted to the tank. This can take the form of an “overpressure protector” or burst disc. Typically, this can take one of two forms. The first consists of disc of breakable material (for example, carbon) held within a frame, which is designed to break at a certain pressure, thus relieving the tank pressure before a level is reached at which damage may occur. The unit is designed so that if breakage does occur, it can be visually identified during a walk-around check of the aircraft. The disc element of the unit must be replaced if breakage occurs. The second consists of a resettable valve, which opens if an overpressure occurs, relieving the pressure. If the secondary means of pressure relief addresses a catastrophic failure mode (i.e., blockage of the vent system causing structural damage), then AC 25.1309-1 requires that this second means of overpressure protection should be non-dormant. This could be addressed by a visual means of confirming that this secondary pressure relief has been activated (for example, a resettable valve that remains open until physically reset, thus allowing activation to be identified in a walk-around check) or the BIT system could be used to monitor this, providing a message indicating that the secondary means has been activated. This aspect may not be applicable to military aircraft and rotorcraft. Note that once the secondary means has been activated, there is the possibility of a fuel leak if there is sufficient buildup of fuel within the surge tank such that this secondary means is submerged. The secondary means should be positioned so that such a fuel leak is unlikely to occur in normal operation.

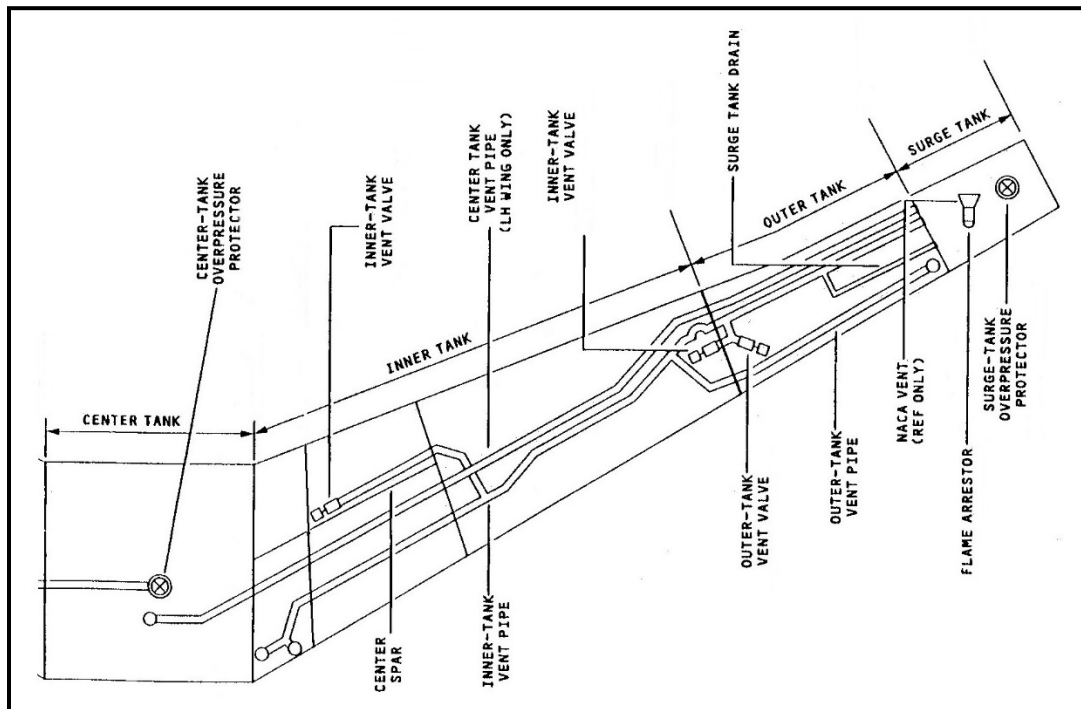


**Figure 11 - Vent system arrangement on swept winged aircraft**

#### 4.4.2 Vent System Sizing

In vent system sizing, the flow of air during climb and descent needs to be considered, as does the expulsion of air from the tank during transfers and refueling, and the possible impact of a refuel overflow case. The sizing case for vent system design is usually the emergency descent case and the refuel overflow case (refer to 14 CFR/CS §25.979(c)); however, alternative protections against refuel overflow can be used. For systems that include an inerting system, a maximum climb condition with maximum inerting system flow should also be analyzed. The discussions below assume a very simple, one tank, one vent arrangement just to show the principles; obviously, in a real aircraft fuel system, multiple tanks have to be considered, and modeling/analysis using modern tools will aid the calculations.

The calculations below take no consideration of any inerting system which may be fitted to a modern aircraft. Although inerting systems are not discussed in detail in this document, they may impact the sizing of any vent system. When considering the vent system design, the desired interaction with the fuel tank inerting system must also be considered (i.e., will the inward flow of air into the tanks be allowed), as this will dilute the inert gas in the fuel tank. If the inerting system is sized so that this is not necessary, this will significantly impact the inerting system size, and the design of an outward only venting system will be needed. Other options can retain pressure in the vent system by use of a climb/dive valve in order to minimize the size of the inerting system.

##### 4.4.2.1 Airflow During Descent

If insufficient air is brought into the tank during descent, then the tank pressure cannot be maintained at the value of the outside ambient air pressure or within the allowable tank negative pressure.