



AEROSPACE RECOMMENDED PRACTICE

ARP594™**REV. F**

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Superseding ARP594E

(R) Fuel Pump Thermal Safety Design

RATIONALE

ARP594 and ARP6385 form a basis for proper safety design of electric, motor driven fuel pumps. Revision F of ARP594 upgrades selected topics with additional design details that have already been included in ARP6385. These revisions are necessary to maintain consistency between the two documents. ARP594, when used in combination with ARP6385 and ARP5794, represents a basis for the proper pump design and testing and support certification of an airframe fuel pump installation.

ARP594F has been reaffirmed to comply with the SAE Five-Year Review policy.

1. SCOPE

The requirements presented in this document address the key considerations for thermal safety in aircraft fuel pump design. Document sections focus on understanding safety relative to an electrically motor driven fuel pump assembly acting as an ignition source for explosive fuel vapors within the airplane tank.

2. PURPOSE

This Aerospace Recommended Practice (ARP) provides fuel booster pump design considerations commensurate with industry requirements for prevention of ignition of explosive fuel vapors and the confinement of spark-initiated explosions by means of key design features, including flame-suppressing devices. Guidelines are presented for proper design of fuel pumps and systems to meet the intent of 14CFR 25.901(c), Amendment 25-40 or later, and 14CFR 25.981, Amendment 25-102 or later, and FAA AC 25.981-1C for in-tank ignition sources and the general safety requirements of MIL-STD-882. In addition, recommendations are presented for proper assembly, testing, and repair/overhaul to verify safe fuel pump design that prevents excessive external surface temperature.

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 negotiated between Seller and Buyer, except where specific revisions have been called out on selected specifications. In this case the cited revision or a later revision shall apply. 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.

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Documents

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2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

ARP4761 Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment

ARP5794 Centrifugal Aircraft Fuel Pump Requirements, Design and Testing, Aerospace Standard

ARP8615 General Specification For Fuel System Components

ARP6385 Aircraft Fuel Pump Mechanical and Electrical Safety Design

2.1.2 U.S. Military Specifications and Standards

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

MIL-STD-810 Environmental Engineering Considerations and Laboratory Tests

MIL-STD-882 System Safety

2.1.3 Other Publications

Federal Aviation Administration Advisory Circular – Fuel Tank Ignition Source Prevention Guidelines, Document Number AC 25.981-1C.

Title 14, Code of Federal Regulations – Aeronautics and Space, Section 25.981, Fuel Tank Ignition Prevention

RTCA DO160 Environmental Conditions and Test Procedures for Airborne Equipment

ASTM E659 Standard Test Method for Autoignition Temperature of Chemicals

2.2 Related Definitions

ARC FAULT CIRCUIT BREAKER – A device that provides circuit breaker protection by detecting electrical arcing faults and interrupts electrical power to the circuit.

AUTO-IGNITION 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. Refer to ASTM E659 for information on standard autoignition test procedures.

CRITICAL DESIGN CONFIGURATION CONTROL LIMITATIONS – A type of Airworthiness limitations that define those features of the design that must be maintained to ensure that ignition sources will not develop within the fuel tank. These parameters must be verified prior to initial installation in the aircraft and also during maintenance and overhaul as determined by the Component Maintenance Manual. (Other types of fuel tank system Airworthiness limitations may include mandatory replacement times, inspection intervals, and related inspection procedures.)

ELECTRICAL ARCS – Electrical arcs occur between electrodes which are in contact with each other and carry excessive current which results in melting at the contact points. This may result in electric arc plasma and/or ejection of molten or burning material. The term thermal sparks is used interchangeably with electrical arcs.

ELECTRICAL SPARKS – A spark that is initiated by a potential difference which causes an electrical breakdown of a dielectric, such as a fuel/air mixture, produced between electrodes which are initially separated, with the circuit initially carrying no current. The term voltage sparks can be used interchangeably with electric sparks.

EXPLOSION PROOF – Components designed and constructed such that an internal arc/spark or explosion is contained and will not ignite flammable vapors or liquids surrounding the component under any normal or abnormal operating condition.

FILAMENT HEATING – Filament heating occurs when current is passed through a metallic material. Testing has shown that a small level of current when passed through steel wool will ignite a flammable mixture.

FRICTION SPARKS – A heat source in the form of a spark that is created by mechanical contact, such as trapped metallic debris contacting with rotating components.

GROUND FAULT INTERRUPTER – A device that provides circuit breaker protection by detecting an electrical current leak to ground condition and interrupting the electrical supply.

HOT SHORT – Electrical energy introduced into equipment or systems as a result of unintended contact with a power source of a different type or voltage, i.e., 115 VAC applied to 28 VAC equipment. Causes could be incorrect installation or damaged insulation on adjacent wires.

HOT SURFACE IGNITION – The initiation of a flame due to a fuel/air mixture coming in contact with a surface which exceeds the fuel's auto ignition temperature. The Hot Surface Ignition Temperature (HSIT) is dependent on many factors including surface geometry, ambient pressure, air flow, how the fuel comes in contact with the surface, as well as fuel and air temperature.

IGNITION SOURCE – A source of sufficient energy to initiate combustion of a fuel/air mixture. Surfaces that exceed the auto-ignition temperature of the flammable vapor under consideration are ignition sources.

MAXIMUM ALLOWABLE SURFACE TEMPERATURE – A surface temperature within the fuel tank that provides a safe margin under all normal and failure conditions, which is at least a delta of 50 °F (27.8 °C) below the lowest expected auto-ignition temperature of the approved fuels. For example, the auto-ignition temperature for kerosene based fuels under static sea level conditions is 450 °F (232.2 °C). This results in a maximum allowable surface temperature of 400 °F (204.4 °C) for an unaffected component surface.

3. RELATED REQUIREMENTS FROM 14CFR 25.981, FAA AC 25.981-1C, AND MIL-STD-882

3.1 Introduction

For commercial fuel pumps, the governing regulations for fuel tank safety are provided in 14CFR 25.981 [Amendment 25-102 or later]. Detailed guidance to demonstrate compliance for fuel tank ignition prevention is provided in FAA AC 25.981-1C. There are four primary phenomena that can result in ignition of fuel vapors within an airplane fuel tank. These categories are as follows:

- Electrical Arcs and Sparks
- Filament Heating
- Friction Sparks
- Hot Surface Ignition or Auto-ignition

For military applications, safety guidance is provided by MIL-STD-882, which does not delineate failure categories but focuses on the System Safety Process of identifying, assessing, documenting, and reducing safety risks. The risks are categorized by severity and probability and ranked in a Risk Assessment Matrix. The focus is on risk reduction through design improvements, warning devices, signage, procedures, training, and personal protective equipment. In addition to the criteria set forth in MIL-STD-882, the design guidelines presented in FAA AC 25.981-1C should be considered for military products to provide the safest product. This document focuses on Hot Surface Ignition or Auto-ignition.

3.2 Relevant Fuel Pump Failure Modes

Table 1 provides a list of potential failure modes applicable to fuel pumps as related to in-tank ignition safety.

Table 1 - Fuel pump failure modes related to safety compliance

Failure Category	Description of Design Issue or Failure Mode
Friction sparks (NOTE: Impeller reference includes main hydraulic impeller as well as secondary impellers used in liquid rings)	Ingestion of pump inlet components into the pump impeller releasing debris into the fuel tank.
	Pump inlet housing degradation, allowing the pump inlet check valve to contact the impeller.
	Premature failure of fuel pump radial or thrust bearings allowing unintentional contact between rotating and stationary parts – if these parts are made of sparking material.
	Use of metal impellers (i.e., steel or other sparking metals) that may produce friction sparks if debris enters the pump.
	Debris lodged inside pumps.
Electrical arcs and sparks	Failure of one or more phases of the stator winding during operation of the fuel pump motor resulting in arcing phase to phase or arcing through the pump housing.
	Arcing due to the exposure of electrical connections within the pump housing that have been designed with inadequate clearance to the pump cover.
	Pump power supply connectors have corroded resulting in fuel leakage and electrical arcing.
	Electrical connections within the pump housing have been designed with inadequate insulation from the metallic pump housing, resulting in arcing.
	Internal wires coming in contact with the pump rotating group, energizing the rotor and arcing at the impeller/adaptor interface.
	Loss or degradation of bonding across component interfaces due to wear or corrosion.
	Insufficient ground fault current protection capability.
	Loss or degradation of bonding of pump components to structure.
	Electrical arcing at connections within electrical connectors due to bent pins or worn contacts.
	Fuel leakage and subsequent fuel fire outside of the fuel tank caused by corrosion of electrical connectors inside the pump motor which led to electrical arcing through the connector housing (connector located outside the fuel tank).
	Selection of improper insulating materials in connector causing degradation of the material because of contact with fuel that is used to cool and lubricate the pump motor.
Hot surface ignition or auto-ignition	Wear of teflon sleeving and wiring insulation on wires in metallic conduits located inside fuel tanks, allowing arcing from wire through the conduits into fuel tank ullages.
	Damage to insulation on wiring routed adjacent to the fuel tank exterior surfaces that resulted in arcing to the metallic fuel tank surface.
	Omission of cooling port tubes between the pump and the motor assemblies during pump overhaul.
	Extended dry running of fuel pumps in empty fuel tanks, which was contrary to the manufacturer's recommended procedures.
Filament Heating	Thermal switches aging over time resulting in a higher trip temperature.
	Locked rotor or dragging rotor condition caused by debris, damaged or deformed inlet screens, or incorrect mechanical clearances.
	Electrically conductive FOD or contamination causing heat generation between pins of an electrical connector.
	Poor bonding of internal components to structure.

3.3 Required Safety Inspections

In order to verify the integrity of the key features of the pump design, all safety related features and dimensions of the design (from the assembly level down to the individual components) will be designated as CDCCL (Critical Design Configuration Control Limitation) on their respective drawings. A CDCCL can be a visual feature (such as the presence of insulative parts), a single component level dimensional feature, or an assembly dimensional feature. The CDCCL verification can also be part of the assembly procedure, i.e., if a design feature is missing, it will prevent the pump from being fully assembled.

Each of these characteristics will be verified by some type of inspection and a permanent record made of conformance. The same inspection verification applies to CDCCL dimensions on affected components that are being overhauled or repaired. Verification of the repair or overhaul plan with the Buyer and Certification Agency is recommended. After initial certification, any changes in CDCCL requirements must be approved by the Buyer and Certification Agency.

3.4 Safety Assessment Methodology

Compliance with 14CFR 25.981 requires a failure analysis for the fuel tank installation to substantiate that ignition sources will not be present in the fuel tanks. An assessment of the fuel pump ignition sources will be used to support that analysis. AC 25.981-1C, paragraph 10 Safety Analysis provides guidance for conducting such an analysis. Designing to a Dual Fault Tolerant methodology is the recommended (but not required) approach to meeting the safety criteria in 14CFR 25.901(c), Amendment 25-40 or later, and 14CFR 25.981, Amendment 25-102 or later, and FAA AC 25.981-1C. Dual Fault Tolerant is defined as providing a minimum of two independent layers of safety protection for each failure mode that could result in a fuel tank explosion. The statistical probability is calculated as the probability of the failure event occurring (such as a spark) multiplied by the probability of the first safety layer failing times the probability of the second safety layer failing. This overall probability is then compared to the minimum required levels.

Per FAA AC 25.981-1C, compliance to 14CFR 25.981(a)(3) involves showing that:

- Each single failure, regardless of the probability of occurrence of the failure must not cause an ignition source.
- Each single failure, regardless of probability of occurrence of the failure, in combination with any latent failure not shown to be at least extremely remote, must not cause an ignition source.
- All combinations of failures not shown to be extremely improbable must not cause an ignition source.

When employing a quantitative analysis approach, extremely remote is defined as an average probability per flight hour on the order of $1e-7$ or lower and extremely improbable is defined as an average probability per flight hour on the order of $1e-9$ or lower. Quantitative analysis of all safety failures is done using the data from the failure mode and effect analysis, associated with the time during which the failure mode remains present or undetected. All safety related failures are linked together and examined utilizing fault tree analysis. The recommended design approach is to provide a minimum of two layers of independent safety protection for each critical safety failure as explained in the definition of Dual Fault Tolerant.

If the statistical analysis shows that the required probability has not been achieved, the reliability of each safety layer should be improved or additional independent safety layers must be added until the above regulations are met.

4. DESIGN RECOMMENDATIONS FOR FUEL PUMPS

- 4.1 Any cavity in the pump that is within the tank boundary and contains potential or actual ignition sources shall be designed to be explosion proof. Explosion proof testing should consider testing with faults per the guidelines on DO160G, Section 9 Users guide for installation in Zone I (see 8.12).
- 4.2 Any cavity in the pump that is in a flammable leakage zone and contains potential or actual ignition sources should be designed to be explosion proof. Explosion proof testing should consider testing with faults per the guidance of DO160G, Section 9 Users guide for installation in Zone II (see 8.12).
- 4.3 Designs should be such that under all operating conditions, including abnormal or failure conditions such as dragging rotor, locked rotor, hot shorts, internal shorts, etc., all exterior pump surfaces that are outside the explosion proof cavity shall not exceed the auto-ignition temperature under consideration (with appropriate safe margin, such as 400 °F (204.4 °C) for kerosene fuels). This includes pump surfaces internal and external to the fuel tank walls.

- 4.4 Designs should be such that under all operating conditions, including abnormal or failure conditions such as dragging rotor, locked rotor, hot shorts, internal shorts, etc., all surfaces that are on the exterior of a designated explosion proof cavity shall not exceed the auto-ignition temperature under consideration (with appropriate safe margin, such as 400 °F (204.4 °C) for kerosene fuels).
- 4.5 Any safety device or design expedient used to accomplish 5.3 through 5.4 (e.g., thermal fuse) should be such that it performs its function without producing an open spark, or if it can produce a spark then it shall be enclosed in an explosion proof cavity.
- 4.6 Pump designs using a brushed motor (which operates with continuous sparking between the brushes and armature) should only be used if such design has been previously negotiated with the appropriate Airworthiness Authority and is considered acceptable. In this case, the appropriate levels of safety required to be compliant with the governing customer specification must be demonstrated.
- 4.7 The addition of any device or feature to the pump design should not result in the pump reliability being less than the minimum value required in the customer's technical specification.
- 4.8 Vents, slots, passages, etc., incorporated in the explosion proof cavity, through which flame could potentially travel to external fuel or vapor containing areas, should be capable of suppressing flame under all normal and abnormal conditions. This shall be demonstrated by explosion testing per RTCA DO160 or MIL-STD-810.
- 4.9 Explosion-proof tests that involve applying electrical power to the pump, such that surface temperatures could exceed a particular limit, should set the ambient temperature condition per the guidelines in RTCA DO160 or MIL-STD-810 or per the customer's technical specification. This may include the self-heating effect of normal operation prior to a failure.
- 4.10 Any device or design expedient used to accomplish 5.3 for fuel-cooled motors is itself subject to fuel cooling. The actuation points of devices used to accomplish 5.3 are generally dependent upon the location of these devices and the thermal mass of surrounding hardware and any cooling effects from the fuel. If these devices are being cooled by fuel while they are being heated by the motor, their actuation point can be seriously affected. Consequently, isolation of these devices from the cooling effect of fuel should be a design consideration.
- 4.11 Provision to prevent arcing from the motor windings to ground shall be implemented. Potential solutions could be geometric clearance, redundant housings, etc. Acceptance should be demonstrated in production by a dielectric test at the highest practical level of assembly.
- 4.12 Bearings should be designed to be contained within the pump's explosion proof boundary. The gap between the shaft journal and the bearing inner diameter should not be included as part of the explosion proof boundary design. If bearing clearance is used as part of the boundary, it must be shown that the minimum required gap is maintained over the useful life of the pump including the effects of wear on any critical clearances.
- 4.13 For fuel pumps located inside fuel tanks that use fuel as the cooling fluid for dissipation of motor heat, the fuel may be diverted back into the tank or recirculated within the pump. The fuel discharge shall not pose electrostatic hazard. If the fuel is diverted out of the pump and into the tank, it must not spray into the air space above the fuel level.
- 4.14 Wire management must be optimized. There are five basic goals for wire management:
- Physically separate phase leads where possible
 - Provide non-conductive walls for wire passages
 - Separate ground wire from phase wires, if practical
 - Prevent wires from contacting motor rotor
 - Provide adequate wire restraint to prevent wire from contacting any abrasive surface

- 4.15 It is recommended that the mechanical design utilize safety features that are integral to the assembly of the pump so that they cannot be left out during initial fabrication or overhaul.
- 4.16 Design electrical feed-through with no internal wire to wire crimps.
- 4.17 When possible, the pump shall be designed so that failures are visible to the operator.
- 4.18 When possible, components should be designed so that they can only be installed one way to prevent incorrect assembly.
- 4.19 The assumption of constant submergence in fuel can only be used as a layer of protection in the safety analysis if approved by the Buyer as part of the overall fuel system analysis.
- 4.20 Potting can only be used as a layer of protection if it can be shown that the process results in a cavity fill with minimal to no voids. Testing should be performed on sample parts to demonstrate acceptability.
- 4.21 Insulating paper can be used as a barrier if it can be demonstrated that the dielectric strength is appropriate for the application.
- 4.22 Thermal fuses should be oriented to make sure they are in the area of the motor cavity that will initially be uncovered if fuel is lost.
- 4.23 Select non-sparking materials where possible, especially for the pump impeller(s), and make sure all materials have proper corrosion resistance.
- 4.24 Detailed attention should be invested in surface preparation for bonding. The guidelines in MIL-STD-464 should be followed. The goal should be to minimize the number of electrical bonding joints in the pump assembly between the motor housing and the aircraft mounting surface.
- 4.25 A best practice is to provide two independent bonding means between the pump assembly and the aircraft.
- 4.26 Detailed attention should be invested to ensure electrical connectors have adequate barriers to prevent leakage.
- 4.27 Design of component parts must take into account variability of the manufacturing process. Tolerances must be set such that at the least and maximum material condition the part will still meet all safety criteria while still being compatible with the method of manufacture. Component wear shall not negate explosion proof capability.
- 4.28 Reservoirs can be considered to maintain fuel within the pump, thereby keeping the impeller wet after the primary fuel tank is empty, thereby avoiding operation in fuel vapor.
- 4.29 Electrical connectors should be oriented to avoid water pooling, i.e., water and potential contaminants drain away from the pump.
- 4.30 When a pump contains an electronic controller, the controller should be designed with all components appropriately de-rated for temperature and voltage. PCB layout shall prevent track cross connection or current overload. Design of the controller housing should consider internal track overload that could result in a plasma jet.
- 4.31 Fasteners should be designed to be trapped in the event of a failure so they do not come in contact with rotating parts or compromise the explosion proof housing. Fasteners should be retained by a locking mechanism.
- 4.32 The system of fuel flow passages within the pump shall be designed to be non-clogging when exposed to FOD and other contaminants. Compliance shall be demonstrated during qualification testing.
- 4.33 Any device or system design expedient used to accomplish 5.3 should be single-action, that is, non-resettable, or resettable within the context of 5.35 and 8.9 only. Resettable switches come in two types. The first type is self-contained, meaning that the sensing element and the power disconnecting switch are contained in a single assembly inside the pump. The second type only contains the sensing element which transmits a signal to a power disconnect switch external to the pump. For this case, the compatibility of the sensing element with the external power disconnect circuit must be verified.