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Heavy-Fueled Intermittent Ignition Engines: Technical Issues

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16. Abstract

This report contains an overview of the technology and engineering issues with nonturbine heavy-fueled engines for general aviation aircraft and Unmanned Aircraft Systems. In recent years, interest in these types of engines has grown, partly due to the cost, safety, and worldwide availability of gasoline fuels. Within 3 to 5 years, up to five engines will seek Federal Aviation Administration certification as heavy-fuel powerplants. Although there has been some progress, there is no universal standard for certification of these engines (under Title 14 Code of Federal Regulations (CFR) Part 33), or their installation into normal category fixed-wing aircraft or rotorcraft (under 14 CFR Parts 23 and 27, respectively). Additionally, the emerging demand to operate unmanned systems within the National Airspace System powered by these new powerplants requires knowledge of their characteristics and operation. A number of known engineering issues are listed for these engine types and the different types of airframes have been identified along with potential mitigation by design or operation. Finally, issues which are of specific concern to an aircraft with no onboard pilot are identified.

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LIST OF ACRONYMS

AC	Advisory Circular
CA	Crank angle
CI	Compression ignition
CFR	Code of Federal Regulations
D	Design
EASA	European Aviation Safety Agency
EMI	Electro-magnetic interference
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Engine Control
HFE	Heavy-fueled engine
HFIIE	Heavy-fueled intermittent ignition engine
hp	Horsepower
LPG	Liquefied petroleum gas
M	Maintenance
NAS	National Airspace System
NATO	North American Treaty Organization
O	Operator invervention/training
OCI	One cylinder inoperative
P-V	Pressure-volume
rpm	Revolutions per minute
UAS	Unmanned Aircraft System
USAF	United States Air Force
U.S.	United States

EXECUTIVE SUMMARY

The Federal Aviation Administration (FAA) has been certifying spark-ignition, gasoline piston engines for use in normal category United States-registered aircraft for many years. The federal aviation regulations reflect this, as they are written with these designs in mind. As emerging aviation powerplant technology looks for certification by both the FAA and other civil aviation authorities, requirements for safe design, installation, and operation must be established.

A handful of new heavy-fueled engines are expected to seek FAA certification for general aviation aircraft within the next 3-5 years, and a thorough understanding of their inherent characteristics is required. The knowledge of engineering issues for these heavy-fueled engines continues to grow as certified installations into normal category, fixed-wing aircraft become more common. An introduction to these engines, their general operating characteristics, behaviors, and technical issues is included in this report. Descriptions of several different fuel types are also provided as background information.

This report includes some of the known issues of heavy-fueled engine installation into Title 14 Code of Federal Regulations (CFR) Part 23 aircraft (nontransport fixed-wing) and less studied 14 CFR Part 27 aircraft (nontransport rotorcraft). These issues are put into the context of the Unmanned Aircraft System (UAS), where operation of a powerplant system is different than manned aircraft. Understanding the characteristics of these engines in a system without an onboard pilot is essential for the design and implementation of a safe UAS.

1. INTRODUCTION.

Since the 17th century, a number of machines have been used to turn burning fuel into useful rotating mechanical energy. In modern powerplants, there are a few distinct methods commonly used to generate mechanical energy with so-called intermittent ignition engines. Such engines have separate (intermittent) events where the fuel is burned [1]. A variety of hydrocarbon fuels may be suitable for such engines.

Aviation piston engines, which have relied nearly solely on gasoline since the World War II era, are one such example. The operation of these engines is very similar to a majority of the automobiles in North America. However, as gasoline costs, taxation, safety, and availability apply increasing pressure to the market, the heavy-fueled engines (HFE), which run on diesel and other similar liquid fuels, are gaining popularity. Additionally, military users have a demand for engines capable of running on kerosene, diesel, or other heavy fuels widely available in their operational areas and used by other vehicles (e.g., trucks and jet aircraft).

The term heavy-fueled intermittent ignition engines (HFIIE) comprises a class of engines that burn heavy fuels, and does not include turbine (continuous ignition) engines. These powerplants, which include familiar diesel engines, have a number of design features not covered by regulation of current aircraft powerplants (e.g., different vibration characteristics and lack of ignition system).

A number of these issues can be mitigated through design, although some may require the input of an operator. Handling operator-related technical issues becomes extremely important for installations into the Unmanned Aircraft System (UAS). Maintaining safe operation of these types of powerplants will likely require systems designed to manage the unique behaviors and failure mechanisms of the HFIIE engines. This report highlights the characteristics that are of important consideration when designing and certifying UAS powered with these new powerplants.

1.1 PURPOSE.

This research was conducted with funding from the Center for General Aviation Research and supports the Federal Aviation Administration's (FAA) goals for implementation of UAS into the National Airspace System (NAS). Specifically, this research looked at the emerging need for certification standards for heavy-fueled engines under Title 14 Code of Federal Regulations (CFR) Parts 23, 27, and 33, as well as specific issues relating to the installation of the heavy-fueled powerplants in unmanned aircraft as part of a UAS.

1.2 BACKGROUND.

As previously discussed, HFEs are gaining popularity for civil, manned installations as well as UAS installations. Although there has been some progress, in general, there is no universal standard for certification of aircraft with these new powerplants under 14 CFR Parts 23 and 27, nor for the certification of the engines under 14 CFR Part 33. As the need to operate civil unmanned systems in the national airspace grows, the need to certify UAS and the HFE that power them grows as well.

1.3 RELATED DOCUMENTS.

Work involving compression ignition (CI), or diesel, aviation powerplants has been underway in the United States (U.S.) for about half a decade. The FAA has released two policies specifically relating to diesel engine design, with fixed-wing aircraft installations in mind. These documents point out a number of engineering issues for such installations and recommend practices for certification of these engines with little operational history.

a. FAA Final Policy Statement on Diesel Engine Installation, PS-ACE100-2002-004.

b. FAA [Draft] Policy for Diesel (Compression Ignition) Engine Certification Policy, document ANE-2006-33.7-4-DRAFT.

Additionally, work currently being produced by RTCA Special Committee 203 contains guidance material on implementation of UAS into the NAS. However, these documents do not cover issues specific to the type of powerplant in terms of operation and fuel use.

1.4 SCOPE.

This report is a review of current heavy-fueled engine technology and the possible fuels used for such engines. Users in both the general aviation market and military customers operating within the civil airspace are taken into consideration. Jet turbines, turboprops, or other constant ignition powerplants are not considered in this review, as they are not intermittent ignition devices encompassed under HFIIE.

The powerplants under consideration in this report are those appropriate for aircraft that could be certified in the normal category. For fixed-wing aircraft certified under 14 CFR Part 23, this includes a maximum weight of less than 12,500 pounds and a maximum of nine passengers. For rotorcraft certified under 14 CFR Part 27, this includes maximum weight of 7,000 pounds or less and nine or less passenger seats. For aircraft of this size, current certified gasoline engines range from 100 to 350 horsepower (hp) each.

A short review of the main differences in types of thermodynamic processes used is followed by the major mechanical methods of running an engine. This is followed by a short description of current and near-future aviation engines using the heavy fuel technology described. A basic review of a number of the different hydrocarbon fuels, including those not particularly well suited for aviation use, is also included for reference.

Engineering issues that may arise when these HFIIE engines are installed into an aircraft are also covered. These issues are known from discussions with manufacturers, FAA guidelines and policy, and other research on the topic.

2. ENGINE AND FUEL OVERVIEW.

2.1 ENGINE BASICS.

2.1.1 Thermodynamic Processes.

All engines operate on the same basic thermodynamic principal—turn a difference in heat into mechanical energy. Liquid or gaseous fuel is burned, converting stored energy into thermal energy. This released thermal energy results in high pressure, which is converted into mechanical work, usually through a rotating shaft. The two most widely used processes used to achieve this in today's engines, the Otto and Diesel cycles, are discussed in sections 2.1.1.1 and 2.1.1.2. Note that these are completely idealized cycles, ignoring fuel added, assuming perfect air acting as a perfect gas, constant pressure through the combustion chamber, and more [2]. Further details about these cycles, as well as several more cycles used in engines, are available in a number of references (for example reference 3).

2.1.1.1 Otto Cycle.

The Otto cycle is named after the German scientist who built some of the first four-cycle stationary internal combustion engines in the 1860s. This process, which is used to generate mechanical energy, includes four distinct phases and is the type of engine used in most automobiles and aircraft that run on gasoline. Figure 1 shows a pressure-volume (P-V) diagram, illustrating the ideal cycle [4].

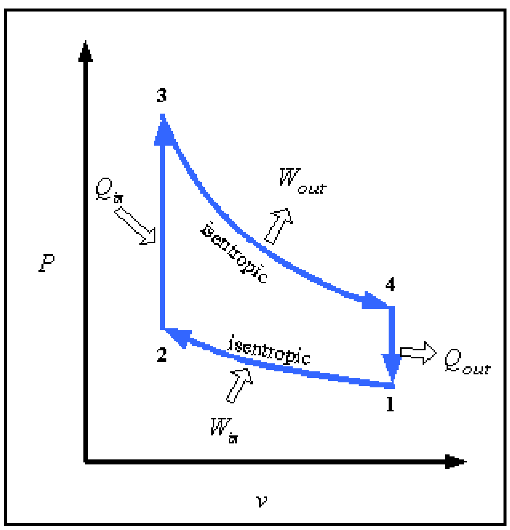

Figure 1. Otto Cycle P-V Diagram [4]

In this cycle, the intake of a mixture of air and fuel (originally coal gas) into the combustion chamber (between points 4 and 1 in figure 1). The mixture is compressed to a small volume (1-2 in.) and then ignited with an electrical spark (point 2). The ignition of the fuel causes a constant volume increase in pressure, shown from point 2 to 3. A power stroke takes place when the pressure of the burning mixture is converted into the expanding volume (points 3 and 4). The burnt exhaust gas is purged (also between points 4 and 1). Other mechanical means may be used to achieve this process (from two-stroke ported gasoline engines to more complex multivalve four-stroke engines), which are not discussed in this review.

2.1.1.2 Diesel Cycle.

The diesel cycle, invented by Rudolph Diesel in 1897 (figure 2), operates with four similar phases to the Otto cycle, with one major change. Instead of a fuel air mixture during the intake phase, the fuel is separately injected at high pressure when the air is at its lowest volume [5]. Since the fuel used is usually of a higher molecular weight (such as kerosene or diesel, as discussed in section 2.3.1), it will burn more slowly than the Otto cycle engines and, thus, is a constant pressure cycle as the volume increases (in the ideal diesel theory).

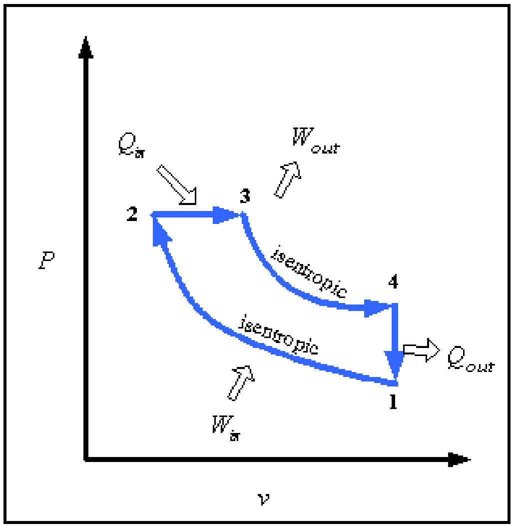

Figure 2. Diesel Cycle P-V Diagram [5]

2.1.2 Reciprocating Engines.

Reciprocating, piston engines are by and large the most common design for intermittent ignition internal combustion engines. This basic design stems from the reciprocating steam-powered engines of the nineteenth century. Using a single crankshaft to transfer the linear motion of the piston into rotational motion has been the most common design feature of many different engines over the years.

While layouts and number of pistons may differ significantly, there are only a few options to operate the basic cycles of the thermodynamic process. The two most widely used are the two-stroke and four-stroke engines, which are discussed in further detail below with the diesel cycle in mind.

2.1.2.1 Reciprocating Two-Stroke Engine.

The basis for a two-stroke engine is that a piston will complete two strokes in the cylinder, resulting in 360° of crank angle, to complete the entire thermodynamic process. To do this, there must be some method of exhausting the burnt gases from the cylinder and replacing it with fresh air. This exchange, or scavenging, can be completed using a variety of mechanisms using ports, valves, or both. Depending on the basic flow of gas during scavenging, these engines can be grouped into loop-scavenged or uniflow scavenging. Part of the complexity in a two-stroke design is that this scavenging must happen quickly when the piston is near the bottom of its travel.

One important aspect of the two-stroke engine (both gasoline and diesel types) is that ignition of fuel and air occurs every rotation of the main crankshaft. This results in a generally lower vibration engine than a four-stroke (although almost any type of engine can be well balanced by design).

Another feature of the two-stroke, due to the ignition in each rotation, is the connecting rods between the piston and crankshaft are under compression for nearly the entire rotation of the crankshaft. This can help reduce fatigue on the connecting rod.

2.1.2.1.1 Ported Two-Stroke Engine.

The use of porting in two-stroke engines yields a relatively simple design with fewer moving parts than an engine that uses valves. This design is fixed in that the ports cannot be changed or altered easily. The so-called charge purity at the end of the scavenging process can be low, leaving some of the burnt air trapped. With careful design and the use of Computational Fluid Dynamics, this problem can be minimized. The reduced efficiency and higher pollutant count are offset by the outstanding simplicity.

2.1.2.1.2 Valved Two-Stroke Engine.

By adding an exhaust valve and using an inlet port to the two-stroke design, the engine will gain a higher degree of charge purity at the cost of slightly higher complexity, parts count, and weight.

2.1.2.2 Reciprocating Four-Stroke Engine.

In contrast to the two-stroke designs that have an ignition event each revolution, the four-stroke design ignites the fuel every two revolutions, or 720º crank angle (CA). The four-stroke design uses separate valves for intake air and exhaust air, and each part of the four-part thermodynamic cycle gets one-half of a crank rotation.

There are a number of tradeoffs associated with this design choice, the foremost being a decrease in the number of power strokes per time (for otherwise equal engines). However, the entire power stroke can now be used to extract the energy of burning gases, as the exhaust stroke will be completed separately after the power stroke is completed.

Since scavenging the exhaust air is not necessary and the exhaust and intake strokes each have an entire cycle to be completed (180° CA each), getting fresh air into the cylinder for the next ignition is more easily done than with a two-stroke design. This results in a more complete combustion, allowing better emissions and the ability to extract more thermal energy from the fuel.

The final result is that a four-stroke engine will generally have about 75% of the power of a comparable two-stroke design, but enjoys higher efficiency and better emissions with an engine that is usually heavier and has more parts [2].

2.1.3 Wankel (Rotary) Engine.

The Wankel design dates back to the 1930s when Dr. Felix Wankel developed seals and pumps for the German military. In 1957, the first rotary engine was running but was not made a commercially viable engine until the 1970s when Mazda began producing the engine for light sports cars.

In a Wankel engine, there are no pistons reciprocating in a cylinder, but a triangular-shaped rotor, which rotates in an epitrochoidial-shaped housing, as shown in figure 3. The result is a very low parts count (as there are no valves or valvetrain, no connecting rods, and no wristpins) and very low vibration.

Figure 3. Wankel Rotary Engine

An interesting feature of the rotary engine is that each rotor has three working chambers, as shown in figure 3. As the engine rotates, all three chambers are engaged in a different part of the thermodynamic cycle, acting effectively as three cylinders. This is partly the reason rotary engines have such high power for a given weight [6].

Wankel engines were not without a downside, as fuel consumption issues plagued the first production engines released by Mazda in the 1970s. The life of the engine was limited due to wear of the seals of the engines. Through computerized engine management, improved port design, and enhanced material technology, the Wankel design problems were solved.

The eccentric shaft, which transmits all the net power in the engine, is not subject to the large changes in torque and torsional fatigue that a piston engine crankshaft experiences. This leads to an inherently robust engine where catastrophic failure is highly unlikely.

True compression ignition in rotary engines is a challenge due to the inherent constraints on the compression ratio in rotary engines. Spark-assist, direct injection offers the most promising solution, as this type of operation may be more feasible for heavy fuel operation without high compression ratios. Fuel economy is a tradeoff, since heavy fuel rotary engines do not achieve the same efficiencies of reciprocating engines.

2.1.4 Boosting.

If higher-pressure air can be supplied to the engine, the result is almost always more power. This is especially important in aircraft, where the power production decreases as air density decreases at higher altitude. There are several methods to compress incoming air to an engine; the two best known devices are turbochargers and superchargers.

These systems can be designed for specific applications, boost levels, and revolutions per minute (rpm) ranges for operation. Bypass valves and wastegates can be used to control the level of boost (if any) for a given power and rpm setting. Compressing air will heat it under most circumstances, so air-to-air intercoolers have become an important method of heat exchange to cool the compressed intake air [7].

Diesel engines may be best suited for these devices due to their durable design that can handle high pressures. The autoignition process also uses high-pressure air to start the combustion process. Some two-stroke diesel engines also rely on a burst of high-pressure incoming air to scavenge the combustion chamber.

2.1.4.1 Turbochargers.

A turbocharger (sometimes referred to as a turbo-supercharger) is a compressor (or centrifugal) driven by a turbine that extracts energy from the burnt exhaust gases after they exit the combustion chamber. This also helps to reduce the thermal energy in the exhaust and, therefore, the exhaust temperature.

2.1.4.2 Superchargers.

Another method of compressing incoming air is to use a gear or belt-driven compressor, known as a supercharger. These superchargers may be used in addition to turbochargers or on their own. Intercooling is generally more complex in supercharged engines due to layout constraints.

2.2 CURRENT AND NEAR-FUTURE ENGINES.

Within the last decade or so, a small number of European and U.S. manufacturers have taken interest in intermittent-ignition, heavy-fueled engines. Sections 2.2.1 through 2.2.5 present a brief description of the engines that are currently certified in the U.S. and Europe, as well as those that may be certified in the next 2 to 3 years. A table covering the basic design of the engine, operation, and some performance specifications, as stated by the manufacturer, are also included. Websites for each engine are included in the table as well. Items left blank are either unknown at this point or will depend upon the certification of the engine in coming years.

2.2.1 SMA SR 305-230 Engine.

The SMA SR 305-230 engine shown in figure 4 and table 1 is a four-stroke diesel cycle engine that is air cooled with a secondary oil cooling system. It is equipped with a direct injection system and is turbocharged with air/air intercooling. The engine is a direct-drive with four flat cylinders, horizontally opposed, and a total displacement of 305 in^3 (4988 cm^3). The SMA SR 305-230 engine produces 230 hp at takeoff power, with no limitation on the power setting. This engine is FAA-certified under type certificate E00067EN, and European Aviation Safety Agency (EASA) certified under certificate number E.076.

Figure 4. SMA SR 305-230 Engine

Table 1. SMA SR 305-230 Details

Engine:	SMA SR305-230
Website:	http://www.smaengines.com/
Manufactured by:	SAFRON Group
Location built:	Bourges, France
Year designed:	~1997
Certified:	EASA- and FAA-certified. STC on Cessna 182.
Type:	Compression ignition
Layout:	Horizontally opposed four-cylinder
Operation:	Four-stroke
Displacement:	305 cubic inches
Compression ratio:	16.0:1
Valves/Porting:	Two valves per cylinder
Blown air:	Turbocharged
Cooling system:	Air, Oil
Fuel type(s):	Jet A and Jet A-1
Gearbox:	None
Control:	FADEC (DO-178B Level C Software) with manual backup
Maximum horsepower:	230 hp
Maximum continuous:	230 hp
Maximum torque:	Unknown
Fuel burn (lb/hp/hr):	~0.35
Altitude restrictions:	Certified to 12,500 ft in U.S.
Weight:	~430 lb (from TCDS)
Estimated price:	
Notes and other information:	STC available for Cessna 182 as a firewall forward kit costs approximately $100,000. Altitude restriction is due to restart limitations.

STC = Supplemental Type Certificate
TCDS = Type Certificate Data Sheet

Control of the SMA SR 305-230 diesel engine is primarily performed by the Full Authority Digital Engine Control (FADEC) but a mechanically linked backup allows manual engine control in the event of computer or electrical failure. The FADEC software is designed to meet DO-178B Level C requirements. Level C development is in accordance with Advisor Circular (AC) 23.1309-1C, where primary systems in small reciprocating (nonturbine) aircraft can be designed to level C or higher. Lightning protection and electro-magnetic interference (EMI) of the FADEC has been tested in accordance with DO-160D.

Since the SMA SR 305-230 is a CI engine, it requires high pressures to ignite the fuel and run. A turbocharger provides this pressure, especially at higher altitudes. At higher altitudes, starting the engine is a challenge because the turbo does not provide the necessary pressure until the engine is running; therefore, the FAA has imposed a flight altitude limitation of 12,500 feet.

2.2.2 DeltaHawk DH160 Engine.

The DeltaHawk DH160, shown in figure 5 and table 2, is a 90°, V-4, two-stroke direct drive turbocharged engine of 202 in^3 (3310 cm^3). The engine can be mounted horizontally, vertically, or inverted. The engine is cooled by both liquid and oil. Control of the engine is fully manual, using a rack of Bosch high-pressure injectors, with fuel delivery controlled by physical rail movement. The FAA type-certification process of the DH160 began in 2005 and is expected to be completed sometime in 2007.

As a two-stroke diesel engine, it uses a loop-scavenging design and uses a high-pressure boost to facilitate the scavenging process. To ensure sufficient scavenging at start-up, a belt-driven, roots-type blower (supercharger) is used in addition to the turbocharger, which takes over once the engine is running. The supercharger is bypassed during normal operation, but this does not result in any significant power loss. In addition, the supercharger may be used as a backup for a small amount of boost in the event of a turbocharger failure.

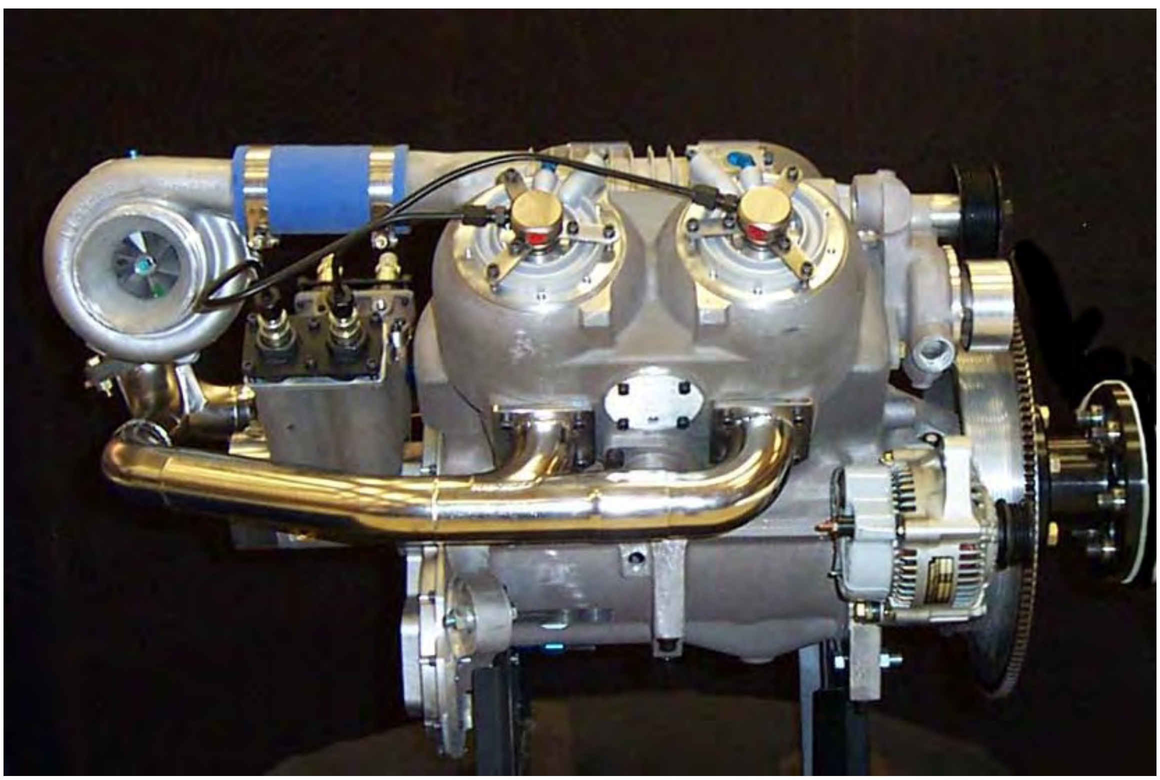

Figure 5. DeltaHawk DH160

Table 2. DeltaHawk DH160 Details

Engine:	DeltaHawk DH160A4
Website:	http://www.deltahawkengines.com
Manufactured by:	DeltaHawk Engines
Location built:	Racine, WI, USA
Year designed:	~1996
Certified:	FAA certification in progress
Type:	Direct Injection Compression Ignition
Layout:	90° V-4
Operation:	Two-stroke scavenge air
Displacement:	202 cubic inches
Compression ratio:	Unknown
Valves/Porting:	Loop scavenged
Blown air:	Turbocharged, belt-driven supercharger used at start
Cooling system:	Liquid
Fuel type(s):	Jet A, No. 2 Diesel (above 20°F)
Gearbox:	None
Control:	Manual
Maximum horsepower:	160 or 200 hp (Configuration Dependant)
Maximum continuous:	TBD
Maximum torque:	Unknown
Fuel burn (lb/hp/hr):	0.390 stated
Altitude restrictions:	TBD
Weight:	~327 lb dry with engine accessories
Estimated price:	$35,000
Notes and other information:	Single cast block. Scavenging performed with roots-type blower (supercharger) at startup, then is bypassed. Supercharger can act as backup. Company states Diesel No. 2 safe above ~20°F, but certification may dictate operating fuels.

TBD = to be determined

2.2.3 Thielert Centurion 1.7 Engine.

The four-cylinder Thielert Centurion, shown in figure 6 and table 3, is a four-stroke, turbocharged, geared engine, which is built from an engine block made by Mercedes-Benz. EASA approval was granted under certificate number E.055, and the FAA adopted this type certificate in 2005 under certificate number E00069EN. Overhaul of this engine is not yet permitted by the FAA Type Certificate Data Sheet, requiring the factory to perform replacement.

Mercedes-Benz has discontinued production of the 1.7 L block, and Thielert is now using the larger 2.0 L block in a design that is otherwise similar (four-cylinder, turbocharged, FADEC-controlled 135-hp diesel). The FAA certified this engine as the Centurion 2.0 (on a revision to the current type certificate number E00069EN) as Model TAE 125-02 in late 2006.

Figure 6. Centurion 1.7 Engine

Table 3. Centurion 1.7 Details

Engine:	Centurion 1.7 TAE 125-01
Website:	http://www.centurion-engines.com
Manufactured by:	Thielert
Location built:	Lichtenstein, Germany
Year designed:	~2000
Certified:	EASA and FAA Part 33. Has STC on Piper PA28, Cessna 172.
Type:	Direct Injection Compression Ignition
Layout:	Inline four-cylinder
Operation:	Four-stroke
Displacement:	105 cubic inches
Compression ratio:	18:1
Valves/Porting:	Four valves per cylinder
Blown air:	Turbocharged
Cooling system:	Liquid
Fuel type(s):	Jet A-1, plus EN590 for EASA
Gearbox:	1.69:1
Control:	FADEC (DO-178B Level C Software) also controls propeller
Maximum horsepower:	135 hp
Maximum continuous:	135 hp
Maximum torque:	302 ft-lb
Fuel burn (lb/hp/hr):	0.330 (Best Econ), 0.374 (T/O)
Altitude restrictions:	Certified to 18,500 ft
Weight:	295 lb, including all accessories
Estimated price:	EUR 48,000
Notes and other information:	Uses a Mercedes-Benz engine block. This requires inspection of every part received from Mercedes-Benz, as Thielert has no control over the part design, material, etc.

T/O = Takeoff
STC = Supplemental Type Certificate

2.2.4 Thielert Centurion 4.0 Engine.

A 90° V-8, four-stroke engine with four valves per cylinder and dual turbochargers make the 244 in^3 (3998 cm^3) the most powerful diesel engine in this study, but it is also the heaviest at nearly 606 lb. The Centurion 4.0, shown in figure 7 and table 4, produces 345 hp for takeoff (5 minutes) and 325 hp for continuous. Thielert is awaiting FAA certification of the engine, but EASA approved the design was in October 2004 (certificate number E.014).

The Thielert uses a similar control philosophy to the smaller Centurion 1.7, with a fully digital FADEC controlling the engine (fuel and power control) and the propeller (rpm control). As with its smaller cousin, the software is designed to DO-178B Level C standards, and lightning and EMI protection meets DO-160D requirements.

Figure 7. Centurion 4.0 Engine

Table 4. Centurion 4.0 Details

Engine:	Centurion 4.0
Website:	http://www.centurion-engines.com
Manufactured by:	Thielert
Location built:	Lichtenstein, Germany
Year designed:	~2003
Certified:	EASA certified October 28, 2004. FAA in progress.
Type:	Compression Ignition
Layout:	90° V-8
Operation:	Four-stroke
Displacement:	244 cubic inches
Compression ratio:	18.5:1
Valves/Porting:	Four valves per cylinder
Blown air:	Two turbochargers
Cooling system:	Liquid
Fuel type(s):	Jet A-1
Gearbox:	1.69:1
Control:	FADEC (DO-178B Level C Software) also controls propeller
Maximum horsepower:	350 hp
Maximum continuous:	330 hp
Maximum torque:	786 ft-lb
Fuel burn (lb/hp/hr):	0.355 (Best Econ), 0.390 (T/O)
Altitude restrictions:	None Known
Weight:	~606 lb, engine complete and dry
Estimated price:	EUR 64,800
Notes and other information:	EASA-approved and waiting for FAA acceptance of the European type certificate.

T/O = Takeoff

2.2.5 Mistral Rotary Engine.

The Mistral rotary engine, shown in figure 8 and table 5, is currently a gasoline-powered experimental aircraft engine. Using the concepts covered in section 2.1.3, Mistral has developed an aviation engine, gear reduction unit, accessory drive, and computerized FADEC system. Current versions of the engine include a two- and three-rotor version with and without turbochargers, ranging from 190 hp through 360 hp.

Jet fuel versions of the engine have successfully been run on the test bench at the factory, but current focus is on FAA certification of the gasoline-powered versions of the engine. The inherent reliability (due to low parts count), good power-to-weight ratio, and low vibration characteristics of the rotary engine are the main benefits.

Figure 8. Mistral Engine

Table 5. Mistral Engine Details

Engine:	Mistral Rotary
Website:	http://www.mistral-engines.com
Manufactured by:	Mistral Engines, S.A.
Location built:	Geneva, Switzerland
Year designed:	~2000
Certified:	Heavy-fueled version still in development
Type:	Spark-assist direct injection
Layout:	Mazda 13B style rotary, also Mazda 20B
Operation:	Four-stroke
Displacement:	Equivalent to 119.7 cubic inches per rotor
Compression ratio:	TBD
Valves/Porting:	Two intake ports, one exhaust per rotor
Blown air:	Optionally turbocharged
Cooling system:	Liquid and oil
Fuel type(s):	TBD
Gearbox:	2.8235:1
Control:	FADEC
Maximum horsepower:	~190 – 360 hp
Maximum continuous:	~190 – 360 hp
Maximum torque:	TBD
Fuel burn (lb/hp/hr):	TBD
Altitude restrictions:	TBD
Weight:	~291 lb for 190 hp, ~365 lb for 360 hp
Estimated price:	TBD
Notes and other information:	Gasoline-powered version running in experimental market. Certification of gasoline version in progress with both FAA and EASA. Heavy-fueled version running on test bench in Geneva, but not yet flying.

TBD = To be determined

2.3 HYDROCARBON-BASED FUELS.

Fossil fuels and other hydrocarbons are refined from crude oil trapped within the Earth's crust. A number of different fuels, most of which are blends of many different individual hydrocarbons, are used for civilian and military applications from power generation, household heating, and appliances, to powering aircraft, ships, trains, and cars.

A number of standards by agencies such as ASTM, along with international North Atlantic Treaty Organization (NATO) designations, outline the limits on fuel properties. For fuels that are otherwise the same product, different standards may call for slightly different properties or additives. Even though some engine designs may not be sensitive to such changes, maintaining a standard is important for aviation powerplants to ensure predictable performance and lifetime operation of the engine and the fuel systems. An overview of the basic classes of these fuels is presented, along with a description of some of them for aviation fuels. A number of the specific standards exist, but are not covered in detail due to their complexity.

2.3.1 Common Hydrocarbon Fuels.

The following sections cover the basics of the chain linked hydrocarbons that make up liquid heavy fuels used in a number of internal combustion engines. It is stated that jet fuel is a blend of over a thousand individual hydrocarbons, therefore no single type of hydrocarbon can characterize its behavior [8]. The same is true for other fuels, which are commonly blends.

2.3.1.1 Liquefied Petroleum Gas.

Liquefied petroleum gas (LPG) is primarily made of two hydrocarbons, propane C_3H_8 and butane C_4H_{10}. Generally, the ratio of these two hydrocarbons changes, depending on the season. LPG is not very good for an autoignition process, so when it is used in diesel engines, a dual-fuel setup is usually employed where a small amount of heavier fuel is used to begin the ignition process. Due to the logistics of carrying and storing this fuel, its use in aircraft is highly unlikely.

2.3.1.2 Ethanol.

Ethanol is an alcohol that is produced by a number of methods, commonly from renewable (crop) sources. Corn is widely used for ethanol production in the U.S. Ethanol fuel is commonly mixed with gasoline in a variety of blends. Pure ethanol has a relatively high octane rating of 129 research octane number [9], which may limit its effectiveness without spark-assist ignition or a dual-fuel setup.

2.3.1.3 Gasoline.

Gasoline is generally made of a blend of molecules with between 5 and 12 carbon atoms [10]. Avgas is an aviation blend of high-octane (100 and 130) fuel that is generally leaded, whereas automotive fuel is usually lower octane and unleaded. Although it is readily available in the U.S. and most of Europe, avgas is harder to find in other parts of the world, particularly developing countries. It is also being taxed at higher rates, primarily in parts of the European Union.

2.3.1.4 Kerosene.

Generally the first of the heavy fuels, kerosene refers to the petroleum products with carbon chains in the C_{12} to C_{15} range.

2.3.1.5 Jet A Fuels.

These kerosene-based fuels consist of Jet A-1, used outside the U.S., and Jet A used in the U.S. The Jet A blend used in the U.S. has a lower freezing point of -47º C versus -40º C. ASTM D 1655 covers the Jet A blend [8 and 11].

2.3.1.6 Jet B Fuels.

Jet B fuels, the so-called wide-cut fuels, are a blend of gasoline and kerosene. Jet B yields some of the advantages of gasoline (such as freezing point) with the ignition characteristics of kerosene fuel [8]. The dangers of handling and transporting gasoline are also carried over, and therefore, it is only used where the cold weather characteristics make it absolutely necessary.

2.3.1.7 JP Fuels.

There are several types of JP fuels, as listed below:

- JP-4: Wide-cut United States Air Force (USAF) fuel (similar to Jet B) contains over 50% gasoline fractions. Originally, JP-4 was used for the low-temperature benefits of gasoline. However, the dangers in storage and handling quickly outweighed those benefits as it is considered extremely volatile, and has a marginal to unsatisfactory cetane number of 23 [11].

- JP-5: Kerosene-based U.S. Navy fuel with additives to improve onboard ship storage safety, as it is considered a nonvolatile fuel.

- JP-6: Specially developed for the XB-70 supersonic bomber program, JP-6 is now an obsolete fuel [12].

- JPTS: A high thermal stability fuel developed in 1956 specifically for the U-2 spy plane built by Lockheed and still used by the USAF [8].

- JP-7: Developed in 1960 as a low volatility, high thermal stability fuel for the SR-71 Blackbird program, no longer in use.

- JP-8: Referred to as basically the same product as Jet A-1, with the icing inhibitors, corrosion inhibitors, and static dissipater additives required under MIL-DTL-83133 [8 and 11].

2.3.1.8 TS-1, T-1, and T-2 Fuel.

The GOST 10277 standard covers the light kerosene-based fuels. A Russian standard mainly used in eastern Europe and in some of the Commonwealth of Independent States. There is not a lot of information about these fuel types freely available.

2.3.1.9 Diesel No. 1.

Diesel No. 1 fuel is a blend of middle- and lightweight hydrocarbons. It does well in cold climates and is commonly used in engines in stop-and-go service. Diesel No. 1 can be blended with other diesel fuels in any amount to improve cold weather performance [13]. ASTM D 975 covers Diesel No. 1 fuel.

2.3.1.10 Diesel No. 2.

Heavier fuels, such as Diesel No. 2 fuel, are blends of two or more refinery distillate streams, including oils, naphtha, and reduced pitch [2]. Diesel No. 2 has a higher-energy density than Diesel No. 1 fuel, but does not do as well in cold climates.

2.3.1.11 Other Fuel Oils.

The larger chains of carbons (up to chain lengths of about 70 atoms) fall under a category known as fuel oils. This category technically includes both Diesel No. 1 and 2 as well as those shown in table 6.

Table 6. Fuel Oils

Name	Alias	Alias	Type	Chain Length
No. 1 fuel oil	No. 1 distillate	No. 1 diesel fuel	Distillate	9-16
No. 2 fuel oil	No. 2 distillate	No. 2 diesel fuel	Distillate	10-20
No. 3 fuel oil	No. 3 distillate	No. 3 diesel fuel	Distillate	
No. 4 fuel oil	No. 4 distillate	No. 4 residual fuel oil	Distillate/Residual	12-70
No. 5 fuel oil	No. 5 residual fuel oil	Heavy fuel oil	Residual	12-70
No. 6 fuel oil	No. 6 residual fuel oil	Heavy fuel oil	Residual	20-70

2.3.1.12 Biodiesel and Blends.

The push for renewable fuels has grown stronger over the last decade or so. Demand for these fuels to be compatible with legacy engines has spawned a new class of biofuels and their blends. Maintaining the quality control over such fuels may be an issue for aviation users, but the feasibility of using such fuels in internal combustion engines has certainly been proven. In the near future, “Green Air Travel” may prove to increase the use of biofuels within the airline industry [14].

Researchers from Purdue University have successfully created fractionated soybean esters blended with Jet A, which meets the current ASTM D-1655 specifications [15]. Additional research at Purdue tested blends to 100% in aircraft auxiliary power units and engines, including engine performance and emission testing.

Ethanol, another nonfossil fuel alternative, can be added to petroleum diesel fuel in quantities up to 15% (resulting in so-called E-diesel). Additives must be used to keep the ethanol emulsified (uniformly blended), as well as control the cetane rating (how readily the fuel self-ignites) and maintain the lubricity of the fuel [16]. Additionally, there is an increased risk of fire and explosion compared to traditional diesel.

2.3.2 Fuel Additives.

A number of chemical additives are commonly used in nearly all types of liquid fuels. These additives can adjust nearly every property of a fuel, from lubricity to freezing point to oxidizing properties. Different fuel requirements, whether they are military (NATO, MIL-F) or other standards (ASTM), may have different additives required or recommended.

3. GENERAL HFIIE ENGINEERING ISSUES.

Through industry knowledge, FAA policy, and engineering research on CI, a number of important engineering, maintenance, and operational issues have been established. A fair number of these issues are directly related to the design of the engines, airframes, and installation. Some operational changes also arise for an aircraft with an HFIIE. A major goal of this project was to identify these issues with respect to implementation in Unmanned Aircraft Systems (UAS).

The following sections cover engineering issues for HFIIEs within the broad context of engine type certification and operation. The tables in the following sections list and number these issues. Relevant CFR sections and mitigation factors from design, operator intervention/training, and maintenance (represented by D, O, and M, respectively) are also listed.

3.1 VIBRATION.

Levels of vibration in CI reciprocating diesel engines are generally higher than in a gasoline, spark ignition engine of comparable horsepower. This means that stress levels transmitted to the airframe have a potential to be higher, and the frequencies of these pulses will likely be different than those introduced by a gasoline engine.

After reviewing the CFRs, sections that relate to the vibration issue are listed in table 7. Most of the vibration issues relate to design and can be traced back to a solid understanding of the vibratory behavior of the installed engine. Additionally, vibration response and natural frequencies of the engine mount and airframe are important.

Table 7. General Vibration Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
3.1.1	21.21	Issuance of Type Certificate	Unsafe conditions must be avoided.	D
3.1.2	33.5	Instruction manual	Vibration data must be provided in the installation manual.	D
3.1.3	33.33	Vibration	Engine must not impart excessive vibration to airframe.	D
3.1.4	33.43	Vibration test	Survey to establish torsional and bending vibration.	D

3.2 ONE CYLINDER INOPERATIVE CONDITION.

CI reciprocating diesel engines have the potential to produce high levels of vibration if a single cylinder becomes inoperative. In the unbalanced one cylinder inoperative (OCI) condition, the engine mount, propeller, and airframe must be able to withstand imposed vibratory loads. This condition could be caused by a number of factors that could lead to the loss of ignition in a single cylinder (e.g., injector failure, compression ring failure) (table 8).

Table 8. General OCI Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
3.2.1	21.21	Issuance of Type Certificate	Unsafe conditions must be avoided.	D
3.2.2	33.5	Instruction manual	Must include vibration data with operating instructions.	D
3.2.3	-	Detection of an inoperative cylinder	Operator should be informed of OCI condition, likely by tactile or aural cues in manned aircraft	O

An engine should be able to withstand this condition on its own in any event without creating an unsafe condition, and the operator of the UAS should be alerted to the situation. In a manned aircraft, an operator would likely feel the change or vibration, and possibly hear a change in the engine sound. Response would likely require aborting the mission and landing as soon as possible.

3.3 ENGINE TORQUE.

The engine mount in an airframe is only as strong as the structure of the engine itself (table 9). It is important that the design limitations be provided by the engine manufacturer as specified under 14 CFR Part 33, and the engine is built to withstand those loads over the life of the engine. This is not an operator-related issue, and failure probabilities should be minimized through proper design and manufacturing processes.

Table 9. General Engine Torque Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
3.3.1	33.23	Engine-mounting attachments and structure	Limit and ultimate loads must be specified by manufacturer.	D

3.4 FUELS AND ADDITIVES USED.

Heavy fuel is different in nature than gasoline fuels many aircraft fuel systems were designed to be compatible with. It is important that the behavior of these fuels is taken into consideration during design of the airframe fuel system. Diesel and kerosene fuels are generally denser (~10%) than gasoline and may interact differently with seals, pumps, hoses, etc. If a powerplant is approved for different fuel usage, than the operator must be aware of any different operating limitations (i.e., temperature) that may result.

Similar to the differences that changing fuels may cause, if different additives are approved for an engine, they must demonstrate compatibility with the entire system under all expected operating conditions (table 10). An operator or technician has the final responsibility not to use incompatible fuels or additives in the aircraft.

Table 10. General Fuels and Additives Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
3.4.1	33.5	Instruction manual		D
3.4.2	33.7	Engine ratings and operating limitations	Approved fuel grades (and their standards) must be listed in the operating instructions.	D, O

3.5 FUEL SYSTEM.

Concerns with the fuel system compatibility (table 11) are mostly addressed during the aircraft fuel system design. Important considerations and requirements for fuel systems should be provided by the engine manufacturer in the installation and operating manual of the engine.

Table 11. General Fuel System Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
3.5.1	33.35	Fuel and induction system	Fuel and induction system must be protected against icing, liquid accumulation, etc.	D

3.6 ENGINE CONTROL AND INSTRUMENTATION.

An operator of an aircraft must have certain information displayed to them for powerplant parameters (table 12), including power output, rpm, and certain temperatures (depending on design and installation). CI engines, because they are slightly different in operation than a traditional gasoline engine, have different parameters that are important. Additionally, it is important that the established limitations be clearly marked regardless of the information that is displayed.

Table 12. General Engine Control Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
3.6.1	33.7	Engine ratings and operating limitations	Limitations must be specified by engine manufacturer	D
3.6.2	91.205	Instruments and equipment	Manifold pressure gauge required; some other power instrument will be needed for CI engines.	D, O

3.7 ENGINE OVERSPEED.

Overspeed limiting devices should be capable of limiting or stopping fuel flow. Part of the concern with CI engines is that the potential for destructive overspeed is higher with an oversupply of fuel. This concern has been addressed by FAA policy, as shown in table 13, and should be mitigated as part of the basic compliance and certification.

Table 13. General Engine Overspeed Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
3.7.1	33.51	Operation test	Prevention of overspeed, preventing and limiting damage if overspeed does occur.	D

3.8 FIRE PREVENTION.

As a rule, heavy fuels are generally less likely to ignite than gasoline. The same considerations to maintain the safety of aircraft should be observed for fire prevention (table 14). If a fire is detected in any system (oil, fuel, deicing fluid, etc.), the ability to detect the source and shutdown that system may be necessary. The applicability of fire control systems in the UAS context is beyond the scope of this research.

Table 14. General Fire Prevention Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
3.8.1	33.17	Fire prevention	Design should minimize risk of fire, and components that carry flammable liquid should be fireproof.	D

3.9 DETONATION.

Diesel engines operate on autoignition and are much less susceptible to detonation than gasoline engines. However, it is still a concern, and FAA policy accepts analysis that detonation is extremely unlikely (table 15). If detonation does occur, reducing power and increasing airspeed (cooling) may temporarily mitigate it, if the operator is aware of the condition.

Table 15. General Detonation Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
3.9.1	33.47	Detonation test	Detonation behavior differs in compression ignition engines, analysis may be required.	D
3.9.2	-	Detonation detection	Detecting and correcting detonation.	O

3.10 IGNITION.

In a true diesel cycle engine, ignition is guaranteed so long as compression and fuel supply are maintained. To maintain an equivalent level of safety, this should be demonstrated to be as reliable as the systems installed in gasoline engines. There must also be some form of controlling the ignition process, which can be used to shut down a spark-ignition powerplant (table 16). This is considered appropriate under the restart and shutdown sections (see section 3.12).

Table 16. General Ignition Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
3.10.1	33.37	Ignition system	Ignition system must be of equivalent reliability to a "dual ignition system with two spark plugs per cylinder."	D

3.11 CATASTROPHIC FAILURE.

The engine design should be inherently capable to avoid unsafe conditions (table 17) that can cause catastrophic failures. Manufacturers of gasoline engines have historically had the benefit of knowing the behavior of powerplant failures. Any unconventional type of engine will likely be subject to a further, more detailed review of potential failure modes.

Table 17. General Catastrophic Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
3.11.1	21.21	Issuance of Type Certificate	Unsafe conditions must be avoided.	D
3.11.2	33.19	Durability	Unsafe conditions, containment of high-energy fragments.	D

3.12 ENGINE RESTART AND SHUTDOWN.

Operational limitations must be established for a certificated powerplant, including altitude restrictions and a restart envelope. An operator of an aircraft under general operating rules (14 CFR Part 91) is required to operate the aircraft in compliance with the operating limitations (table 18). This is also important for the UAS operators, who must be aware of any established limitations of the air vehicle.

Table 18. General Engine Restart Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
3.12.1	33.5	Instruction manual	Instructions for starting	D
3.12.2	91.9	Civil aircraft flight manual requirements	Operation of aircraft must comply with all operating limitations	D, O

4. FIXED-WING AIRCRAFT HFIIE CONSIDERATIONS.

A review of 14 CFR Part 23 looked at specific sections that might pertain to installing a CI engine into a fixed-wing aircraft. The FAA released guidelines in 2002 for installations of CI engines into 14 CFR Part 23 certified airplanes. A number of the issues were outlined in this policy and are discussed in the following sections.

4.1 VIBRATION.

Fixed-wing aircraft vibration issues are discussed in a number of sections in 14 CFR Part 23 (table 19). Most of the vibration concern lies in the design of the aircraft, but flutter issues in the aircraft design may need to consider pilot input. Flutter and aeroelastic behavior are generally related to the aerodynamic forces (and therefore, airspeed) and can be influenced by controlling of the aircraft [17].

Fatigue in airframe structure is caused by cyclic loading. Engine vibrations, which have higher stress amplitudes, can potentially reduce the design life of a structure. Maintenance inspections may be required to ensure that increased vibration will not lead to premature failure.

Table 19. 14 CFR Part 23 Vibration Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
4.1.1	23.251	Vibration and buffeting	CI engines may have higher vibration levels.	D
4.1.2	23.572	Metallic wing, empennage	CI engines may have higher vibration levels.	D
4.1.3	23.573	Damage tolerance, fatigue evaluation	CI engines may have higher vibration levels.	D, M
4.1.4	23.574	Damage tolerance fatigue evaluation	CI engines may have higher vibration levels.	D, M
4.1.5	23.613	Material strength properties and design values	CI engines may have higher vibration levels.	D
4.1.6	23.627	Fatigue strength	CI engines may have higher vibration levels.	D, M
4.1.7	23.629	Flutter	Higher vibration levels/different frequency may excite flutter.	D, O
4.1.8	23.901	Installation	Carcass vibration characteristics.	D
4.1.9	23.907	Propeller vibration	All types of propellers must be tested, for each installation.	D

4.2 ONE CYLINDER INOPERATIVE CONDITION.

In normal operating conditions, CI engines are likely to have higher vibration levels with an OCI condition than with a comparable gasoline engine. The vibration characteristics of this condition should be considered with respect to the sections outlined in table 20. Flutter is of importance to an operator due to their ability to detect and influence this behavior.

Table 20. 14 CFR Part 23 Cylinder Inoperative Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
4.2.1	23.629	Flutter	Flutter excitation and detection.	D, O
4.2.2	23.901	Installation	Airframe and installation must withstand operation with OCI condition.	D
4.2.3	23.907	Propeller vibration	Propeller must be tested when used with CI engines.	D

4.3 ENGINE TORQUE.

Mounting a diesel engine to an airframe generally requires stronger mounts than a conventional gasoline engine. This is partly due to the higher vibratory loads and torque, as discussed previously. FAA policy for installation into manned aircraft requires a torque multiplier of 4.0 above the mean torque level for an engine with four or more cylinders, unless data is provided to show a lower level is acceptable (table 21). The engine mount design, with respect to static and flight loads (yaw loads, load factor, and gyroscopic loads due to aircraft maneuvers), does not warrant special consideration for diesel engines.

Table 21. 14 CFR Part 23 Engine Torque Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
4.3.1	23.361	Engine torque	Diesel engines of four cylinders or more must use a 4.0 mean torque multiplier. Sudden stoppage must be considered.	D

4.4 FUELS AND ADDITIVES USED.

The fuel system must be compatible with all fuels or additives for which an installed engine is approved, in any conditions (temperature, humidity) expected. These are design issues (shown in table 22) to ensure proper compatibility and performance with all fuels and additives in every expected operating condition (temperature, humidity, altitude, etc.). Testing may be required to support these findings.

Table 22. 14 CFR Part 23 Fuel and Additive Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
4.4.1	23.991	Fuel pumps	System must be compatible with any fuels and additives.	D
4.4.2	23.993	Fuel system lines and fittings	System must be compatible with any fuels and additives.	D
4.4.3	23.994	Fuel system components	System must be compatible with any fuels and additives.	D
4.4.4	23.995	Fuel valves and controls	System must be compatible with any fuels and additives.	D
4.4.5	23.997	Fuel strainer or filter	System must be compatible with approved additives.	D

4.5 FUEL SYSTEM.

Due to differences in the fuels used and operation of the high-pressure fuel system common to CI engines, the airframe fuel system should be designed accordingly. Most of the issues outlined in table 23 are design-related, although it is important for the operator to follow established limitations.

Table 23. 14 CFR Part 23 Fuel System Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
4.5.1	23.951	Fuel system: general	Water and icing	D
4.5.2	23.955	Fuel flow	100% flow beyond engine needed. Turbine requirements used.	D
4.5.3	23.961	Fuel system: hot weather operation	Heated return fuel may heat fuel further. Test must be performed to establish limitations.	D, O
4.5.4	23.973	Fuel tank filler	Prevention of mis-fueling is a ground operator issue.	D
4.5.5	23.991	Fuel pumps	High-pressure and fatigue of system in CI fuel systems.	D
4.5.6	23.993	Fuel system: lines and fittings	High-pressure and fatigue of system in CI fuel systems.	D

Table 23. 14 CFR Part 23 Fuel System Issues (Continued)

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
4.5.7	23.994	Fuel system components	High-pressure and fatigue of system in CI fuel systems.	D
4.5.8	23.995	Fuel valves and controls	High-pressure and fatigue of system in CI fuel systems.	D
4.5.9	23.997	Fuel strainer or filter	High-pressure and fatigue of system in CI fuel systems.	D

4.6 ENGINE CONTROL AND INSTRUMENTATION.

Generally, controlling a CI engine is different than a gasoline engine, as shown in table 24. Mixture controls are usually not used for most diesels, and power is solely controlled by the amount of fuel provided, instead of throttling the airflow, as in gasoline engines. In the same regard, manifold pressure would be a useless parameter, and power is usually a parameter calculated from rpm and fuel flow.

Table 24. 14 CFR Part 23 Engine Control Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
4.6.1	23.777	Cockpit controls	Required engine controls may be different for HFIIE.	D
4.6.2	23.1141	Powerplant controls	Required engine controls may be different for HFIIE.	D
4.6.1	23.1549	Powerplant instruments	Limitation on instruments must be marked.	D, O

4.7 FIRE PREVENTION.

Fixed-wing aircraft requirements for fire prevention are listed in table 25. It is unlikely these requirements will have special interpretation with an HFIIE installed, since they relate to the safety of the systems aboard the aircraft. Ensuring that no more than 1 quart of flammable liquid will continue to flow after a system is disabled should also be required, and compliance should be shown by tests.

Table 25. 14 CFR Part 23 Fire Prevention Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
4.7.1	23.1189	Shutoff means	Preventing flammable liquid from flowing after a fire is detected.	D, O
4.7.2	23.1203	Fire detection	Detector should be installed in any engine not readily visible to the pilot.	D, O

4.8 IGNITION.

Ignition systems in a fixed-wing aircraft must provide a means to control and shutoff ignition on each engine (table 26). In a CI engine, ignition of the fuel in the combustion chamber is accomplished via high pressure (a function of compression and the rings or seals) and fuel delivery (fuel injectors).

Table 26. 14 CFR Part 23 Ignition Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
4.8.1	23.1145	Ignition switches	Means to control and shutoff ignition on each engine.	D, O
4.8.2	23.1165	Engine ignition systems	Alternate source of electrical power must be available to battery-powered ignition systems	D

4.9 CATASTROPHIC FAILURES.

Potential failures in CI engines have raised some concern within the FAA, due to the higher energy associated with CI engines. The higher energy is usually associated with heavier parts of a CI reciprocating engine (pistons, connecting rods, crankshaft, and propeller), which must be absorbed in the event a sudden stoppage occurs due to a failure. Therefore, the mount and airframe must be designed to withstand these loads. Testing or analysis should be performed to ensure that the engine mount, airframe, and propeller are capable of withstanding sudden stoppage loads (table 27).

Table 27. 14 CFR Part 23 Catastrophic Failure Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
4.9.1	23.361	Engine mount	Sudden stoppage must not damage the engine mount or airframe.	D

4.10 ENGINE RESTART AND SHUTDOWN.

Restarting the engine in flight is also a requirement. An aircraft must have operating limitations, as shown in table 28, established during certification, which may be set by the restart envelope of the installed powerplant. Testing may be appropriate to ensure restart is possible at any combination of altitude, pressure, or temperature within the operational envelope. The aircraft operator must follow the established limitations.

Table 28. 14 CFR Part 23 Startup Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
4.10.1	23.903	Engines	Restart capability and envelope must be established.	D, O
4.10.2	23.1521	Powerplant limitations	Any limitations must not be exceeded by operator.	D, O
4.10.3	23.1527	Maximum operating altitude	Limitations due to powerplant.	D, O

5. ROTORCRAFT HFIIE CONSIDERATIONS.

A number of the same considerations, with respect to HFIIE installation, occur with rotorcraft. Rotary wing aircraft are generally more susceptible to vibration issues and have a more complex drive train, transmission, and control system, which must be designed to withstand the higher torque pulses of CI engines. The following review of rotorcraft contains some overlap with the fixed-wing considerations, as well as rotorcraft-specific sections that have been designated for further review.

5.1 VIBRATION.

Vibration issues are critical in rotorcraft when a number of critical parts are constantly subjected to cyclical stresses, as shown in table 29. As with fixed-wing aircraft, combinations of speed and power that may result in excessive vibration should be avoided. For situations that may occur during flight, the pilot of a manned aircraft can take corrective actions, which may include the propel speed and power combinations by following the procedures outlined in the approved flight manual.

Table 29. 14 CFR Part 27 Vibration Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
5.1.1	27.241	Ground resonance	Tendency to oscillate on ground must be avoided.	D
5.1.2	27.251	Vibration	Excessive vibration must be avoided under speed and power combinations.	D, O
5.1.3	27.307	Proof of structure	Proof of strength compliance tests must include dynamic and endurance tests of rotors, drives, and controls.	D
5.1.4	27.547	Main rotor structure	Withstanding limit torque from engine as specified in 14 CFR 27.361.	D
5.1.5	27.571	Fatigue evaluation of flight structure	Evaluation of flight structure and loads/stresses in critical conditions.	D, O, M
5.1.6	27.907	Engine vibration	Engine installation must prevent harmful vibration to all parts of the rotorcraft.	D

A vibration investigation is required for rotorcraft under 14 CFR 27.907(b). Testing can ensure that any calculated frequencies or modes of vibration from this investigation are accurate. Some form of airframe excitation (e.g., electrodynamic actuators) could be used to study airframe response. The rotor system, transmission, and other rotating parts should also be subject to this analysis.

Fatigue life is an important consideration, because as stress levels increase, there is generally a decrease in the number of cycles until failure occurs [17]. Analysis and testing should ensure that there has not been a dangerous increase in the stress levels of any critical parts within the airframe, which is required for compliance normally required by 14 CFR 27.907(b) regardless of engine type. Additional testing of the rotor drive system and control mechanism is required under 14 CFR 27.923 and 27.927, but these focus primarily on engine torque, not vibration.

5.2 ONE CYLINDER INOPERATIVE.

The concerns for an OCI condition are the same for rotorcraft and fixed-wing aircraft. Vibration characteristics for this condition should be provided by the engine manufacturer and analyzed for safety with respect to the flight structure, controls, and rotor system (table 30).

Table 30. 14 CFR One Cylinder Inoperative

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
5.2.1	-	-	Excessive vibration or differing torque from OCI must be evaluated. Detection of OCI.	D, O
5.2.2	27.571	Fatigue evaluation of flight structure	Flight structure must be capable of withstanding OCI vibrations.	D

If OCI data is available from the manufacturer, critical components of the airframe transmission/rotor system should be either tested or analyzed (as deemed appropriate by the FAA) to ensure they are capable of withstanding the OCI condition.

5.3 ENGINE TORQUE.

Rotorcraft engine mounts should be treated similarly to fixed-wing aircraft engine mounts. Side loads, gyroscopic, and aerodynamic load requirements are not specified in 14 CFR Part 27. As of the writing of this document, a limit torque multiplier has not been specified by the FAA for CI installation in rotorcraft. Data and analysis should be provided unless otherwise directed. It is also important to note that the limit torque calculated for gasoline engines (table 31) is also applied to the main rotor structure; this should be similar for the HFIIE installations.

Table 31. 14 CFR Part 27 Engine Torque Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
5.3.1	27.361	Engine torque	Engine mount must be designed to withstand engine torque.	D
5.3.2	27.547	Main rotor structure	Rotor structure must be designed to withstand mean engine torque.	D
5.3.3	27.549	Fuselage, landing gear, and rotor pylon structures	Engine torque must also be considered with landing and accelerated flight conditions.	D
5.3.4	27.923	Rotor drive system and control mechanism tests	Minimum of 100 hours of testing shall prove that the rotor system is in serviceable condition after tests.	D

Table 31. 14 CFR Part 27 Engine Torque Issues (Continued)

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
5.3.5	27.927	Additional tests	Any dynamic/vibratory investigations necessary must be performed under maximum expected torque.	D

Testing components, or analysis when appropriate, should be provided to the FAA to show that the rotorcraft is capable of withstanding torque pulses. Torque data may be provided by the engine manufacturer.

5.4 FUELS AND ADDITIVES USED.

Maintaining compatibility with the fuels used requires proper design and material choice of the aircraft's fuel system (table 32). Compatibility with Jet A or similar jet fuels commonly used in HFIIE engines is well known. If other fuels or additives are considered for operational use, their compatibility should be tested in accordance with an FAA-approved method.

Table 32. 14 CFR Part 27 Fuel and Additive Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
5.4.1	27.991	Fuel pumps	Fuels must be compatible with aircraft fuel pumps.	D
5.4.2	27.993	Fuel system lines and fittings	Fuel lines and fittings must be compatible with fuels and additives.	D
5.4.3	27.995	Fuel valves	Valves in fuel system must be compatible with fuels.	D
5.4.4	27.997	Fuel strainer or filter	Fuels and additives must be compatible with fuel system.	D
5.4.5	27.999	Fuel system drains	Fuels and additives must be compatible with fuel system.	D

5.5 FUEL SYSTEM.

Due to different temperature responses of heavy fuels (compared to gasoline), it should be shown by testing that icing considerations (cold weather) or vapor lock (high altitude/hot weather) does not pose a threat in the most critical conditions, as shown in table 33. These issues may be considerations to the operator, who is responsible for ensuring that the aircraft is operated within the bounds of any temperature/altitude restrictions.

Table 33. 14 CFR Part 27 Fuel System Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
5.5.1	27.951	General	Icing of fuel cooled to most critical condition.	D, O
5.5.2	27.961	Fuel system hot weather operation.	Vapor lock at high temperatures.	D, O

5.6 ENGINE CONTROL AND INSTRUMENTATION.

In reference to engine control and instrumentation (table 34), HFIIE installation in a rotorcraft will not be significantly different from a fixed-wing aircraft. Some form of power indicator will be required, but manifold pressure will likely not be an appropriate measure of engine power. Mixture controls are unlikely on an HFIIE, and this not an issue because the CFRs incorporate this by stating "If there are mixture controls" (14 CFR 27.1147).

Table 34. 14 CFR Part 27 Engine Control Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
5.6.1	27.1305	Powerplant instruments	Instruments for standard installations may not be applicable.	D
5.6.2	27.1549	Powerplant instruments	Limitations on operating powerplants.	D, O

5.7 FIRE PREVENTION.

Minimizing fire risk within a rotorcraft can be achieved by separating flammable liquids from ignition sources. This should not change with the installation of a HFIIE, or within the context of an unmanned system. For manned aircraft, 14 CFR Part 27 requires fire detection for turbine-powered rotorcraft (table 35), but not for reciprocating engine. Detection of a fire, and the response to that threat, should be discussed within the UAS context.

Table 35. 14 CFR Part 27 Fire Prevention Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
5.7.1	27.1185	Flammable fluids	Flammable fluid tanks should be separated from the engine by a firewall or shroud, or provide equivalent degree of safety.	D
5.7.2	27.1191	Firewalls	Separation must be maintained between at-risk areas and personnel, and components critical to a safe landing, etc.	D
5.7.3	27.1195	Fire detector systems	Turbine-powered rotorcraft must have fire detector systems.	D, O

Fire prevention is also partially covered by the CFRs in terms of containment; fire should not be able to spread through a firewall, for example 14 CFR 27.1191. The design of a firewall may be sufficient to show compliance with this requirement.

5.8 IGNITION.

Switches for ignition systems, as described in 14 CFR Part 27 and shown in table 36, are intended to provide a means to shutdown all engines quickly. In most HFIIE designs, as well as turbine (continuous ignition engine) powered aircraft, this would not apply. In CI engines, maintaining compression ratios of about 16:1 or higher (depending on design) is a critical part of the combustion process. This could require the components, which ensure compression, to be as reliable as ignition systems in spark-ignition engines. In HFIIE, combustion can be stopped by cutting off the air or fuel supply.

Table 36. 14 CFR Part 27 Ignition Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
5.8.1	27.1145	Ignition switches	Shutdown of engines by preventing ignition.	D, O

5.9 CATASTROPHIC FAILURES.

The higher energy associated with heavier parts of HFIIE engines (particularly reciprocating CI engines) raise concerns in the event of a catastrophic failure. Sudden stoppage of the engine can be important due to inertia of the transmission and rotor system—this is addressed for manned turbine-powered rotorcraft, as shown in table 37. Torque-limiting devices are currently used but must allow the continued control of the rotorcraft when operating.

Table 37. 14 CFR Part 27 Catastrophic Failure Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
5.9.1	27.1461	High-energy parts	Rotorcraft structure must be capable of sustaining damage from most energetic parts likely to strike in the event of a failure.	D
5.9.2	27.361	Sudden stoppage	Transmission and rotor systems should be able to withstand torque due to sudden engine stoppage.	D
5.9.3	27.917	Design	Rotor torque-limiting devices must allow continued control when operating.	D

High-energy parts that may become liberated and cause damage to the airframe structure, controls, or rotor system are also of concern. Safety-critical assemblies that control the rotorcraft's safe landing should be protected accordingly.

5.10 ENGINE RESTART AND SHUTDOWN.

Shutdown of spark-assisted engines in rotorcraft should be capable of a quick shutdown by ignition switches (table 38). This requirement is not necessary for turbine engines that do not require continuous ignition. For HFIIEs where spark ignition is not necessary for engine operation, some form of fuel or air supply cutoff may need to be incorporated.

Table 38. 14 CFR Part 27 Engine Restart and Shutdown Issues

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
5.9.1	23.1145	Ignition switches	Must be able to shutdown engine(s) quickly.	D, O

14 CFR Part 27 does not contain specific requirements for in-flight restart capability of normal category, manned rotorcraft. The operation of rotorcraft may limit the feasibility of a restart after engine failure, thus maintaining control of the aircraft for autorotation and a safe landing may be more important considerations.

6. UNMANNED AVIATION SYSTEMS CONSIDERATIONS.

Issues not flagged as "design" in the previous sections raise special considerations for the implementation into a UAS. This is due to the unique situations of having no pilot in the aircraft. These issues are now grouped by the type of issue, called scope.

Table 39 outlines general issues that may be mitigated by operator intervention. Two major considerations arise from the five issues. The first involves situation awareness and the detection of adverse situations (OCI, detonation). Without an onboard pilot, some detection systems may be necessary (such as an audio or tactile systems). The second group of issues involves the instrumentation and operating limitations. Similar to manned aircraft, it is important for any operational limitations (powerplant and otherwise) to be established. The operator is responsible for operating the aircraft within these limitations (e.g., restart altitude). Whether a pilot has authority or the capability to operate beyond these limitations for any reason should be discussed during certification.

Table 39. General UAS Considerations

Issue No.	Relevant CFR Sections	Title	Issue	Mitigation Factors
3.2.3	-	Detection of an inoperative cylinder	Operator should be informed of such condition, likely by tactile or aural cues in manned aircraft.	Situational Awareness
3.4.2	33.7	Engine ratings and operating limitations	Approved fuel grades (and their standards) must be listed in the operating instructions.	Operating Limitations
3.6.2	91.205	Instruments and equipment	Manifold pressure gauge required; some other power instrument will be needed for CI engines.	Operating Limitations
3.9.2	-	Detonation detection	Detecting and correcting detonation.	Situational Awareness
3.12.2	91.9	Civil aircraft flight manual requirements	Operation of aircraft must comply with all operating limitations.	Operating Limitations

Fixed-wing UAS issues, as shown in table 40, with HFE include the two considerations found in the general issues section (i.e., situational awareness and operating limitations). Additionally, requirements on engine shutdown and restart should be agreed upon and established—an issue that may extend beyond HFIIE-powered UAS. Fire detection and response (another issue not limited to HFIIEs) is also a topic to be reviewed with the certifying agency.

Table 40. Fixed-Wing UAS Considerations

Issue No.	Relevant CFR Sections	Title	Issue	Scope
4.1.7	23.629	Flutter	Higher vibration levels and different frequencies may excite flutter.	Situational Awareness
4.2.1	23.629	Flutter	Flutter excitation and detection.	Situational Awareness
4.5.3	23.961	Fuel system hot weather operation	Heated return fuel may heat fuel further. Testing must be performed to establish limitations.	Operating Limitations
4.6.1	23.1549	Powerplant instruments	Limitation on instruments must be marked.	Operating Limitations
4.7.1	23.1189	Shutoff means	Preventing flammable liquid from flowing after a fire is detected.	Shutdown
4.7.2	23.1203	Fire detection	Detector should be installed in any engine not readily visible to the pilot.	Fire Detection
4.8.1	23.1145	Ignition Switches	Means to control and shut off ignition on each engine.	Shutdown
4.10.1	23.903	Engines.	Restart capability and envelope must be established.	Operating Limitations
4.10.2	23.1521	Powerplant limitations	Any limitations must not be exceeded by operator.	Operating Limitations
4.10.3	23.1527	Maximum operating altitude	Limitations due to powerplant.	Operating Limitations

Table 41 outlines issues similar in scope to those found in the fixed-wing review. Awareness of potentially unsafe situations such as OCI or excessive vibration is important in a rotorcraft installation. The established limitations and ensuring operation within those limitations is important, as well as systems or instruments needed. Fire detection and shutdown considerations may be handled in a similar fashion to the fixed-wing UAS.

Table 41. Rotorcraft UAS Considerations

Issue No.	Relevant CFR Sections	Title	Issue	Scope
5.1.2	27.251	Vibration	Excessive vibration must be avoided under speed and power combinations.	Situational Awareness
5.1.5	27.571	Fatigue evaluation of flight structure	Evaluation of flight structure and loads/stresses in critical conditions.	Situational Awareness
5.2.1	-	-	Excessive vibration or differing torque from OCI must be evaluated. Detection of OCI.	Situational Awareness
5.5.1	27.951	General	Icing of fuel cooled to most critical condition.	Operating Limitations
5.5.2	27.961	Fuel system hot weather operation	Vapor lock at high temperatures.	Operating Limitations
5.6.2	27.1549	Powerplant instruments	Limitations on operating powerplants.	Operating Limitations
5.7.3	27.1195	Fire detector systems	Turbine-powered rotorcraft must have detector systems.	Fire Detection
5.8.1	27.1145	Ignition switches	Shutdown of engines by preventing ignition.	Shutdown

From these three categories (general, fixed-wing, and rotorcraft), the resulting considerations for HFIIE installation into a UAS fall into four groups and outline some important considerations for manufacturers and the certifying agency. Design considerations extend beyond the scope of the following:

1. Situational awareness:

   a. Detection of engine failures (e.g., OCI)

      - What failure modes are most likely?
      - What systems are necessary to detect these failure modes?
      - How can the system determine the cause?

   b. Detection of excessive/uncharacteristic vibrations

      - What defines excessive?
      - Should a system be installed to detect excessive vibrations?

c. Detection of flutter

- Is a detection system necessary?

3. Instrumentation and Limitations

a. Appropriate powerplant instruments

- Each certified HFIIE should have determined appropriate instruments.

b. Operating within established limitations

- Will the UAS ensure these limitations are not exceeded?
- What systems/instrumentation is then necessary?

4. Shutdown

a. Fuel or air shutoff system

- What are the appropriate requirements and performance standards?

4. Fire detection

a. Detection and response

- What type/size of UAS should fire detection be installed on?
- What type/size UAS should extinguishers be installed on?

7. RECOMMENDED TESTING FOR 14 CFR PART 27 INSTALLATIONS.

A number of HFIIE issues for the rotorcraft installation should be subjected to testing and analysis to demonstrate the system's ability to safely operate with an HFIIE installed. Review of 14 CFR Part 27 showed that while rotorcraft are not subjected to a large number of special considerations with respect to UAS, an HFIIE installation does require special consideration and testing. Table 42 recommends a starting point for future discussions in certification on related projects. Some of the concerns listed overlap other tests.

Table 42. Rotorcraft HFIIE Testing

14 CFR Section	Title	Concern
27.251	Vibration	Testing should ensure that the entire rotorcraft structure is free from excessive vibration.
27.307	Proof of structure	Dynamic and endurance tests should be conducted on rotors, rotor drives, and rotor controls.
27.361	Engine torque	Torque limitations should be established (or provided by the manufacturer) for HFIIE.
27.547	Main rotor structure	The main rotor must be designed to withstand torque limitation tests should confirm analysis.
27.549	Fuselage, landing gear, and rotor pylon structures	The engine mount and adjacent structure should withstand flight and landing loads plus engine torque, test may validate this analysis.
27.571	Fatigue evaluation of flight structure	Parts whose failure could be catastrophic must be identified and evaluated for fatigue. This will include in-flight testing and measurement.
27.659	Mass balance	Rotors must be balanced to prevent excessive vibration, this should be proven by testing.
27.663	Ground resonance prevention means.	Ground resonance and means to prevent ground resonance should be evaluated and tested.
27.903	Engines	Fans and cooling systems attached to the engine must not operate at resonance conditions.
27.907	Engine vibration	Installed engine must not cause excessive vibration to the engine or rotorcraft, this should be shown at all operating conditions.
27.923	Rotor drive system and control mechanism tests	Drive system and control mechanism should be subjected to a 100-hour (minimum) test on the rotorcraft.
27.927	Additional tests	Any additional tests (vibratory, endurance, operational, etc.) must be performed.
27.965	Fuel tank tests	Fuel tanks must be tested for vibration conditions over the operational rpm range.
27.1141	Powerplant controls: general	Vibration must not cause controls to creep; this should be demonstrated in a test.

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