Single Fault Tolerance and LOPC in Electric Engines: Level 1 and 2 Normal-Category Aeroplanes in General Aviation

A Certification Management Team Decision Document

ANAC-EASA-FAA-TCCA Certification Management Team

Task Specific Team on Electric and Hybrid-Electric Propulsion Systems

October 12th, 2023

Revision Table

Issue number	Reason for issuance	Date
1	New document	12 Oct 2023

Table of Contents

Table of figures

1 Summary

This document outlines a joint proposal from the Certification Management Team (CMT) member authorities, providing a certification path for electric engines that will need to comply with the requirement that all engine control systems must be essentially single Fault tolerant for electrical and electronic failures with respect to Loss of Power Control (LOPC) events. The intent of the requirement itself remains unchanged and, as always, applicability depends on a product's certification basis. Existing guidance defines a LOPC event for reciprocating engines (including power loss below 85% existing ratings), which will remain an accepted certification approach for electric engines intended to be installed on Level 1 and 2 General Aviation aircraft. The scope of this document is limited to fully-electric single-engine Level 1 and 2 General Aviation aircraft.

Industry has stated, however, that this definition may be overly restrictive when electric engines are installed in an aircraft in a manner that the aircraft safety objectives are still met. Having been identified as a challenge that all authorities will face individually, and which would be susceptible to disharmonisation, it was decided to develop a commonly accepted approach that allows for the certification of these new and novel technologies.

While the combustion engine total loss of power (such as an in-flight shut-down) is considered a minor engine event during the engine certification process, an assessment of in-service LOPC event data and associated root causes on General Aviation (GA) airplanes concluded that engine power loss may result in a higher classification at the aircraft level, identifying take-off and ascent as the most critical flight phases.

Some fundamental differences between fuel burning and electric engines are discussed, including general architecture and typical physical limitation of existing designs. Consequently, new power ratings of a new kind, the *Single Fault Ratings* (SFR), are proposed to define the power and limitations of the electric engine in the event of a single electrical or electronic failure that does not qualify as LOPC. The document proposes the use of Emergency Short Duration Power (ESDP) and Emergency Continuous Duration Power (ECDP) but applicants may propose other Single Fault Ratings structure.

Finally, a new definition of LOPC for electric engines is presented. Generally, the definition states that an engine operating at *Single Fault Ratings* (SFR, such as ESDP/ECDP) will allow for the aircraft to perform a Continued Safe Flight and Landing and demonstrate compliance with CS/FAR 23.2410, as agreed with the Certifying Authority. A modified LOPC definition for electric engines is given (LOPC-E), including events where the engines cannot deliver the SFR power. Associated Installation and Operating information is discussed along with the link to aircraft certification. Additionally, some guidance on developing compliance methods is provided.

2 Applicability and scope of the current work

The applicability of this paper is limited to electric engines, of Permanent Magnet Synchronous Motor (PMSM) type, used in levels 1 and 2 normal class, single engine General Aviation airplanes to support near-term certification projects.

The CMT task team plans to define LOPC/LOTC for electric engines used within the applicability of this paper, with the intention of achieving the same safety record for electric powered aircraft as today's reciprocating engine powered aircraft (with regards to Power Loss events). Accordingly, the safety and performance targets for electric engines, in this category of aircraft products, are based on those of reciprocating engines.
A future revision of this document will propose associated safety objectives for LOPC-E and PPL events.

Future work of the Task Specific Team on EHPS will expand the topic to higher classes or types of aircraft in accordance with the safety continuum.

3 Introduction

Recent advances in battery technologies have allowed the aviation industry to consider electric engines as a new propulsion option for the aviation sector. Electric engines have enabled new aircraft designs with powered-lift and forward flight capabilities. These advanced propulsion concepts are currently being applied in the General Aviation (GA) domain.

EASA, FAA, TCCA and ANAC are currently working on several electric engine certification projects. The authorities have developed new airworthiness requirements for electric engines and propulsion systems that use electric engines, with the shared goal of making the safe implementation of these new propulsion concepts possible.

Differences between combustion and electric engines have prompted the agencies and industry to re-evaluate several requirements typically applied to aircraft engines. In particular the requirement that mandates "the essentially single fault tolerance of the engine control system to electrical and electronic failures leading to LOPC/LOTC".

EASA intends to address the single fault tolerance issue in the Means of Compliance to EASA Special Conditions E-19, EHPS.350 - EHPS Control System. EASA SC E-19 is intended to cover diverse propulsion systems and aircraft applications. The FAA, ANAC and TCCA are addressing individual projects via Special Conditions within existing regulatory framework.

Single fault tolerance can be assessed at the engine level but may also be assessed at the aircraft level by virtue of the propulsion system configuration. For example, increasing the number of electric engines in a distributed propulsion system may be a way to meet the intent of the single fault tolerance requirement without having to address it through electrical and electronic design redundancy in each engine used in the propulsion system.

Consequently, applying this requirement may have a significant impact on the architecture of an electric engine that is type certificated as a product. The associated means of compliance, as it applies to fault tolerance in aircraft engines, also presents significant challenges when aircraft flight capabilities are used to determine the acceptability of the engine's power capabilities following the failure of a single electrical or electronic component.

This CMT task team has decided to rank single fault tolerance at the highest priority. The intended outcome is a harmonized proposal for how to address this requirement during the electric engine certification process.

The CMT task team have defined a set of objectives for the proposed electric engine specific LOPC criteria:

1. to achieve the same safety record for electric powered aircraft as today's reciprocating engine powered aircraft,
2. to establish safety criteria for aircraft during in flight phases where a power loss event is critical, and
3. to develop performance-based criteria that encompass a diverse range of engine and aircraft designs.

Note: in the document, the term LOPC is used interchangeably with LOTC.

4 Checklist for developing means of compliance to the LOPC/LOTC single fault tolerance requirement

Several activities have been identified that will enable the development of adequate means of compliance to the LOPC/LOTC single fault tolerance requirement:

1. *Define engine control system scope*: Decide which components of the electric engine system are included in the single fault tolerance assessment. At the request of the Authorities, it is being addressed by the SAE E36/E40 committees who intend to publish a new AIR document that addresses this issue. The topic is briefly discussed in Section 5.

2. *Review existing rules and guidance*: Determine the historical application and underlying intent of existing regulatory and guidance material. This is presented in Section 6.

3. *Determine safety objectives:* This task will need to consider the safety goals of existing FAA and EASA special conditions, and any available Means of Compliance published by the Authorities. A joint study on in-service events is discussed in Section 8. Safety objectives, with corresponding failure rates leading to the use of Single Fault Ratings (such as ESDP/ECDP) and LOPC-E events, are needed and are to be used in engine and aircraft system safety assessments. This will be addressed in the second issue of this document.

4. *Define LOPC/LOTC for EE:* Develop an LOPC/LOTC definition that is appropriate for electric engines. The activity considers the installed engine's ability to meet safety objectives. The topic is addressed in Sections 9 and 10 of this document.

5. *Provide relevant powerplant information:* Identify the related monitoring, inspection and maintenance activities in the Instructions for Continued Airworthiness and Instructions for installing and operating the engine using any emergency ratings (SFR). This is discussed in Section 10.2.

6. *Develop component reliability data:* Collect and examine reliability data for components used in electric engines to support the engine system safety analysis. There are already some existing databases[1] which may be used in this study. The SAE AE-10/E-36 committee proposed to develop guidance for all-new components (such as SiC MOSFETS). This not addressed in this document.

[1] See MTBF using Siemens SN 29500| Thomas Reiter (applied-statistics.org)

5 Engine components to be considered for single fault tolerance

The requirement that all engine control systems must be single-fault tolerant to electrical or electronic failures resulting in an LOPC event (CS E-50(c)(2) or equivalent) has historically been applied to, naturally, the engine control system.

As shown in Figure 1, for turbine engines, this definition includes the electronic engine control unit (EECU), associated sensors and electric components such as actuators. It typically excludes separate or hydro-mechanical components such as parts of the Fuel Control Unit (FCU), and evidently does not include the rest of engine, such as the turbomachinery.

For electric engines, the distinction between the engine control system, associated electric or electronic components and the rest of the engine is ill-defined. While internal combustion engines (ICE) also have mechanical parts and rotors, the motive forces that create torque for propulsion are mainly created by exploiting a thermodynamic process. Electric engines, conversely, convert electrical energy into torque by exploiting electromagnetic forces within the electric motor. As such, unlike typical ICE designs, a single electrical or electronic failure in an electric engine can directly affect its ability to function as an aircraft engine. For this reason, the scope of the components that will have to be considered under the engine controls single fault tolerance requirement will have to reflect these characteristics inherent to electric engines.

Figure 1 presents a possible definition for the engine control system for electric engines, as considered within CS E-50(c)(2) or equivalent. However, a definitive list of components that need to be considered and that will apply to all engine designs, is outside the scope of work. The certifying authorities will continue to assess individual proposals from their respective applicants and request that industry working groups consider the topic in the development of industry consensus standards.

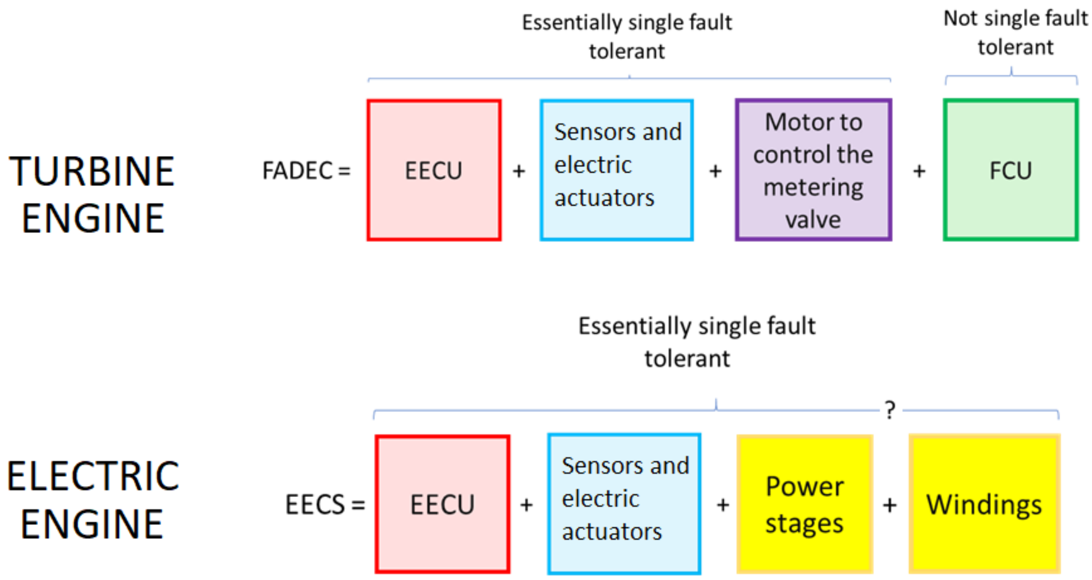

Figure 1 - Possible scopes of engine electronic control system definition

6 Existing requirements and guidance material

6.1 Relevant regulatory text

Current regulations call for the engine control system to be essentially single fault tolerant of electrical and electronic failures leading to a LOPC/LOTC event. At the time of writing, an equivalent requirement is included in the cert basis of all electric engine applicants.

CS-E 50:
(c) *Engine Control System Failures.* The Engine Control System must be designed and constructed so that:

(1) The rate for Loss of Thrust (or Power) Control (LOTC/LOPC) events, consistent with the safety objective associated with the intended aircraft application, can be achieved,

(2) **In the Full-up Configuration, the system is essentially single Fault tolerant for electrical and electronic failures with respect to LOTC/LOPC events.**

(3) Single Failures of Engine Control System components do not result in a Hazardous Engine Effect,

The equivalent paragraph in Part 33 is 33.28(d).

The existing definitions of LOPC/LOTC is provided in guidance material, wherein AMC 20-3B (Section 7(d)(ii)) and AC 33.28-3 (Section 6-2(d)) state:

Table 1: Existing LOPC/LOTC definition and safety objectives for reciprocating and turbine engines

	Reciprocating engines	Turbine engines
LOPC /LOTC definition	An LOPC event is defined as an event where the Engine Control System: • **has lost the capability of modulating power between idle and 85% of maximum rated power at all operating conditions**, or • suffers a Fault which results in a power oscillation greater than the levels given in paragraph (7)(c) of this AMC, or • has lost the capability to govern the Engine in a manner which allows compliance with the operability specifications given in CS-E 390.	7(b)(iii) A LOTC/LOPC event is defined as an event where the Engine Control System: • has lost the capability of modulating thrust or power between idle and 90% of maximum rated power or thrust, or • suffers a Fault which results in a thrust or power oscillation that would impact controllability in the intended installation, or • has lost the capability to govern the Engine in a manner which allows compliance with the operability specifications given in CS-E 500(a) and CS-E 745, as appropriate.
Safety objectives	7(d)(ii) For piston Engines: An LOPC rate of 45 per million engine flight hours (or 1 per 22,222 engine flight hours) has been shown to represent an acceptable level for the most complex EECS.	7(d)(i) For turbine Engines: The EECS should not cause more than one LOTC/LOPC event per 100 000 engine flight hours.

Note that the LOPC/LOTC definition provided in AMC 20-3B (and FAA AC 33.28-2) uses the term "*85% of maximum rated power at all operating conditions*", which includes all declared ratings, such as such as Maximum Continuous Power (MCP) and Maximum Take-Off Power (MTOP).

AMC 20-3B also provides guidance describing the use of the term "essentially" in CS E-50(c)(2).

6.2 Historical rationale for the 85% threshold for reciprocating engines

A series of authority-industry meetings were held in 2000 to address the use of electronic engine controls on reciprocating engines in various applications. At the time, FADECS used on turbine engines was common and relatively rare in reciprocating engines. They were introduced, in part, to increase the reliability of ignition systems and improve pilot control of the power setting. Discussions focused on developing guidance that could be applied directly to reciprocating engines used in Part 23 Class I, II, and III aircraft powered by reciprocating engines. Relevant conclusions were that:

- FAA draft Advisory Circular (AC) 33.28-2, "Guidance Material for 14 CFR 33.28, Reciprocating Engines, Electrical and Electronic Engine Control Systems" was reviewed.
- The 15% power loss definition is consistent with the single magneto failure case on current reciprocating engines in which up to a 15% power loss can be experienced.
- For Part 25 turbine-powered aircraft, SSA primarily considers power losses of 10% and greater. Power losses less than 10% were determined to be inconsequential to flight safety because twin-engine transport category airplanes are certified to take-off using only one engine after reaching V1 speed (a runway excursion hazard may result from asymmetrical thrust in a multi-engine aircraft during take-off below V1, or on landing). However, take-off performance of Part 23 single- and twin-engine airplanes used in GA can be marginal, as well as the ability to tolerate asymmetric thrust. Therefore, the effects of a minor power loss (MPL) are evaluated during the engine certification program. To address the potential safety impact from minor power loss in GA airplanes, an agreement was reached to specify a maximum allowable event rate of $5X10^{-4}$ (1 per 2000 hrs) for MPLs between 5% and 15% of rated take-off power. Power losses greater than 15% are considered Loss of Power Control (LOPC) events.

The full summary of the discussions and participants can be found in Appendix B: Historical Record – Reciprocating Engine LOPC definition.

6.3 Intent of the existing requirement

The intent of the existing requirement is to ensure that no single electrical or electronic component failure of the engine could lead to a loss of power that would preclude continued safe operation of the aircraft; allowing the pilot to safely assess the situation, clear ground conditions, maintain control of the aircraft and land safely. The existing definitions also consider the feasibility of achieving single fault tolerance in reciprocating and turbine engine designs, resulting from the adoption of dual channel ECS's. The reason for single fault tolerance stems from the need to accommodate the random nature of failures in these components.

The objective of the single fault tolerance requirement is to avoid or minimize the impact of random failures, malfunctions and degradation on aircraft function and safety. The fault tolerance can be achieved by a combination of hardware/software design features, and monitoring, inspection, and maintenance procedures.

Within the aircraft type applicable to this document (see Section 2), the intent of this Decision Document is to provide a path towards the certification of electric engines to achieve the same safety record on electric engine powered aircraft as today's reciprocating engine powered aircraft.

7 Use existing LOPC definitions for reciprocating or turbine engines (LOPC-R/T)

Considering the intent to maintain the safety record on electric engine powered aircraft as on today's reciprocating engine powered aircraft, the participating authorities have determined that electric engine applicants may choose to use the existing reciprocating engine LOPC definition (referred to as LOPC-R in this document, where "R" indicates Reciprocating engines, and "T" for Turbines). However, early industry feedback indicated that the 85% LOPC threshold would cause significant challenges for electric engine designs and their integrations in Level 1 and 2 GA aircraft. Nonetheless, the LOPC definition provided in AMC 20-3B or AC 33.28-3 for reciprocating engines is considered to be an acceptable Means of Compliance.

However, the electric engine OEM will still have to identify and substantiate which components to include in the assessment that will show compliance to the essentially single fault tolerance requirement. As with reciprocating engines, the applicant will demonstrate that the results of the safety assessment for the particular engine meets the associated safety objectives.

8 An assessment of the LOPC failure classification at aircraft level

The current engine regulations consider a loss of power or thrust to be a minor engine event (e.g. 14 CFR 33.75(g)(1) and CS-E 510).
At the aircraft level, however, power loss could be regarded as a more severe event depending on the outcome of the failure. For electric engines and electric propulsion systems, the safety and reliability criteria may depend on the aircraft type and its safety objectives.

It is important to recognize that an engine LOPC/LOTC safety assessment classification at the engine level and at the aircraft level may be different. Furthermore, there has been no consensus among the agencies and industry on how to classify an LOPC/LOTC for a single engine, Part 23, Level 1 and 2 normal category airplanes. The following study presents in-service data provided by the FAA and EASA and outlines a proposed classification that would be applicable to electric aircraft applicants, encouraging a harmonized assessment amongst certifying authorities.

Failure condition classification will depend on the effect on the aircraft, occupants and flight crew workload using criteria shown in Table 2, and the effects will depend on the magnitude of power loss or malfunction, flight phase, environment, terrain variations and human factors.

Table 2: Excerpt from ASTM F3230-17

TABLE 2 Failure Condition Classifications

		Classification of Failure Conditions				
		Negligible[A]	Minor[A]	Major[A]	Hazardous[A]	Catastrophic[A]
Classification Considerations	Effect on Aircraft	No effect on operational capabilities or safety	Slight reduction in functional capabilities or safety margins	Significant reduction in functional capabilities or safety margins	Large reduction in functional capabilities or safety margins	Normally with hull loss
	Effect on Occupants	Inconvenience for passengers	Physical discomfort for passengers	Physical distress to passengers, possibly including injuries	Serious or fatal injury to an occupant	Multiple fatalities
	Effect on Flight Crew	No effect on flight crew	Slight increase in workload or use of emergency procedures	Physical discomfort or a significant increase in workload	Physical distress or excessive workload impairs ability to perform tasks	Fatal injury or incapacitation

[A] Refer to Section 3.

8.1 Study of LOP events in General Aviation single engine A/C powered by reciprocating engines

This section presents a joint study, conducted by EASA and FAA specialists, with the objective of recommending an aircraft level classification of LOP events for single-engine general aviation aircraft. FAA and EASA sourced data are presented, followed by a joint conclusion and recommendations. The FAA dataset was taken from NTSB accident reports dated from January 2020 to Apr 2021. The EASA dataset includes incidents and accidents reported from 2016-2021.

It is important to note that the FAA data includes in-service LOP events resulting in Major or more severe classification. While the EASA data includes Minor or more severe events, the Minor and Major incidents are not identified separately. However, Minor event reporting is believed to be incomplete and under-reported and can only be considered with the understanding that they likely heavily outnumber higher level events. The EASA dataset, for example, includes 477 Minor or Major events out of 573 events (83%). EASA has not provided an assessment regarding the potential consequence to safety from under-reporting. An attempt was made to obtain further industry data, but GAMA could not provide any that would help address the gap from under-reporting power loss events.

As shown in Table 3, both the FAA and EASA datasets shows that for single engine aircraft, LOP events have led to multiple incidents classified Major and more severe, up to and including Catastrophic. While it is difficult to compare values directly, an assessment of the two datasets determined they are in general agreement. As the EASA dataset includes a number of Minor events, percentages are presented as a conservative estimate of incident rates (as a % of total reported LOP events). As such, up to 11% of events led to Hazardous category causing serious injury, and 6% resulted in fatalities.

Table 3: FAA and EASA single engine general aviation engine power loss events (reported)

	NTSB Reports (Jan 2020 - Apr 2021)	EASA (2016-2021)
Total Engine Power Loss Events (reported)	**95**	**573**
MINOR: discomfort, slight increase in workload	*not included*	477 (83%)
MAJOR: significant increase in workload, significant reduction in aircraft capability, occupant distress or minor injuries	57	
HAZARDOUS: accidents with serious injuries	17	62 (11%)
HAZARDOUS: accidents with single fatality	14	17 (3%)
CATASTROPHIC: multi-fatality crashes	7	17 (3%)

While the 2020-21 FAA dataset does not include the root cause of each event, a survey of the EASA dataset was able to determine a root cause for each HAZ and CAT event. The results are shown in Table 4. EASA found that all events leading to Hazardous or Catastrophic outcomes occurred during the initial climb after take-off, except one which occurred during the landing phase of flight. In some cases, the pilot may have been tempted to reach the airport/airfield instead of focusing on piloting and controlling the airplane to maintain airspeed above the airplane stall speed. The root cause of Hazardous events, when only due to LOP, typically resulted from an abnormal runway contact (ARC), such as a collision with trees. Note that a single fatality was attributed solely to LOP.

Table 4: EASA incidents - root cause identification

		Root Cause Identified		
	Number of incidents	Only due to LOP	LOP + incorrect pilot action*	Unknown
HAZARDOUS: accidents with serious injuries	62	23 (4.0%)	31 (5.4%)	8 (1.4%)
HAZARDOUS: accidents with single fatality	17	1 (0.2%)	11 (1.9%)	5 (0.9%)
CATASTROPHIC: multi-fatality crashes	17	0 (0%)	13 (2.3%)	4 (0.8%)
* Indicates the pilot applied the wrong emergency procedure following a LOPC event.				

The EASA study highlights that emergency procedures are crucial to avoiding Hazardous and Catastrophic outcomes, as the leading cause of HAZ+ events is a combination of LOPC and incorrect pilot action.

8.1.1 Correlation with previous studies

The Australian Transport Safety Bureau (ATSB) issued a report in 2013 "Managing partial power loss after takeoff in single-engine aircraft", showing the results from a study of events involving partial loss of power during take-off. The report is based on 242 occurrences between 2000 and 2010. The study shows that pilots receive little training for managing partial power loss during take-off, even though data shows this flight condition occurs more frequently, results in more serious consequences, and is more complex to manage than a total loss of power. Pilot response to total power loss is an integral part of the VFR training and it is practiced regularly, but partial power loss is more rarely mentioned in the VFR training syllabus. This is a significant observation because a total loss of power always leads to a forced landing, whereas partial power loss challenges the pilot to decide whether to continue the flight or execute a forced landing. The correct decision should be included in the fundamentals in training.

In France, the BEA recorded 350 accidents and incidents between 2000 and 2015 related to engine power loss during the initial climb after takeoff. The data show 23 accidents were fatal (6,5%), from which 18 accidents (78% of the fatal events), resulted from a loss of control while the airplane was in flight.

The US NTSB data for 2000-2017 showed 439 fatal engine power loss events in single engine aircraft primarily close to the ground (51% in Takeoff phase, 10.5% in maneuver, 9.1% in approach); and secondarily in cruise (27%). Cruise events are particularly present in Level 2 aircraft, which have longer flight lengths.

These studies are consistent with the current study, highlighting the safety concerns regarding LOP during the take-off and ascent phases of flight.

8.1.2 Conclusions of the in-service LOP data review

The following conclusions can be drawn from the various studies:

1. It is known that reports of MAJOR and MINOR events are incomplete, so the real occurrence of power loss is under-reported in general aviation. Therefore, the rates (in %) for HAZ and CAT used in this study are conservative.
2. LOP events in single engine GA aircraft can result in incidents across the severity spectrum and can be expected to result in injury and/or fatalities, especially when the pilot do not apply the appropriate emergency procedure.
3. Power loss events can result in Hazardous and Catastrophic outcomes during initial climb after takeoff, as well as during the landing phase of flight.
4. In order to avoid loss of control of the aircraft, correct pilot execution of engine failure procedures is critical, especially during the take-off, initial climb and landing phases of flight.
5. In flight, partial power loss can be difficult to manage because the pilot may delay the application of emergency procedures because he tries to assess if the engine delivers enough power to attempt to reach the departure airport/airfield or to perform an emergency landing. The prevailing philosophy within the authorities is that some power is better than none: having more power can help provide options for the pilot to locate and manoeuvre to a suitable site for the unplanned landing.

8.2 Classification of the LOPC failure condition for single engine general aviation.

Based on the conclusions from the LOP event study, and within its scope, the working group proposes to classify LOP events as at or a above **Major** for single engine, Part 23, level 1 and 2 normal category airplanes. This is consistent with the current EASA definition of a “**Major +**” event.

The rationale for this proposal is:
1. The classification for at least “Major” is because pilots are trained to cope with loss of power from an engine failure. This situation requires a significant increase in pilot workload, and
2. the “+” is because:

- there is a reliance on the pilot’s training for executing the appropriate emergency procedure in response to the LOPC event to avoid Hazardous and Catastrophic outcomes, and
- the landing location following a power loss may not be always adequate.

The proposed classification for “Major” is consistent with the definition provided in the ASTM F3230-17 with regards to the effect on Flight Crew (see Table 2).
The « + » implies that other design requirements than CS/FAR 23.2510 are required to minimize the frequency of those events. This is the objective of the “essentially single fault tolerance” requirement in CS-E and 14 CFR Part 33.

Examples of higher classification than Major are FAA Special Conditions 23-253-SC (2011) and 23-260-SC (2013) which state “The classification of the failure condition for LOTC/LOPC event on a single engine airplane ranges from Hazardous to Catastrophic”.

For the purposes of this document, the proposed classification demonstrates that operating the aircraft at power losses above Minor Power Loss presents a safety risk that must be addressed. This has been considered in the drafting of the proposed LOPC-E definition.

9 Single Fault Ratings (SFR): Emergency Short or Continuous Duration Power

9.1 Definition of SFR

Assessing the effects from electrical or electronic failures of electric engines requires a different approach than for internal combustion engines (ICEs). As the latter produces power using mechanical and thermodynamic processes that may be controlled by electrical or electric means, but that can be made redundant or designed to function independently from them. In contrast to ICE, all electric engines can lose a significant amount of power when it is subjected to a single electrical or electronic failure.

Generally, electric engines can be designed such that they will continue to provide power following the failure of some electrical components. Typical approaches will require a level of redundancy in the design, with a resulting increase in current in the remaining components power producing. Additionally, induced current may energize isolated components that are connected to the windings of a rotating motor. In most cases, continuing to run an electric engine in a degraded state will lead to higher internal temperatures. This effect can be offset by reducing the power demand, limiting the duration of the power delivered, providing additional cooling, or a combination of all three.

In order to benefit from the ability to continue to produce power in a degraded mode, the manufacturer may, for a particular engine design, elect to declare special ratings associated with operating the engine with an active electrical fault. To codify this type of operation, this document proposes the introduction of **Single Fault Ratings** (SFR), such as *Emergency Short Duration Power (ESDP)* and *Emergency Continuous Duration Power (ECDP)*. These are declared ratings that define the power capability of the electric engine in the event of a single electrical or electronic failure other than LOPC.

As described in the next section, the concept of Single Fault Ratings, such as ESDP and ECDP, is used in the proposed LOPC definition for electric engines. SFR are not meant to be used as a way to by-pass the single-fault tolerance requirement, but to be used for single fault cases that are inherent to a design and cannot be further minimized. The purpose of the SFR is to supply the power required for the pilot to safely fly and land the aircraft following a single fault or failure within the engine that results in a power loss.

Table 5 illustrates a hypothetical set of declared SFR that include possible ESDP and ECDP values. The example considers a fully redundant electric engine design that includes: two independent controllers with fault accommodation software features, each controlling an independent power stage that provides power to an independent set of windings, where each set is comprised of three winding phases.

*Table 5: Example ratings and limitations for an electric engine**

Declared ratings	Duration	Power	Temperature limitation	
MCP	unlimited	80%	130°C	Typical ratings
MTOP	5min	100%	130°C	
ESDP	3min	80%	200°C	SFR: guaranteed during identified single fault cases. Must declare an associated occurrence rate.
ECDP	unlimited	50%	200°C	
**Values given are for illustrative purposes only*				

9.2 Example of SFR use during a flight profile

Figure 2 shows an example of how SFR operating conditions may be assigned to various phases of a typical flight profile. Selection of SFR, such as ESDP and ECDP (used in the example) needs to consider their sequential application and the worst possible thermal state of the engine at the onset of each application. Note that it is possible to applicant to elect to define additional, or alternate types of SFR, such as a longer time-limited but lower power SFR for climb.

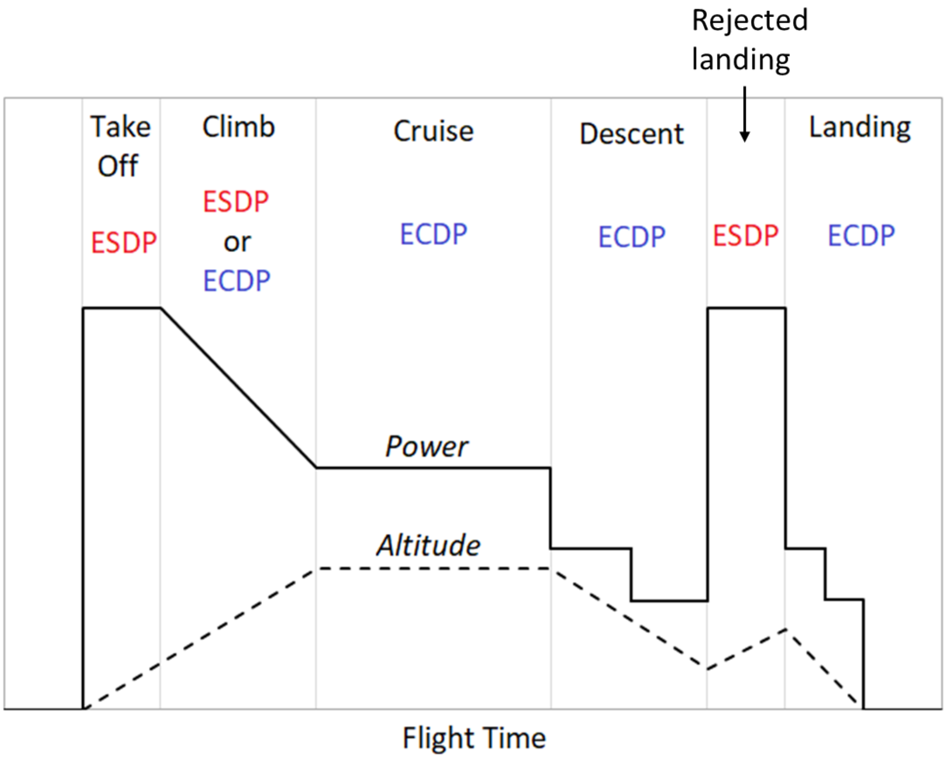

Figure 2 - Example flight profile with SFR allocations

10 An alternate definition LOPC in electric engines (LOPC-E)

10.1 MPL, PPL and LOPC-E

As discussed in previous sections, most Electric Engines designs include electric or electronic systems that inherently result in the possibility of single faults resulting in a loss of power. However, they have the potential of doing so infrequently and in a manner where the reduced power can be guaranteed. It is believed that these features can be exploited in order to develop powerplants for electric aircraft that can achieve the same safety record for electric engine powered aircraft as today’s in-service reciprocating engine powered aircraft. In order to accommodate a larger loss of power resulting from a single fault than the existing LOPC-R definition for reciprocating engines, the proposed LOPC-E (“E” for electric engine) definition introduces three compensating measures:

1. The definition of *Single Fault Ratings* (such as ESDP and ECDP), unique to an engine model, that ensure the power, duration and temperature limitations associated with operating the engine with a single fault,
2. the SFR ratings will be sufficient to allow the aircraft to perform a Continued Safe Flight and Landing, and demonstrate compliance with CS/FAR 23.2410, in a manner that is acceptable to the certifying authorities, and
3. adequate safety targets (rates) are established for each degraded operating mode.

Table 6 presents the proposed LOPC-E definition:

Table 6: proposed alternate definition

<table>
<tr><th></th><th>Electric engine</th></tr>
<tr><td>LOPC-E definition</td><td>An LOPC-E event is defined as an event where:
• an electric engine has lost the capability of modulating power above Single Fault Ratings* (e.g. ESDP and ECDP)** at applicable operating conditions, or
• an electric engine suffers a Fault which results in unacceptable power oscillations, or
• has lost the capability to govern the Engine in a manner which allows compliance with its operability specifications</td></tr>
<tr><td>Safety objectives</td><td>--- to be addressed in Issue 2 ---
For Electric Engines:
A PPL*** rate of ____.
A LOP rate of ____, including LOPC-E rate, total power loss and other mechanical failures.</td></tr>
<tr><td colspan="2">* Single Fault Ratings (SFR) are emergency ratings that specify the power available following a single electronic or electrical fault
** Emergency Short Duration Power (ESDP) and Emergency Continuous Duration Power (ECDP)
*** Partial Power Loss: includes failures leading the engine to deliver partial power equal to or greater than the SFR but lower than 85% of the rated powers</td></tr>
</table>

The intent of the SFR is to allow the aircraft applicant to demonstrate compliance to CS/FAR 23.2410 while in PPL following a single electrical or electronic failure in an electric engine. Table 7 provides performance-based criteria that may be used in this assessment.

Figure 3 illustrates the concept of introducing SFR for electric engines in relation to current reciprocating engines. At the aircraft level, this results in a degraded mode of operation not currently considered in existing CS-E / Part 23 regulation. Therefore, the usage of the SFR must be assessed in aircraft certification.

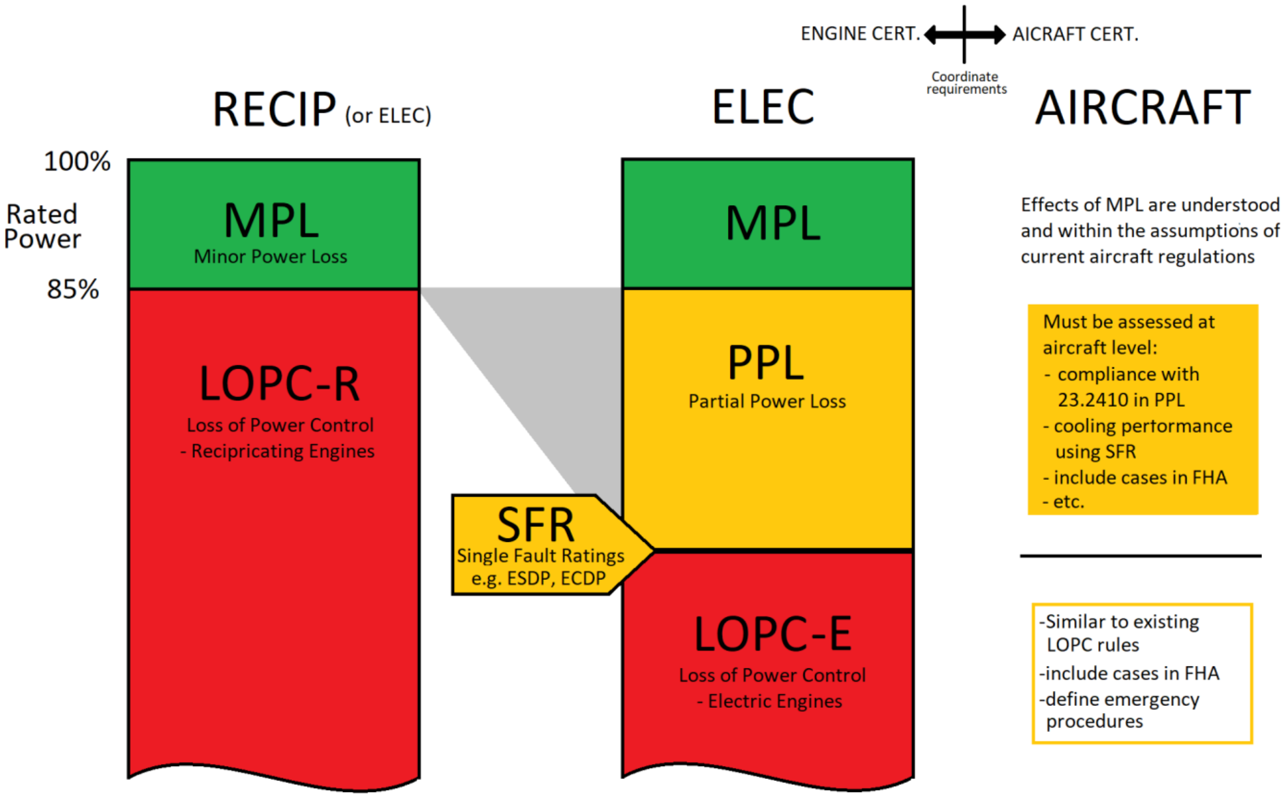

Figure 3 - Introduction of Single Fault Ratings

10.2 Engine Installation and Operating Instructions

Engine certification requires that the engine Installation and Operating instructions (I&O) include all the information necessary for an airframer to install the product. The engine manufacturer must ensure that any underlying certification assumptions are stated in the Installation and Operating instructions, and that all necessary information is provided to the airframer to allow for the engine to be installed and operated without violating these assumptions.

Specifically, the I&O of an electric engine using the LOPC-E definition should include:

1. The Single Fault Ratings definitions (performance, duty cycles and limitations): such as for ESDP and ECDP ratings.

2. The information to be required for airframers to complete an aircraft level safety assessment, such as anticipated failure rates of PPL (single failures resulting in power loss below MPL down to SFR) and LOP. At the moment there are no specific limits on SFR rates, but it expected to be addressed in the second issue of this document. Acceptability will be established on a case-by-case basis in the interim.

3. Information typically included in the I&O instructions still apply, if applicable to electric engines. The above items constitute information deemed relevant to the subject LOPC-E definition.

11 Impact on aircraft certification

Essentially, the above proposal allows engine manufacturers to use SFR ratings to define a reduced threshold value for the LOPC definition of electric engines. The result is a set of emergency ratings that may be used to perform a Continued Safe Flight and Landing of the airplane in a manner that is acceptable to the aircraft's Certifying Authority, and complies with CS/FAR 23.2410. Traditionally, airframers have installed piston engines that had no single faults or failure of the EECS leading to LOPC-R (i.e. more than 15% power loss). On the other hand, failures resulting in significant power loss would simply result in the loss of the engine. Existing aircraft performance criteria does not address operations in degraded modes such as those defined in this document.

The CMT Task Team proposed that in order to ensure that the intent of LOPC-E definition is met, the assessment at aircraft level of the usage of SFR should be considered within the aircraft's Powerplant Installation Hazard Assessment (FAR/CS-23.2410, or equivalent), which states:

> *§ 23.2410 Powerplant installation hazard assessment.*
>
> *The applicant must assess each powerplant separately and in relation to other airplane systems and installations to show that any hazard resulting from the likely failure of any powerplant system, component, or accessory will not—*
>
> *(a) Prevent continued safe flight and landing or, if continued safe flight and landing cannot be ensured, the hazard has been minimized;*
>
> *(b) Cause serious injury that may be avoided; and*
>
> *(c) Require immediate action by any crewmember for continued operation of any remaining powerplant system.*

Therefore, the ability for the SFR (ESDP/ECDP) to allow the aircraft to perform, including demonstrating compliance to CS/FAR 23.2410 following a failure is to be determined during the aircraft certification and is subject to the certifying authority's assessment and approval. Accordingly, aircraft manufacturers and certifying authorities will establish acceptability of an aircraft's capability while using SFR.

An airframer will need to document the Single Fault Ratings, the associated faults or failures, and crew indications in operating manuals, and define emergency procedures associated with the use of SFR.

Table 7 presents elements to be considered as part of the assessment:

Table 7: Considerations when assessing compliance to 23.2410 using SFR

Flight phase	**Objective**	**Proposed Criteria**
Close to the ground (e.g. Take-off, climb Landing, etc.) [typical of ESDP]	*Ensure controllability of the airplane and avoid stall*	Maintain airplane speed above 1.2 x airplane stall speed* (Vs)
	To exit the ground conditions and clear obstacles	To be determined with Certifying Authority
	Ability to climb to safe altitude at maximum weight	
In other flight phases (e.g. cruise, descent) [typical of ECDP]	*Ensure controllability of the airplane and avoid stall*	Maintain airplane speed above 1.2 x Vs
	Allow the pilot to and reach an acceptable landing location	To be determined with Certifying Authority
**Defined as per FAR 23.2110 (see also AC 23-8C)*		

The ability to perform a Continued Safe Flight and Landing and demonstrate compliance with FAR 23.2410, should be assessed for the worst declared OAT condition, at maximum take-off mass, and using the worst-case power loss for a given flight phase.

It should be apparent that the LOPC-E definition precludes showing compliance to the electric-engine single-fault LOPC requirement without consideration for an aircraft installation. When possible, compliance should be coordinated between the engine and aircraft OEMs. However, it is possible for engine OEM to certify an engine without an intended aircraft, as long as assumptions are made about the installation and that the eventual aircraft application can accommodate them.

Table 7 is intended to be used, in interim, as a baseline set of criteria for aircraft certification applicants that are establishing their means and methods of compliance with their Certifying Authority. At an appropriate time, the topic may be revisited by the CMT Task Team or industry working group(s). Over time, it is possible that the electric aviation industry will converge on fixed LOPC-E values if electric engine designs converge.

12 Some guidance on compliance demonstration

12.1 Engine certification activities

As with the traditional engine certification process, manufacturers must declare all engine ratings such as MCP, MTOP. Additionally, electric engines may now have to declare Single Fault Ratings, such as ESDP and the ECDP. Therefore, duty cycles should be associated to each rating and declared as engine limits.

Air-cooled, or otherwise cooling-limited, electric engines may not be able to achieve stabilized temperatures at high power and could therefore limit the availability of these emergency power ratings as internal temperature limits are reached. This case needs to be considered in defining the temperature limit associated with these Single Fault Ratings. However, it has been pointed out that an engine's ability to operate at these ratings for the prescribed duration may be dependent on the initial state of the engine (i.e. internal temperature) or environmental conditions (OAT or altitude) when the ratings are first applied. Therefore, the definition of these ratings and the associated engine performance data should account for the worst-case conditions in accordance with the engine's I&O instructions.

Considering the LOPC-E definition proposed in Section 10.1 and the example provided on Figure 2, it is understood that the ESDP rating will be used close to the ground to allow the aircraft to reach a safe altitude. Therefore, the applicant should consider the maximum expected engine temperature before using this rating. This will likely be the greater of:

1. At the maximum declared OAT, the temperature of the engine reached at a critical point during take-off (likely near rotation) where MTOP has been applied for a short duration before falling to the ESDP rating.

2. At the maximum declared OAT, the temperature of the engine reached at a critical point during descent prior to performing a go-around using ESDP after a rejected landing.

It needs to be recognized that the pilot may need to utilize the ESDP rating more than once during a flight for climb or manoeuvring, to reach a suitable landing site and complete the emergency landing (see Figure 2). Consequently, there is a trade-off in the selection of power level and duration of a ESDP rating.

Conversely, the ECDP will be used for other flight phases where the power requirements are less than they are at the MCP and MTOP rating. Note that ECDP will often be used after using ESDP, so applicants should assess whether the final temperature following a full application of ESDP will allow for the continuous application of ECDP.

Table 8 shows example values of assessed worst-case initial engine temperatures that are consistent with the example give in Table 5. Note that this worst-case initial temperature is not a rating limitation, but a consequence of operating the engine in accordance with the information provided in the I&O instructions.

*Table 8: Maximum initial temperature concept (example)**

Declared ratings	**Duration**	**Power**	**Temperature limitation**	***Worst-case maximum initial temperature***
MCP	unlimited	80%	130°C	*130°C*
MTOP	5min	100%	130°C	*70°C*
ESDP	3 min	80%	200°C	*100°C*
ECDP	unlimited	50%	200°C	*200°C*
**Values given are for illustrative purposes only*				

These ratings and their associated duty cycles should be provided in the Installation and Operating Instructions of the engine as part of the engine certification process.

The use of the SFR should be accounted in the related engine certification activities, such as lifing, vibration survey, endurance test, durability test, environmental test, etc.

The rate of failures leading to operating in a PPL state (includes rate of SFR use as well as other contributors) and the LOP rate (any power loss below SFR at an operating condition) should be provided in the Installation and Operating Instructions of the engine as part of the engine certification process.

12.2 Aircraft certification activities

During the aircraft certification process, the aircraft applicant will have to demonstrate that SFR allow the airplane to demonstrate compliance with CS/FAR 23.2410 when installed and operated in accordance with the engine’s I&O instructions. This document proposes two flight tests:

1. A cooling test to demonstrate that, for the whole declared flight envelope:
    a. the engine temperature remains below the engine temperature limits, and
    b. the maximum initial temperatures are not exceeded before using the respective ratings (the example in Section 12.1 used ESDP and ECDP)
2. Flight tests to demonstrate that at the worst declared OAT condition:
    a. When using the ESDP, the aircraft meets the agreed *near-ground criteria* (such as in Table 7) for the “Close to ground” flight phases.
    b. When using the ECDP, in flight phases where power requirements are less than they are at MCP and MTOP ratings, the aircraft meets the agreed *in-flight criteria* (such as in Table 7) associated to “In other flight phases”.

Where analysis is used, the adequacy of these power levels needs to be performed by the aircraft manufacturer accounting for aerodynamic modelling uncertainties for the terrain and ambient variation expected in service.

The rate of failures leading to the use of SFR (so-called PPL rate) and the LOP rate defined in the Installation and Operating Instructions of the engine as part of the engine certification process, should be assessed in the aircraft safety assessment as per CS/Part 23.2510.

Although this document specifically mentions the requirements 23.2410 and 23.2510, it has to be kept in mind than other requirements from CS/Part 23 remain applicable.

Additionally, if the electric engine and aircraft applicants proposes to use Time Limited Operation, the impact of SFR on the proposal and supporting analysis needs to be reviewed with the Certifying authority, as the existing FAA policy was written based on the traditional LOPC definition and criteria.

13 Conclusions and future work

Early generation electric engine designs are incapable of meeting the criteria established in the existing LOPC definition for reciprocating engines. Typically, this is due to an engine, having suffered a single electrical or electronic component failure, being either (1) unable to produce the power levels for the prescribed duration and/or (2) unable to adequately cool the engine providing partial or full power. In other words, an electric engine may deliver less power after a failure and may only be able to do so for a limited time before reaching an operating temperature limit.

While the existing LOPC-R definition will remain acceptable for electric engines, it was concluded that a strict application of the existing approach would be overly restrictive (due to the diversity of engine configurations) and could force design choices (sizing, redundancy, and cooling) that would compromise design efficiency and performance of these products in the aviation domain. It is the opinion of the CMT Task Team that an effort should be made to support the certification of these novel technologies and allow the industry to mature on small products to gain experience and understanding that can be used to substantiate the use of electrical propulsion technology on higher certification category products.

13.1 Future work topics:

The CMT Task Team intends to publish a second issue of this document to establish for Single Engine Level 1 and 2 General Aviation aircraft:

a. Safety objectives, with acceptable failure rates resulting in use of Single Fault Ratings and LOPC-E events.
b. Objective criteria for aircraft performance when using SFR (i.e. at Partial Power Levels).

Then, the CMT Task Team will address how the single fault tolerance requirement will be applied to hybrid-electric propulsion systems and emerging electric engine concepts (Level 3 A/C, VTOL and other categories of products).

This first issue of the CMT EHPS document is intended to provide material that can be immediately useful to applicants, with future issues and documents expanding on the topics identified above.

Appendix A: Acronyms and Abbreviations

- AGL: Above Ground Level
- CAT: Catastrophic
- CMT: Certification Management Team
- ECDP: Emergency Continuous Duration Power
- EE: Electric Engine
- ESDP: Emergency Short Duration Power
- EHPS: Electric / Hybrid Propulsion System
- GA: General Aviation
- HAZ: Hazardous
- I&O: Installation and Operating Instructions
- ICE: Internal Combustion Engine
- IFSD: In-Flight Shut down = total loss of power
- LOP: Loss Of Power
- LOPC: Loss Of Power Control
- LOPC-E: LOPC on Electric engines
- LOPC-R: LOPC on Reciprocating engines
- LOTC: Loss Of Thrust Control
- MAJ: Major
- MCP: Maximum Continuous Power
- MIN: Minor
- MPL: Minor Power Loss
- MSL: Mean Sea Level
- MTOM: Maximum Take-Off Mass
- MTOP: Maximum Take-Off Power
- Nb: number
- OAT: Outside Air Temperature
- PMSM: Permanent Magnet Synchronous Motor
- PPL : Partial Power Loss
- SFR: Single fault Rating
- Vs: A/C stall speed

Appendix B: Historical Record – Reciprocating Engine LOPC definition

Meetings were held in 2000 where a number of engine companies proposed to develop Engine Electronic Controls or FADECs (Full Authority Digital Engine Controls). At the time, FADECS used on turbine engines was common, and they were rarely used on reciprocating engines. The major reason for using FADECS on reciprocating engines was for increasing the reliability of ignition systems, and to make pilot control of the power setting much easier.
This led to a new advisory circular for electronic control systems used on reciprocating engines. Advisory Circular (AC) 33.28 -1 was created for turbine engines. It had restrictions and requirements based on part 25 transport aircraft equipped with turbine engines. The consensus at that time was, the requirements in 14 CFR 33.28 were reasonable but the guidance in the AC needed to be re-interpreted to be useful for Part 23 Class I, II, and III aircraft powered by reciprocating engines.

The meetings held in 2000 were focused on developing guidance that could be applied directly to reciprocating engines used in these aircraft types.

The first meeting was hosted by the Engine and Propeller Standards Staff (ANE-110) at the FAA New England Regional Office in early April of 2000. The working group began planning the steps for developing certification policy for General Aviation (GA) reciprocating engine electronic control systems. Representatives from the FAA, NASA, and industry attended the meeting. Some of the representatives that attended the April, 2000 meeting are still involved in the design of GA engine electronic control systems.

The second meeting was also convened at the FAA New England Regional Office on April 25 and 26, 2000 to review the FAA draft Advisory Circular (AC) 33.28-2, "Guidance Material for 14 CFR 33.28, Reciprocating Engines, Electrical and Electronic Engine Control Systems". The purpose of the meeting was to solicit comments from industry and regulatory authorities on the guidance material contained in the draft AC, and to further refine the draft AC and meet FAA safety requirements. The attendees were:

Regulatory Authorities		**Industry**	
Mark Rumizen	FAA/Engine Directorate	Mike Krynski	Orenda
Cos Bosco	FAA/Engine Directorate	Bill Coyle	Piper
Hals Larsen	FAA/NRS	Steven Adams	Piper
Jerry Robinette	FAA/Atlanta ACO	Zohueir Abdelnour	Unison
Scott Geddie	FAA/Atlanta ACO	Thierry Francon	SMA/Renault
Tim Smyth	FAA/Chicago ACO	Miriam Dunn	SMA/Renault
Scott Sedgwick	FAA/Small Airplane Dir.	Kevin Brane	TCM
Roop Dhaliwal	Transport Canada	Helmut Messmer	BGT/Germany
Raphael Goriot	DGAC/JAA	Jabe Luttrell	Aerosance
		Steve Smith	Aerosance
		Scott Armish	Lycoming
		Germain Beaulieu	Software DER
		Paul Fiduccia	SAMA

The meeting minutes captured the following working group agreement: "an LOTC event was defined as any engine event in which greater than 15% HP loss occurs. This is consistent with the single magneto failure case on current reciprocating engines in which up to a 15% power loss can be experienced. Undetected power losses up to this 15% level need not be included in the installation data." Meeting minutes recorded from subsequent working group meetings indicate no further changes were made to the LOTC/LOPC definition.

A third meeting was convened at the FAA Headquarters Building, in Washington, D.C., from July 11 to 13, 2000 to review FAA draft Advisory Circular (AC) 33.28-2. The attendees included representatives involved in design and certification of reciprocating engine electronic controls (REEC) systems from both industry and regulatory authorities, from the U.S.A. and Europe.

Regulatory Authorities		Industry	
Mark Rumizen	FAA/Engine Directorate	Mike Krynski	Orenda
Cos Bosco	FAA/Engine Directorate	Gerald Mayr	Rotax
Hals Larsen	FAA/NRS	Josef Furlinger	Rotax
Gunnar Berg	FAA/Atlanta ACO	Zohueir Abdelnour	Unison
Scott Geddie	FAA/Atlanta ACO	Bruno Mandon	SMA/Renault
Ed Cuevas	FAA/Ft. Worth ACO	George Braly	GAMI
Scott Sedgwick	FAA/Small Airplane Dir.	Kevin Brane	TCM
Roop Dhaliwal	Transport Canada	Helmut Messmer	BGT/Germany
Raphael Goriot	DGAC/JAA	Jabe Luttrell	Aerosance
		Steve Smith	Aerosance
		Scott Armish	Lycoming
		Charles Bonnen	Williams
		Paul Fiduccia	SAMA

The purpose of the meeting was to pool the technical knowledge and experience of the meeting attendees to refine and/or develop FAA policy and guidance for turbine engines used on transport category airplanes.

The meeting minutes noted that the SSA primarily considers power losses of 10% and greater. Power losses less than 10% were determined to be inconsequential to flight safety because transport category airplanes are certified to take-off using only one engine. However, take-off performance of part 23 single- and twin-engine airplanes used in GA can be marginal. Therefore, the effects of a minor power loss (MPL) are evaluated during the engine certification program. To address the potential safety impact from minor power loss in GA airplanes, an agreement was reached to specify a maximum allowable event rate of $5X10^{-4}$ (1 per 2000 hrs) for MPLs between 5% and 15% of rated take-off power. Power losses greater than 15% are considered Loss of Power Control (LOPC) events.

A fourth meeting was convened at the FAA Headquarters Building, in Washington, D.C., from October 3 to 5, 2000 to review proposed FAA guidance for certification of reciprocating engine electronic controls (REECs).
The guidance in draft Advisory Circular (AC) 33.28-2, "Guidance Material for 14 CFR 33.28, Reciprocating Engines, Electrical and Electronic Engine Control Systems" was presented for public comment. The attendees included representatives involved in design and certification REEC systems from both industry and regulatory authorities, from the U.S.A. and Europe.

Regulatory Authorities		Industry	
Mark Rumizen	FAA/Engine Directorate	Mike Krynski	Orenda
Gary Horan	FAA/Engine Directorate	Gerald Mayr	Rotax
Hals Larsen	FAA/NRS Control Sys	Pete Pierpont	Embry-Riddle Univ
Leanna Rierson	FAA/NRS Software	Zohueir Abdelnour	Unison
Scott Geddie	FAA/Atlanta ACO	Bruno Mandon	SMA/Renault
Norm Perenson	FAA/NYACO	George Braly	GAMI
Scott Sedgwick	FAA/Small Airplane Dir.	Kevin Brane	TCM
		Helmut Messmer	BGT/Germany
		James Nell	Consulting DER
		Steve Smith	Aerosance
		Scott Armish	Lycoming
		Charles Bonnen	Williams
		Paul Fiduccia	SAMA
		Brian Klinka	Consulting DER

The purpose of the meeting was to pool the technical knowledge and experience of the meeting attendees to refine and/or develop FAA policy and guidance.

Subsequent to this meeting there are no records indicating changes or challenges to the 15% power loss threshold for distinguishing a significant power loss.