SPECIAL CONDITION VTOL: AIRWORTHINESS REQUIREMENTS AS A FIRST BUILDING BLOCK FOR VTOL SAFETY

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Abstract

On 2 July 2019, the European Union Aviation Safety Agency (EASA) released the Special Condition VTOL (vertical take-off and landing), the first airworthiness criteria for the design of VTOL aircraft. Based on the public expectations for these new means of transport, safety objectives have been tailored to different types of operations, with the highest level of safety provided for Commercial Air Transport of passengers and for third parties being overflown. Adaptation of aeroplane and rotorcraft requirements as well as development of novel material were necessary to address the specificities of the new technologies, architectures, and operations. The airworthiness requirements were designed to interface with the operational elements, for example on vertiport design. Complementing requirements to the special condition, for integration in the airspace or environmental protection, are also considered.

1. NOTATION

Symbols:

d	largest overall dimension
D	diameter of the smallest enclosing circle

Abbreviations:

AAIB	Air Accidents Investigation Branch
AFM	Aircraft Flight Manual
ANAC	Agência Nacional de Aviação Civil
ATSB	Australian Transport Safety Bureau
CEL	Controlled Emergency Landing
CFP	Critical Failure for Performance
CMP	Certified Minimum Performance
CS	Certification Specifications
CSFL	Continued Safe Flight and Landing
EASA	European Union Aviation Safety Agency
EU	European Union
EU-ROCAE	European Organisation for Civil Aviation Equipment
FAA	Federal Aviation Administration
FATO	Final Approach and Take-Off area
FH	Flight Hour
ICAO	International Civil Aviation Organization
MOC	Means of Compliance
MTOM	Maximum Take-Off Mass
NTSB	National Transportation Safety Board
OEI	One Engine Inoperative
Pax	Passenger
SC	Special Condition
UAM	Urban Air Mobility
VCA	VTOL-capable aircraft
VTOL	Vertical Take-Off and Landing

2. INTRODUCTION

“How to certify a flying taxi or an electric air ambulance?” is the unconventional question that landed on the desk of EASA in 2017. EASA is an agency of the European Union tasked, among others, with the certification of aircraft. The Agency received several requests for the type certification of vertical take-off and landing (VTOL) aircraft which differ from conventional rotorcraft or fixed-wing aircraft. It was assessed that the existing technical requirements prescribed in Certification Specifications (CS) were not sufficient to address the unique characteristics of these products and a complete set of dedicated technical specifications in the form of a special condition was developed. SC-VTOL was first published as a proposal in October 2018. The public consultation generated more than 1000 comments, which were individually evaluated and answered in a Comment Response Document released simultaneously with the first issue of SC-VTOL in July 2019. A second issue was released in June 2024 to start introducing the results of ongoing harmonization work with the FAA, with participation of Transport Canada and ANAC Brazil. This paper will present some key concepts of the special condition and related material, as they stand as of 1 July 2024.

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While SC-VTOL is a standalone special condition, it incorporates elements of CS-23, the Certification Specifications for Normal-Category Aeroplanes, and CS-27 for Small Rotorcraft. It is formatted similarly to CS-23 post amendment 5, with only high-level objectives being prescribed, while details on how to comply are provided at the level of Means of Compliance (MOC). EASA has identified in conjunction with stakeholders the MOC having the greatest impact on the design and has developed corresponding MOC released so far in four phases. The SC as well as all the related material are available in Ref. 1. Additionally, EASA has initiated within EUROCAE a working group, WG-112, dedicated to developing MOC for SC-VTOL with all interested parties. The working group has published 16 technical standards since its creation in 2019, and 14 more are under preparation.

3. GENERAL

3.1. Applicability

The airworthiness requirements for small and large rotorcraft have been defined for decades through CS-27 and 29. Innovative Air Mobility however intends to perform operations beyond what has been performed commonly by rotorcraft, such as high-volume passenger transport and extensive operations within cities. Manufacturers have the ambition to increase the safety level of the aircraft using redundant propulsion. EASA has thus decided to differentiate between conventional rotorcraft and aircraft falling under the scope of SC-VTOL based on distributed propulsion, namely by redefining rotorcraft and defining VTOL-capable aircraft in Ref. 2:

“rotorcraft” means a power-driven, heavier-than-air aircraft that depends principally for its support in flight on the lift generated by up to two rotors;

“vertical take-off and landing (VTOL)-capable aircraft (VCA)” means a power-driven, heavier-than-air aircraft, other than aeroplane or rotorcraft, capable of performing vertical take-off and landing by means of lift and thrust units used to provide lift during take-off and landing;

Having more than two rotors necessitates advanced flight controls, and the integration of the different systems presents challenges but also opportunities to increase the safety level through redundancy and tolerance to single failures.

The possibility to discriminate between aircraft based on some amount of lift being provided by fixed airfoils was considered but not retained, as a guiding principle for developing the airworthiness criteria was to provide a level playing field between all aircraft architectures for similar types of operations. Determining an appropriate threshold would have been in practice also extremely difficult for certain configurations, for example when having a large horizontal stabilizer, rotor ducts or airframe parts providing lift, wings needing functioning propulsion to provide lift, etc.

The choice was also made to not restrict the applicability to electric propulsion in order to remain technology agnostic. An example of alternate architecture is provided in Ref. 3, proposing to rely on hydraulic rather than electric motors.

3.2. Public expectations

One of the first application envisaged for VTOL aircraft is Emergency Medical Services, where a doctor/paramedic and medical equipment are brought to the accident scene, as illustrated in Figure 1. A corresponding feasibility study is for example available in Ref. 4.

Figure 1: VTOL aircraft are foreseen to provide Emergency Medical Services.

The public may however be more familiar with the air taxi application, providing shuttle services to points of interest in the city (UAM), or outside, for example to an airport. To assess the public expectations, EASA commissioned a study which included a survey of 4000 European residents. The results are available in Ref. 5 and it was identified that the highest percentage of respondents, 37%, ranked safety in their top 3 concerns while the second highest concern was security, for 29%. It is also of interest to note that environmental impact and noise are ranked at similar levels, around 38% each, when their different components are summed. The corresponding recommendation for regulatory authorities is:

Address safety, ensuring that UAM has a safety level equivalent to that of current aviation operations for passengers and for people on the ground;

Similar concerns were expressed during the public consultation regarding the opening of a vertiport in Paris documented in Ref. 6.

3.3. Categories

EASA has decided to address the public expectations through the introduction of two Categories, Basic and Enhanced, linked to the type of operation. Category Enhanced is foreseen when the aircraft is performing Commercial Air Transport of passengers. The highest level of safety is then provided to the fare-paying passenger, regardless of the number of fellow passengers or the terrain overflown. Category Enhanced is also requested for aircraft overflying congested area, such as a city, regardless of the type of operations being conducted, to ensure that the highest level of protection is provided to people on the ground being overflown.

Category Basic instead provides a level of proportionality in the safety objectives depending on the number of occupants. It is foreseen for all other types of operations, for example General Aviation or Special Operations such as infrastructure surveys, as long as they are conducted outside congested areas.

3.4. Safety Objectives

A comparison with the categories from existing aircraft is provided in Table *1*.

Table 1: Comparison of Categories per aircraft type.

CS-23 aeroplanes	CS-27 rotorcraft	SC-VTOL
	Category A[a]	
	Category B[b]	
10 to 19 pax	0 to 9 pax	Enhanced
7 to 9 pax		Basic 7 to 9 pax
2 to 6 pax		Basic 2 to 6 pax
0 to 1 pax		Basic 0 to 1 pax

[a] capable of continued safe flight and landing in case of engine failure

[b] no guaranteed capability to continue safe flight in the event of an engine failure, and unscheduled landing is assumed

Normal-Category aeroplanes are divided in a further four certification levels depending on the maximum passenger seating configuration. For small rotorcraft, at the time SC-VTOL was published, the safety objectives were independent of the number of passengers, however the rotorcraft can be certified under Category A, with the capability of continued safe flight and landing in case of engine failure, or under Category B where an unscheduled landing must be assumed. SC-VTOL combines both frameworks with Category Enhanced corresponding to Category A and the highest level of CS-23, while Category Basic corresponds to Category B and lines up with the lower CS-23 levels.

For each Category a quantitative safety objective is defined as illustrated in Table *2*. For Category Enhanced the objective is set at the same level as for CS-27 Category A rotorcraft, that is for Catastrophic failure conditions less than 10^{-9} per Flight Hour.

Table 2: Quantitative safety objectives for Catastrophic failures (Cat) per Flight Hour.

Assesm. level	CS-23 aeroplanes pax	CS-23 aeroplanes Cat	CS-27 rotorcraft pax	CS-27 rotorcraft Cat	SC-VTOL pax	SC-VTOL Cat
IV	10-19	10^{-9}	0-9	10^{-9}	Enhanced	10^{-9}
III	7-9	10^{-8}			Basic 7-9	10^{-9}
II	2-6	10^{-7}			Basic 2-6	10^{-8}
I	0-1	10^{-6}			Basic 0-1	10^{-7}

For Category Basic, a comparison was made to the Assessment Levels used for CS-23 aeroplanes, which depend essentially on the number of passengers, with some upwards adjustment for certain engine configurations. While the levels are aligned in terms of numbers of passengers, it was decided to increase the safety objectives for SC-VTOL by one level compared to CS-23. This is justified by the following consideration extracted from Ref. 7, a document that originally defined CS-23 classes and objectives:

Generally, the classes deal with airplanes of historical equivalent levels of system complexity, type of use, system reliability, and historical divisions of airplanes according to these characteristics. However, these classes could change because of new technologies.

The new technologies implemented on VTOL, such as advanced flight controls and lift/thrust units used for control and vertical flight, are sufficiently different from the configuration of historical small aeroplanes to justify this increase by one class. Category Enhanced and the upper Category of Basic have then similar quantitative safety objectives. Proportionality is however maintained between these categories as some other technical requirements apply only to Category Enhanced.

An objective has also been introduced that single failures must not be Catastrophic. This requirement is already existing for conventional aircraft, but typically only in guidance material such as industry standards. It was elevated to an objective as increasing safety through redundancy makes sense only if the aircraft is tolerant to single failures. A study of design concepts to meet this requirement is presented in Ref. 8.

3.5. Safety assessment

The application of air taxi is foreseeing to provide an alternative to existing modes of transport. A safety assessment has thus been conducted in Ref. 9 to evaluate the safety levels corresponding to the different objectives. The average fatality rates for different modes of transport in the EU are compared in Table *3* with simulations for VTOL aircraft in two different scenarios: VTOL$_{intra}$ is based on a Concept of Operations for short flights within a city, while VTOL$_{inter}$ refers to operations between cities. The relevant operational and design parameters are derived from existing projects. Several metrics were analyzed and the one presented here is the number of fatalities per billion passenger travel kilometers, which measures the safety for a passenger traveling from A to B. With this metric the quantitative safety objective of 10^{-9} allows to reach a safety level between a car and a bus. This analysis considers only random system failures, which are the only failures affected by the quantitative safety objectives. Any other type of failure, for example structural, or operational or pilot-related causes will further degrade the safety level. For conventional aircraft, operational causes are considered to degrade the safety level by one additional order of magnitude. The reported fatality rates for the other modes of transport instead include all causes. It should also be highlighted that with this metric the simulation results are independent from aircraft occupancy or fleet size.

While for the passenger risk no operational mitigation can be provided for Catastrophic failures, such as loss of fly-by-wire flight controls, for the risk to people on the ground measures can be taken, such as limiting operations to flight corridors. Ref. 9 provides corresponding analyses for the ground risk as well as the risk for other users of the airspace.

Table 3: Comparison of safety levels between modes of transport.

Mode of transport	Safety objective	Fatalities per billion pax travel km
VTOL$_{intra}$[a]	10^{-7}	83
VTOL$_{inter}$[b]	10^{-7}	67
powered 2- wheeler		37
VTOL$_{intra}$	10^{-8}	8.3
VTOL$_{inter}$	10^{-8}	6.7
car		2.7
VTOL$_{intra}$	10^{-9}	0.83
VTOL$_{inter}$	10^{-9}	0.67
bus/coach		0.23
train		0.10
airline		0.06

[a] operations within a city
[b] operations between cities

In front of the expectations from the public, it was thus assessed that the lowest quantitative safety objective acceptable for commercial air transport of passengers is 10^{-9}. To come closer to the safety level of current commercial aviation, a higher safety objective would even be desirable, but 10^{-9} represents today the state-of-the-art for the aviation community and the analyses with smaller probabilities become difficult. Other means to prescribe a higher safety for random system failures could thus be useful, and EASA remains open to proposals from the community. For other types of failures, specific measures were taken in the rest of the Special Condition to limit further degradation of the safety level and will be presented for different domains in the next sections.

4. FLIGHT

4.1. Performance

Performance objectives have been defined for each Category as depicted in Figure 2. For Category Enhanced, in case of a failure in flight, the aircraft must be able to still reach the intended destination or must be able to divert to a pre-identified location. This objective is named "Continued Safe Flight and Landing" or CSFL. For Category Basic, it is only requested that in case of a failure the aircraft can land in a controlled manner, similarly to an autorotation for a rotorcraft, or to a gliding landing for an aeroplane. This objective is referred to as a "Controlled Emergency Landing" or CEL.

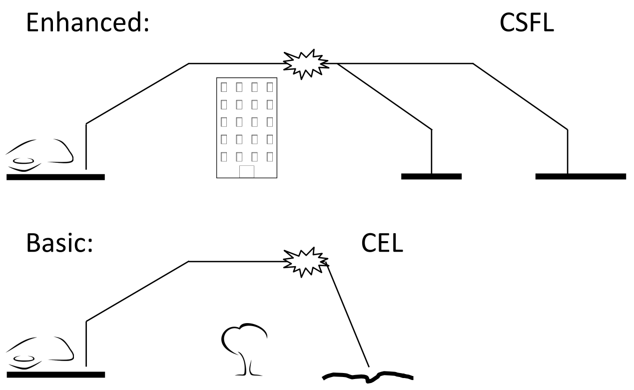


Figure 2: Performance objectives for each Category.

The intent of CSFL is that the pilot or operator has identified in advance vertiports or diversion locations appropriate for:

- the aircraft, such as a minimum area as prescribed in the AFM,
- the route, such as obstacle clearance on the approach path,
- the mission of the day, for example if a diversion location cannot support the aircraft actual weight,
- other conditions at dispatch, for example if a diversion rooftop vertiport is closed due to high winds.

The CSFL procedures are expected to not injure the occupants and to not introduce additional damages to the aircraft due to the landing, similarly to rotorcraft where Category A procedures are demonstrated through flight test during certification. A CEL is also expected to not injure the occupants if achieved on a flat solid surface, however some damage to the aircraft is acceptable.

4.2. Critical Failure for Performance

The failures to be considered for the performance objectives are the Critical Failures for Performance or CFP. They are best explained by considering the existing requirements for rotorcraft, as depicted in Figure 3.

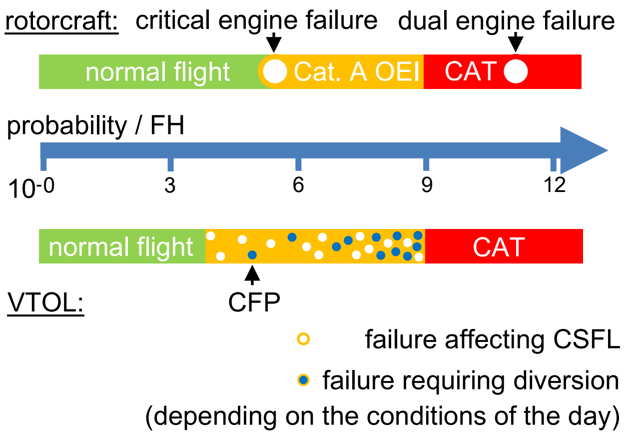


Figure 3: Critical Failure for Performance compared to the rotorcraft framework.

For rotorcraft performance the loss of the critical engine must be considered. Historically the probability of this failure is of the order of 10^{-5} to 10^{-6} per Flight Hour for turbine engines. The Category A certification then verifies that the One Engine Inoperative performance is available with a reliability of 10^{-9}. Catastrophic failures (CAT) must be shown to be less probable than 10^{-9} and do not need to be considered for performance. One exception is the dual engine loss, with the capability to autorotate having to be demonstrated during certification, but which does not need to be considered for Category A operational planning.

This framework had to be adapted for VTOL aircraft. While for rotorcraft the loss of an engine is the worst failure to be considered for performance, for VTOL aircraft other systems failing could degrade performance more severely, for example in some architectures the loss of a battery. “Loss” is one type of failure, but others may also affect the capability to perform a CSFL, for example a frozen motor RPM command resulting in a degraded turn rate. Some VTOL architectures have dozens of engines. To keep a consistent safety level, it is required to consider all single failures and combinations of failures not extremely improbable. Depending on the reliability of the engines, the CFP could thus consist of simultaneous engine failures. Lastly, different failures may affect different flight parameters, for example range or rate of climb, differently in different phases of flight. A CFP is thus defined as the failure or combination of failures that results in the maximum degradation for a given flight phase and performance parameter.

As illustrated on Figure 3, Catastrophic failures must also be less probable than 10^{-9} for Category

Enhanced but there is no upfront probability objective for the CFP, due to the lack of historical data on the new technologies introduced. Consequently, a diversion should have no safety effect. While many single and combinations of failures may somewhat degrade a flight parameter linked to CSFL, only certain ones will result in requiring a diversion depending on the conditions of the day, for example outside air temperature. The most detrimental one for a given flight parameter is the CFP. The set of CFP is then used to determine the Certified Minimum Performance (CMP), which is in turn utilized in the Operational rules to plan the flights, as will be illustrated by an example in the next subsection.

4.3. Certified Minimum Performance

It can be useful to go through an example to see in practice how the CMP is used for flight planning. Let us assume an aircraft that has a standard flight of 15 min at 60 kt and we will focus for this example on range. We will also assume that this flight parameter is most affected by a battery loss, and that this aircraft has 8 independent batteries. To determine the corresponding CFP, we need to consider all single failures, thus we must assume that a battery has failed. We also have to consider combinations not extremely improbable. If we assume for this example that the reliability of a single battery is of the order of 10^{-4}/FH, we must consider two failed before reaching the domain of extremely improbable for Category Enhanced. The CFP for cruise is thus a dual battery failure depicted on Figure 4.

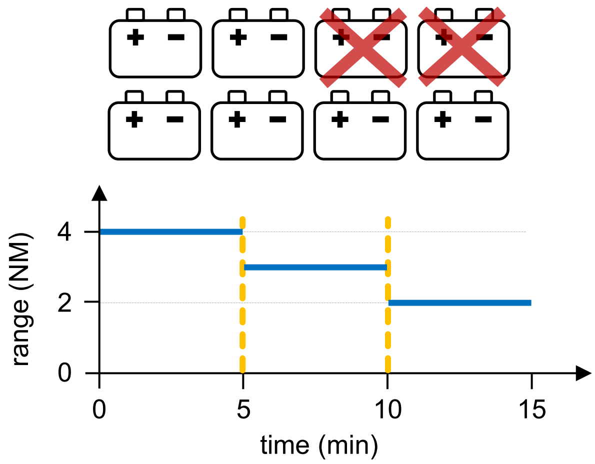


Figure 4: Example of CFP and CMP for range

The applicant then determines the corresponding Certified Minimum Performance. Let us assume for this example that the range remaining if the CFP occurs during the first 5 min of the flight is 4 NM, during the following 5 min 3 NM and if occurring during the last 5 min of the flight 2 NM. The flight parameter considered here is "range" for simplification. For an actual dispatch the situation is more complex, for example to take into account winds, and more generally use can be made instead of a State of Function, as described in Ref. 10. With the above simplification, a given 15 NM flight from A to B can be divided with range arcs at the 5 and 10 NM marks, as illustrated on Figure 5.

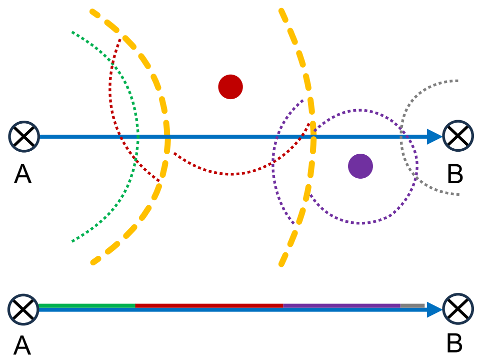


Figure 5: Flight planning with the CMP.

The departing vertiport at A can still be reached after the CFP up to 4 NM, after which another vertiport or diversion location must be available. On the schematic, the diversion location depicted in red is reachable almost up to the 10 NM mark, after which another vertiport or diversion location must be identified, here drawn in purple. Finally, for the last 2 NM of the flight the destination vertiport B can be reached even after the CFP. In this manner the pilot/operator can plan the flight and can ensure that a CSFL is possible at any point even with the most critical failure. This approach is similar to ETOPS / EDTO (Extended-range Twin-engine Operations Performance Standards / Extended diversion time operations) used for large aeroplanes and has been found essential to address the particularities of the urban environment and the specific performance characteristics of electric VTOL aircraft, such as constant weight and diminishing power with lower battery state of charge.

The applicant has also the possibility to present additional performance information in the AFM besides the mandated CMP and nominal performance, to help pilot decision-making during the flight. In our example this could be the performance with a single battery failure, as illustrated on Figure 6.

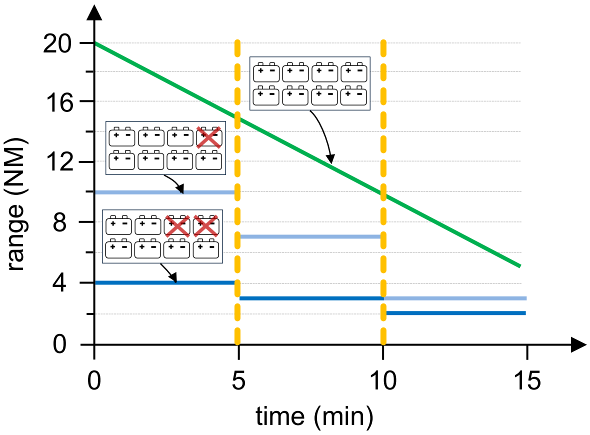


Figure 6: Example of performance provided in the AFM.

4.4. D-value

The so-called "D-value" is used extensively when designing heliports to ensure sufficient obstacle clearance. The community has expressed interest in having vertiports come even closer to the users to provide intermodal connectivity, for example to provide transport to and from a train station. Obstacle protection is thus essential for vertiports as well, and it will be shown in this subsection that the definition of the D-value had to be adapted for VTOL aircraft.

The D-value for helicopters is defined as the largest overall dimension of the helicopter when rotor(s) are turning. As illustrated on Figure 7, this dimension, here noted "d", is on most helicopters the distance from the forward tip of the main rotor to the aft tip of the tail rotor or tail cone projected on a horizontal plane.

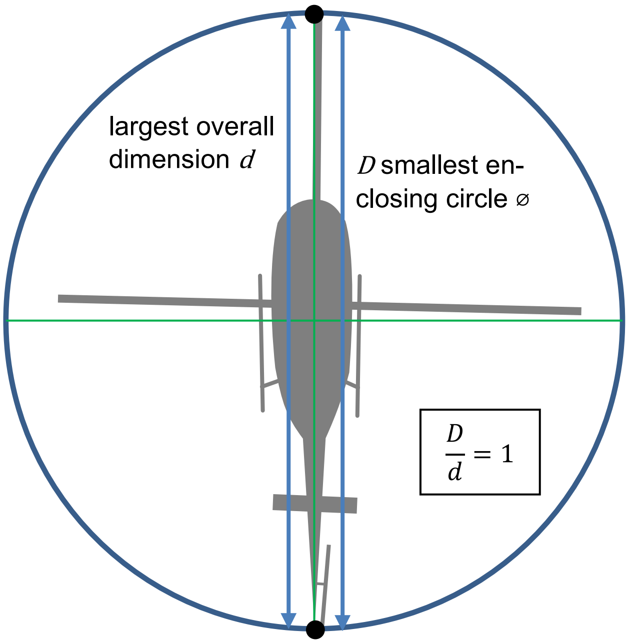


Figure 7: For a helicopter the largest overall dimension is equal to the diameter of the smallest enclosing circle.

For obstacle protection however, the key dimension is the diameter of the smallest enclosing circle, as this circle is the smallest in which the aircraft can fit without hitting nearby obstacles. For a helicopter this circle touches the projection of the helicopter at the same two forward and aft points. If we denote the diameter as "D", we then have $d=D$ and we can use the two concepts interchangeably.

The situation is more complex for VTOL aircraft, where the planform can have an arbitrary shape due to the variety of architectures being considered. A closed form expression of the ratio D/d can be derived with some simplifying assumptions described on Figure 8.

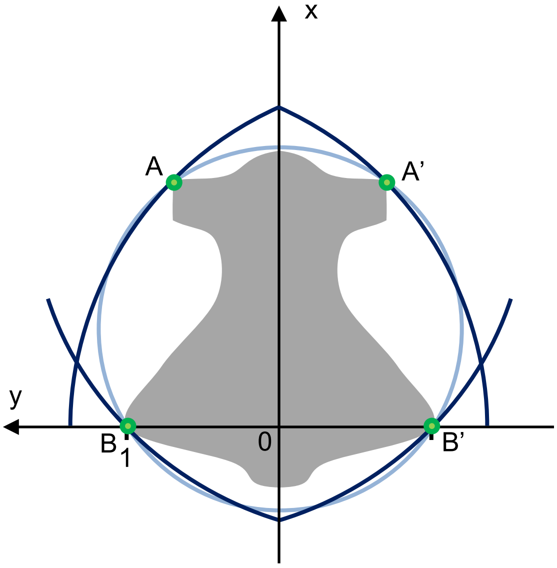


Figure 8: VTOL aircraft planform with simplifying assumptions to derive a closed form expression of D/d.

The planform is assumed to be symmetrical with respect to the longitudinal axis x. It touches the smallest enclosing circle in four points, A forward, B aft and their symmetrical A' and B'. The axes are placed and normalized so that the coordinates of B are (0,1) and A (x,y). The largest overall dimension is assumed to be no greater than AB', that is the planform is contained within the dark blue arcs depicted on Figure 8.

With these assumptions we can derive, as detailed in Ref. 11, the following expressions:

$$d = \max\left(\sqrt{x^2 + (y+1)^2}, 2y, 2\right)$$

and

$$\text{if } \sqrt{x^2 + y^2} \leq 1 \text{ then } D = 2$$

$$\text{else if } \sqrt{x^2 + 1} \leq y \text{ then } D = 2y$$

$$\text{else } D = \sqrt{\left(x + \frac{y^2 - 1}{x}\right)^2 + 4}$$

The above expressions are used to plot the ratio D/d in the (x,y) plane in Figure 9.

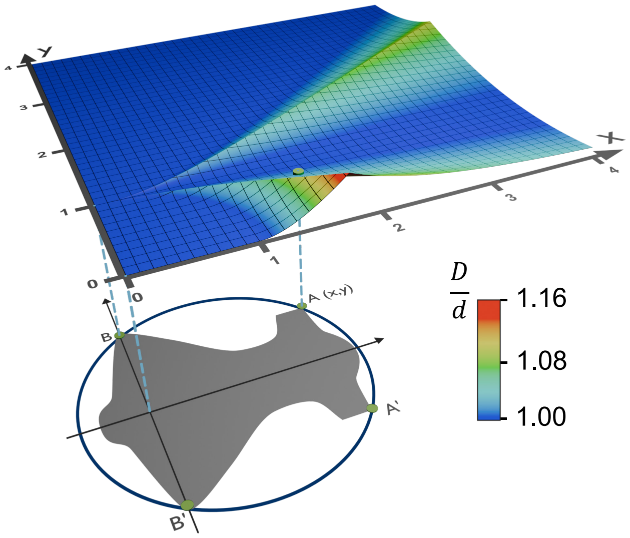


Figure 9: Ratio of the smallest enclosing circle diameter to the largest overall dimension, as a function of the normalized coordinates of point A.

It can be seen that for a large portion of the design space d=D, however, in some regions D becomes greater than d. A general relationship, valid for any planform, is provided by Jung's theorem, derived in Ref. 12:

$$1 \leq \frac{D}{d} \leq \frac{2}{\sqrt{3}}$$

This relationship shows that if we were to keep the current definition for the D-value, we could have up to a 15% error for obstacle protection, always on the unsafe side. EASA is thus redefining for VTOL aircraft the D-value as the diameter of the smallest enclosing circle and will propose to ICAO to make a similar adaptation for the corresponding definition in that international framework. We will see that the D-value is used for performance and vertiport design in the next subsection, and it is utilized in other parts of the Special Condition as well, for example Handling Qualities, aligning the different requirements through this common reference.

4.5. Vertiports

EASA has decided to provide communities maximum flexibility to develop vertiports that fit their needs and has defined the required aircraft performance accordingly. In this sense, three different types of take-off trajectories are recognized, as depicted on Figure 10.

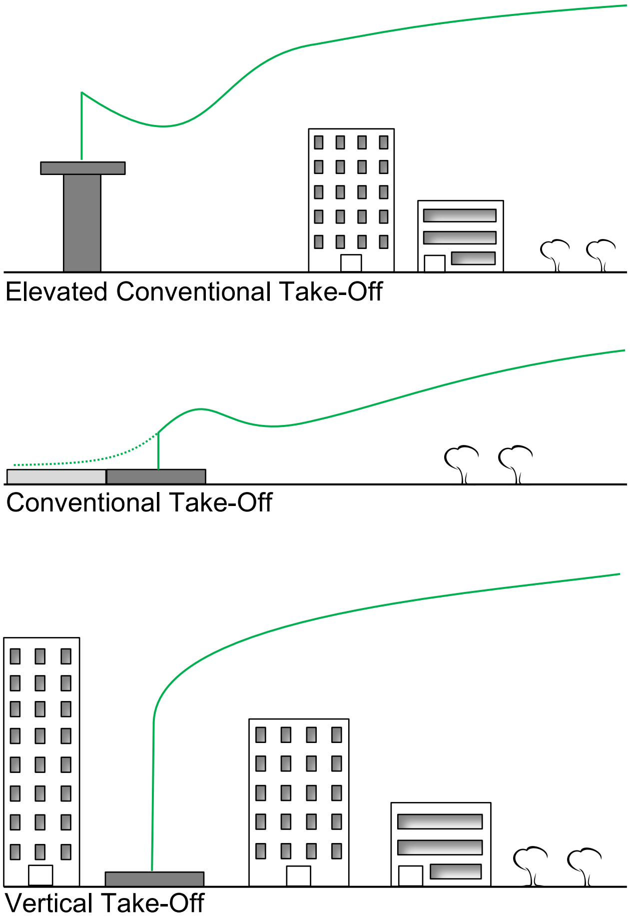


Figure 10: Types of take-off trajectories.

The first type, denoted “elevated conventional take-off”, corresponds to an existing type for helicopters, where departure from an elevated surface allows to clear nearby obstacles, even in the case of a dip in the trajectory following the loss of the critical engine. The same approach is extended to VTOL aircraft using the Critical Failure for Performance. The second type, referred to as “conventional take-off”, is also existing for helicopters. In that context the obstacle environment is such that the take-off can start at ground level and still clear all obstacles after a dip. Under “conventional take-off” EASA is also considering take-offs that are using a runway, as for some missions the VTOL aircraft may use a runway at either end of the flight to save energy.

The third type, named “vertical take-off”, is novel and was developed specifically for challenging obstacle environments, for example city centers. For this trajectory the performance of the aircraft is sufficient to maintain a vertical climb even after a CFP, and it is verified during certification that the aircraft can operate repeatably within a certain volume, depicted on Figure 11. The volume starts at the FATO and is raised vertically to clear nearby obstacles such as fences or lampposts. It then widens with a funnel shape to leave more space for the aircraft to maneuver, up to a certain height where the Obstacle Limitation Surfaces start for approach and departure. The different dimensions of the volume are left up to the aircraft designer, so that the volume can be tailored to the performance of a particular aircraft. Several trajectories can also be certified and provided in the AFM, so that the pilot/operator can select the most energy efficient trajectory for a given environment. In turn the infrastructure designer can use an aircraft published volume, add a safety area at ground level and then raise the volume to provide some additional buffer. The resulting volume, depicted in green on Figure 11, is denoted Obstacle-Free Volume and provides the space above the vertiport for the aircraft to operate.

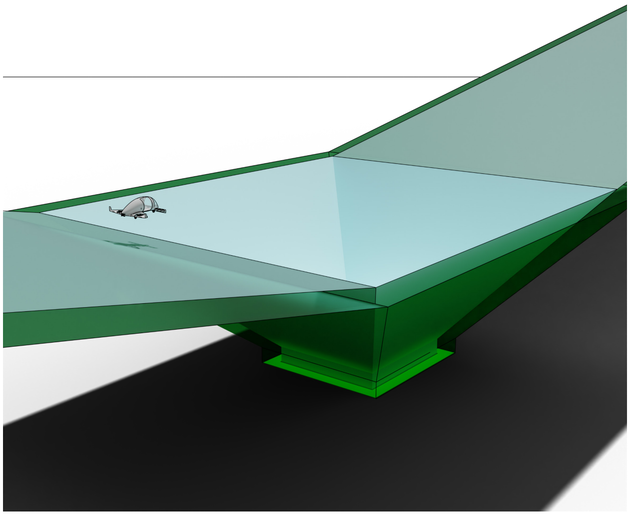


Figure 11: Obstacle-Free Volume.

This framework provides flexibility to the aircraft manufacturer but may be challenging for the infrastructure designer as different aircraft may be certified with different volumes. To facilitate standardization, EASA is proposing on a voluntary basis for applicants to demonstrate the capability to operate in certain reference volumes with given dimensions. For now, a working group composed of airframe manufacturers, infrastructure designers and aviation authorities has developed a first volume called “Reference Volume Type 1”, depicted on Figure 12. This volume was designed specifically for the most challenging obstacle environments with a reduced vertiport footprint.

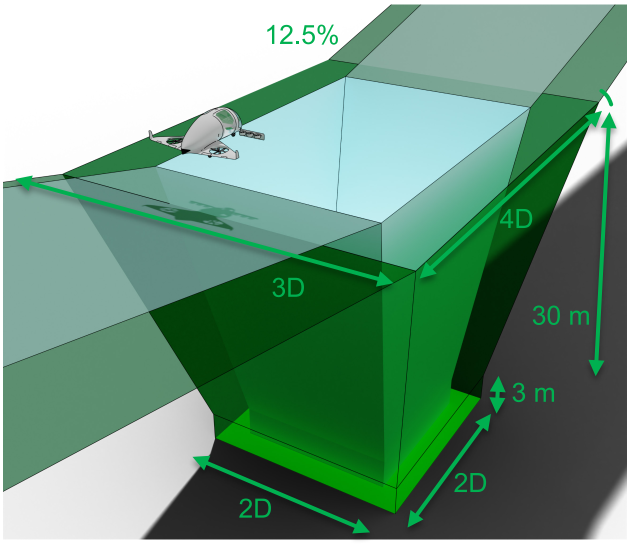


Figure 12: Reference Volume Type 1.

The vertical portion of the volume has a height of 3 m. It then goes up to a height of 30 m with Obstacle Limitation Surfaces climbing with a 12.5% slope. Footprint at the FATO is 2D by 2D while at height the dimensions are 4D by 3D. If the aircraft has been designed with sufficient performance, the applicant can choose to demonstrate that it can operate reliably in this particular volume. If this option is chosen, it will be verified during certification that the trajectory can be maintained by an average pilot, including with Critical Failures for Performance and various wind conditions, and that it provides sufficient visual references and margins to eventual Vortex Ring State susceptibility. To visualize how this volume can clear obstacles in the urban environment, Figure 13 shows a Reference Volume Type 1 with a D-value of 12 m placed on the Breslauer Platz in downtown Cologne, Germany, between the EASA Headquarters and the main train station. With this framework proposal, the Agency intends to facilitate standardization between aircraft and infrastructures, and further Reference Volumes can be designed if the community identifies a need.

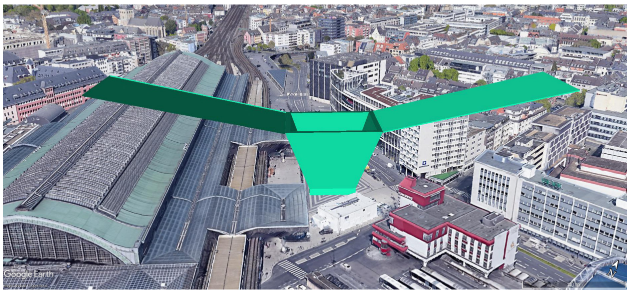


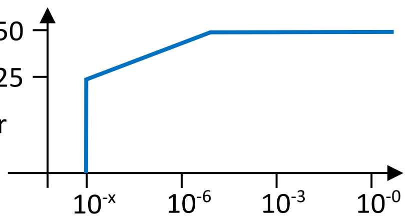
Figure 13: Reference Volume Type 1 in an urban environment (Google Earth).

5. STRUCTURES

5.1. Probabilities in drop tests

Several airworthiness requirements for rotorcraft are demonstrated by drop tests, for example for the landing gear shock absorption. It was identified that in some cases it would be advantageous to introduce probabilistic considerations in such tests to address the characteristics of VTOL aircraft. An example is depicted in Table *4*, comparing with existing requirements for landing gear shock absorption.

Table 4: Limit and reserve energy absorption tests adapted for VTOL.

Limit drop test		
class	failure	drop height (m)
CS-27	power-off	0.33 or no less than 0.2
CS-29	not power-off	no less than 0.2
VTOL	CFP	no less than 0.2
Reserve energy absorption drop test		
class	(/FH)	10^{-9} 10^{-6} 10^{-3} 10^{-0}
CS-27	factor 1.5	
CS-29	factor 1.5	
VTOL	factor	

For rotorcraft two types of tests are required, called limit drop test and reserve energy absorption drop test, with slight differences depending on the category CS-27 or CS-29. The limit drop test for CS-27 must consider the power-off condition and the resulting sinking speed to determine a corresponding drop height. A default value of 0.33 m can be chosen, or a lesser value can be demonstrated, not less than 0.2 m. For CS-29 no specific failure case is prescribed but it is indicated that power-off does not need to be considered. Typically the OEI condition is chosen. No default drop height is given but again it should be no less than 0.2 m. The limit drop test is then used to substantiate the landing inertia load factor. The reserve energy absorption drop test takes the drop height determined for the limit drop test and applies a factor 1.5. The test is passed if the landing gear does not collapse.

The previous section explained how the "critical engine failure" condition from rotorcraft was replaced with the Critical Failure for Performance. This concept is used for the limit test, where the applicant must determine the CFP that results in the highest sinking speed. The corresponding height must be no less than 0.2 m. For the reserve energy absorption test, EASA saw an opportunity to promote lowering the probability of the CFP by providing an incentive to the designer in the test requirements. To understand this approach, it is useful to consider the probabilities implicitly associated with the current tests. We have seen that the probability of an in-flight shutdown for a turbine engine is typically of the order of 10^{-5} to 10^{-6} per Flight Hour. For CS-29, the probability of a dual engine loss, which could be estimated to be of the order of 10^{-10} if they were totally independent, does not need to be considered. In turn, SC-VTOL provides a factor that varies depending on the probability of the CFP. It is equal to 1.5 for a CFP more probable than 10^{-5}, and then decreases linearly on the logarithmic scale, down to 1.25 for 10^{-x}, where 10^{-x} is the probability associated with a Catastrophic failure requirement for the Category being considered. It should be noted that the CFP for the reserve drop test may be different from the limit one, as the CFP resulting in the highest product of the sinking speed times the corresponding factor must be used. A similar approach is used for other structural domains, for example for interactions of systems and structures.

5.2. Single failures and high energy fragments

The general objective that the applicant must prevent single failures from resulting in a catastrophic effect is extended from systems to structures, to preserve the safety benefits provided by redundancy. Some adaptations are made specifically for structures, for example on high energy fragments. Two accidents of VTOL prototype aircraft have already occurred with blade release as one step in a chain of cascading failures, as detailed in Ref. 13 and Ref. 14, highlighting the criticality of this topic. Figure 14 presents the approach proposed for Category Enhanced.

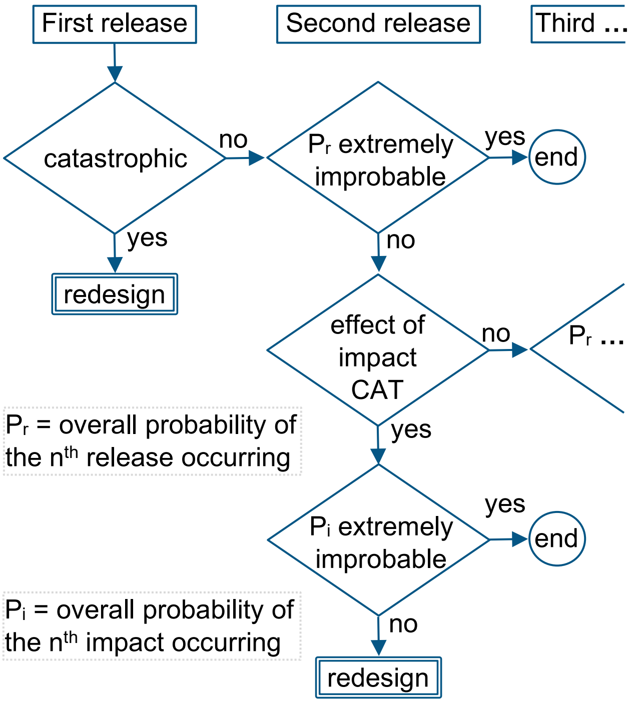


Figure 14: High-energy fragments analysis for Category Enhanced.

The first release of a high-energy fragment is assumed to occur. The size of the fragment to consider depends on the construction of the blades, for example whether redundant load paths are integrated. The direct consequence of this first release should not be catastrophic, in line with the "no single failure catastrophic" principle. For cascading consequences however, probabilities can be introduced. The applicant can first consider the overall probability P_r of an initial fragment release triggering the release of another fragment from a second lift/thrust unit. If P_r is extremely improbable, the analysis does not need to be carried further. If it is not, the direct consequences of the second release should be evaluated. In case the impact is catastrophic, the applicant has one more opportunity to use probabilities by considering P_i, the overall probability of this second impact occurring. If it is extremely improbable, the analysis can stop, otherwise a redesign is necessary. Should the direct consequences of the second release not be catastrophic, the cascading effect on the third lift/thrust unit should be considered, in a similar manner, and then carried out until an overall probability of 10^{-9} is reached, or all lift/thrust units have been analyzed. As probabilities are potentially used extensively in the analysis, an overall residual risk requirement is provided additionally. A robust methodology for handling mechanical lift/thrust failures is crucial in front of the many uncertainties that the new types of operations bring, such as bird strikes in the urban environment.

6. DESIGN FOR WATER OPERATIONS

An attractive application for VTOL aircraft is transport over water, for example for cities with waterways, to bypass bridges or cross bays. Flying over water also provides a means to reduce risk to third parties in congested area. Different categories related to water operations have thus been developed and can be selected by the applicant for certification from the list presented in Table 5. The operational rules can then request specific categories for different types of operations.

Table 5: Categories for water operations.

Emergency Operations
Ditching
Emergency flotation
Limited overwater operations
Normal operations
Operations on water
Operations on floating surfaces

The categories for emergency operations are constructed by increasing the requirements so that an aircraft certified in a more demanding category also satisfies the requirements of a lower category, as illustrated on Figure 15.

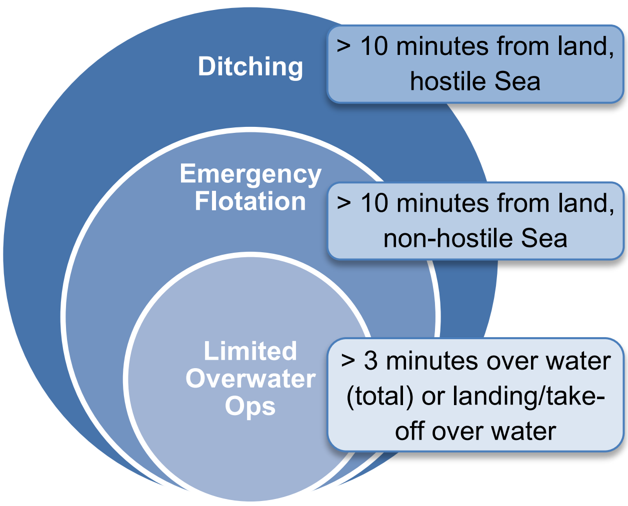


Figure 15: Articulation of the water emergency operations categories.

The ditching category has the most demanding airworthiness requirements and exists already for rotorcraft. It is requested when operating more than 10 minutes away from land over hostile sea, for example the North Sea in Europe. The emergency flotation category is less demanding, also exists for rotorcraft, and is requested when operating more than 10 minutes away from land over non-hostile sea, for example the Mediterranean Sea. The limited overwater operations category is novel and has been introduced to cater to the new types of operations foreseen. It aims at providing a level of crashworthiness over water, similarly to what is provided over land, to give the occupants a reasonable chance to survive. The associated airworthiness requirements are illustrated on Figure 16.

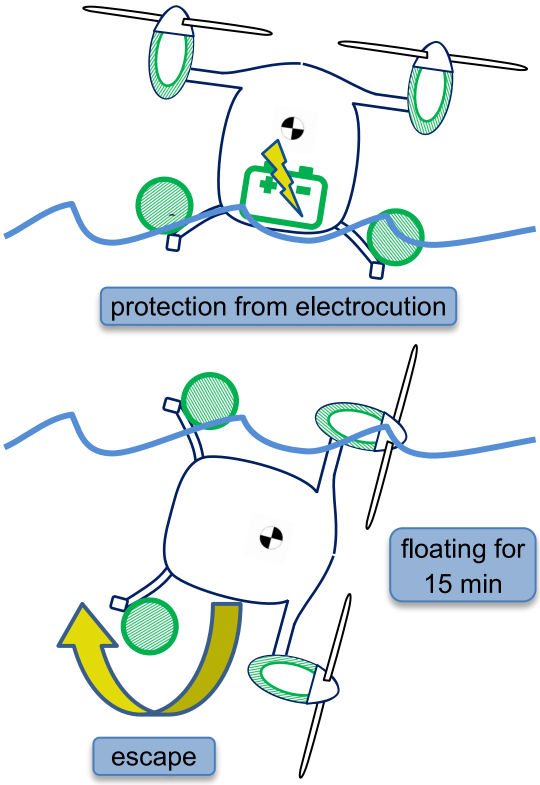


Figure 16: Airworthiness requirements for limited overwater operations.

It is requested that the occupants and eventual rescuers are protected from electrocution. For this less demanding category the aircraft does not have to stay upright but it should float for a minimum of 15 minutes to leave the occupants a chance to exit and hang on to the aircraft until rescue arrives. The cabin can be submerged in some stable floating attitudes but in such case the exit must be accessible and operable underwater to give each occupant every reasonable chance of escaping.

For normal operations the aircraft can be designed for operations on water, similarly to a seaplane or an amphibious helicopter. It was also identified that waterfronts may be an enticing location for communities to operate VTOL aircraft, for example on pontoons, to remediate the lack of available space, especially in the urban environment. In the longer term VTOL aircraft may also provide opportunities in the maritime environment, for example for sea pilot transfer or offshore wind farm servicing as illustrated on Figure *17*.

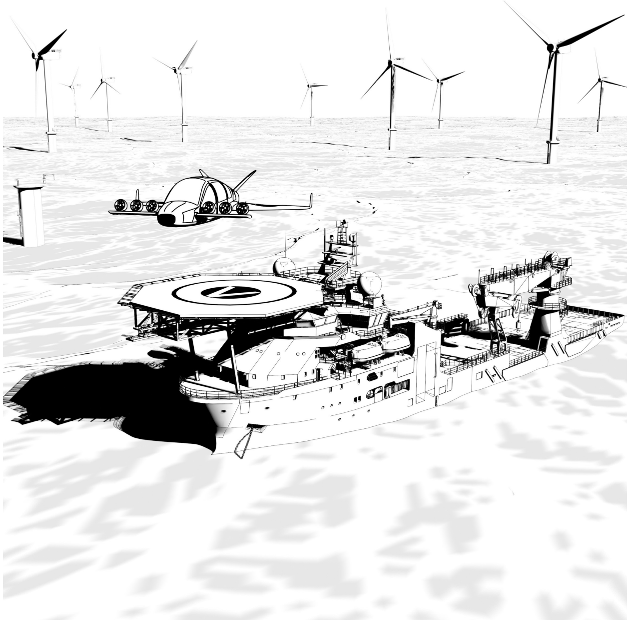


Figure 17: VTOL aircraft can be certified to operate on floating surfaces.

The applicant has thus the possibility to certify the aircraft for operations on floating surfaces within chosen surface motion limits. Some of the elements that may need to be considered are the loads on rotors that are typically not articulated and more rigid than for a helicopter, response of the airframe, and the effect on fly-by-wire controls that rely on inertial measurements.

7. HAZARDS IN OPERATION

7.1. Downwash

The rotorcraft community is familiar with the safety risks from rotor downwash, as reported for example in Ref. 15. VTOL aircraft proposed come however in a wide variety of architectures and the downwash hazards may be different. The desire of communities to place the vertiports closer to the users may compound the risk to third parties. A requirement has thus been introduced to evaluate and report a measure of the aircraft downwash/outwash. While more extensive surveys will be necessary to understand the detailed downwash characteristics, the methodology proposed aims at providing one indicative value, similarly to the noise reporting requirement, and is illustrated on Figure 18.

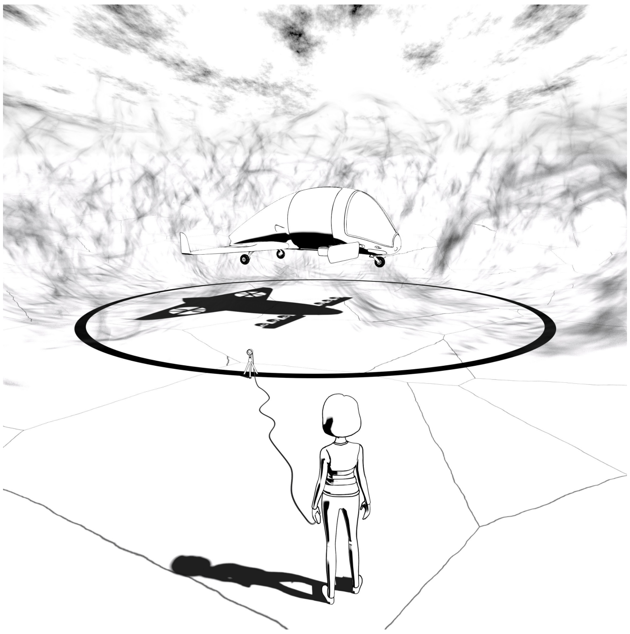


Figure 18: The radial component of the downwash / outwash is measured on the 2D-circle at a height of 0.5 m and 1.5 m.

The aircraft is held in a 1-m high hover and the radial component of the downwash is measured on the 2D-circle, at a height of 0.5 m and 1.5 m. The peak value is taken over a period of at least 10 seconds at several positions on the circle, and the maximum of all measurements is then reported in the AFM. In a similar manner to noise, the communities and infrastructure designers have then an easily accessible first indication of the impact of the downwash / outwash of a particular aircraft.

7.2. Hazard areas

Special attention has been given in the Means of Compliance to Lithium-ion batteries and the fire hazard that they pose. Several layers of protection are requested, starting from cell qualification up to installation requirements. Crashworthiness requirements are also imposed, with a battery drop test from a height of 15 m onto a hard surface, depicted on Figure 19, similar to the drop test for rotorcraft fuel tanks.

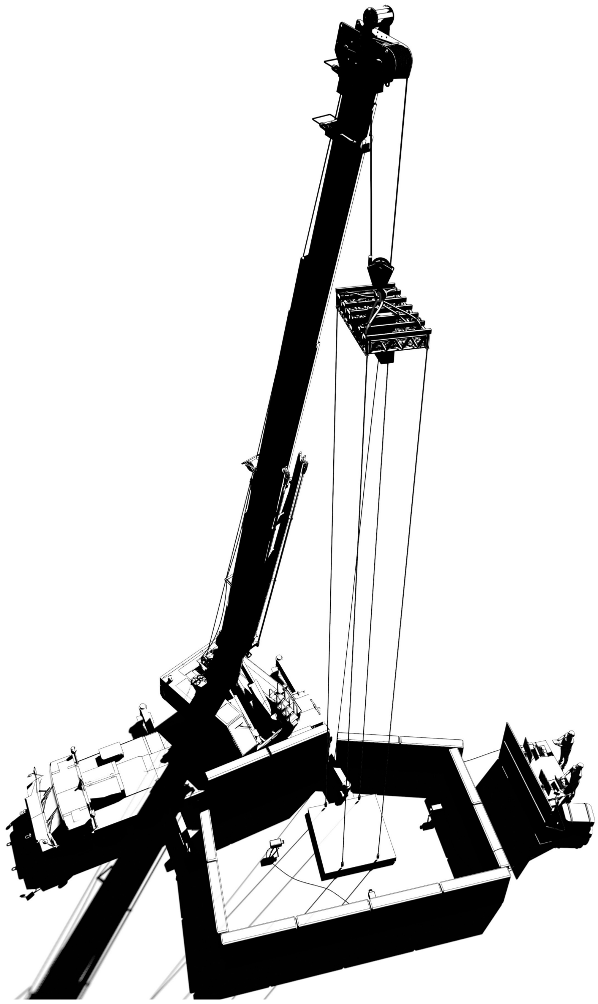


Figure 19: To demonstrate crashworthiness the battery is dropped onto a hard surface from a height of 15 m.

An important difference from rotorcraft Category A requirements is that the capability to extinguish a fire is not requested, as it would be impractical for a lithium-ion propulsion battery. Instead, explosive fire zones must enclose the batteries so that surrounding structure and systems can support a CSFL or CEL depending on the category. To lessen the pressure and temperature that may be experienced by the explosive fire zone during a thermal runway, it is allowed to vent overboard. In such case, the corresponding hazard areas, as illustrated in Figure 20, must be identified and published in the AFM, as it is important information for the infrastructure designer and operator. Hazard areas can also be established to mitigate other risks to ground personnel and third parties, such as risks from moving surfaces.

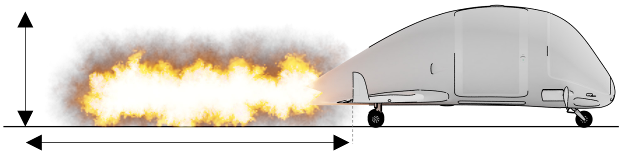


Figure 20: Example of battery fire venting hazard area depiction.

8. SYSTEMS AND EQUIPMENT

The new technologies introduced, and the new types of operations being envisaged lead to uncertainties for the whole community, including the aircraft designers and the regulators. A requirement for in-service monitoring of important parts and systems has thus been established for Category Enhanced, to provide a feedback loop verifying that the assumptions made during design and certification were correct. It would for example check that the Mean Times Between Failures observed in service are compatible with the reliability requirement for the corresponding failure condition criticality. This can be done through maintenance instructions with reporting obligations, or more elaborate means, such as a Health and Usage Monitoring System (HUMS).

Operations in the urban environment present an obvious risk to third parties which EASA must take into account as per its establishing regulation Ref. 16 (Article 4). It was also observed that existing guidance material sometimes provides different definitions of the criticality for different requirements. As an example, the following definitions related to Catastrophic are all extracted from the same document Ref. 17:

- *“an event that could prevent Continued Safe Flight and Landing”*
- *“means the inability to conduct an autorotation to a safe landing”*
- “*any structural failure, which results in death, severe injury, or loss of the aircraft*”
- “*Hazardous: Adverse effects on occupants, including serious or potentially fatal injuries, to a small number of those occupants.*”

It was thus decided to consolidate the definitions of criticality, introducing proportionality between the categories, and taking into account third parties. Failure conditions are thus considered Catastrophic as per Table 6.

Table 6: Proportionality in the definition of Catastrophic failure conditions.

Category	failure causing	failure preventing
Basic	multiple fatalities	CEL
Enhanced	1 or more fatality	CSFL

The new definitions tie the criticality to the performance objectives of each category. The fatalities to be considered include people on the ground and are Catastrophic starting with one fatality for Category Enhanced, which aligns with the approach taken for drones. Similarly to existing definitions for rotorcraft, incapacitation of a flight crew member and loss of the aircraft are also included.

9. COMPLEMENTING REQUIREMENTS

While SC-VTOL provides the core of the aircraft requirements, complementing material is also typically requested. For propulsion, the engines can be either type-certified by themselves or certified with the aircraft. In case of electric or hybrid propulsion, requirements are mandated through the Special Condition E19, Ref. 18. This special condition has a format similar to SC-VTOL, with high level objectives complemented by Means of Compliance that depend on the type of technology considered for the electric or hybrid propulsion system.

Integration in the airspace is also covered by separate requirements, contained in the Certification Specifications for Airborne Communications, Navigation and Surveillance (CS-ACNS). For now, the equipage requested is similar to rotorcraft in the conventional airspace. It is expected however that CS-ACNS will integrate elements for U-Space operations once corresponding services are provided, as foreseen in Ref. 19.

Environmental considerations have their own supporting documents, with noise covered by two sets of Environmental Protection Technical Specifications (EPTS) so far, focusing on specific aircraft architectures. Under preparation are also Product Environmental Footprint Category Rules (PEFCRs), which follow the European Commission methodology described in Ref. 20 and will provide an assessment of the environmental performance of a particular aircraft, for communities to evaluate the benefits of introducing a new means of transportation. The assessment considers the aircraft life cycle stages, from raw material acquisition and processing, through use stage and up to end of life. It evaluates different category indicators beyond global warming potential, such as particulate matter and land use.

10. CONCLUSIONS AND FUTURE WORK

Airworthiness requirements have been developed through the special condition SC-VTOL to establish design objectives for VTOL aircraft. By aligning the requirements with emerging regulations in other domains, for example operations and vertiports, a first building block for VTOL safety is established. Some of the key takeaways are:

1. Categories linked to the type of operations are introduced to provide proportionality in the safety objectives, with the highest level provided when performing Commercial Air Transport of passengers and when overflying congested area.
2. The highest category, Category Enhanced, requests a quantitative safety objective of 10^{-9} per flight hour. This corresponds for fatalities per billion passenger travel km due to random system failures, to a safety level between a car and a bus. Complementary objectives are introduced to mitigate additional design-related causes of accidents that would reduce further the safety level.
3. Category Basic instead is foreseen for General Aviation or Special Operations, outside of congested area. It requests lower quantitative safety objectives and lesser objectives in numerous domains such as performance or bird strike resistance.

The harmonization work with international authorities that led to Issue 2 of the special condition is ongoing, with the goal to reach the highest common level of safety protection, while facilitating exchanges of products. Once enough experience has been gained through projects, the intent is to replace the special condition by certification specifications, as detailed in the European Plan for Aviation Safety, Ref. 21. The need for additional Means of Compliance has also already been identified by the community, and development will continue as new technologies are introduced, for example hydrogen power.

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