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Risk Assessment on Flight Test of High Altitude Paratroopers Airdrop Missions

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This paper presents a comprehensive risk assessment for a flight test aimed at validating a new cargo aircraft for high-altitude paratrooper airdrop missions. These operations, conducted at altitudes ranging between 35,000 and 40,000 feet, expose crew and paratroopers to extreme environmental conditions, such as hypoxia, decompression sickness, barotrauma, and frostbite. The study begins with a theoretical introduction to the physiological challenges posed by high-altitude, unpressurized flight. It then details the principles of risk assessment using a risk matrix and explores the application of fuzzy inference to refine the evaluation process. The assessment identified eight key risk factors, categorized by probability and severity, and quantified the risks through fuzzy logic and defuzzification. Mitigation strategies were proposed, including phased testing, medical support, enhanced safety equipment, and hypoxia recognition training. These measures effectively reduced the overall risk level from high to medium, ensuring safer conditions for flight operations. The analysis highlights the importance of combining quantitative and qualitative methods to reduce subjectivity in risk assessments. Future studies will validate the proposed mitigation measures and expand the framework to include cargo drops in similar conditions.

Keywords: High-altitude flight, risk assessment, fuzzy inference, paratrooper airdrop, flight test, aerospace medicine.

1. Introduction

With the improvement of techniques and gear for paratroopers and airborne equipment drops, different tactics were developed, such as high-altitude free-fall jumps and high-altitude cargo drops. These are usually military operations in which paratroopers or cargo are dropped from altitudes above 12,000 ft, aiming to bring stealth to the action, thus increasing the chances of success in a surprise attack Barros (2023).

In such missions, the crew and paratroopers involved will be exposed to a hostile environment in terms of pressure and temperature regarding the human body physiology. Life support in these extreme circumstances relies entirely upon the aircraft and the gear of the crew and skydivers. During the development of a new aircraft that must fit these missions, the manufacturer is challenged to conjugate operational requirements, equipment reliability and the human factor involved to provide a safe condition for the flight test crew, who will ultimately attest the readiness and safety of the final product. In the aeronautical industry, the common practice is to categorize the risks of these flights based on subjective risk matrices and modes of failures analysis.

This work presents an incremental proposal to the risk assessment made for the flight test of a new cargo aircraft in order to confirm the applicability of the vector for high altitude jumps missions until its operational ceiling, considered to be between 35.000 and 40.000 ft of altitude. Unlike the usual risk assessment made solely over a subjective risk matrix classification, this analysis is corroborated with fuzzy inference over the elements of the matrix to account for different opinions and experiences of flight test professionals. After consideration of the mitigation actions, the evaluation was repeated, resulting in a revised risk categorization for the test.

For the presentation of these data, a theoretical introduction to health hazards in high-altitude flight is first provided, followed by an explanation of the principles of risk assessment using a risk matrix. Also, it is provided a very brief discussion about the fuzzy inference principles. Next, it is show how the methodology was applied over the flight test in issue. Subsequently, the results of the analyses are discussed, concluding with the presentation of the study's main findings.

2. Theoretical Basis

2.1. *Dangers of High Altitude Depressurized Flights*

Aircrafts flying at altitudes above 12.000 ft are exposed to an environment of low temperatures and rarefied air. In this scenario, whenever a depressurization occurs, which is necessary in airdrop missions, skydivers and crew members are prone to suffer harmful events such as hypoxia, decompression sickness, barotraumas, and frostbite.

Hypoxia is a condition in which the body's vital systems are impaired due to a state of oxygen deficiency, potentially compromising the health and behavior of the individual and, in more severe cases, leading to death. Its effects are usually noticeable in pressure environments corresponding to altitudes above 10,000 ft Hackworth et al. (2003). Aviation records report at least two fatal events resulting from crew hypoxia, a Boeing 737-300 that suffered gradual cabin depressurization which led to hypoxia of everyone onboard AAISB (2006) and Learjet 35 that suffered depressurization during cruise, resulting in hypoxia of the crew and passengers as well NTSB (2000).

Decompression sickness results from the formation of inert gas bubbles in tissues caused by a reduction in ambient pressure. These bubbles can enter the bloodstream and travel to vital organs or affect the central nervous system AGARD (1991). To minimize its occurrence, protocols for preparation for flight in a depressurized cabin are adopted, which involve a minimum period of breathing pure oxygen before depressurization USAF (2020).

Barotrauma refers to the different manifestations of the body in response to abrupt altitude changes affecting teeth, ear, sinus, gastric and digestive organs Haberland et al. (2023). Specifically, otological barotrauma refers to an injury caused by the imbalance between atmospheric pressure and the middle ear pressure when the pressure changes more than the eardrum can compensate for between the atmosphere and the middle ear Krebs et al. (2013). In this work, future references to barotrauma refers to ear barotrauma.

Frostbite is a burn injury caused by exposition to extreme cold conditions, usually below -15ºC. These burns can be superficial, with no special treatment needed, or can also be severe, causing gangrenous necrosis, resulting in the amputation of the affected limb, indeed Gupta et al. (2021).

2.2. *Risk Assessment*

Given the hazards that surrounds a high altitude flight with cabin depressurization, a thorough risk analysis is needed prior to flight. The classical methodology related to risk assessment involves mapping danger sources, identifying the causes of each source, determining the consequences of the associated danger, and establishing mitigation measures for occurrence and damage Berg (2010).

In this process, different types of analyses can occur. Some methods are more qualitative and subjective, such as the use of experts' opinions alongside with the use of linguistic variables. Others are more quantitative, such as failure and effect analysis based on equipment reliability McDermott et al. (2009).

One of the tools used to perform a risk assessment and risk management is the risk matrix. A matrix can be defined as table used to store and organize data. The risk matrix is a table that may have two or more dimensions and where in each dimension is stored a risk parameter of evaluation. Each parameter can be broke down in as many levels as the evaluator judges necessary and, from the cross-reference between the parameters, is obtained the final risk score for an event. According to the parameters used, the risk can be assessed qualitatively or quantitatively Moseman (2024).

2.3. *Fuzzy Inference*

The evaluation of an object inside a class might differ from person to person. While someone might consider a 40 year old person to be young, another one might judge this individual as old. So, it is possible to propose a function that indicates the level of membership of an object, in this case the age, to a certain class, young or old. Each of these functions is a fuzzy set Zadeh et al. (1996).

It is possible to define fuzzy sets to different attributes and establish rules between them in a manner that the combination of the characteristics implicates over a new factor. For example, if a painting is beautiful and cheap, it is attractive, and if it is beautiful and expensive, it is unattractive. So, based on the membership grades of each attribute, on the defined logic from the rules and on the fuzzy sets for the resulting characteristic, it is possible to obtain the membership grade function for this final desired factor Cardoso Jr. (2024). This process is called fuzzy inference.

Finally, from the inferred function, it is possible to apply a process called "defuzzification", in which the obtained final attribute qualitative classification is turned in quantitative value. Different methods can be used for that. The centroid method calculates the value associated to the center of mass of the final fuzzy set Cardoso Jr. (2024).

3. Methods

This section presents how the risk assessment of the flight test applicable to high altitude paratroopers airdrop missions was actually performed by the flight test engineer alongside with the flight test pilot.

3.1. *Risk Factors*

Initially, it was identified the possible risk factors associated to the flight itself. The focus was on the risks related to the procedures executed during the jump preparation and those that could affect directly the health of the crew during the exposition to the unpressurized environment in altitude.

The expected risks to the health of the participants were studied through aerospace medicine articles and reports regarding physiological training, specially those performed in hypobaric chambers. Also, it was consulted doctors with specialization in aerospace medicine and experienced skydivers who had participated of high altitude jumps, as well.

3.2. *Risk Matrix*

After gathering the risk factors, to each one of them was made a initial categorization in terms of probability of occurrence and of severity of the event. For these evaluation it was used linguistic variables in which the probability could be assessed as described in the Flight Test Safety Program IPEV (2023) of the Brazilian Flight Test and Research Institute (IPEV).

- **High (H)**: risk factor is expected to occur in a specific event of the flight test;
- **Medium (M)**: risk factor may occur during the tests but it's not expected; and
- **Low (L)**: risk factor occurrence considered improbable.

The severity of the event followed the categorization below in accordance to the System Standard on the Investigation of Aviation Occurrences with Military Aircraft of the Brazilian Air Force FAB (2018).

- **Accident (A)**: any occurrence that results in personal serious injury or death, aircraft structural failure or damage that affects its structural strength, performance, or flight characteristics;
- **Serious Incident (SI)**: any incident involving circumstances that indicate a high risk of an accident related to the operation of an aircraft;
- **Incident (I)**: any occurrence, not classified as an accident, that affects or could affect the safety of the operation; and
- **Dangerous Situation (DS)**: not classified under any of the previous categories, where the aircraft does not operate under the prescribed conditions, requiring the adoption of corrective measures.

The combination of probability and severity of a risk factor resulted in the risk level of that particular event. The result was based in the risk matrix proposed in IPEV (2023), as the risk description below. Table 1 presents the risk matrix used.

- **High (H)**: significant risk to personnel, equipment, or facilities;
- **Medium (M)**: above-normal operational risk;
- **Low (L)**: normal operational risks.

3.3. *Fuzzy Inference*

The fuzzy inference was performed based on the linguistic variables used in the risk categorization

Table 1. Risk Matrix.

	Probability		
Severity	High	Medium	Low
Accident	H	M	L
Serious Incident	H	M	L
Incident	M	M	L
Dangerous Situation	L	L	L

within the risk matrix. For the probability and for the severity each variable was described as a normal distribution and for the risk level the variables were described using triangular functions. The universe of all the functions was limited between zero and 100. The standard deviation for the distributions related to the probability was 12 and to those related to severity was 10. The cone radius for the triangular functions was 30. Figure 1 illustrates the proposed system.

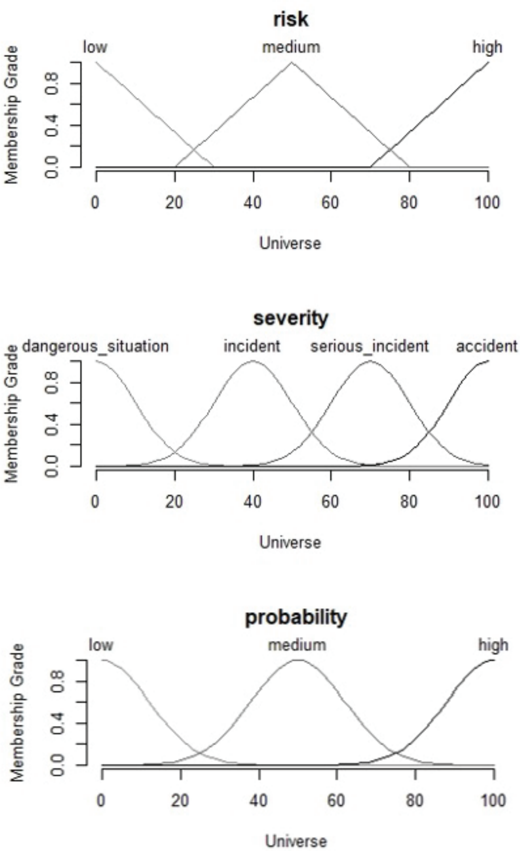

Fig. 1. Fuzzy system for the risk categorization.

After mounted the system, the values of probability and severity for each risk factor were applied to it resulting in a membership function of the risk level for that risk factor. So, it was performed the defuzzification of the function applying the centroid method to obtain a quantitative value of the risk. It is important to register that all the values used to mount the system and to assess the risk factors were based on the flight test crew experience combined with the theoretical data gathered in the risk factors research.

3.4. *Mitigation Process*

Once done the primary risk assessment of the mission, it was designed some mitigation actions to try diminish specially the probability of the event and, also, to try minimize the impacts of its happening. These actions were analyzed by a group of flight test pilots and engineers, with different backgrounds, in order to provide completeness to the evaluation. After that, a new evaluation of the probability and severity of each event was performed so it could be obtained the final risk of the mission, which was assumed to be the higher of all risk factors. Regarding the impacts of the mitigation actions on the quantitative values applied to the system, once again, they rely on the flight test experience of the contributors.

4. Results and Analysis

There were eight different risk factors for a flight test validation of high altitude paratroopers airdrop altitude envelope that were identified in this work. Four of them are applied to general paratroopers airdrop missions such as conflicts with other aircraft in the launch area, collision with obstacles, inadvertent release of persons or materials in flight and the inadvertent drop of a crew member from the aircraft. Despite the high impact that the occurrence of any of these events would have during flight, their probability was considered very low once followed the usual procedures of safety fastenings and of flight preparation and coordination with the air traffic control. Furthermore, added the mitigation actions that encompass the increase of crosschecks, the request of an exclusive area for the flight, among others, the probability is even lower, resulting in a low risk for each event.

The other four risk factors are directly linked to the peculiarity of the mission regarding the altitude and the unpressurized condition of the aircraft. They were the risk of hypoxia, of decompression sickness, of barotrauma and of frostbite, which will be scrutinized more thoroughly.

4.1. *Risk Assessment*

This assessment was made considering the realization of the flight test by any member of the flight test community and not only the manufacturer. Obviously, the company that designed and did developed the aircraft would have much more data, specially regarding to systems reliability. When one's available information sources about the aircraft is basically the operator manual and systems description contained in it, the basic routine of the flight test crew while planning the tests and assessing risks is to search for data in the literature, interview specialists and interact with the manufacturer, if possible.

As previously discussed, the initial risk assessment was made based on the flight test crew experience combined with theoretical data gathered from the quoted sources. This way, table 2 presents the initial assessment for each risk factor's probability, severity and risk level in qualitative and quantitative forms. Figure 2 illustrates the membership functions for the associated risk to each factor.

From the analysis of the function of the risk of hypoxia, this mishap represents a high risk in all instances. At the aircraft's operational ceiling, in which it is desired to validate the aircraft capacity to perform airdrops, between 35.000 and 40.000 ft, the oxygen partial pressure in the air is more than five times lower than at sea level, so it is to-

Table 2. Risk Matrix.

Risk Factor	Probability	Severity	Risk
Hypoxia (HY)	H (85)	A (95)	H (86)
Decompression Sickness (DC)	L (23)	A (80)	L (32)
Barotrauma (BT)	H (90)	SI (70)	H (88)
Frostbite (FB)	M (40)	SI (60)	M (50)

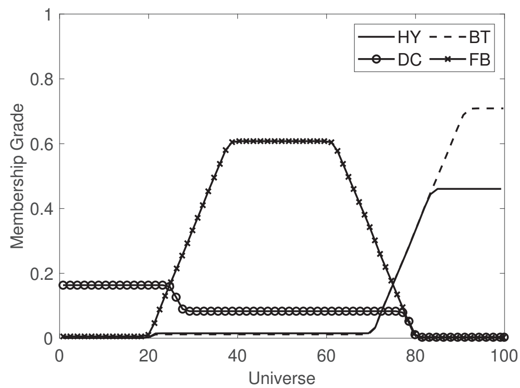

Fig. 2. Risk functions.

tally up to the aircraft's, or external equipments', oxygen system to provide conditions for human breathing. These systems despite their high reliability, demanded in the certification process, are prone to failure such as leaks due to bad maintenance. Also, there are other factors that may contribute to hypoxia such as a inappropriate fitting of the oxygen mask to the crew member's face, for example. Once it occurs, the available conscious time for the individual to react will depend of the altitude and of personal characteristics such as age and general health status, and, in average, at 36.000 ft, this time is lower than a minute FAA (2015). So, this mix of different potential starters and factors with short time to react contributes to elevate the risk of hypoxia.

Regarding the decompression sickness, after applying the centroid method to defuzzify the risk, the encountered value could either result in a medium or low risk, both with low level of membership in accordance to the membership functions for the risk levels. Observing the function for the risk of decompression sickness, the low risk level stands out more. Despite the potential danger of the decompression sickness to human health, cases that may lead to death or cause a complete impairness are extremely rare, less than one in a million USAF (1992). Also, airdrop missions in altitude follow a blood denitrogenation protocol that diminishes the probability of its occurrence, but doesn't extinguishes it when considered the possibility of human error adjusting the oxygen mask during the procedure or of neglect to the full time of pure oxygen pre-breath. In this manner, the combination of low probability of occurrence allied with the low probability of a high impact mishap is consistent with a low risk event.

The happening of a barotrauma during the test is also a high risk, according to the results. The usual consequences for this mishap are related to ear pain or temporary loss of hearing capability, but it can, in some more extreme cases, have serious outcomes as total or partial deafness MacKenzie (1943). Also, not only the consequences, but the occurrence of the event itself is very dependable of each individual characteristics. The simple exclusion of members carrying clear disabilities as nose obstruction, soar throat and similar diseases doesn't abolish the risk in asymptomatic participants Morgagni et al. (2012). In this sense, the potential impact of the mishap over the crew members health in association with the uncertainty regarding the inclination of each individual to show symptoms make the barotrauma a high risk factor.

Analyzing the function of the risk of frostbite, the highest membership grade is associated to medium risk. The range of atmospheric temperatures at operational ceiling are close to -50ºC, considering the International Standard Atmosphere (ISA), clearly favoring the mishap. However, some aircrafts have environmental systems that try to warm-up the cargo compartment, even with doors open. Also, the level of injury is more linked to the time the tissue kept exposed Reamy (1998), in a manner that the more serious ones are associated with hours of exposure. Nevertheless, despite the fact that the needed time with ramp door open for the tests is lass than half hour, it is considered the possibility of unintentional contact of the skin with any cold metal part of the aircraft during the execution of the cabin procedures, which could result in a serious injury. So, taking into account the definition applied to medium risk level, the categorization attributed to frostbite is consistent to an event that is not expected but could occur.

4.2. *Risk Mitigation*

To reduce the risks associated to the test, several mitigation measures were proposed. The basic focus was to set a step approach to the most critical condition, that is flying in the operational ceiling with aircraft depressurized. In this manner, if any system failure or individual problem came up, it would be in a less aggressive environment, reducing the chances of more serious consequence.

One of these measures is to have onboard medical staff, being at least one member in the cockpit and another one in the cargo compartment. Their presence has the purpose of assessing crew members health status during flight and to give a more immediate assistance in case of an emergency. Notwithstanding, these elements are supposed to perform consciousness checks in the crew during the unpressurized flight phases, reducing the chances of unnoticed hypoxia.

Another mitigation action is to check equipments and simulate procedures to be executed in flight on the ground, previous to the test. So the systems operation could be evaluated safely, helping to identify any incompatibility or difficulty of operation while wearing the oxygen masks, specially related to motion in the cargo bay.

Besides, the average oxygen consumption during test must be planned according to systems characteristics and supervised along flight. Any discrepancy should be followed and might lead to a test interruption, starting a corrective action like cabin pressurization or emergency descent, if that's the case. In parallel, backup systems like portable oxygen cylinders or chemical generated oxygen masks must be available.

Another measure is to provide hypoxia symptoms recognition training to every member of the crew, in a way each participant becomes aware of its individual organism characteristics when beginning a hypoxia state, reducing the reaction time to initiate a emergency procedure, since the time to identify hypoxia varies between subjects Leinonen et al. (2021). In order to help the self and medical staff monitoring, each member must wear a portable blood oxygen saturation measurement equipment, and it was set a threshold of 90% saturation to cease test and take emergency actions.

Also, to increase risk gradually, it was decided that the first cabin depressurization would occur at 15.000 ft of altitude. At this altitude, if hypoxia

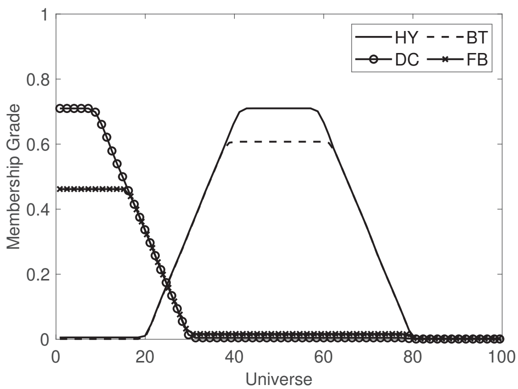

Fig. 3. Final risk functions.

would occur the time of useful consciousness is more than 30 minutes. Also, there would be no need of pure oxygen pre-breath regarding decompression sickness. Still, the cabin altitude climb process could be assessed to check for discomforts caused by pressure variation rate. Finally, the outside temperature would be about 40ºC higher than at the aircraft's operational ceiling, considering ISA, reducing the chances of a frostbite injury, once wearing proper clothing. Having the tests being performed without issues, the next step would be to repeat them at 25.000 ft and, finally, at the maximum altitude supported by the aircraft.

Related to decrease the impact of an eventual mishap, some procedures were already commented as reestablishment of pressurization onboard alongside with the provision of immediate medical assistance. Also, depending on the case, it is possible to execute an emergency descent to an altitude close to 10.000 ft, in which the dependence on the oxygen masks would no longer be an issue. Still, the rate of descent could be controlled in order to minimize effects of barotrauma. At last, another measure is to have a medical setup prepared on ground to provide quick assistance and transportation to a health facility.

Then, considering the implementation of these measures, table 3 presents the final assessment of the main risk factors identified in this work in a flight test validation of altitude envelope for paratroopers airdrop. Figure 3 illustrates the new membership functions for these factors risks. So, considering the highest risk encountered, the general classification of this flight test is medium risk.

Table 3. Final Risk Assessment.

Risk Factor	Probability	Severity	Risk
Hypoxia (HY)	M (40)	A (75)	M (50)
Decompression Sickness (DC)	L (10)	A (75)	L (11)
Barotrauma (BT)	M (50)	SI (60)	M (50)
Frostbite (FB)	L (15)	I (40)	L (14)

These general risk assessment elements and categorization were consistent with the conclusions of a group of flight test pilots and engineers of IPEV, in a flight test safety forum to discuss the risk of a flight test campaign of this scope. Nevertheless, it's never enough to point out that this is a dynamic and situational dependent activity, so new nuances regarding aircraft's equipment capabilities or operational requirements can come up in a way that specific assessment may be required.

5. Conclusion

This work presented a method that apply qualitative and quantitative data in risk assessment for a flight test using risk matrix and fuzzy inference combined. The primary intent, which was accomplished, was to reduce the level of subjectivity associated with risk matrices using solely linguistic variables. So, based on the flight test crew experience and in the data gathered during test preparation, quantitative values were attributed to the probability and severity of different risk factors in order to obtain a quantitative perspective o the risk level of the mission.

Most of the data used to support the values applied to severity and probability of the risk factors are based on hypobaric chambers trainings perceptions and findings. This is usually a controlled environment, quite different of the real flight conditions. The same applies to the expert's opinions, which some may be linked to similar, but different experiences. So, the risk score must be taken as much as a reference than as an immutable value and that's why it is important to obey the step approach during the real flight test.

Taking these points into consideration, the initial assessment was a high risk associated to some of the risk factors identified in this work in a flight test validation of high altitude paratroopers airdrop altitude envelope. Post analysis contemplating the implementation of mitigation measures, resulted in a medium risk level for the flight.

So, the next step of study could be to assess the real effectiveness of the proposed mitigation measures. Also, after the validation of the altitude envelope for paratroopers airdrop, it can be included in the analysis the risk factors associated to a cargo drop in the same conditions. Some of them might be associated to jammed cargo restricting a emergency descent or door closing, for example. Notwithstanding, related to cargo drop from altitude, it must be considered a more detailed study of the security area for the release, indeed.

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