Within the space industry it is well understood that each space flight involves a high degree of safety risk. The catastrophic loss rates for orbital space flights are also well known from historical data and this can assist in deriving safety targets (or acceptable levels of safety) for future space operations i.e. as part of the Commercial Crew Transportation System Requirements. However for the nascent suborbital space flight domain there is no specific historical data and at present authorities in the United States are not dictating specific safety targets or safety objectives in order to let the industry grow; hence the approach is to evolve the regulatory standards as the industry matures. It is argued that when suborbital space flight operations commence, the safety risks will be declared as required to the authorities, the flight crew and spaceflight participants, but this still does not answer whether the vehicle is acceptably safe; indeed it will beg the question ‘how safe is safe enough?’ As well as detailing the methodologies for deriving safety targets and safety objectives the paper discusses perception of risk; both from the industry perspective and a societal perspective. This paper addresses the problematic issue and presents discussions concerning explicit and implicit safety targets and safety objectives in order to derive a rationalised approach for the emerging commercial space flight industry. The paper notes the differences between launch licensing and certification approaches and concludes that having an acceptable level of safety is essential, irrespective of regulatory approach. The author of this paper contend that it is more appropriate for the authorities to have rationalised and explicit safety requirements and safety targets or safety objectives (depending on selected approach), together with effective guidelines, such that prospective design organisations and operators can strive for a recognised and acceptable level of safety in the commercial space flight industry.

I. INTRODUCTION
Within the aerospace and space sectors there are regulations, standards and guidance material to govern the activities and to assist the designers and operators in attaining the required level of safety. In the first instance, aircraft designers build aircraft to prescriptive airworthiness codes to provide assurance to the regulators that the aircraft has met the acceptable level of safety. They can then sell their certified product to many operators; thus when they deliver the aircraft their main part of the job is done and they then provide additional information such as Service Bulletins (in the event of serious issues) and so on. The operator then begins their involvement in the safety effort by identifying operator safety risks and then managing Air Safety Reports (ASRs) when incidents occur. Any aircraft functional issues are then fed back to the design organisation. Therefore from an airworthiness perspective the aircraft maintains its intent of meeting its safety objectives in order to meet the acceptable level of safety for aviation.

The existing space domain has fewer design organisations and operators and follows launch license regulations and has mishap occurrence reporting. In terms of attaining an acceptable level of safety, the previous governmental orbital programs and current FAA-AST commercial spaceflight regulations provide an Expected Casualty (Eₐ) target of 30x10⁻⁶ per mission. This target concerns protecting the public and property from harm only and does not constitute any levels of safety for those on board.

Both aviation and spaceflight acceptable levels of safety will be discussed in this paper but to whom does this ‘acceptability’ apply? Arguably this could be an acceptable level of safety (risk) for the particular industry and concerns that industry’s group of personnel exposed to the risks (individual risks). But acceptability of a risky activity can also be based on acceptability to the society – both for the individual risky activity and its comparison to other risky activities. In the UK (Health & Safety Executive [HSE]) the ‘Tolerability of Risk’ (individual risk per work population) is detailed and this is then compared to other industries. These methods will be discussed alongside similar European risk tolerability frameworks.
II. CURRENT LEVELS OF SAFETY IN AVIATION

In aviation the general acceptable level of safety is 1 accident per million flying hours i.e. 1E-6 per flying hour (this rate is based on historical accident rates and is detailed below in II.III).

II.I Worldwide Accident Rates

The International Air Transport Association (IATA) rate [1] (measured in hull losses per million flights of Western-built jets) was 0.37, the equivalent of one accident every 2.7 million flights. In relation to the ALOS of 1 in a million flying hours this is better than the safety target for all aircraft (because flights tend to be more than one hour); however the target relates to commercial airliners only and so the IATA worldwide figures would have to be broken down i.e. the UK Civil Aviation Authority have broken this down [2] to UK aircraft and this results in 0.1 per million flight hours (10 times better than the safety target for large jets).

II.II Design Organisation Safety Analysis

The current approach towards safety is to undertake analysis to meet requirements and targets (objectives) as applicable to the boundaries of said requirements. The metrics involved are different for designers and operators and therefore a contiguous approach is not employed.

II.III Derivation of Safety Objectives

In the Civil Aviation industry the designers must meet certification baseline requirements and in terms of safety this includes meeting specified safety objectives for failure conditions i.e. for a catastrophic failure condition the designer must meet 1E-9 per flying hour. The Aircraft Loss target stated in Federal Aviation Regulations (FAR)/Certification Specification (CS) 25.1309 [3] is based on the world-wide accident rate which is about one per million flight hours, i.e. a probability of 1E-6 per hour of flight. The accident rate was first analysed in the UK for the British Civil Aviation Requirements (BCAR). It was deduced that 10% of accidents were attributed to failure conditions involving critical aircraft systems, i.e. 1E-1 therefore the overall target is 1E-7. Arbitrarily it was deduced that there were approximately 100 system level catastrophic failure conditions assumed to exist on civil aircraft, i.e. 1E+2. Therefore to prevent a deterioration of the current fatal accident rate, DOs must show that the probability of occurrence of each catastrophic failure condition was at least 1E-8 x1E-1/1E+2 = 1E-9 per flying hour.

This criteria and logic follows to ‘hazardous’, major and minor failure conditions and these have apportioned safety objectives.

![Figure 1: Relationship between Probability and Severity of Failure Condition Effects – from CS-25](image)

Failure Conditions are recognised events from standard Functional Hazard Analysis (FHA) such that DOs must meet the associated safety objective. The following examples are from Advisory Circular §23.1309 [4]

- **Catastrophic Failure Condition:**
  - Misleading attitude information to control roll and pitch

- **Hazardous Failure Condition:**
  - Total Loss of altitude information

So to attain an acceptable level of safety (1E-6 per hour of flight) in aircraft design analysis and systems safety analysis provides evidence that all failure conditions meet their safety objectives and therefore the airworthiness codes are met for certification.

III. UAS ACCEPTABLE LEVELS OF SAFETY

Unmanned Aircraft Systems (UAS) development has been rapid over the past decade and regulators are still developing their frameworks to accommodate the different types in terms of size and level of autonomy. The European Aviation Safety Agency (EASA) is working towards a certification specification (CS) (CS-UAS) by 2016 [8]. The framework is anticipated to be based on a Total Systems Approach in order to
IAC-12-D6.1.2

encompass the different and vital systems that comprise a UAS; namely the Remotely Piloted Aircraft (RPA), the Remote Pilot Station (RPS), the Communications-Navigation Systems and Air Navigation Systems (CNS-ANS) and the RPA Operator (the remote pilot in command). This phase of UAS is akin (or slightly ahead) of commercial spaceflight for instance and the discussions surrounding the framework includes whether to use a safety target approach (top-down methodology which could include the Total Systems approach) or to follow a safety objectives approach (bottom-up as detailed in section II.III above). This latter case is clearly a known certification approach whereby the regulator would expect a RPA to meet airworthiness codes and also that the RPS is certified. However the author contends that, to arrive at a probability of a Mid-Air Collision (MAC) accident or Loss of Control accident resulting in a risk to 3rd parties on the ground (based on kinetic energy), the CNS-ANS and RPA Operator mitigation must be included. Hence one is not now detailing airworthiness codes (per the certification specification requirements for a Type Certificate [TC]) but including operating procedures and limitations; hence this is more suited to a safety-target approach.

Also there is the issue over UAS certified for segregated airspace. This scenario (which is also akin to current proposed suborbital and orbital flights) involves limitations concerning segregated airspace whereby a reduced ALOS may be appropriate – meaning MAC accidents can be ruled out and therefore the cumulative probability is likely to be reduced by an order of magnitude.

In terms of an ALOS for UAS it is anticipated that the regulators will still require a certification approach to obtain a TC for the RPA; hence this depends on the mass of the vehicle and for those above 150kg the catastrophic safety objective is 1x10^{-7} per flight hour (per AC23.1309) for vehicles of Class II category as an example. However there is no explicit quantitative guidance for the technical requirements for the RPS or CNS-ANS as yet. Hence the author contends that an ALOS should be set that takes into account the Total Systems Approach; thereby multiplying the different events from the different systems to derive at accident probabilities from which a cumulative ALOS can be set.

IV. ACCEPTABLE LEVELS OF SAFETY IN SPACEFLIGHT

IV.1 Previous NASA Approach
Previously NASA provided standards for the Space Shuttle (and International Space Station). However the systems were introduced prior to formal safety management systems and systems safety engineering approaches evolved and therefore these complex space systems did not derive acceptable levels of safety. Instead the standards provided qualitative criteria and safety/design requirements for designers and operators to follow.

IV.2 Current NASA Approach
Today the FAA-AST have provided Advisory Circular 437.55-1 [6] to supplement the Code of Federal Regulations (CFR) requirements and standards; these are however still qualitative standards. The AC defines the ‘Acceptable Level of Risk’ to protect public safety and details example Hazard Severity and Hazard Likelihood categories used to determine the level of risk. The FAA does not mandate any level of acceptable risk for passengers. The FAA allows passengers to fly at their own risk and requires only that they are informed of the risk they are taking, by the spaceflight Operator. The FAA does mandate qualitative requirements for the crew; as part of the FAA’s requirement to protect public safety, they mandate that the crew must be able to control a Reusable Launch Vehicle (RLV) and be capable of acting in emergency scenarios. Crew actions and RLV operability are covered in the hazard analyses that a ‘permittee’ and licensee must supply and show compliance with the FAA acceptability matrix in order to be approved for operation. This acceptability matrix is based on the ‘example’ Risk Matrix which is in effect similar to Figure 1 in that a single line defines the acceptability (as opposed to a tolerability region of risk):
In contrast the FAA-AST’s previous System Safety Process AC431-35-2A [7] provided a tolerability of risk region as depicted below:

![Figure 2: FAA-AST AC 437.55-1 Risk Matrix](image)

Without acceptable levels of safety defined for crew or participants, the FAA-AST have retained their goal to protect the public and property; this being the same Ec target as applicable to the previous NASA regime (30x10⁻⁶ per mission).

For future orbital missions NASA [8] has declared the following safety targets for the prospective commercial design organisations:

a. The Loss of Crew (LOC) probability distribution for the ascent phase of a 210 day ISS mission shall have a mean value no greater than 1 in 1000

b. The LOC probability distribution for the entry phase of a 210 day ISS mission shall have a mean value no greater than 1 in 1000

c. The LOC probability distribution for a 210 day ISS mission shall have a mean value no greater than 1 in 270.

IV.III United States Independent Viewpoint


While the Panel applauds the effort to establish safety thresholds, we are concerned that the specific levels chosen by NASA for these criteria unfortunately are significantly less conservative than those that were being used for the now-cancelled Constellation Program. For example, the Exploration Program requirement for probability of LOC on an ISS mission has changed from 1 in 1,000 to 1 in 270. This new Agency criterion for future human spaceflight missions is less than one-third as safe as the old criterion. This is especially worrisome considering the fact that the criterion only considers the risks that are already known, not the always-present hazards that have not yet been discovered. This observation is compounded by the fact that recent detailed analysis on Shuttle, as noted above, revealed that the initial flights were not nearly as safe as predicted. Thankfully, those flights did not result in crew loss, but the risk they posed illustrates a profound problem. When estimating probabilities of failure in areas where there is no history, limited experience, and only a partial understanding of what can go wrong, analysts tend to produce optimistic numbers. If a design process is initiated using a high value of acceptable loss criteria, this tendency is exacerbated by setting goals too low and hence creates a larger potential for failure than might be anticipated.

NASA ASAP comments on risk criterion:

One key finding was that the risk on a new system that has not been flown before and thus has not been through the rigors of real-life flight is probably much higher than what the initial risk assessments show. The reason for this difference is that at the beginning of operations, all the failure mechanisms are not fully known. In the language of risk analysis, such unknown failure mechanisms are often called “unknown-unknowns.” In the Shuttle’s case, the first flight risk as now retrospectively calculated was in actuality 1 in 12 for LOC, yet at least one analysis that existed at the time of the initial launch estimated the risk to be 1 in 1,000 or better. In other words, the system was almost 100 times more dangerous than the early analysis indicated. This type of disparity must be remembered when future targets for reliability and LOC numbers are chosen for new programs. One thing that has always been
said in the design business is that engineering design standards take care of the “knowns”; factors of safety take care of the “known-unknowns”; and margin is what takes care of the “unknown-unknowns.” A significant margin for error should be allowed for the unknown-unknowns as well as to create a robust design.

*Note* - By constant improvements, that risk was lowered to 1 in 90 by the last flight, which is still a high number compared to many endeavours.

So the new NASA ‘certification’ requirements adopt a top-down ALOS which has been derived from the Shuttle era as a baseline and then tailored to require better design standards (by at least one order of magnitude to that of Shuttle).

**IV.IV Current European Space Approach**

The European Cooperation for Space Standardization (ECSS) [10] does not set specific quantitative criteria but instead states levels of safety should be no greater than that experienced by other comparable professions;

a. Probabilistic safety targets should conform to the requirements given by launch safety authorities and national and international regulations.

b. With respect to safety targets for the ground and flight personnel, the individual risk should not exceed that accepted for other professionally and comparably exposed personnel.

*NOTE* E.g. risk for crew members should not exceed that for test pilots, risk for ground personnel should not exceed that for similarly exposed industrial workers.

c. With respect to safety targets for the civil population, the total risk for the exposed ground population should not exceed that caused by other hazardous human activities. *NOTE* E.g. risk from over-flight of commercial aircraft or chemical plants.

So the ECSS requires an ‘equivalent’ level of safety (to that of comparable professions) which by definition is then acceptable.

**V. PERCEPTION OF LEVELS OF (SAFETY) RISK IN SOCIETY**

**V.1 UK Health & Safety Executive**

In the UK the Health and Safety Executive (HSE) use the principle of As Low As Reasonably Practicable (ALARP) to demonstrate the risks have been reduced so far as is reasonably practicable. The HSE Reducing Risks, Protecting People (R2P2) [12] state the following concerning ALARP:

At the core of ALARP is the concept of ‘reasonably practicable’ which involves weighing the risk against the trouble, time and money to control it. Thus ALARP describes the (acceptable) level to which it is expected that workplace risks are controlled to.

The following figure depicts the Tolerability of Risk framework. The ALARP triangle shows’ decreasing risk towards the bottom (pointed end) and has upper and lower boundaries:

- Upper Level of Tolerability is 1 in 1000 risk of death per person per year
- Lower Level of Tolerability is 1 in 1 million risk of death per person per year

These tolerability boundaries concern individual risks at the workplace per population group and this is taken into account when applying the ALARP principle.

![Figure 4 : UK HSE ALARP Tolerability of Risk](image-url)

Examples of societal risk include:
People’s perception of (acceptable) risk can be ‘skewed’ by various factors as detailed in a literature review [11]:

The socially constructed nature of risk mandates an understanding of risk perceptions. There are often mismatches between perceived risk and measurable probabilities of risk. This discrepancy suggests that other factors are clearly important in clarifying how people understand and respond to risk. For example, the characteristics of risk are a significant influence on perceived risk – different types of risk generate different reactions (e.g. voluntary activities are not considered as ‘risky’ as involuntary activities, new risks viewed differently from familiar hazards). The psychological dynamics of decision-making are important as well. Formed opinions can be difficult to change, particularly when people feel they have knowledge about an issue. When people see benefits from an activity, they may be more receptive to the risks. People are more inclined to judge an event more probable if they can readily recall an occurrence of it or something similar. And hazards that have potentially severe consequences on people’s lives, even if the statistical likelihood of their occurrence is ‘insignificant’, attract considerable attention.

The author has underlined important statements within the above review summary. Today it is clear that people want to fly and also to fly into space; in the latter case it is important that there are no ‘mismatches’ between the prospective spaceflight participant’s perception of risk and the measurable probabilities of risk (presented by the designer and operator).

V.II Other Nation’s Methodologies

The FAA does not include ALARP methodology however it is recognised in the American National Standards Institute (ANSI) Standard (Best Practices for System Safety Development and Execution) [13]. European countries do not employ the ALARP process however some countries do use similar processes:

- France: Globalement Au Moins Aussi Bon (GAMAB)
  
  *This is whereby a new system must offer a level of risk globally as least as good as the one offered by any equivalent existing system*

- Germany: Minimum Endogenous Mortality (Rm), (MEM)
  
  *This is hazards due to a new system should not significantly augment Rm (equal to 2.10^(-4) fatalities/person year*)

In conclusion to this section the perception of risk and tolerability of risk have highlighted that in addition to the derivation of an acceptable level of risk for the aviation or space industry it is also necessary to derive acceptable levels of safety in terms of a different metric – that is the risk of death per person (population group) per year. The reason is to simplify the risk to the individual because an accident rate per flying hour could appear misleading; instead society would wish to know what the risk of death is per year (or journey) as a participant on a suborbital or orbital flight.

VI. RELEVANCE TO COMMERCIAL SPACEFLIGHT
In the commercial spaceflight domain the designer and operator arguably have a much closer relationship than their aviation counterparts and in a lot of cases may be the same organisation i.e. in the suborbital domain XCOR will design and work closely in the operations of their ‘Lynx’ vehicle and for orbital flights ‘Space X’ will design and operate their Falcon spacecraft for orbital launches. So it is important that the designer AND operator understand the cumulative risks presented by their vehicles and have taken into account any operator-based controls such as limitations (flight corridors and cleared operating zone, altitude limitations, etc.) and procedures. This can only be done effectively within a contiguous safety model and within a safety target approach.

VI.1 Safety Target Approach
The NASA Commercial Crew Development Program is a chance to enforce proper design and safety requirements in a formal and recognised approach (as opposed to a disparate approach for Space Shuttle and the International Space Station). NASA has provided the 1100-series as their top-level system requirements and embedded are the safety requirements.

So here is a new development and a contiguous safety model can arguably be applied for the orbital domain. The ‘System’ is a vertical reusable launch vehicle with expendable rocket boosters. Using the IAASS- ISSB Space Safety Standards Manual [14] we have a catastrophic (loss) safety target of 1 x 10^−7 per mission. The next question to ask is can we use the same methodology per aviation to derive system level risk budgets? i.e. 10% of failures are due to critical systems therefore the catastrophic target is 1 x 10^−4 per mission. Then in aviation there are 100 arbitrary critical systems and therefore in this case the safety objectives for catastrophic failure conditions would be in the order of 1 x 10^−6 per mission. Is this practical? – some may say not when considering the Rocket Propulsion System (RPS (2)) would be in the order of 1 x 10^−4 per mission (thereby using up the entire risk budget).

But by using a top-down safety target approach (with implicit safety objectives & requirements for lower level failure conditions as required and in accordance with certification or licensing requirements) it drives the designer to build in redundancy; only then will the safety targets be close to being met from the design perspective.

This is even more important to demonstrate this explicitly and in a contiguous manner should the safety target not be met i.e. the design fails to meet the safety target (but is within an order of magnitude for instance) and therefore the claims are on operator procedures and mainly (in the early years) limitations i.e. restricted/segregated airspace; this will therefore provide a more convincing argument to the authorities as to why the Spacecraft is ‘acceptably safe’.

The same approach can also be used in the suborbital domain; even more so where some designs are aircraft-based and employ similar ‘known’ sub-systems. Here a suborbital catastrophic (loss) safety target may be in the order of 1 x 10^−4 per mission (flight hour equals a mission in this case). This is also challenging in that the Rocket Propulsion System will be the main contributor once more and the design analysis will have to include the exposure factor (circa 90 seconds) which will assist in the calculations. Once again the safety model can explicitly detail the failure conditions and then accident risks via key hazards at the platform level; thus assisting with certification or launch license approval.

VI.2 Aid to Certification/Launch Licensing
This close relationship can only assist in gaining certification or gaining a launch license approval from the authorities. Not only will the company be able to demonstrate the design (system safety) analysis they will be able to explicitly detail the accident risks involved with the vehicle. They will be able to demonstrate the ‘barrier’ controls in the design analysis (such as in Fault Trees) and also demonstrate the operator ‘recovery’ controls within the contiguous accident sequence.

This contiguous safety approach works within the Total Systems Approach and also within a safety target (ALOS) framework.

VII. CONCLUSIONS
This paper has highlighted that it is essential that design organisations and operators have
rationalised safety targets provided by the appropriate regulator. Even though in the aviation domain the focus is on safety objectives (a catastrophic failure condition is $1 \times 10^9$ per flying hour for large aircraft) this is derived from the historical (acceptable) accident rate of 1 fatal accident per million flying hours. Here the public have accepted this level of safety and the regulators and designers are working to maintain or improve on that level.

The regulators of new vehicles within new or existing domains (orbital, suborbital and even UAS) should derive an ALOS based on existing methods and statistics but tailored to their industry. This will assist in the certification or approval of launch licenses where it is envisaged that a safety target approach will be required i.e. a catastrophic (loss) safety target of $1 \times 10^{-3}$ per mission for orbital operations and $1 \times 10^{-4}$ per mission for suborbital operations as an example. Here the designer/operator will be able to demonstrate the achieved failure condition probabilities and then demonstrate the explicit contribution of operator controls (procedures, training and limitations) within the accident sequence. This may be an important factor because the Rocket Propulsion System will no doubt be the main contributor to the catastrophic loss case and the analyst will have to include exposure factors (along with safe design measures) to assist in achieving the required ALOS. Then the operator will have to assimilate this metric (per mission) into the risk to the spaceflight participant per flight so that they are properly informed of the risks and are assured that the vehicle meets the regulators Acceptable Level of Safety.

VIII. REFERENCES
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### VIII. ACRONYMS/ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Advisory Circular</td>
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<tr>
<td>ALARP</td>
<td>As Low As Reasonably Practicable</td>
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<td>ALOS</td>
<td>Acceptable Level of Safety</td>
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<td>AMC</td>
<td>Acceptable Means of Compliance</td>
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<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
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<td>ARAC</td>
<td>Aviation Rulemaking Advisory Committee</td>
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<td>ASAP</td>
<td>Aerospace Safety Advisory Panel</td>
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<td>ARP</td>
<td>Aerospace Recommended Practice</td>
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<td>AST</td>
<td>Commercial Space Transportation</td>
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<td>CFR</td>
<td>Code of Federal Regulations</td>
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<td>CS</td>
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<td>DO</td>
<td>Design organisation</td>
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<td>European Cooperation for Space Standardization</td>
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<td>ELOS</td>
<td>Equivalent Level of Safety</td>
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<td>FHA</td>
<td>Functional Hazard Analysis</td>
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<td>GAMAB</td>
<td>Globalement Au Moins Aussi Bon</td>
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<td>HRI</td>
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<td>Health &amp; Safety Executive (UK)</td>
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<td>IATA</td>
<td>International Air Transport Association</td>
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<td>ICAO</td>
<td>International Civil Aviation Organisation</td>
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<td>LOC</td>
<td>Loss of Crew</td>
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<td>Mid-Air Collision</td>
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<td>Minimum Endogenous Mortality</td>
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<td>NASA</td>
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<td>RLV</td>
<td>Reusable Launch Vehicle</td>
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<td>Remotely Piloted Aircraft</td>
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<td>Remote Pilot Station</td>
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<td>RPS(2)</td>
<td>Rocket Propulsion System</td>
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<td>Suborbital Aircraft</td>
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