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Reaction time evaluation for events governed by wear out process

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Abstract

Once that an Aircraft family enters into service, a continuous monitoring of the fleet is performed to ensure its Airworthiness. Occasionally, some system malfunctions having a potential impact over the aircraft safety are detected, without being possible to impose any immediate alleviating action such as an inspection or limitation. The objective of this report is to provide some guidelines to adapt the reaction time evaluation process provided by the PART21 to specific cases not covered by this guidance material, like the case of the failure modes governed by a wear-out process, in which the failure rate increases with time.

1. Introduction

The International Civil Aviation Organization (ICAO), through the Airworthiness Manual [1], defines the Continuing Airworthiness as "The set of processes by which an aircraft, engine, propeller or part complies with the applicable airworthiness requirements and remains in a condition for safe operation throughout its operating life."

Based on the recommendations captured in the ICAO Airworthiness Manual [1], European Regulations provide, through the Implementing Rules [2] and the Interpretative Material [3], specific requirements to the Type Certificate Holder:

- Put in place a system for collecting, investigating and analyzing reports and information related to occurrences which cause or might cause adverse effects on the continuing airworthiness of the product.
- Inform about the implemented system to all known operators
- Report to the Airworthiness Authorities (AA) any failure, malfunction, defect or other occurrence of which it is aware related to a product and which has resulted in or may result in an unsafe condition (not later than 72 hours after the identification of the possible unsafe condition).
- Investigate the reason for the deficiency and report to the AA the result of its investigation and any action it is taking or proposes to take to correct the deficiency.
- Submit the relevant data to the Airworthiness Authorities (AA) in case that the Agency finds that an action is required to correct the deficiency.

When evidence shows that the safety level of an Aircraft may be compromised (an unsafe condition has been determined to exist in an aircraft), and no immediate alleviating actions such as an inspection or limitation can be imposed, the AMC/GM PART 21 [3] establishes some guidance to evaluate the maximum time in which some particular deviations regarding the applicable regulation can be accepted, by means of ensuring that the global average risk of the aircraft fleet still meets the airworthiness requirements, avoiding in this way the immediate grounding of the whole aircraft fleet.

As these guidelines have been developed for those failure modes that can be modelled with a constant failure rate, main purpose of this report is to present an adaption of the evaluation process of the reaction time described by the AMC/GM PART 21 [3], to cover the specific case of failure modes governed by a wear-out process, in which the failure rate increases with time.

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2. Risk allowance definition as per AMC/GM to part 21

Main purpose of Paragraph GM 21.A.3B(d)(4), included within the AMC/GM PART 21 [3], is:

a) To postulate basic principles which should be used to guide the course of actions to be considered to maintain an adequate level of airworthiness after a defect has occurred which, if uncorrected would involve a potential significant increase of the risk level.

b) For those cases where it is not possible fully and immediately to restores an adequate level of airworthiness risk by any possible alleviation action such an inspection or limitation, to state the criteria to assess the residual increase in risk and to limit it to an appropriate small fraction of the aircraft life.

In line with this second point, as the period of the corrective action will not be instantaneous, the AMC/GM PART 21 [3] declares the necessity of limiting the exposure time of a proposed campaign of corrective actions as a function of the risk level induced by the defect during the campaign, defining a not to exceed risk allowance which keeps the average airworthiness level within a reasonable value [see Eq. (1)].

$$\sum(\boldsymbol{Campaign\ Risk}) \cdot (\boldsymbol{Exposure\ Time}) < \boldsymbol{Risk\ Allowance} \quad \textbf{(1)}$$

As the risk allowance value could be evaluated based on different criteria, the following qualitative judgements are considered by the Guidance Material to cover the case of defects associated to Catastrophic failure conditions for which the safety objectives defined by the applicable certification specifications are not meet:

- Failure rate for an aircraft catastrophic event due to airworthiness reasons is 1E-07/FH
- Acceptable through life risk of an aircraft equal to ¼ of the individual aircraft's whole life
- A total of 10 emergency periods might arise during the life of an individual aircraft

Thus, using these criteria, maximum risk allowed during each of these emergency periods for an aircraft design life of 30.000 hours will be [see Eq. (2)]:

$$\boldsymbol{Risk\ Allowance_{CAT}} = \mathbf{1 \cdot 10^{-7} \cdot \frac{1}{4} \cdot \frac{1}{10} \cdot 30.000 = 7{,}5 \cdot 10^{-5}} \quad \textbf{(2)}$$

Additionally, to avoid exposure to high risk levels even for very short periods of time, the guidance material proposes a maximum risk level of 2E-06 / FH for Catastrophic Failure conditions so that no flight carries a risk greater than 20 times the original target. For this particular condition, grounding appears to be the only alternative, with the possibility of specially authorized high-risk flight to allow the aircraft to return to base empty.

A similar approach is also proposed to cover the case of defects associated to Hazardous failure conditions, but with a higher margin regarding the allowable probability for each failure condition [see Eq. (3)]:

- Failure rate for an aircraft hazardous event due to airworthiness reasons is 1E-05/FH
- Maximum risk level of 2E-04 / FH

$$\boldsymbol{Risk\ Allowance_{HAZ}} = \mathbf{1 \cdot 10^{-5} \cdot \frac{1}{4} \cdot \frac{1}{10} \cdot 30.000 = 7{,}5 \cdot 10^{-3}} \quad \textbf{(3)}$$

3. Reaction time evaluation for random failures involved in Catastrophic Failure Conditions

The definition of the risk allowance as per Eq. (4) establishes an inverse proportionality between the maximum Exposure Time of a proposed campaign of corrective actions (Reaction Time) and the Risk Level achieved during this campaign (Campaign Risk). This relationship will allow having higher Reaction Times for campaigns with lower risk, but reduced Reaction Time for those campaigns in which the risks is higher:

$$(\boldsymbol{Campaign\ Risk}) \cdot (\boldsymbol{Reaction\ Time}) = \boldsymbol{Risk\ Allowance} \quad \textbf{(4)}$$

From the pure geometrical interpretation of this equation, the geometric place of the points that matches this equation is a rectangular hyperbola in a Cartesian coordinate chart, representing Reaction Time in one axis Vs Campaign Risk in the other (Figure 1), that can be transformed into a straight line if both axis of the chart are expressed in logarithm format (Figure 2).

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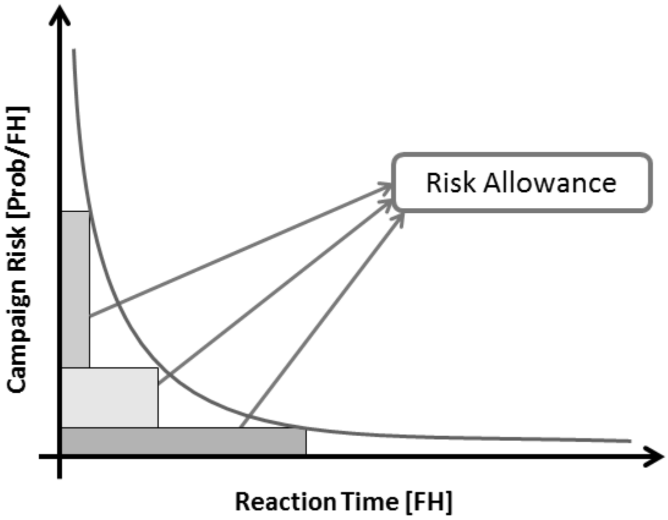

Figure 1: Risk allowance geometric place in Cartesian coordinate chart (rectangular hyperbola)

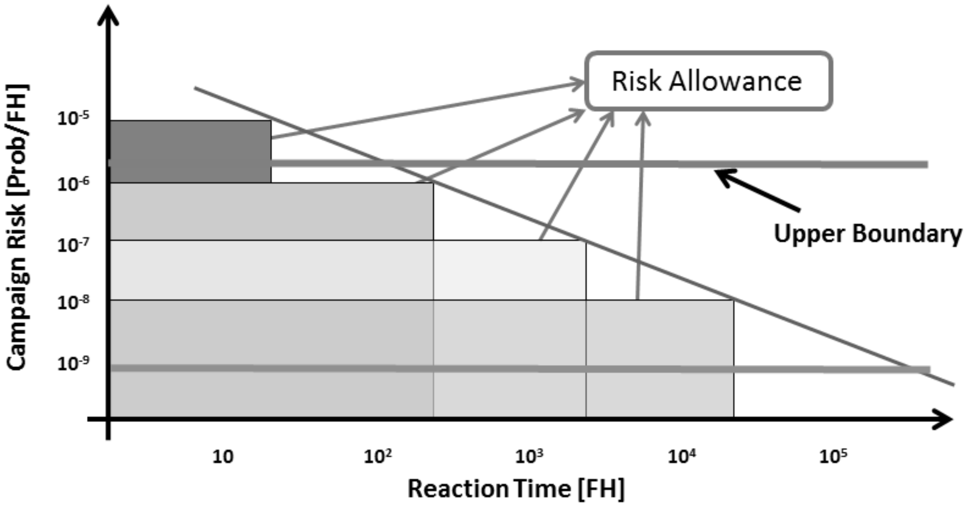

Figure 2: Risk allowance geometric place in log-log chart (straight line)

Moreover, as mentioned in previous section, to avoid exposure to high risk levels even for very short periods of time, a maximum risk of level 2E-06 / FH shall be considered, and therefore this value shall be taken into account as the upper boundary of the risk allowance chart (Figure 2)

This interpretation allows, for those cases in which the failure rate of the defective component remains constant with the time (random failures), performing a quick evaluation of the maximum Reaction Time recommended to correct the defect detected either by:

- Calculating directly the Reaction time, using the Risk allowance definition [see Eq. (4)] for a given campaign risk
- Calculating graphically through the Log-Log Risk allowance chart (Figure 3)

In both cases it is necessary to evaluate the Campaign Risks, which corresponds to the probability associated to the Failure Condition in which the defective component is involved, considering the new failure rate after the defect detection. It shall be noted that, when calculating this risk, all the risk should be attributed to those aircraft which may carry the defective item, and should not be diluted by including other aircraft in the fleet which are known to be free of risk (It is only permissible to spread the risk over the whole fleet when a source is known to exists without knowing where) [3]

In case that the defective component is involved in several Failure Conditions, then all the Reaction Time shall be evaluated, being the applicable one the lower of all of them.

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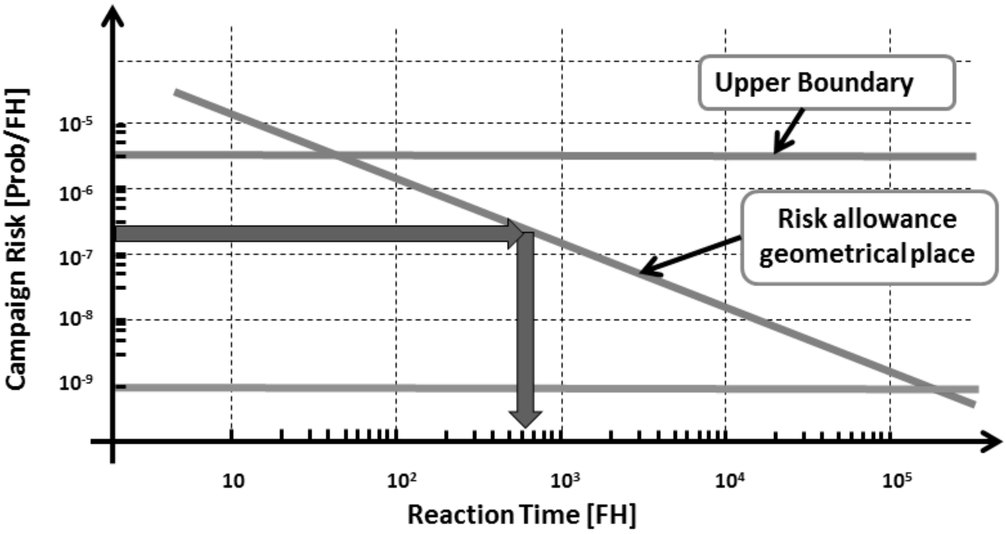

Figure 3: Reaction time evaluation for given campaign risk, assuming that the origin of the detected defective is a random failure (constant failure rate)

4. Campaign risk evaluation for wear out failures involved in Catastrophic Failure Conditions

Although the AMC/GM PART 21 [3] only describes the methodology to evaluate the reaction time for a random failure defect, it shall be noted that a significant percentage of the defects detected during the operation of the Aircrafts along their life corresponds to non-expected early degradation of the affected components, and thus a wear-out model shall be used to evaluate its potential repercussion on the A/C airworthiness.

The most frequent methodology used in the aviation industry to assess the reliability of the failed airplane systems or components is the two parameter Weibull analysis [4]. The main reasons for its wide spread use are [5]:

- Quantifies reliability (or risk of failure) as a function of the age of the product.
  - Infantile failure: Reliability improves with age / Decreasing hazard rate
  - Random failure: Reliability constant with age / Constant hazard rate
  - Wear-out failure: Reliability decreases with age / Increasing hazard rate
- Provides reasonably accurate failure analysis and failure forecasts with extremely small samples
- Provides a simple and useful graphical plot of the failure data
- May consider the effect of Non failed units

The Weibull distribution has two parameters, the Characteristic Life (η) and the Slope (β). The Characteristic Life is the location parameter, and represents the age at which 63,2% of the units will fail. The Slope is called the Shape parameter and determines which member of the Weibull family of distributions is most appropriate (Figure 4):

- Infantile failure: $\beta < 1$
- Random failure:$\beta \approx 1$
- Wear-out failure: $\beta > 1$

Data recorded during the investigations of the in-service occurrence will be the input data for the two parameter Weibull statistical analysis. To perform this analysis, all the items affected by the detected defect shall be considered, avoiding considering components known to be free of risk, as this consideration may increase artificially the value of the Characteristic Life, being the results more optimistic.

Once that the Weibull statistical analysis of the data recorded during the investigations of the in-service occurrence is performed, and there are evidences that the system defect is in line with a wear-out failure mode approach, the next step is the evaluation of the campaign risk based on the predicted failure rate. This will imply the reevaluation of each failure condition, in which the defective component is involved, several times in order to characterize its evolution as a function of the time (Figure 5).

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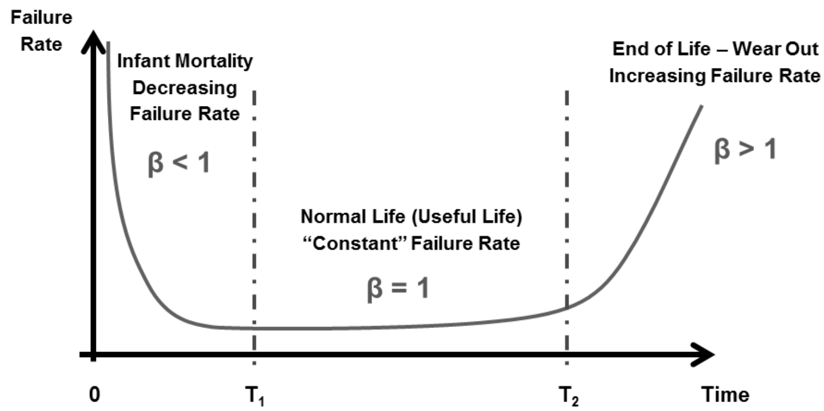

Figure 4: Relationship between beta and failures throughout the life of a component

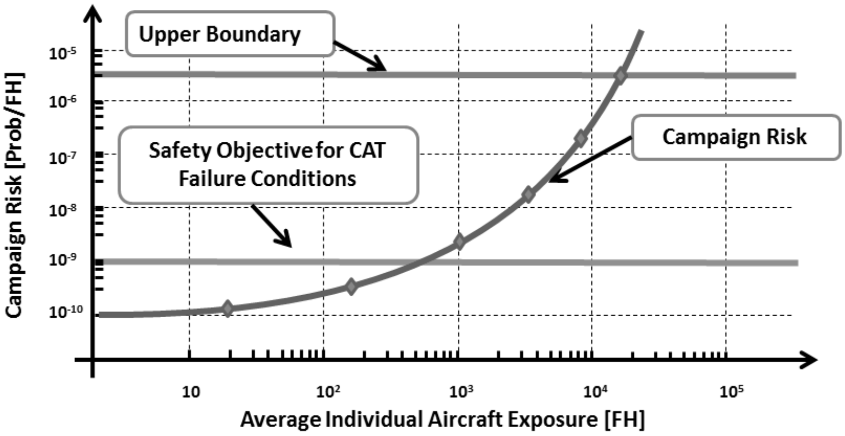

Figure 5: Typical evolution of the A/C campaign risk for a system defect ruled out by a wear out process

5. Reaction time evaluation for wear out failures involved in Catastrophic Failure Conditions

Due to the nature of this particular analysis (wear out process with increasing campaign risk), the reaction time cannot be evaluated directly through the risk allowance equation defined for constant failures rates [see Eq. (4)], being necessary to recover the initial definition of the risk allowance as per Eq. (1).

This equation captures the necessity of assessing the product of the campaign risk by the exposure time for each dedicated flight, in order to predict the number of flight hours at which the sum of the risks accumulated in each flight will reach the maximum risk allowance. This approach defines the reaction time as the maximum time, at which the area behind the curve of the campaign risk, as a function of the exposure time, is equal to the risk allowance.

Therefore, proposed methodology to evaluate the reaction time for failures ruled out by wear-out process consists of the following steps:

1. To predict the failure rate evolution as a function of time for the detected wear-out failure mode through the Weibull Analysis (or any other alternative method)
2. To discretize the aircraft life in intervals.
3. To evaluate the average failure rate of the system component in each time interval defined in step 2
4. To evaluate the average aircraft campaign risk in each time interval (Failure Condition probability per flight hour in which the defective item is involved), considering the average failure rate obtained in Step 3. This evaluation can be done using the traditional Fault Tree methodology, assuming that in each time step discretization the failure rate of the defective equipment remains constant.
5. To evaluate, for each time interval, the cumulative risk in accordance with Eq. (4).
6. To perform the sum of the cumulative risk and to compare it with the risk allowance established in Eq. (2).

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7. To evaluate the Reaction time (RT_1) as the maximum time at which the cumulative risk is equal to the risk allowance
8. To compare the Reaction time obtained in step 7 (RT_1) with the time at which the Campaign risk overcome the upper limit of 2E-06 / FH (RT_2), being the final reaction time the lower value between RT_1 and RT_2.

Note: The cumulative risk shall be evaluated from the first time interval in which the campaign risk overcome the safety objective (1E-09 / FH for CAT Failure Conditions), as before this situation the airworthiness of the A/C is not at risk.

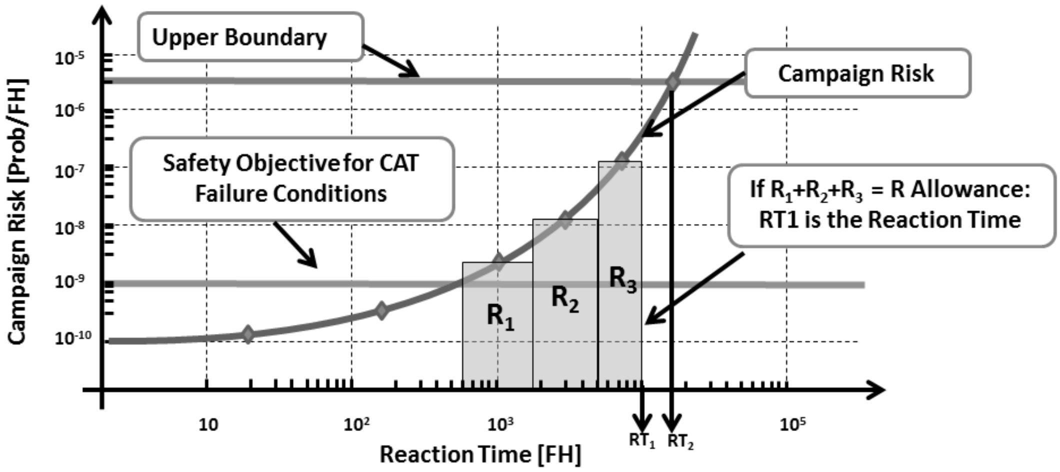

Figure 6: Discretization process for cumulative risk evaluation in case of a wear out failure mode

6. Application

As an example of application of this methodology, the analysis of a potential defect declared in engine equipment that could lead directly to an engine in flight shut down is proposed.

For the purpose of this analysis, the following input data will be considered:

- The individual equipment failure mode can be modelled by means of the following Weibull parameters:

  $$\beta = 2{,}9 \text{ and } \eta = 470 \text{ FH}$$

  As the β parameter is higher than 1, it is assumed that the source of the failure is ruled out by a wear-out process, and therefore the failure rate increases with time [5].
- The campaign risk will be evaluated considering that the most impacted Failure Condition at A/C level due to this defect is the “Two engine failure during Take Off” condition, which is assessed to have Catastrophic safety repercussions. For a four engine aircraft, the Fault Tree associated to this event is shown in Figure 7, where the Risk Time exposure of 0,03 hours corresponds to the duration of the take-off phase.

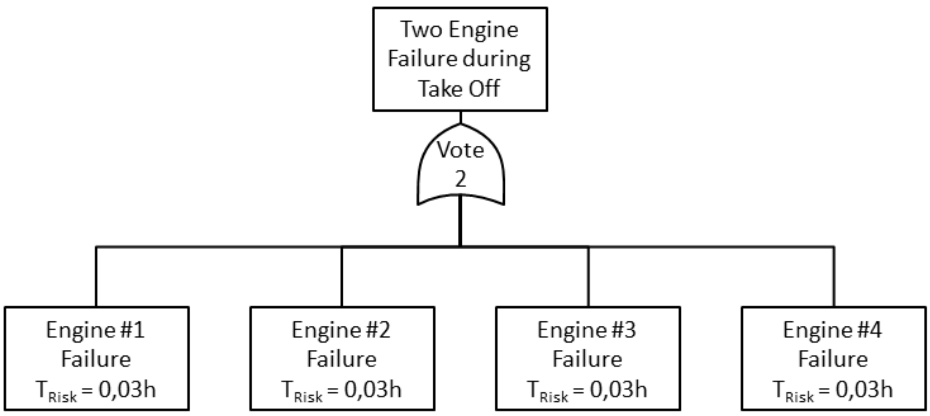

Figure 7: Fault Tree associated to Failure Conditions “Two engines failure during Take Off”

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Based on the above points, Table 1 compiles the following intermediate results for the evaluation of the Reaction Time:

1. Time reference: Central value of the time interval defined for the evaluations [Time Interval is 20 FH].
2. Failure Rate: Individual failure rate of each affected components based on the Weibull parameters.
3. Average Campaign risk: Results of the Fault Tree evaluation, considering that the failure rate remains constant in each timeframe defined. It shall be noticed that final result has been evaluated considering an average flight length of 4 hours.
4. Time Frame Cumulative Risk: Cumulated Risk in each particular timeframe [Product of the average campaign risk by the time frame duration].
5. Total Cumulative Risk: Cumulated risk since the declaration of the unsafe condition, when the campaign risk overcomes the safety objective.

From the results shown in Table 1, it can be observed that:

- The time at which the safety objective for Catastrophic Failure conditions is overcome (starting of unsafe condition period) is 180 FH
- The time at which the maximum total cumulative risk is equal to the risk allowance is RT_1 = 820 FH
- The time at which the Average Campaign risk overcomes the upper limit of 2E-06 / FH is RT_2 = 1260 FH

Reaction time to implement the corrective actions due to the detected event corresponds to the lower value between RT_1 and RT_2, being therefore RT_1 = 820 FH the maximum allowable time to implement a corrective action that restores the original airworthiness of the Aircraft fleet.

Table 1: Summary of the intermediate evaluations for the definition of the Reaction Time

Time Reference [FH]	**Failure Rate [1/FH]**	**Average Campaign Risk [1/FH]**	**Time Frame Risk [-]**	**Total Cumulative Risk [-]**
20	1,51E-05	1,55E-13	[-]	[-]
160	7,87E-04	6,69E-10	[-]	[-]
180	9,84E-04	1,07E-09	2,14E-08	2,14E-08
300	2,60E-03	8,06E-09	1,61E-07	5,44E-07
400	4,49E-03	2,48E-08	4,95E-07	2,24E-06
500	6,86E-03	5,89E-08	1,18E-06	6,59E-06
600	9,69E-03	1,19E-07	2,38E-06	1,58E-05
800	1,67E-02	3,61E-07	7,22E-06	6,31E-05
820	1,75E-02	3,97E-07	7,94E-06	7,10E-05
840	1,84E-02	4,35E-07	8,71E-06	7,97E-05
1240	3,85E-02	1,94E-06	[-]	[-]
1260	3,97E-02	2,06E-06	[-]	[-]

7. Reaction time evaluation for wear out failures involved in Hazardous Failure Conditions

Methodology proposed in sections 4 and 5 can also be applied to those cases in which the defective equipment is involved in Hazardous Failure Conditions. In this case, it shall be considered that the reaction time will be defined as the lower value between:

- The time at which the cumulative risk is equal to the risk allowance defined in Eq. (3)
- The time at which the Average Campaign risk overcomes the upper limit of 2E-04 / FH

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8. Conclusions

This article reviews proposed methodology in AMC/GM Part 21 [3] to evaluate the allowed reaction time to implement any corrective actions to eliminate any potential emergency situation that may arise over the aircraft fleet, ensuring a minimum level of airworthiness.

Current reaction time evaluation process compiled in AMC/GM Part 21 [3] only covers the case in which the detected failure mode follows a random failure approach where the failure rate remains constant with the time.

An alternative methodology has been described to cover those cases in which the failure mode is ruled out by a wear-out process, where the failure rate increases with time.

This methodology allows being more precise in the evaluation of the allowed time to impose the corrective actions, thus minimizing the disturbance to the operators but ensuring an acceptable level of Airworthiness.

References

[1] Airworthiness Manual. 2014. Airworthiness Manual. ICAO 9760 Ed. 3. International Civil Aviation Organization (ICAO).

[2] Commission Regulation. 2012. Laying down implementing rules for the airworthiness and environmental certification of aircraft and related products, parts and appliances, as well as for the certification of design and production organizations. Commission Regulation (EC) Nº EC 748/2012 of 3 August 2012. European Union Aviation Safety Agency (EASA).

[3] Acceptable Means of Compliance and Guidance Material. 2012. Acceptable Means of Compliance and Guidance Material for the airworthiness and environmental certification of aircraft and related products, parts and appliances, as well as for the certification of design and production organizations. AMC and GM to Part 21 – Issue 2, Amendment 7. European Union Aviation Safety Agency (EASA).

[4] Aerospace Recommended Practice. 2013. Safety Assessment of Transport Airplanes in Commercial Service. SAE ARP5150. Society of Automotive Engineers (SAE International).

[5] Dr. Robert B. Abernethy. 2004. The New Weibull Handbook, Fifth Edition.