Constant speed drive – time between overhaul extension: a case study from Italian Air Force Fleet.

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ABSTRACT

Scheduled maintenance can be very expensive in economics terms, but also in operational terms. This cost is not sustainable particularly if it is possible to demonstrate that item's life can be extended.

In this paper are shown the statistical considerations that the Italian Air Force made to extend the time between overhaul (TBO) of the Control Speed Drive (CSD), the mechanical part of the Tornado's Integrated Drive Generator, the main item generating alternate electric power for the aircraft.

Maintenance data are investigated using the General Theory of Reliability, Fault Tree Analysis and Risk Assessment. Results are compared with German and Royal Air Forces maintenance policy for the same item and similar studies on other components.

1.0 INTRODUCTION

During the last few years every Air Force Fleets management have become more appreciative of any study or research oriented to saving funds without reducing the combat readiness, with the aim of optimizing any phase of the integrated logistic support [1].
Moreover the always reducing availability of human and economical resources, makes more important, and in many cases fundamental, such studies.
The attention is generally concentrated on managing logistics aspects. However it's not possible to neglect the costs related to the technical management of the aircraft fleet.
In this context, the Italian Air Force carried out many studies to identify some items from the Tornado aircraft for whose maintenance policy could be modified, whilst maintaining the same safety standards by adequate Risk Assessment and Risk Management.
Because the scheduled maintenance approach is very expensive in economical terms and also in operational terms, the chance to improve the time between overhaul (TBO) operations' phasing is highly recommended whenever it is possible to demonstrate that an item's life could be extended.
In this paper the case of Constant Speed Drive (CSD) TBO extension will be described; it is the mechanical part of the Tornado's Integrated Drive Generator (IDG), the main item generating alternating electric power on the aircraft.

2.0 AIRCRAFT ELECTRIC SYSTEM: BACKGROUND

2.1 Short description

The Tornado's electric power system is essentially composed by two low fixed-frequency generators (integrated drive generators – IDG). These systems, left and right, supply alternate tri-phase electrical power (115V 400Hz) and are actuated by two gearboxes, connected to the engines. If one IDG fails, the other will generate all the electrical power the aircraft needs. Electrical generation is lost only if both IDGs fail (except for the first 20 minutes, for which the electrical power is provided by an Emergency Power System).

The IDG is divided into a generator and a rotational speed converter (constant speed drive - CSD):

- The generator is composed of statoric windings, a rotor with its own windings and a permanent magnet. Rotor is actuated by CSD. The manufacturer's fixed generator's TBO is 1200 flight hours.
- The CSD operates hydro-mechanically and is composed by differential gearing, a clutch, a hydraulic pump, a centrifugal regulator and a RPM transducer. The manufacturer's fixed CSD's TBO is 600 flight hours.

The CSD's role is to convert variable rotational speed arriving from gearbox to constant rotational speed, before supplying this motion to the generator; in this way it will produce the right constant alternate electrical power.

2.2 Maintenance

The CSD works with the electrical generator, together composing the IDG, but their scheduled TBO lives were different: even if the CSD demonstrated high reliability, its overhaul was fixed by the manufacturer to 600 flight hours despite the generator's fixed to 1200 flight hours.
This was a heavy recurrent operating cost not only from the direct economic point of view: in fact, there were often many difficulties caused by the non-availability of both items at the same time.

3.0 RELIABILITY'S THEORY – BASIC CONCEPTS AND DEFINITIONS

Here are summarised some basic concepts and definitions of the reliability's theory that will be used in the statistical analysis.

3.1 Reliability

The reliability of a product is the probability that this item could be efficient after a period of operational life:

$$R(t) = \frac{N_E(t)}{N}$$

With

- $N_E(t)$ number of efficient items at "t" time;
- N total number of the units under test.

3.2 Unreliability

The unreliability of a product is the probability that this item could become inefficient after a period of operational life, so it's the complementary part of the reliability, referring to an unitary space of events:

$$F(t) = 1 - R(t) = \frac{N_F(t)}{N}$$

Where,

- $N_F(t)$ number of inefficient items to the "t" time;
- N total number of items under test.

3.3 Density of Damage probability

The previous definitions are all related to the cumulative distributions functions (CDF), but they could be calculated analytically starting from the definition of Density of Damage probability: the probability for a system to become inefficient at the instant "t".

We can write the previous equations as:

$$F(t) = \int_0^t f(t)dt$$

consequently,

$$f(t) = \frac{dF(t)}{dt} = -\frac{dR(t)}{dt} = \frac{1}{N} \cdot \frac{dN_F(t)}{dt}$$

3.4 Failure rate

The failure rate, λ, is defined as the probability that, in a well determined time range Δt, the system fails, under the hypothesis of perfect working condition at the starting time. Based on the previous definitions we have,

$$\lambda = \frac{R(t) - R(t + \Delta t)}{R(t) \cdot \Delta t}.$$

And,

$$\lim_{\Delta t \to 0} \lambda = \frac{f(t)}{R(t)}$$

3.5 Parallel and series systems

By schematizing systems as block diagrams it is easy to distinguish two particular cases: parallel and series systems.

For the series kind, if only one component fails, the serviceability of all the system is lost.

We assume that the probabilities of failure of each component are stochastically independent: if a subpart fails, the probability of failure of the other subparts do not change.

Therefore the reliability at a generic moment "t" is the product of the reliabilities of all the subparts:

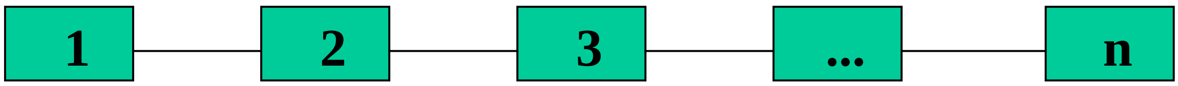
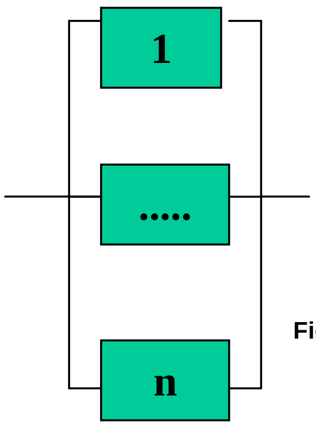


Figure 1: Block diagrams - Series System

$$R_S(T) = \prod_1^n R_i(T)$$

In a parallel system all the subparts have to fail to make the whole unserviceable. So the reliability is expressed as the complement to the product of each unreliability.



$$R_P(T) = 1 - \prod_1^n F_i(T)$$

Figure 2: Block diagrams - Parallel System

3.6 Tools

3.6.1 Exponential distribution

In this paper we will assume as the mathematical model the exponential distribution with constant failure rate because:

- it represents very well random failures on parts;
- the failure rate tends to become constant even when subparts show reliability curves very different between them. Therefore is possible to specialize the above definitions as:

$$\lambda = const \Rightarrow \begin{cases} R(t) = e^{-\lambda t} \\ F(t) = 1 - e^{-\lambda t} \\ f(t) = \lambda e^{-\lambda t} \end{cases}$$

3.6.2 Fault Tree Analysis

The Fault Tree Analysis (FTA) is a methodology applied in statistics. Whenever an event happens, named the Top Event, it is subordinate to other events, Base Events, related to the previous and related to each other by some equations that identify intermediate events, named Dependent Events.
The probability for the Top Event is therefore evaluated starting from the probabilities of the Base Events, assumed as known, using the block diagram's equations.
We use the following table:

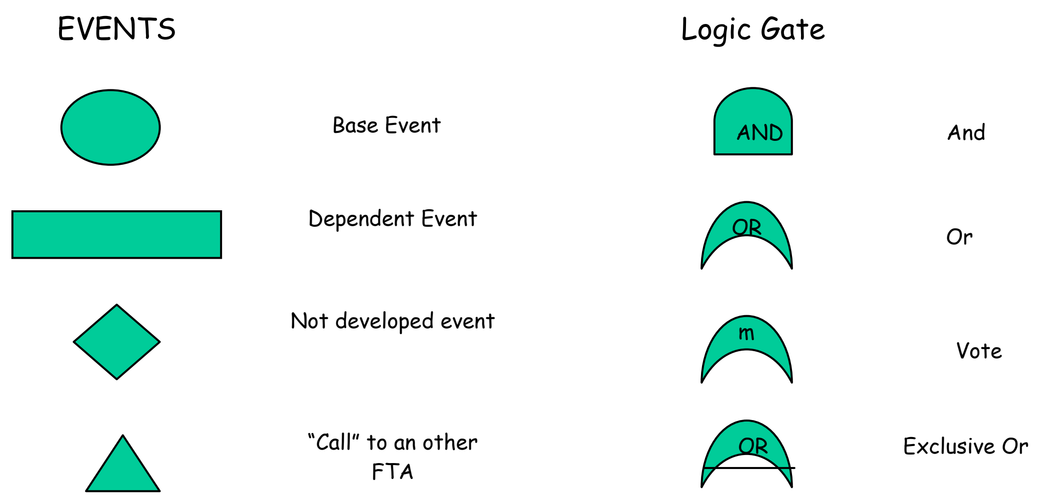
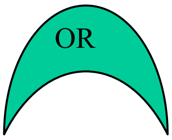


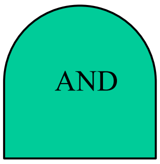
Figure 3: Block diagrams - symbols

Using the introduced symbols, the equations for the subsystems should be written in the following way



$$R = \prod_{1}^{n} R_i$$

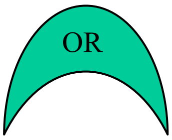
Series System



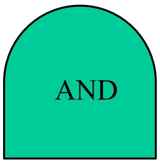
$$R = 1 - \prod_{1}^{n} (1 - R_i)$$

Parallel System

And, assuming constant failure rate:



$$\lambda = \sum_{1}^{n} \lambda_i$$



$$\lambda = \prod_{1}^{n} \lambda_i$$

4.0 DATA ANALYSIS

Data for this paper, related to CSD and Generators from 1998 up to 2005, were provided by the IDG Work Area of IAF Main Depot, 1°RMV, devoted to Italian Tornado Fleet Maintenance.
Considering the following maintenance actions:

- Serviceable after testing in 1°RMV Work Area: 1°RMV has a very limited maintenance capability for IDG items;
- Sent to Manufacturer for Overhaul (O);
- Sent to Manufacturer for Overhaul and Modification (OM);
- Sent to Manufacturer for Overhaul and repair (OR);
- Sent to Manufacturer for Overhaul, Repair and Modification (ORM);

The following table summarizes the data which are shown graphically in Figures 4 and 5:

	1998		*1999*		*2000*		*2001*		*2002*		*2003*		*2004*		*2005*		*TOTALS*	
	GEN	*CSD*	*GEN*	*CSD*	*GEN*	*CSD*	*GEN*	*CSD*	*GEN*	*CSD*	*GEN*	*CSD*	*GEN*	*CSD*	*GEN*	*CSD*	*GEN*	*CSD*
Serviceable	**62**	**77**	**67**	**79**	**57**	**64**	**56**	**45**	**41**	**73**	**38**	**47**	**51**	**85**	**21**	**24**	**393**	**494**
O	**0**	**32**	**0**	**29**	**0**	**36**	**0**	**32**	**4**	**26**	**0**	**31**	**10**	**42**	**16**	**39**	**30**	**267**
OM	**0**	**16**	**0**	**10**	**0**	**5**	**0**	**4**	**0**	**2**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**38**
OR	**19**	**6**	**19**	**4**	**11**	**0**	**8**	**2**	**11**	**2**	**9**	**2**	**6**	**1**	**9**	**3**	**92**	**20**
ORM	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**
TOTALS	**81**	**133**	**86**	**122**	**68**	**105**	**64**	**83**	**56**	**103**	**47**	**80**	**67**	**129**	**46**	**66**	**515**	**821**

Table 1: IDG maintenance data

By analyzing the data from the table is possible to obtain the percentages related to the column of totals. In particular,

- CSD OR and ORM percentage with 600 flight hours of TBO is less than 3%;
- Generator OR percentage with 1200 flight hours of TBO is about 18%;

It's evident there is no relation between defect rate and TBO for Generator and CSD.

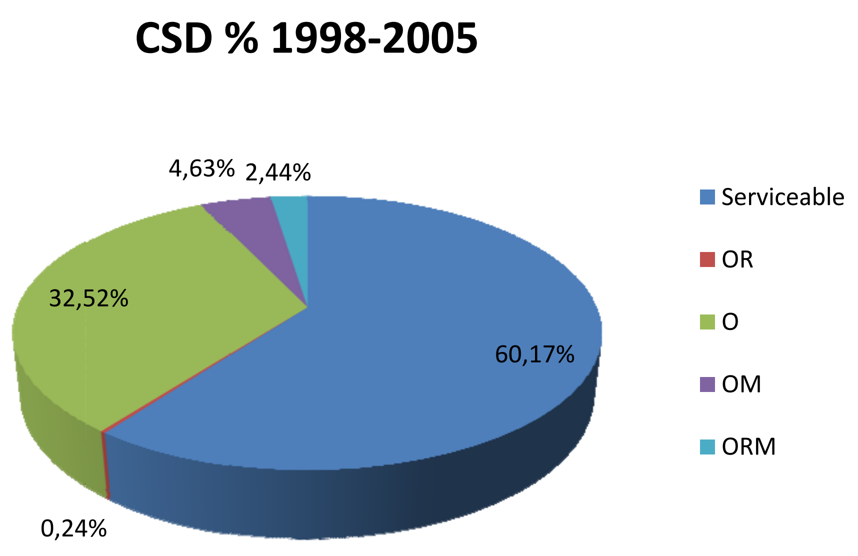


Figure 4: CSD maintenance data diagram

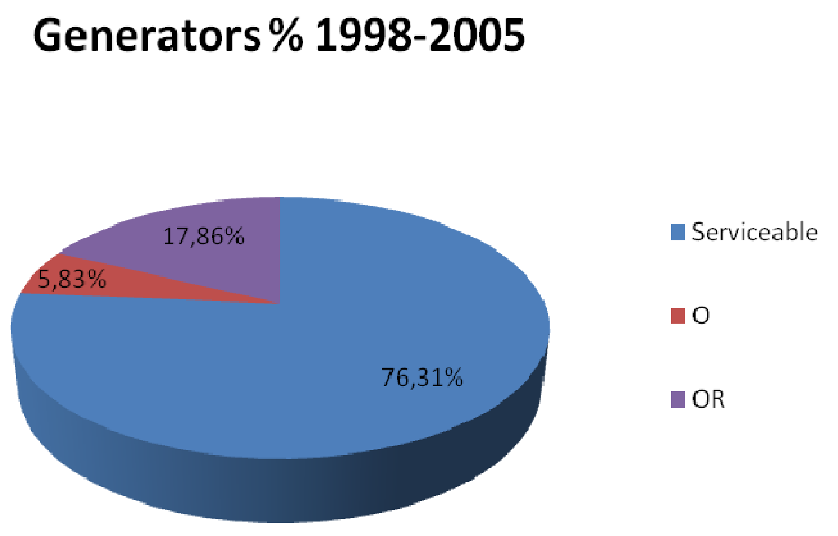


Figure 5: Generator maintenance data diagram

4.1 Failure rates evaluation

The calculation required the total flight hours flown by the Tornado Fleet (IDS, ECR and ADV, IDG components are common to any version of the aircraft) from 1998 up to 2005: 96965 flight hours.

Moreover it's necessary to considerate the system's double redundancy. Therefore CSD average failure rate is:

$$\overline{\lambda}_{CSD} = 1.134 \cdot 10^{-4} \quad \text{[1/flight hour]}$$

While the Generator failure rate is:

$$\overline{\lambda}_{GEN} = 4.744 \cdot 10^{-4} \quad \text{[1/flight hour]}$$

Now considering 1998, 13139 flight hours, we take in account for the worst case:

$$\lambda_{MAX\_CSD} = 3.044 \cdot 10^{-4} \quad \text{[1/flight hour]}$$

$$\lambda_{MAX\_GEN} = 7.230 \cdot 10^{-4} \quad \text{[1/flight hour]}$$

5.0 IDG – FAULT TREE ANALYSIS

The loss probability of the whole AC generating system will be evaluated, therefore the failure of both the IDGs at the same time is considered.

5.1 Worst Case Scenario

The failure rate of the worst case scenario is evaluated using block diagrams and the maxima failure rates of CSD and Generator. So,

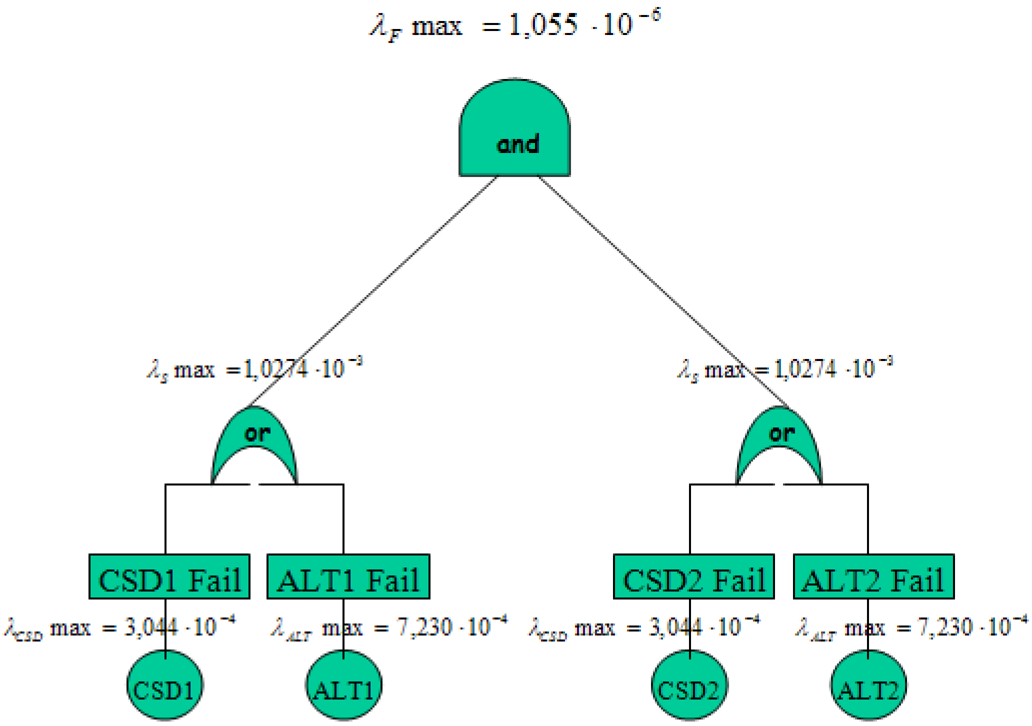


Figure 5: FTA – worst case scenario

5.2 Normal Failure Rate Scenario

We will now consider the average failure rate of CSD and generator to evaluate the normal failure rate of the whole AC generating system.

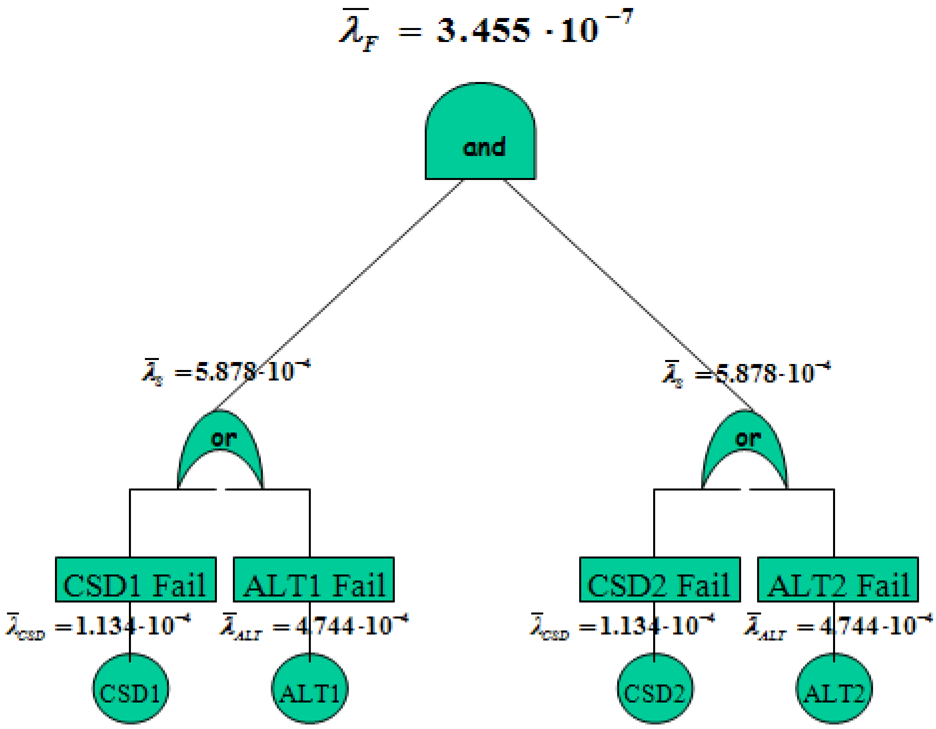


Figure 7: FTA – normal case scenario

5.2.1 Independent total failure rate

Using the average values of CSD and Generator failure rate and assuming alternatively one of the two items as an "infinite reliability system" (λ=0), we can calculate the independent total failure rate:

$$\overline{\lambda}_{F\_CSD} = 1.28 \cdot 10^{-8} \quad \text{[1/flight hour]}$$

$$\overline{\lambda}_{F\_GEN} = 2.50 \cdot 10^{-7} \quad \text{[1/flight hour]}$$

6.0 EVALUATIONS FROM COMPARISONS

6.1 Crew Escape System Mods Package

Before introducing four modifications to the Tornado Crew Escape System BAE Systems developed similar statistical studies: indeed the new parachute diminishes the physical gap between the navigator and canopy.

These modifications could lead to a malfunction to the canopy's Plexiglass explosion system with the resultant possibility of crew loss.

The manufacturer demonstrated that with the introduction of the modifications, the improvements resulted in a negligible crew loss probability rate, evaluated as $1.287*10^{-8}$ per hour. This rate was shown to be lower than that for the unmodified system.

6.2 CSD maintenance in GAF and RAF

It was also interesting to compare different maintenance philosophy for the same item in other Air Forces:

- CSD's TBO in GAF is 1200 flight hours;
- In RAF CSD is an on condition item;

7.0 RISK MATRIX AND RISK INDEX

The failure rates obtained are analyzed using a risk matrix, described in the following tables [4]. These classify the probability of an event happening and its consequences.

DESCRIPTION	CATEGORY	DEFINITION
Catastrophic	I	Death and/or main system loss
Critical	II	Severe injury, severe occupational illness and/or major system loss
Marginal	III	Minor injury, minor occupational illness and/or minor system loss
Negligible	IV	Less than Marginal

Table 2: Hazard severity categories

Description	Level	Individual item	Fleet	Frequency
Frequent	A	Likely to occur frequently	Continuously experienced	$F \geq 10^{-3}$
Probable	B	Will occur several time in life time of an item	Will occur frequently	$10^{-5} \geq F \succ 10^{-3}$
Occasional	C	Likely to occur some time in life of an item	Will occur several times	$10^{-7} \geq F \succ 10^{-5}$
Remote	D	Unlikely but possible to occur in life time of an item	Unlikely but can reasonably be expected to occur	$10^{-9} \geq F \succ 10^{-7}$
Improbable	E	So unlikely, it can be assumed occurrence will be not experienced	Unlikely to occur but possible	$F < 10^{-9}$

Table 3: Hazard frequency categories

Therefore we can compose the risk matrix. Each risk index is associated with a corrective action.

PROBABILITY \ SEVERITY	I	II	III	IV
A	1	3	7	13
B	2	5	9	16
C	4	6	11	18
D	8	10	14	19
E	12	15	17	20

HRI	Assessment	Action
1-5	High Risk	Unacceptable
6-11	Moderate Risk	Acceptable with review
12-20	Low Risk	Acceptable without review

Table 4: Hazard risk index (HRI)

Considering that Tornado has a back-up system, the Emergency Power System, that guarantees electric power for twenty minutes in case of complete loss of the generating system, it's reasonable to assume a Severity level of III. This value combined with the independent CSD failure rate gives a Risk index of 14. Therefore no corrective actions or checks are needed.

8.0 CONCLUSIONS

8.1 Results:

- Generator's probability of failure is higher than the CSD's;
- Generator percentage of items sent to the manufacturer, calculated by maintenance data, is nine time higher than the CSD's; In RAF the CSD is an on condition item;
- Generator had TBO fixed to 1200 flight hours, while CSD was 600 flight hours;
- Complete system failure's rate is in the lower range magnitudes of acceptable risk.

8.2 Considerations:

In this paper maintenance data have been used to provide evidence that there is no relation between defect rate and TBO for the generator and CSD.
Moreover the statistical analysis highlighted the possibility of extending the CSD's life without safety related problems.
Comparisons with GAF and RAF fleet highlighted further the extreme conservatively TBO limit imposed by the manufacturer.

8.3 Subsequent Actions:

The studies and results described in this paper were addressed in a technical document to propose an extension to the CSD's TBO from 600 to 1200 Flight hours.
MoD authorized the TBO extension.

8.4 Consequences for the IAF Tornado fleet:

- Generator's and CSD's overhauls are performed at the same time; this implies a better maintenance organization and an improved readiness;
- Economical benefit are attained due to the longer CSD's TBO.

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