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# ADP010437

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# Aging Aircraft Subsystems
# Equipment Life Extension within the Tornado Program

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## Abstract

Restrictions on nations military budgets require that Air Forces will operate high sophisticated weapon systems such as military aircraft far beyond their original designed life. Modernization, life extension and aging aircraft programs are defined to ensure that future mission requirements can be fulfilled and the airworthiness of the aircraft is maintained until the out of service date.

Whilst the operational life is increasing, various aging effects take place and impair the structural and functional integrity of high aged aircraft subsystems even before their design life are reached. An integrated process was defined between customer and industry with the aim of extending the operational life of the aircraft under limited budgetary conditions and tight timescales.

Under the scope of this task, aging of equipment and components, the impact of aging problems on structural and functional integrity, the impact of customer extended operational requirements on equipment limitations and the consequences of age related failures on flight safety have been assessed.

Recommendations for revised maintenance and inspection programs and revised limitations have been or will be worked out by industry for safety and non-safety relevant equipment to enable formal certification of the aircraft for the extended period.

This work is generally accompanied by equipment design review, review of the in-service usage, investigation of reported in-service problems and related statistics, master inspections of subsystems in high aged aircraft and investigation of aged loan equipment, provided by the Air Forces. Additionally, programs are conducted to establish revised in-service operational conditions.

Various programs have been defined by the FAA and US Air Force, which aim on addressing safety issues in aging aircraft structural and non-structural systems.

For the 20 years old Tornado aircraft, a life extension program for structure, subsystems and engine is presently being carried out, whose results should enable certification of the aircraft for the extended operational phase and support safe operation of the aircraft for the next 25 years which means a life extension by roughly one aircraft life.

This paper discusses the various aspects related to aging of subsystems and the content and philosophy of the Tornado equipment life extension program. Furthermore specific problems identified in various subsystems are presented together with a description of the way ahead for life extension.

## Overview

This lecture comprises of four major parts:

**Part 1:** Introduction and a general review of the aging system problematic and other problem areas related to an aged aircraft

**Part 2:** A description of the subsystem life extension program for the Tornado IDS variant

**Part 3:** Subsystem Life extension approach and experiences

**Part 4:** Conclusion

# Part 1

# Review of the aging system problematic and other areas of concern

## Introduction

When aircraft are getting older operators are increasingly confronted with problems, which are caused by the aging process to which the aircraft are exposed. Aging could degrade the integrity of structures, equipment and other components to such an extend that the consequences of failures could be catastrophic.

In the civil aviation very spectacular accidents occurred where aging was or probably was the dominating factor through which the accident was caused:

*Paper presented at the RTO AVT Lecture Series on "Aging Engines, Avionics, Subsystems and Helicopters", held in Atlantic City, USA, 23-24 October 2000; Madrid, Spain, 26-27 October 2000, and published in RTO EN-14.*

- the Aloha Airlines 737 accident where due to hidden corrosion in the lap splices the aircraft lost a big portion of the upper front fuselage during flight
- the TWA Flight 800 in July 1996, where the explosion of the center fuel tank might be caused by wiring problems.

Both accidents revealed that

- existing maintenance procedures are not adequately addressing aging problems in areas, which are inaccessible for visual inspections
- the effects of aging on structural and functional integrity of aircraft subsystem components and flight safety could be catastrophic

To operate flight systems safely within their certified life, maintenance procedures have been defined taking into account their fail-safe design philosophy. This means that any failure within the subsystem, which could lead to a safety critical hazard, would be extremely improbable and fly to failure is the prevailing philosophy. This is a major reason why the On-condition Maintenance Concept (OCM) is applied to the majority of subsystem components.

As aircraft age, the number of failures due to aging in functional equipment or other system components increases. Aircraft availability and mission success will be increasingly impaired due to unscheduled maintenance actions required.

Under the view of declining budgets and the necessity to operate aircraft beyond their design life investigations are performed in order to review the aging process of subsystem components in aging aircraft.

But it is important to recognize, that the aging process of any component cannot be prevented but the velocity of aging can significantly be reduced by e.g.

- identifying critical areas and components where aging could have serious consequences
- reviewing the current aging process of subsystem components in high aged aircraft or of high aged components
- reviewing the current maintenance procedures and policy regarding the aging problematic
- improving preventive maintenance actions in order to address aging in an early stage.

Fig. 1 presents the current age of the Tornado IDS fleet. It indicates that the oldest Tornado aircraft have already reached a service life of 20 years.

Considering a further planned usage beyond the year 2020 for the IDS variant, some IDS aircraft will stay in service for nearly 50 years.

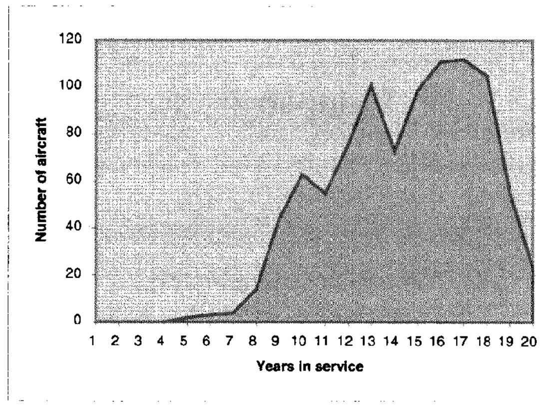



**Fig. 1:** Age of the Tornado IDS fleet

This, however, does not mean that the equipments and components of subsystems will remain in service such a long time: it is very probable that many equipment and components of systems have usually already been replaced during regular or unscheduled maintenance by overhauled, repaired or new items. A uniform in-service life for all subsystem components in an aged aircraft does not exist.

It is therefore important for critical equipment to record in-service operational and maintenance data in order to be able to assess the usage history and life consumption and define the point of retirement or where maintenance actions or overhaul is required to ensure safe operation..

Certification rules require replacement of equipment when its certified life is reached. As system components have often a life potential which is bigger than the certified life and in order to get the maximum benefit of equipment in terms of performance and costs, an subsystem life extension program is carried out.

Within this life extension process, which will be described in a later chapter, aging problems within each subsystem have been investigated and taken into account for defining appropriate measures for life extension.

The following chapter discusses briefly which effects are generally contributing to aging of subsystem components.

## Aging mechanisms

Aging is understood as a process, where the structural and/or functional integrity of equipment / components will be continuously degraded by the exposure to environmental conditions, under which the equipment is operated.

This could lead in the worst case to a situation where the aged equipment / component cannot fulfill any more its designed function, even before the design life of the item is reached. In this case, subsystem functions, which the item has fulfilled or supported, could be lost or degraded, which may also affect flight safety.

There are various mechanisms, which alone or in combination are responsible for equipment aging.

- Exposure to normal or salty atmosphere, heat, water, oil, grease, fuel, ultraviolet light, etc., which could lead to corrosion, embrittlement, swelling, overheating, melting or other material degradation, electrical interruptions, short circuits, etc.
- Exposure to vibration and acoustic environment, which could lead to fatigue damages, wear and tear, etc.
- Endurance, which could lead to leakage, wear and tear, etc.
- Storage, which means exposure to storage conditions, specified by the equipment supplier or in-service practice
- Maintenance activities, which can induce accidental damages (which could be a particular problem for wiring)

It is likely that reliability and availability of equipment will be impaired by these mechanisms.

Additionally, incorrect installation of equipment could also have a detrimental effect and support the aging process, e.g. enable chafing of wire bundles on surrounding structure (this can be the result of poor design but also of poor maintenance).

*Aged* equipment and components will be removed from service if further use is not recommended for safety reasons or if further safe operation is uneconomical due to required inspection and maintenance activities.

*Life expired* equipment can be defined by the fact that any in (equipment) specification specified and certified life limitations are reached by the in-service usage and therefore need to be replaced.

Life extension might be possible and needs to be investigated. In case, the design and certification authority permit further on aircraft operation under clearly defined conditions, further use of the equipment can be tolerated without formal re-qualification and for a limited time: as the aircraft runs out of certification (>4000 FH) and the formal certification process up to 8000 FH has not been completed yet, the definition of such conditions and requirements for further usage up to 5000 FH is part of the Tornado life extension program.

## Influence of maintenance on aging

As already mentioned, aging of equipment and components cannot be prevented but slowed down. It is reasonable to say that if maintenance is poorly or not timely conducted certain aging effects (e.g. wear and tear, contamination, corrosion, etc.) could be accelerated or even started.

This means that the physical condition of aged equipment and components in different aircraft can vary due to different quality of maintenance carried out which could result in earlier retirement of components than assigned.

Aircraft maintenance programs will always be a compromise as beside others logistic costs and overall fleet management are important issues, which drive their definition.

The Tornado is operated by three different air forces, which have different maintenance programs and procedures. The major depot inspection for the RAF and GAF is currently at 2400 FH (or 14 years, RAF only) and 2000 FH for the IAF. Considering the fact that at the beginning of the Tornado program the DI was at 1600 FH, the time where a thorough investigation of the aircraft condition is performed has significantly increased (by 50%).

In view of this and to address aging problems, it is important to include preventive maintenance actions for critical equipment and areas, at shorter intervals in periodic servicing schedules or in special inspections, to ensure that aging problems will be detected in an early state where the effort for repair is still acceptable and an airworthiness critical situation far away.

Within the Tornado subsystem life extension program aging effects on equipment and components are investigated as far as they are obvious and known. The results of these investigations will be used by the manufacturers to establish revised maintenance procedures for their equipment where necessary.

## Other problems areas

Besides the aging problematic, other topics which are not related to aging but causes problems in an aged aircraft need to be considered and investigated. The list might not be complete but describe the major problem areas.

- *Operational conditions*

  These might have changed during the lifetime of the aircraft.

  For an aged aircraft where life extension is an issue the current and future planned operational conditions need to be investigated and compared to the original design requirements. This can be done by engineering assessments or if the conditions cannot be established on an theoretical basis by Operational Load Measurement (OLM) programs.

The outcome of such programs will be used to calculate existing clearances and life potential or provide a basis for further qualification testing.

The establishment and conduction of OLM programs are often very costly and time consuming. Therefore, any decision for such programs should be taken early enough to ensure that results are available in time.

In the Tornado program such Operational Load Measurements (OLM) are conducted in the Landing Gear System as presented later.

- *Usage history, life consumption*

As required by formal certification rules, equipment, which exceeds stated life limits are formally out of certification. Therefore, the usage history needs to be established and this requires the availability of complete in-service documentation (LOG cards, maintenance documentation).

Unfortunately, it has been experienced that it is sometimes very difficult to get all the information necessary to assess service life and life consumption. For safety relevant and life limited components this causes many problems as it might be not possible in these cases to establish whether an equipment is already life expired or not.

- *Repairs and concessions*

The influence of repairs and concessions on life limitations needs to be assessed.

Normally, minor concessions should not affect life limits, but if the operational conditions have changed in the past, the classification of concessions needs to be reassessed.

- *Obsolescence*

Obsolescence is a problem, which becomes more problematic with increasing age of the aircraft.

Materials and components, which have been used in the original design, could be no more available and this could require redesign and re-qualification activities if no proofed and certified alternatives exist.

Especially for electronic parts obsolescence is a critical and costly issue as technology progress over the last 20 years was so enormous that certain items remain only available in a limited quantity. A strategy for future support of electronic equipment needs to be established.

- *Availability of original supplier*

For most of the major equipment there was only one supplier selected, who has designed and qualified the item. This supplier might have disappeared or no more able to produce the required component. Introduction of alternative supplier will cause problems in terms of time and costs. Dependency on one supplier is critical but usual.

- *Costs for procurement of equipment*

The procurement of equipment for replacing aged or life expired equipment after 20 years in service could be very costly as e.g. original supplier are no more existent, design and qualification of new components are necessary or the required number of equipment is very small.

- *Inspections and inspection efficiency*

With the aging of the aircraft aging effects will increasingly require inspections of critical equipment and components to ensure that any aging effect will not lead into a safety hazardous situation. The success of inspections is very dependent on the selection of the appropriate methods, availability of required equipment, clearly defined inspection procedures, availability of trained personal.

- *Maintenance documentation*

Existing maintenance procedures, which do not address aging as experienced by investigations or sampling, needs to be revised. Requirements or recommendations of the equipment manufacturer, defined during the life extension process, should be included.

- *Failure and maintenance reporting systems*

Most aircraft users are maintaining comprehensive databases to collect and evaluate failure and maintenance reports for the whole aircraft down to equipment and component level in order to identify unreliable equipment and other problem areas.

However, in service data collection systems are mainly defined by the aircraft users and reflect <u>their</u> specific needs and points of interest. The definition of data elements and the level of detail may significantly vary, even between the different users of the same aircraft type.

For this reason, the probability, that failure and maintenance data collected during service are compatible with design analysis and predictions is fairly low.

Moreover, in service data are not always available to the system design authority at a level required e.g. for equipment aging investigations.

The value of an in service database can only be as good as the entries. It is therefore important to consider that any analysis or curves derived from databases need specific interpretation and should be taken with care.

The major "lessons learnt" for future data collection systems are therefore continuous availability to both user and manufacturer and the need for compatibility with design analyses, in order to gain maximum benefit over the aircraft lifetime.

Similar problems are mentioned in other publications. It is therefore important to consider that any analysis or curves derived from databases should be taken with care.

## Aging of Tornado subsystems

To get an overview on the magnitude of subsystem aging problems, the increase of aging related failure rates have been investigated, Fig. 2.

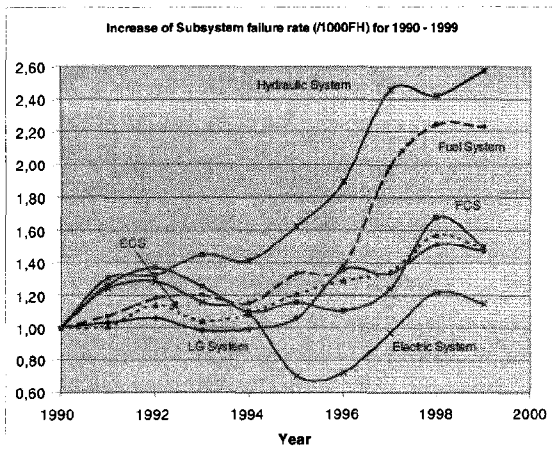



**Fig. 2:** Reported in-service failures due to aging

For these trend curves failures are considered which could be attributed to aging, such as corrosion, wear and tear, leakage, contamination, porosity, brittleness, contact damage, isolation damage, etc.

However, it should be noted that these curves are only trend curves as it is very difficult to analyze whether the reported failures are really due to aging or other influences.

The analysis has been performed for the following subsystems and for the period 1990 until 1999:

- Landing Gear subsystem
- Flight Control subsystem
- Electric Subsystem
- ECS Subsystem
- Fuel Subsystem
- Hydraulic Subsystem

The investigation show an significant increase of aging related failures over the last decade for the

- Hydraulic Subsystem by 160%
- Fuel Subsystem by 120%
- Landing Gear, Flight Control and ECS subsystem by 50%
- Electric Subsystem by 15%.

The biggest contribution to the above curves in the Hydraulic and Fuel System is leakage with 43%, respectively 19%.

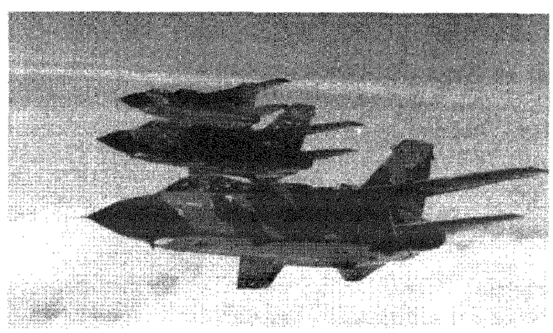
After the description of general aspects of the aging problematic and additional problem areas, we have encountered in the Tornado program, part 2 will describe the Tornado Subsystem Life Extension program for the Tornado IDS variant, as it is presently being carried out.

# Part 2

# Tornado subsystem life extension program

As introduction a very brief survey of the Tornado program should be given, before describing in detail the philosophy and process of the Tornado Subsystem Life Extension program.

## Tornado Program



The Tornado aircraft was designed and developed in three European countries, the United Kingdom (42,5% share), Germany (42,5%) and Italy (15%) according a set of tri-national agreed Performance and Design Requirements (PDR) which form a compromise between national requirements.

The major aerospace companies in these three countries were in charge to build this aircraft, which have been British Aerospace, BAe, (now BAE SYSTEMS), Messerschmitt-Bölkow-Blohm, MBB, (now DaimlerChrysler Aerospace, DASA) and Aeritalia (now Alenia).

The PANAVIA Aircraft GmbH was formed by these three companies (PANAVIA Partner Companies, PPCs) in order to manage the program on industry side.

On the customer side, the program is controlled by NAMMO, the NATO MRCA Development and Production Management Organization, and today managed by the NATO European EF2000 and Tornado Agency, NETMA (former NAMMA). NAMMO and NETMA are staffed by specialists from all three Nations.

The first flight of Tornado was successfully performed in 1974 and the first production aircraft was completed in 1980.

In total 977 aircraft have been built in two major variants, that are the

- Interdiction Strike/Attack (IDS) variant, which is operated by all three Nations Air Forces (RAF: 228 aircraft, GAF: 357, IAF: 99) and also the Royal Saudi Air Force (RSAF) (96)

and the

- Air Defense Version (ADV), which is operated by the RAF (173) and the RSAF (24). Today also the IAF operate ADV aircraft, leased from the RAF.

Single stick and trainer versions exist for both variants. Additional, for the IDS various sub-variants, e.g. the Electronic Combat Reconnaissance (ECR) variant, exist, differently equipped to perform specific missions and to carry specific external stores.

The development and production of Tornado was shared between the three Nations roughly according the intended number of aircraft they wished to procure.

The responsibilities for design and production of the airframe were shared between BAE SYSTEMS (front and rear fuselage), DASA (center fuselage) and Alenia (wing).

For the development and qualification of subsystems, System Design Responsibilities (SDR) for each system and Equipment Design Responsiblies (EDR) were defined. SDRs and EDRs were shared between BAE SYSTEMS and DASA but they were not necessarily in one hand.

As there are some differences in subsystem design between IDS and ADV, a separate life extension task has been defined for the ADV variant. This task deals with the life extension of ADV specific equipment and equipment, which is common to IDS but differentially loaded in service and therefore different life limitations needs to be established. Common items to IDS with same operational loading conditions are covered by the IDS life extension process.

In this lecture, only the IDS life extension process will be described where the fundamentals of this process have been discussed and defined.

# Tornado IDS Subsystem Life Extension Process

The subsystem life extension program is integral part of the aircraft life extension program, which includes also engines and structures. Aircraft certification will be a compilation of the output of all three separate tasks.

Nations requirements for the extended use of Tornado IDS are shown in Fig. 3.

The basic tri-national requirement for life extension was that PANAVIA should establish the basis for aircraft certification up to 8000 FH, based on the original PDR requirements.

Additional to that, UK wish to extend the life of their IDS for a further 2000 FH up to 10000 FH.

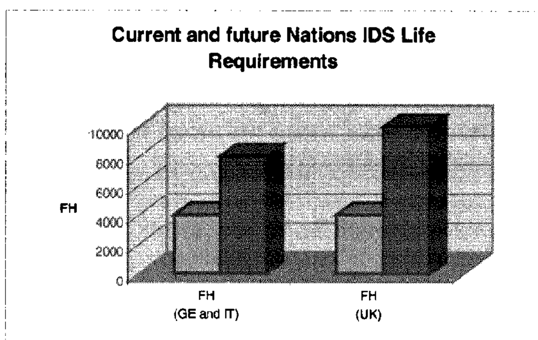



**Fig. 3:** Life extension requirements

The current planning of Nations air forces revealed that they intend to operate the IDS Tornado aircraft beyond the year 2025 (GE and IT) and 2020 (UK), which means that the oldest aircraft will stay in service for about 50 years.

Certification documentation of the aircraft and its equipment includes life limitations. Consequently, operational use by the air forces beyond this limitation is at Air Forces own risk and absolves PANAVIA and their supplier from any product liability.

Therefore, Nations via NETMA required that PANAVIA should be tasked to perform work that would allow PANAVIA to resume the product liability for the extended period.

In 1995 PANAVIA was contracted to carry out a program, which aims on extending the life of TORNADO IDS and ECR variants significantly beyond the current life limits up to 8000 FH, which means a doubling of the aircraft operational life.

The overriding constraint upon extended certification is that no significant reduction of flight safety is acceptable, although equipment reliability in some cases may be degraded with time. This requires the identification and assessment of equipment and components which failure would be safety critical.

The certification of equipment for the extended period requires that the equipment *Declaration of Design & Performance* (DDP) will have to be updated stating the new life limits as outcome from the life extension process.

The approach of identifying equipment, which should be regarded for life extension activities, considers that aircraft subsystems are generally designed to fail safe design principles and thus comprise of equipment and components which can fail to perform their function without presenting or significantly contributing to a hazardous situation.

The philosophy of this approach was agreed with NETMA and PANAVIA was tasked to focus on safety relevant items which definition for the purpose of this task has been defined as follows:

> Components are considered to be *safety relevant*, where a single failure would cause a hazard or which in combination with other failures would significantly contribute to a *hazardous situation*.
>
> A *hazardous situation* occurs when conditions arise which threaten the safety of the crew, aircraft, ground crew or third parties.

For this life extension task the term *safety relevant* covers both "Flight Safety Critical" and "Flight Safety Involved" incidents.

The following list states the Tornado flight systems, which are subject of life extension activities:

- Crew System
- Electric System
- Environment Control System
- Fire Detection & Suppression System
- Flight Instruments
- Flight Guidance & Control System
- Flight Control System
- Fuel System
- Hydraulic System
- Landing Gear System
- Pitot Static System
- Propulsion System
- Secondary Power System
- Weapon delivery system
- UK Armament Control System

The assessment of the safety relevance of equipment attachment structures was also part of the task. Each EDR performed the assessment of attachment structures for his area of responsibility and defined in conjunction with the relevant structure SDR appropriate measures for life extension, if necessary.

For financing and managing purposes, the whole life extension task was structured into 4 different phases, in which the level of involvement of the customer, PANAVIA and the PPCs and the supplier varies significantly.

**Phase A:** Identification of Safety Relevant Equipment and Attachment structures

**Phase B:** Nations review of Phase A recommendations and selection of items which should be subject of further life extension work

**Phase C:** Equipment extended certification activities

**Phase D:** Aircraft extended certification and preparation of a new PANAVIA Lifed Items List.

It is currently planned to finish the IDS subsystem life extension program at the end of 2002 including UK IDS life extension to 10000 FH and aircraft certification activities.

## Phase A

### Identification of Safety Relevant Equipment and Attachment structures

A process flow diagram for Phase A and B is given in the annex.

For each system, review of the existing *System Safety Assessments Reports* was the agreed approach to determine the safety or non-safety relevance of equipment according to their contribution to a hazardous situation.

As these reports have been issued a considerably time ago during the design phase of Tornado, new experiences and in-service arisings have also been taken into account as well as the effects of equipment failure on surrounding area and also where failure effects cross the boundaries of different subsystems.

Completeness was ensured by use of equipment lists (WUC) and illustrated part catalogues.

As a result of the safety assessments during Phase A, a *Flight System Hazard Analysis Report* has been produced by PANAVIA covering separately each subsystem.

For each safety relevant item a proforma was written by the Equipment Design Responsible (EDR), which provides informations of the equipment as for instance part number, DDP, qualification status, life limitations and overhaul requirements, its function within the subsystem, failure mode and hazard contribution. The proforma format ensured consistent information for all equipment and components for all subsystems. The overall responsibility of the content of the proforma rests with the SDR for each subsystem.

This report also provide a subsystem equipment list supporting the aircraft level certification for all items which are no more further considered as they are of negligible or low risk.

The final phase A report was subject of a system review meeting attended by NETMA, Nations and PANAVIA in order to further refine the safety relevance of equipment into one of the subsets of safety relevance as described below:

**CAT1:** Item Safety Relevant, qualification life limitations are critical and to be observed

**CAT2:** Item Safety Relevant but qualification life limitations are unlikely to be critical and further qualification or analysis to extend life should be considered.

**CAT3:** Item Safety Relevant, failure or malfunction of the item has no significant airworthiness consequences.

The general guidelines for determination of the safety relevance are presented in the following table.

| Severity of hazard | Catastrophic | Critical | Marginal (Major) | Negligible |
|---|---|---|---|---|
| Single failure Safety critical | CAT1 OR CAT2 | CAT1 OR CAT2 | | |
| Double failure common mode contribution | CAT1 OR CAT2 | CAT1 OR CAT2 | Not Safety Relevant | Not Safety Relevant |
| Double Failure Dormant Item | CAT1 OR CAT2 | CAT1 OR CAT2 | Not Safety Relevant | Not Safety Relevant |
| Double Failure Significant contribution / known problem | CAT1 OR CAT2 | CAT1 OR CAT2 | Not Safety Relevant | Not Safety Relevant |
| Double Failure Non-Dormant Item | CAT3 | CAT3 | Not Safety Relevant | Not Safety Relevant |
| > OR = Triple Failure condition | CAT3 | CAT3 | Not Safety Relevant | Not Safety Relevant |
| | Safety relevant | | Non Safety Relevant | |

This guideline chart cannot be regarded as definitive. It essentially required system specialist engineering judgment to establish the severity of any failure or failure combination consequences.

Additional, the following criteria have been considered in the categorization refinement review:

- Level of resulting hazard
- Probability of occurrence
- Subsystem design philosophy
- Dormancy
- Prevailing poor reliability
- Fatigue, endurance or any other life-limiting factor
- Impact on existing overhaul or maintenance

All components, which have not been categorized in one of the above categories, have been defined as *Non Safety Relevant* (**NSR**).

After each subsystem review, each proforma were reviewed and amended to include statements declaring the agreed safety relevant categorization together with the justification argument or evidence.

It was agreed at the end of this phase that equipment, which has been categorized as CAT3 or NSR, could be regarded as suitable for continued service in accordance with an On Condition lifing policy (OCM), which means a concept of maintenance that is free from scheduled actions. Maintenance action is taken only when an item of equipment is found to be defective. Exceptions to OCM are permitted only when a scheduled action is necessary to prevent a safety hazard, inability to meet safe life design criteria, or on grounds of economy to preclude expensive damage.

There are specific items, which need special consideration in terms of life extension:

## PANAVIA Standard Items

There is a big number of standard parts as connectors, screws, relays, switches, clamps etc. used all over the aircraft and commonly in different subsystems.

These items are normally not limited to flying hours but are specified to operations, cycles etc. There are also numerous items for which no life limitations exist.

The general approach for standard items is to reduce the list to items for which a life limitation was stated and which is not sufficient in view of the lifing requirements of this task. Additionally, items are considered which contain any degradable or perishable materials.

For these items an assessment on their safety relevance in above terms has been conducted and a categorization defined. This approach is shown in detail in a flow chart in the annex.

All other standard items, which are not safety relevant, are considered to remain on-condition.

### Electrical Wiring

Electrical wiring is largely used in the aircraft. It comprises of PANAVIA wire of various construction and materials, electrical connectors, loom supporting devices etc. The life extension strategy for wiring is discussed in Part 3 of this paper.

### Attachment structure items

The system engineers have reviewed the criticality of attachment structure items. It became obvious that not all structure items need specific actions for life extension.

Attachment structure items are generally designed to static stress conditions, loads resulting from crash and maneuver accelerations and stiffness requirements. Additional, the installation uses good design practices related to bend radii, hole edge distances and minimizing tension cleat loading. These criteria result in equipment supports, which are sufficiently robust for any normal aircraft lifing.

It is further considered that fatigue is not a dominating factor for

- Large bore Pipes in the air and Fuel subsystem
- Small bore pipes in the Hydraulic and Oxygen subsystem
- Flying Control Linkages

Whilst good design practices were used in order to reduce the risk of failures, in-service maintenance programs and inspections have to ensure that the integrity of such components due to corrosion, contamination, foreign damages etc. are not impaired.

Attachment structure items, which fall under the above, are no more subject to fatigue life extension activities.

All other components and specific equipment mounting structures are covered by the structure life extension task.

In Phase B now, the results of Phase A activities, laid down in the *System Hazard Analysis Report* formed the basis for the customer review of safety relevant items.

## Phase B

### Nations review of Phase A recommendations and selection of items which should be subject of further life extension work

During this phase NETMA and Nations reviewed the recommendations provided by PANAVIA within the *System Hazard Analysis Report* with their own specialists and took decisions on which safety relevant component they wish to support for extended certification.

The following criteria (beside others) might have been used by the customer for their decisions:

- Premature failures predominant in-service, i.e. the item does not generally achieve its current design life
- Financial and economic aspects as life extension will be too expensive or too long, low cost item, economic of overhaul, obsolescence arisings
- Modification is already planned to replace existing item

At the end of this phase the customer stated to PANAVIA which equipment should be subject of further life extension activities in Phase C.

## Phase C

### Equipment extended certification activities

A process flow diagram for Phase C and D can be found in the annex.

This phase consist in detail of

- requesting suppliers proposal for life extension of safety relevant CAT2 equipment which have been selected with a declared preferred option for life extension
- assessment of suppliers proposal and agreement on a technical and financial issues
- issuing the proposal to the customer awaiting authorization for start of work
- conducting of life extension technical work based on original specification requirements
- update of equipment DDP reflecting the latest qualification status and finally
- update of the System Hazard Analysis Report at conclusion of work within a specific subsystem

## Phase D

### Aircraft extended certification and preparation of a new PANAVIA Lifed Items List.

After completion of the equipment extended qualification activities, this Phase D covers the aircraft level certification activities.

Also within this phase, a new PANAVIA Lifed Items List will be issued, containing

- lifing requirements for all safety relevant items, which have not achieved full qualification evidence (with respect to the LE lifing requirements)
- mandatory overhaul requirements for the extended period

Part 3 will now describe in some detail for various subsystems the agreed specific approach for life extension and major findings and problem areas related to aging experienced during the life extension work.

# Part 3

# Subsystem Life extension approach and experiences

## Life extension measures

Most of the Tornado equipment were only qualified according the life requirements stated in subsystem and equipment specifications and only some equipment have already been subject to extended qualification. For many equipment, where no significant failure at the end of their original qualification was found, the final life is unknown.

The definition of the appropriate measure for equipment life extension was made in cooperation with the equipment supplier taking into account all information available from original qualification, in-service experience and future service requirements.

In principle the following questions must be answered:

a) Is the presently stated clearance still valid and is there any life potential for extended use beyond 4000 FH based on the existing or changed service requirements or under which conditions is the extended use acceptable?

b) Are there any limiting factors, as for instance aging problems, low reliability, economical reasons, which would not recommend further usage of the item?

The answers on both items will define future usage requirements.

Item a) will generally be investigated by

- review of the original qualification
- assessment of validity of original specified operational requirements, e.g. supported by OLM programs
- analysis
- conduction of re-qualification programs covering aspects such as fatigue and endurance testing (taking into account revised operational conditions, where agreed with the customer)

Item b) will generally be investigated by

- review of the in-service experience (reported failures, repair and overhaul experience, ...)
- review of MTBF data where available
- sampling of aged equipment from service, for which a full service history can be provided, where the consumed life can be established, which have not been overhauled and where the operational usage is representative for the normal fleet usage
- Master inspections of complete subsystems, which take place on one or several different aircraft, which have a service life near to 4000 FH
- Zonal inspections of critical zones, which have been defined for instance by the results of the Master Inspection or by available experience from service

Although difficult to say generally, the following table tries to give an overview on the measures which are conducted for a certain type of equipment / component. (however this does not mean that all measures are conducted in the same time)

| Equipment / Component | Life extension measure |
|---|---|
| Mechanical equipment | Analysis, fatigue test, overhaul |
| Mechanical / Hydraulic equipment | Sampling, overhaul, analysis, fatigue, impulse fatigue and endurance testing, definition of inspection and overhaul procedure |
| Electronic equipment | Sampling, definition of inspection and overhaul procedure |
| Pipework | Master and Zonal inspections, overhaul, definition of maintenance procedure |

| Equipment / Component | Life extension measure |
|---|---|
| Hoses (hydraulic fuel, nitrogen) | Sampling, replacement of high pressure and nitrogen hoses |
| Standard parts | Review, analysis |
| Wiring | Sampling, Master and Zonal inspections, definition of test concepts, definition of inspection and maintenance procedure |
| Attachment structure | Review, fatigue analysis, fatigue test |

Following, more detail informations are given for various subsystems:

## Landing Gear Subsystem

### General

Landing gear systems consist of very different type of components, as for instant load carrying structures, electric components (switches, relays, wiring and connectors, circuit breakers), mechanical / hydraulic components (piping, couplings, hoses, valves, swivels, actuators, manifolds), which are necessary to provide various system functions:

- Take off, landing and ground operation capability
- Retraction & Lowering and emergency lowering
- Steering
- Braking and anti-skid
- Arrested landing capability

Major system failure modes are:

- Collapse of gears due to structural failures
- Inability to lower gears by the normal and emergency system
- Loss of steering and braking
- Inability to provide arrested landing capability

Based on these safety critical failure modes, which have been identified in the *System Safety Assessments Reports*, a list of safety relevant equipment and components have been established.

It should be noted that the load carrying structure is designed according *safe life* principles, i.e. a crack free structure during operation is mandatory as no structural redundancies are provided. Therefore these components have been categorized either as CAT1 or CAT2, for which life extension will be assessed.

Other equipments for which life extension is carried out, are for instance amplifiers, valves, servo valves, main wheel brake, hydraulic swivels, foot motors, actuators, locks, nitrogen bottle, anti-skid generator, etc.

### Life extension philosophy

The basic philosophy of life extension of landing gear system components is

- Review of original qualification test results
- Theoretical assessments of the fatigue life using existing or in-service OLM measurements
- Extended fatigue tests of structural components
- Extended endurance and impulse fatigue testing of mechanical / hydraulic components
- Investigation of high aged items (sampling) regarding their physical condition after 4000 FH in service and investigation of problem areas
- Establishing of overhaul and/or revised equipment maintenance procedures which take into account aging problems as experienced during sampling and define preventive actions for further safe use
- Re-provisioning, replacement of items whose life cannot be extended

All subsystem components which are critical for the retraction & lowering function as actuators, locks, but also attachment lugs have already been subject to life extension activities and evidence for an extended use up to 16000 FH has been already demonstrated.

### Landing gear structure

Life extension of structural components of the landing gear and its back-up structure are of special concern, as it is known that the operational loading conditions have changed during the lifetime of the aircraft, for instance due to the increased aircraft masses, which are operated today.

It was therefore decided some years ago to carry out an extensive in-service operational load measurement program (OLM) to investigate the operational loading conditions on the landing gear back-up structure and the legs with the aim to review existing clearances and establish the basis for future life extension activities.

Two sets of gears were strain gauged and installed in a GAF and RAF aircraft where also the attachment and back-up structure was strain gauged. In total more than 325 flights have been recorded and assessment of the measured data is in progress.

As these aircraft were operated in different squadrons, by different pilots, with different masses and different store conditions, the loading information provides a good cross-section of the operational service loading of the landing gear and its back-up structure in different air forces.

Initial results of these investigations showed that the loads are partially much more severe than originally anticipated.

The influence of these in-service loads on landing structure clearances is a major part of the life extension activities. As the Tornado Nose Landing Gear (NLG) was only tested up to the original life requirement of 4000 FH, it was decided to carry out a new fatigue test taking into account the in-service loading conditions, which take place on MAFT (Major Airframe Fatigue Test specimen).

For the Main Landing Gear structure, a theoretical assessment of the fatigue clearance has started and later this year, when this assessment will have been finalized, a decision on the way forward will be taken, whether or not an additional fatigue test will be required in order to provide the best possible clearance statement.

## Landing Gear Equipment

Landing gear equipment life extension base on the topics already described above. Equipment suppliers have defined their requirements by reviewing own experiences of the in-service behavior of their equipment.

Mostly they have required different numbers of high aged equipment from service for investigation of wear and tear, corrosion, fatigue cracks, etc.

Review of the original qualification and test results and the results of the sampling investigations were primarily used to establish whether life extension of the equipment is possible or not. If life extension seemed possible, the method, which the supplier has agreed with the SDR , is applied.

Aging problems on equipments, which have been identified so far (wear and tear, leakage), will be covered by required overhaul at the end of the original design life of 4000 FH before further use up to 8000 FH will be allowed. The required overhaul should also identify the serviceability of that equipment as being the prerequisite for further use.

## Aging and age related problems

It has been already shown in the chart (Fig. 2) that the failure rate for aging related failures has increased over the last 10 years by approximately 50%.

Wear and tear and leaking are the major reported failures. For extended use it is necessary that the problem areas are identified and addressed by modifications, inspections and maintenance.

Beside the life extension program, a very thorough inspection for corrosion, wear and tear of high aged Main and Nose Landing Gears, which were in service for more than 15 years, has been carried out

Corrosion and wear has been found in some areas, for which repairs are defined. But it will be also important to address these areas by inspections and a revised maintenance policy.

Two areas were found which are of special concern as they demonstrate what can happen if maintenance procedures are inadequate in addressing aging effects in time.

These areas are not directly inspectable and would require partially disassembly. As existing maintenance procedures do not require disassembly of the gears to inspect these areas it could happen that the gears are for years on the aircraft or in stock and the condition of components in certain areas, which are not visible inspectable, are not known:

1. Severe corrosion has been found on the outside of the turnable MLG shockabsorber, Fig. 4, which is made of high strength steel 300M, in an area, which is covered by the Main Fitting and belongs to a closed volume where moisture could stay for a long period of time. Outside of this area no corrosion was found on the shockabsorber.

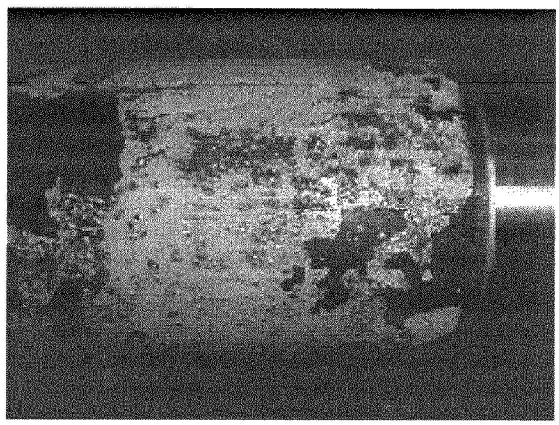


**Fig. 4:** Corrosion of MLG Shockabsorber

It is considered that corrosion is to be due to localized attacks of the base metal as a result of prolonged exposure to moisture. It is assumed that moisture in this volume is a result of condensation when descending from altitude. The effect of corrosion with regard to stress corrosion and fatigue has been reviewed and not considered critical providing an inspection program is introduced and the component repaired in time. This is important as due to the brittleness of the material 300M, any crack in this area could cause immediate fracture.

An inspection procedure has been issued which address this area in a timely manner.

2. Severe corrosion has also been found at the NLG Steering Collar, Fig. 5.

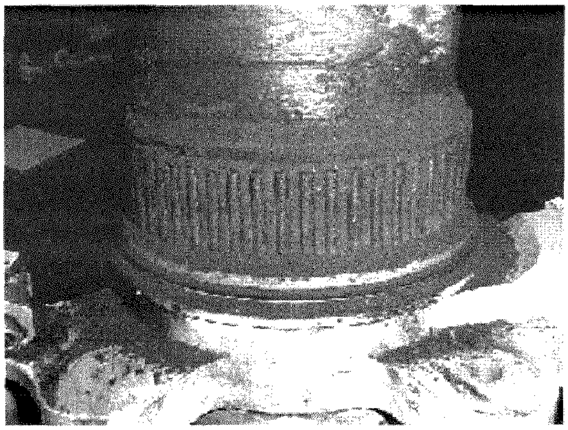


**Fig. 5:** Corrosion found at the NLG Steering Collar

Access to this area requires also disassembly of the gear. As water was found in this area, it is considered that the sealing becomes insufficient with time. The corrosion became so big that the torque moment required to turn the slider increases far beyond the specified values.

Fortunately, the investigation revealed, that repair is possible, if the repair is applied in time.

*Electronic components*

All electric and electronic components are sufficient for life extension with the exception of the Anti Skid Control Box, which cannot be life extended due to aging problems due to increasing number of failures of the PCB (printed circuit boards) soldering joints. A repair is not possible because the components and the board is dipped in plastic coating. The exchange of PCBs is not cost effective because the box shelf represents only marginal value of the total box price.

Additional there are other aspects related to the *in-service history and built standard* of Landing gear components.

Unfortunately it has been experienced that the in-service documentation for landing gear components are not always available. This is considered to be a very critical situation as for instance landing gear structural components are of safe life design with no backup available. The ignorance of service history and consumed life creates many problems, which need to be addressed urgently otherwise the airworthiness is difficult to control.

In case no history can be established any more, a risk assessment has to be performed for each gear and replacement of items before reaching its final life could be necessary. This situation will become more critical if the life extension activities results in lower clearances for structural components than original stated due to different in-service loading conditions.

## Fuel Subsystem

### General

The major function of the fuel system is to provide engine fuel supply under all normal operational and emergency conditions.

Two major safety critical system failures as stated in the *System Safety Assessments Report* are

- Insufficient engine fuel supply
- Fire hazard due to fuel leakage

Based on these system failures, equipment and components have been identified whose failure would lead or contribute to these system failures.

Additional, the arrangement of the fuel system within the aircraft fuselage in conjunction with the forced ventilation of compartments / ducts during aircraft operations has been considered for the assessment of the fuel system component safety categorization. Consideration of the general arrangement and operational aspects has revealed that fuel leakage or fuel mist can be carried from the leaking component, which may be located in an area without fire / explosion hazard, into areas with potential ignition sources.

### Life extension philosophy

The basic philosophy of life extension of fuel system components is

- Definition of inspection and overhaul procedures for safe pipework operation beyond 4000 FH up to 8000 FH. This will be supported by
    - Master inspections
    - Zonal inspections
- Sampling and re-qualification testing for fuel hoses
- Review of original qualification test results and compare to future operational usage requirements
- Analysis
- Extended qualification by endurance, vibration and pressure cycling tests
- Establishing of future maintenance policy for equipments

Following, (preliminary) results from the life extension work will be presented.

## Fuel system Pipework

Fuel pipework is of special concern as fuel leakage due to a broken or leaking pipe or leaking coupling could significantly contribute to safety relevant hazards. The customer requirement for fuel system pipework was that PANAVIA should define inspection / overhaul procedures, which ensure that the safe operation of the pipework is ensured up to 8000 FH.

The procedures will be defined by analyzing the findings gained during *Master* and *Zonal Inspections*, which have been performed on two high aged aircraft from the RAF and GAF (fleet leader) during aircraft depot inspections (DI).

The following activities have been part of the *Master Inspection*:

- visual inspection of all fuel system pipework items, associated fuel system couplings and support / attachment parts
- examination of critical elements, which have been defined prior to the Master Inspection. Special emphasis was given to surface damages, corrosion, connection and attachment areas, dimensional checks
- proof pressure test of each critical element
- X-Ray examination of all welded and brazed joints
- Fluorescent penetrate tests of all welds
- NDT investigation of critical items which experience more than 200 °C during service in order to detect materials alteration due to the exposure to high temperatures
- Examination of seals
- definition of inspection areas and maintenance measures which should be considered for the final pipework inspection / overhaul procedure to be applied on all aircraft beyond 4000 FH

*Zonal Inspections*, which took place on two RAF and two GAF fleet leader aircraft, based on the findings of the *Master Inspection*. They should confirm the findings of the Master Inspection and provide additional practical evidence for definition of the final pipework Inspection / Overhaul procedure.

Master Inspections have revealed that there were no cracks and no problems with welds. The only problem related to aging was corrosion.

The results of these investigations can be summarized:

- Corrosion was detected on 35% of all pipework items; 14% of these items were classified as "*reusable*" and 21% as "*to be scrapped*"
- 40% of all pipework items inspected in the ventral duct area have shown corrosion
- 28% of all pipework items inspected in the spine area have shown corrosion

Fig. 6 shows the propagation of intercrystalline corrosion in the fuel pipe structure (Aluminum) in the marked area.

The findings during the master inspection require inspections and an optimized maintenance policy. Fortunately, the degree of corrosion, which was found on pipes and couplings, need no immediate replacements due to an imminent safety hazard but those pipes which have been classified as "to be scrapped" have been replaced.

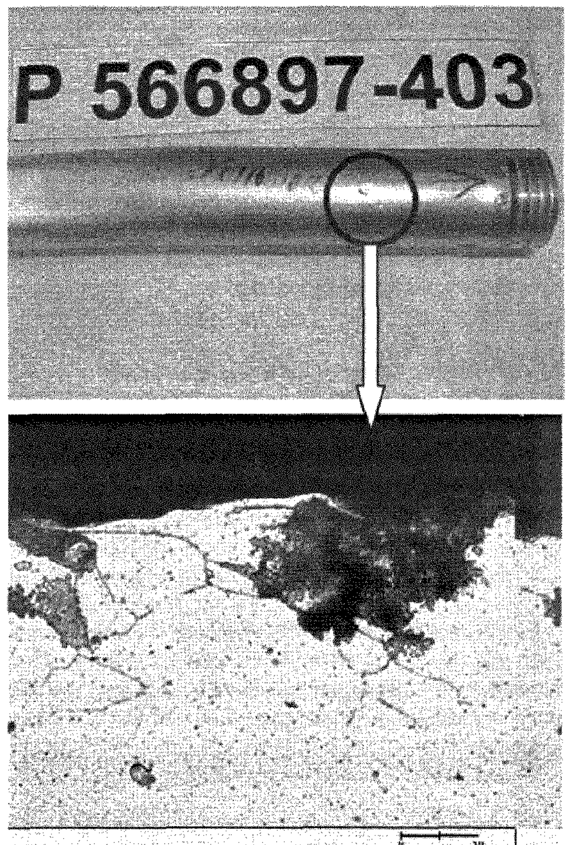



**Fig. 6:** Corrosion on a fuel pipe and Micrograph Examination of corrosion mark

## Fuel flexible Hoses

Flexible hoses using Teflon or rubber have been defined as CAT 1 and they will be replaced after their certified life is reached (Teflon hoses after 4000 FH, rubber hoses after 6 years). This is a preventive measure to prevent any problems with material aging and consequently leakage.

For fuel flexible metallic hoses the supplier was tasked to carry out sampling and qualification testing.

A sequence of different testing will be performed, which comprises of

- visual inspection and dimensional check
- proof pressure and leakage tests
- x-ray and fluorescent penetrate examination
- pressure pulse test
- vibration test
- microscopic examination

The results of these tests are still outstanding.

### Fuel Valves

During the Life Extension Program those valves were considered

- where high stresses are caused by medium pressure / hot fuel environment etc.
- where in-service experience had identified units to be safety critical and
- which are installed in areas where any leakage will cause a fire / explosion hazard. On-condition operation of these valves beyond their certified life of 4000 Fh could cause additional safety hazards (fire / explosion), since the failure rate which has to be considered for these valves beyond their certified life is not known.

Each valve assembly consists of the valve and the actuator assembly. As far as the valve assemblies are concerned, the suitability for life extension is related to the valves only. Methods for extending the life of the valves beyond 4000 FH will be defined by the Supplier by means of Master Inspections performed with sample units. Part of this Master Inspection are the

- examination of all parts for corrosion, damage, wear and tear
- check of all rubber and elastomeric parts for hardness and quality
- examination of all critical parts with non-destructive and X-ray methods (where applicable)
- Direct comparison of the condition of the individual sample units.

In the event that the approved method of achieving the required 8000 FH Life Extension should entail Life Extension Qualification Testing, then this testing in general will comprise endurance and vibration testing

The Supplier has declared all actuator assemblies unsuitable for Life Extension due to their suspected poor in-service MTBF and known design limitations. He proposed therefore to replace these actuator assemblies with superior equipment. These consist of a permanent magnet motor, which negates the use of the clutch assembly currently used on the Tornado actuators and offers improved switching characteristics with self-cleaning action. The new actuator will also offer better reliability than the existing one, consist of a hermetically sealed electrical connector and provides better EMC performance.

### Fuel subsystem equipment

Many equipment from the fuel subsystem are part of life extension activities as they have been classified as safety relevant. These items are manly different type of pumps, flexible sliding joints, thermal diffuser, etc.

Current results of the life extension process from sampling, analysis and re-qualification revealed that most of these equipment could be life extended. The DDPs will state the revised clearances and additional requirements for overhaul in some cases.

For the double-ended boost pump, the electrical harness, which is a safety critical component (high voltage power line which is submerged in fuel), shall be replaced after its original design life limits are reached.

Life extension of fuel coolers requires surge pressure measurements to establish in-service realistic conditions.

### Fuel Tanks

The Tornado fuel tanks consist of bladder type cells of different construction. The tanks are <u>not</u> part of the life extension program as PANAVIA has already recommended to maintain the tanks in accordance with an "on-condition" lifing policy with no significant adverse effect on the flight safety of the aircraft, although reliability may be degraded.

## Electrical Wiring

### General

Electrical wiring is used all over the aircraft in all flight systems. Cable looms are distributed in and through many zones of the aircraft, where different environmental conditions exist as for instant heat, moisture, in case of leakage fuel, hydraulic oil, but also vibration, acoustic, etc. All these environmental effects need to be assessed for life extension of the electrical wiring.

The general design philosophy of the electrical system is as for other flight safety critical systems, that no single failure does cause a hazardous situation. Therefore the wiring system is categorized as CAT3.

However wiring degradation with time is a significant problem as if not maintained it could cause a hazardous situation.

Wiring can fail in two ways:

a) as an open circuit conductor and

b) with a short circuit to another wire or frame

Case a) is not considered to be safety critical as flight systems are of fail-safe design. It is assumed that any functional failure within a flight system caused by the wire failure will be found by functional on aircraft tests.

Case b) is the much more significant failure as a short circuit to a metallic component or another wire can produce an electrical arc which in turn can cause a hazardous arcing condition.

The probability of this failure condition is considered to be quite small, as a series of correct conditions need to be present in the same time. But with increasing age of the wiring this probability will increase and thorough inspections need to be placed in order to slow down the increase.

## Life extension philosophy

It has been evaluated that life extension of wiring by extended qualification activities may not lead to a life increase, as it could be shown that the consumed life is dependent on many factors which accelerate the aging of the wire insulation. Such factors are for instance the location, contamination by aggressive fluids, heat but also maintenance activities by which the wire looms are manipulated.

Therefore, the definition of a most cost-effective maintenance policy is the basic strategy for Tornado wiring life extension.

The following engineering activities are performed and methods investigated:

- Assessment of the suitability of the RAF **WIDAS** (Wire Insulation Deterioration Analysis System) as a sampling tool that provides for a preventative maintenance program of timely wire replacement.
- Zonal analysis (ZA), identifying the risk of wiring failure on a zone by zone basis considering the environment and other components installed in this zone. The main objective of these activities is to identify risk areas that would allow the definition of dedicated maintenance policies. These areas could then be subject to further investigation by other methods. The definition of risk areas would also remove the need of further investigation of low risk areas and so reduce costs.
- Infrared Thermography (IRT) for detection of wire failures or high-risk conditions will be investigated.
- Wire extended qualification testing in conjunction with the supplier. These tests consist of dry and wet arc and thermal life tests. Tests will be conducted by an independent laboratory and tests results send to the wire manufacturer for assessment.
- Investigation of other methods including high voltage (HV) testing.
- Review of other existing wiring policies within airlines, wire manufacturer, etc.

## Electrical wiring survey

An investigation of the wiring condition in a large number of aircraft (49) has been performed in order to assess the state of wiring within different aircraft, which are operated in different air forces, at different environmental conditions, which are subject to different maintenance, etc.

It has been established that wiring deterioration is dependent mainly on the four topics:

a) Applied maintenance policy:
   - Better quality of preventive maintenance (removing of oil leakage, dirt, ...) results in better condition of the wiring system.
   - The use of de-humidifiers has a significant, positive influence on the level of corrosion.

b) Operational environment:
   - Aircraft operating under coastal or wet climatic conditions have shown more electrical and general corrosion.
   - As the aircraft spend only 2% of their total life flying, the conditions of the hangars are important regarding deterioration effects: warm and dry hangar conditions have positive effects compared to the aircraft standing outside.
   - Long duration flights at high altitude in dry air lead to a better state of the wiring system compared to for instance trainer aircraft, which perform much more cycles (take off and landing) and fly in lower height with much higher air humidity

c) Materials used in the wiring system
   - Embrittlement and dry-out of tie wraps exacerbate chafing at tie wraps position, especially where tie wraps have been applied too tightly when fitted, which could be the result of unsuitable tooling.

- Use of heavy plastic spiral wrapping as a sleeving on flexible looms is unsuitable as encouraging insulation cracking at the point where the flexible part leaves the main loom.
- Perished rubber sleeves if they perish allow the wiring loom to open up, which could lead to increased chafing and rubbing
- Use of heat shrink material is not suitable as flexible looms become hard and can make wiring looms rigid.

d) Time in service:

- It has been established that contamination of the wiring system by dirt and oil can be related to the aircraft age but is also dependent on the frequency of cleaning activities

The findings of this survey will be used to establish recommendations for further usage of the wiring system for a limited period of time.

# Flight Control System

### General

The flight control system consists of various components, as for instance hydraulic and mechanical actuators, ball-screw actuators, electrical motors, computers, wiring, switches, control rods, lever, etc.. As for other systems, the effect of failures of any FCS component on flight safety hazards has been investigated taking into account the system hazards as defined in the safety analysis documents.

The major problems, which have been identified for many components, are related to fatigue and endurance. Failures due to wear and tear are the most reported service failures (Fig. 2).

### Life extension philosophy

Although the FCS consists of a variety of different components, such as mechanical/hydraulic as well as electric/electronic components, life extension of these equipment will base on the following general work:

- Sampling of high aged ex-service units
- Analysis of the MTBF data.
- Theoretical analysis of life potential
- Re-qualification tests (endurance, fatigue)
- Investigation of aging effects on materials and components by sampling
- Establishing of overhaul, maintenance procedures
- Replacement

### Mechanical, hydraulic components

The majority of safety relevant components have equipment DDPs, which define operational and other life limits.

Life extension of hydraulic components such as actuators will be based on sampling of high aged equipment, theoretical assessment of possible further life potential, re-qualification programs where possible and overhaul at defined intervals.

Life extension of mechanical components as for instance linkages, control rods, control stick rods, levers and rudder pedal mechanism are covered by the structure statement (chapter 2) and no fatigue life extension activities are necessary.

### Flight Control Computers

The Flight Control Computers are designed and constructed according to MIL-Specs and safety requirements and consist of a triplex multi-channel computing system in two computer boxes (Lateral and Pitch), Fig. 7 (CSAS computer).

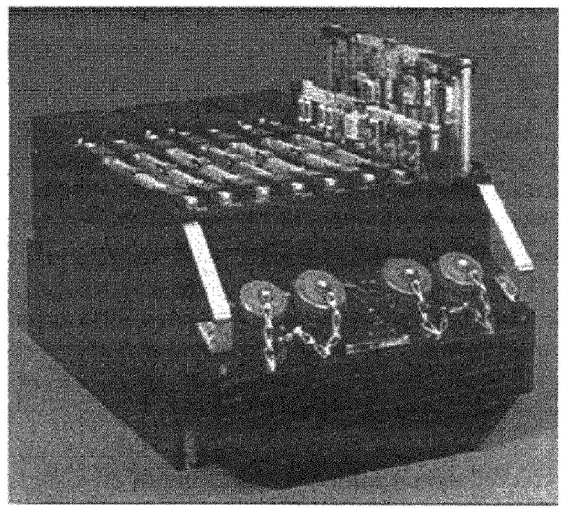


**Fig 7:** CSAS computer

The technology used in these computers is developed in the seventies and is therefore no longer state of the art. In-service support becomes more difficult the longer the computers will stay in service.

Within the life extension program the supplier have investigated various computer, which have been in service nearly 4000 FH. The general result of the survey is that only partially degradation of equipment was found which could be directly attributed to aging.

Some problems have been found which could be regarded to

- poor standard of repair and
- the application of conformal coating

but it is considered that these findings will not degrade the functional performance and also reliability.

Additional, minor damages were found, which could be caused by mishandling during maintenance work. It is therefore proposed to review the current handling practices so that no undesirable mechanical or electrical failures are introduced, which could have an influence on the performance.

The survey of aged electronic components has revealed additional problem areas as following described.

## Aging problems with electronic components

- *Relays*

Relays are not pure electronic components but consist of many mechanical parts like springs, special contacts, coil and printed circuits and all parts are subject to continuous aging.

Relays are designed for a certain (high) number of operations and the degradation of the contact will result in an increase of contact resistance.

The relays which have been investigated in-depth were found in a good condition and replacement is only proposed if any failure is found or if they are physically damaged.

- *Potentiometers*

Variable resistors include mechanical and "Pertinax" parts which produce an electronic resistor by moving a mechanical part on the surface of a small "Pertinax" part.

During the aging process, environmental conditions and load could have an adverse effect on the performance of this type of resistor, which might result in a negative influence on the Build-In-Test-Equipment (BITE).

Investigation of aged potentiometers has revealed in some cases a degradation of the case seal and also the existence of hairline cracks, which would under certain conditions allow the ingress of moisture.

It is therefore proposed to investigate the general mechanical and functional condition of these components and replacement, if the component is defined as unserviceable.

- *Capacitors*

Capacitors of different style are used.

Aging problems have been experienced for instance with 'castanet' wet tantalum capacitors. The major findings are

- change in state of the liquid electrolyte, in which gas bubbles have been found
- loss of the electrolyte which results in corrosion around the anode/cathode seal, which results in a reduction of the capacitance value (μF).

- *Printed Circuit Boards (PCB)*

PCBs in old computers are partly wired. Furthermore, they carry connectors for the Dual Card Assemblies.

Problems have been experienced with surface leakage currents, which could be a dormant failure, contamination and condensates in conjunction with humidity.

Also local delamination of the top layer of the PCB was found in areas where solder pads have been repaired and probably excessive heat were introduced. It is therefore considered that the delamination is attributed to poor standard in-service rework.

Additionally, aging of the PCB´s solder joints have been found, as shown in Fig. 8.

- *Connectors*

Similar problem as described for the PCBs have been experienced with connectors, which have connections to the PCBs and to the wiring via solder joints.

- *Wiring (within Computers)*

The major problems with wiring within the computers are cable chafing with nuisance effects.

- *Resistors*

It has been experienced that aging could change the tolerance of resistors. Therefore the logic circuit which the related resistor belongs to will change and this can produce failures and No-Go´s during BITE.

- *Transistors, Integrated Circuits (ICs), OP-amplifiers*

Load-Life during different usage of the aircraft and maintenance may stress these electronic components.

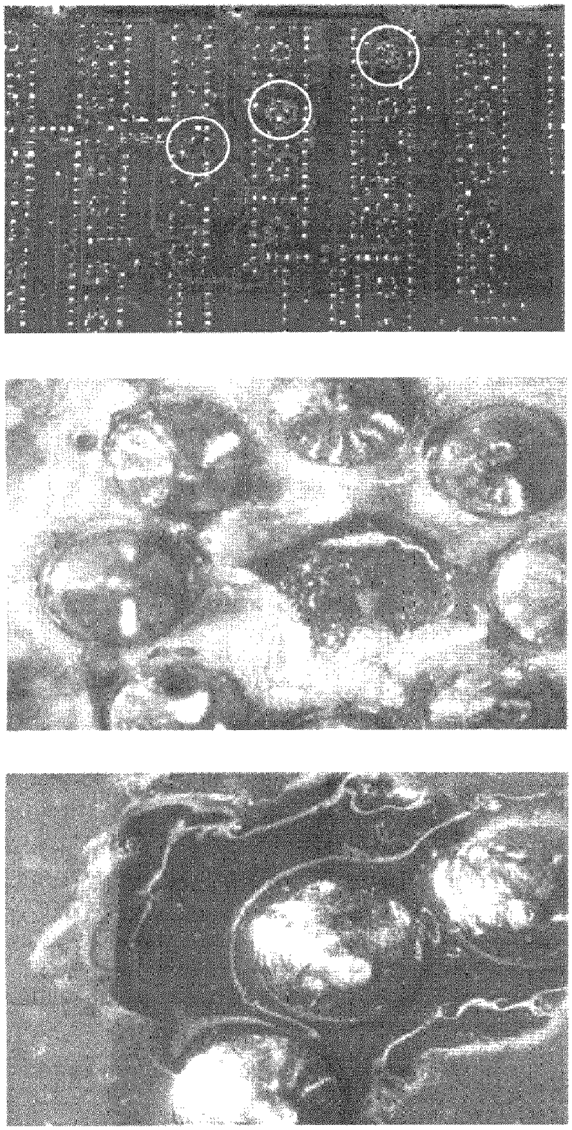


**Fig. 8:** Aged solder joints of PCB´s

## Influences of operational Environment

The Tornado aircraft is operated by different airforces in different environmental conditions. The Tornado is also used as a Navy variant. Therefore very different operational conditions exist, which have a different influence on aging.

The following should describe briefly the major environments which contribute to aging of electronic components of the Flight Control Computers and which influence is assessed during the life extension work:

- BITE-Runs (Preflight/First Line)
- High altitude flights
- Power ON/OFF cycles
- Different Weather conditions such as high/low temperature, high humidity, lightening, salty atmosphere

An example for corrosion due to environmental influences is the corrosion around power resistor leads found due to Doghouse - environmental influence, Fig. 9.

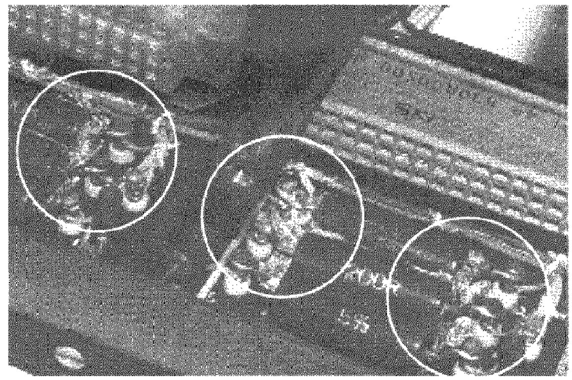


**Fig. 9:** Corrosion around power resistor leads

Additional, the following influences could have a degrading effect on component integrity

- *Operation in Navy / Air Force*

  The Tornado is designed for different combat roles. The equipment, which is operated within Navy aircraft, is exposed to salty atmosphere and therefore the effect of corrosion becomes more critical for these types of aircraft as they are often flying over ocean.

- *Wars*

  Wars like the past Gulf and Bosnia will have special influence as normal flying in squadrons from home base. Heavy stores and more agile flying will stress not only the airframe but also the electronic equipment (cards, boxes, wiring, connectors).

- *Parking*

  Normal Parking of A/C in a shelter with covers on all potential sensors like the ADD-Probe is needed for a long life. Parking on and outside airfield and sensors not covered is a potential hazard for fast aging of electronic equipment and their sensoric system.

- *Storage*

  Storage of electronic equipment is not the same as for mechanical parts. The electronic items will age under these conditions as well as under normal usage.

To investigate the life consumption of electronic parts, the correct service history need to be assessed. Therefore it is essential that configuration control is possible for all critical equipment and components.

### Life extension of FC computer by overhaul

As for other equipment, the supplier will give a guarantee for his equipment only for usage within the specified operational and life limits.

Extended qualification of the Flight Control Computers was discussed to fulfill the customer requirements for life extension. But due to the high costs of this re-qualification process a different approach was examined with the supplier customer.

It was decided that life extension of the FC computer will base on overhaul after the equipment has reached its certified service life.

The procedure base on knowledge of the supplier maintenance work and by sampling of high aged service equipment:

- Survey of early manufactured computers to identify time dependent effects, which will be used to produce test and inspection procedures
- Research failure and repair records required from service
- In depth investigations of
  - PCBs
  - Connections
  - Active components (i.e transistors)
  - Passive Components (i.e capacitors)
  - Case structure

These investigations will be used to establish overhaul procedures for the different type of computers. These procedures are currently under strong discussion with the customer and the suppliers and the following general measures are foreseen:

- Detail examination of the physical condition, identifying of aging problems and components which need to be replaced
- functional check
- cleaning
- EMC Test: Early standards of the Flight Control Computers are EMI hardened. Therefore an EMC test will be conducted after the overhaul procedure has been successfully performed.
- Conducting of an Automatic Test Procedure (ATP)
- Release to service

### Obsolescence of electronic components

Review of the availability of electronic components for the FCS computer revealed that the obsolescence problem becomes more and more critical.

To overcome this situation the following options are in discussion:

a) Lifetime buy of components, which will be no more available in the future. Presently up to 50 electronic components are no more available on the market. This concerns especially FET switches, Power Transistors, PROMs, Optic couplers, special A/D converter, TTL components, Resistor - Thickfilm networks, etc.

b) Redesign using actual standards of components and modern production processes to achieve compatible equipments on LRU level.

c) Development of new concepts, new technology with new hardware as well as software, together with limited measures related to alternatives a) and b) for the interim period of years until completion of introduction in service.

Presently the way forward is not yet decided and will base on the experience and requirements established within the life extension program

## Hydraulic System

### General

Safety relevant hydraulic subsystem equipment and components have been identified based on assessment of the *System Safety Assessments Report.*

The major subsystem failures modes are

- Loss of hydraulic power and hydraulic flow which would lead to loss of aircraft control
- Loss of emergency equipment function required in the event of an emergency

The evaluation of age related system failures, Fig. 2, have shown that leakage is the most significant reported in-service occurrence, which is well understood, as endurance of hydraulically functional equipment will lead over time to a degradation of the seals. This means that the older the equipment stays in service the often unscheduled maintenance will be required to address these problems.

### Life extension philosophy

The life extension philosophy for the hydraulic subsystem equipment and components base mainly on sampling and re-qualification of equipment and the definition of maintenance and overhaul requirements.

A Master Inspection for investigation of the condition of hydraulic subsystem components in aged aircraft is currently not performed.

### Hydraulic Subsystem equipment

Many equipment and components have been selected for life extension as for instance pumps, pressure switches, accumulator, valves, self sealing couplings, reservoir, slide and swivel joints, etc.

Aged equipment from service have been delivered to the suppliers for detail investigation of the condition after 4000 FH in service and to state the serviceability for further usage.

Most of the hydraulic equipment will be re-qualified by extended impulse-fatigue tests, endurance and fatigue tests.

Current results indicate that most of the equipment, which are subject to life extension, will be suitable for 8000 FH. An overhaul after 4000 FH will probably be required by the supplier after the original specified life is reached.

During this overhaul the units will be resealed and areas, which have shown wear and tear needs to be repaired, if necessary.

Aging of equipment (corrosion, wear and tear) as well as contamination of e.g. filters need to be addressed by appropriate in-service maintenance procedures.

### Hydraulic piping

Fatigue life of hydraulic pipes is not of concern. Therefore no activities for life extension are foreseen.

Aging effects, as corrosion of the high-pressure steel pipes need to be addressed by appropriate maintenance activities. Nevertheless, leakage is not considered as safety critical and severe leakage will be detected early by pre-flight or post flight checks.

### Hydraulic hoses

Life extension of hydraulic hoses is in discussion and there will be different solutions for high and low pressure hoses. It is likely that high-pressure hoses need to be replaced after normal service life.

Significant aging effects on high aged hoses have not been experienced.

## Environment Control System

### General

The ECS subsystem consists of a number of sub-subsystems as for instance cabin pressurization, engine anti-icing system, temperature control system, windscreen heating system, etc.

Again, based on the original *System Safety Assessments,* safety relevant equipment have been identified and the customer has defined equipment for which life extension should be carried out.

Mainly all equipment and components, which belongs to the high pressure and high temperature part of the ECS system and subject to engine bleed air conditions are critical.

The components which belongs to the low pressure ECS part are categorized as non safety relevant. No specific life extension measure are foreseen and also no investigations into aging problems are performed.

### Life extension philosophy

Life extension measures for ECS equipment and components are basically:

- Sampling of aged equipment
- Stress, fatigue analysis
- Definition and conduction of re-qualification tests
- Master inspection for critical zones of intercooler ejector line
- Definition of maintenance procedures

### ECS Subsystem equipment

Equipment, which is subject to life extension activities, are for instance valves, pre-cooler, reservoir bottle.

These items are subject to life extension measures as defined before. The investigation of aging effects on equipment is performed during sampling of high aged components.

### ECS ducting system

A Master Inspection is proposed, which should investigate the critical zone of the intercooler ejector line.

The main objectives of the Master Inspection are

- Investigation of installation aspects to support of life extension of ducts and critical bellows including investigation of bellows inner condition to enable decision for re-qualification testing of bellows / structural interface
- Investigation of the physical condition related to aging aspects, mainly external corrosion beneath the insulation

The investigations have not yet started.

# Part 4

# Conclusion

The Tornado life extension program was defined to extend the life of the aircraft up to 8000 FH. Within this program, which is still in progress, a clear process has been defined for subsystem life extension, which focuses mainly on safety relevant equipment and components.

Part of this process are investigations into the aging condition of equipment and components, which are near to the end of their certified life. The results of these investigations, mainly got by sampling of aged equipment, Master and Zonal Inspections, are used to support the definition of requirements for further extended use of equipment beyond their certified life.

Aging problems, such as corrosion, wear and tear, leakage, or degradation of electronic components, etc. have been identified in many subsystems but fortunately none of them required immediate action to prevent a safety critical hazard. Aging problems will be addressed by overhaul, repair or replacement actions, dependent on the condition of the item investigated, but also on factors like economics, spares availability and overall fleet management.

Experiences we made during the time carrying out the life extension program:

- Supplier are mostly unaware of the in-service experience with their equipment

- Strong and time consuming discussions were necessary between customer, SDR and supplier to define a by all involved parties agreed approach for life extension for certain equipment

- Service history and life consumption cannot be provided for many equipment, which means that the point where the equipment should be subject to agreed life extension measures (i.e. overhaul, replacement of the complete unit or detail parts) is difficult or even not possible. Recording equipment life woulf help minimising operating costs as the full performance of the equipment can be used.

- Non availability of service documentation resulted in the fact that provision of suitable loan equipment for investigation at the supplier was difficult to locate.

- The effort unertaken to re-qualify equipment beyond their original certified life is often significant. Since in the Tornado program most equipment have in nthe past only been quaified up to their original specification requirements it should be considered much more cost effective, if the equipment would have been tested to failure ideally just after normal qualification to spec has been completed.

As general conclusion it can be stated that life extension of Tornado subsystems is successful as in many cases the customer requirements can be met.

PANAVIA and their supplier have or will clearly specify overhaul, inspection and maintenance requirements for equipments which failure would be hazardous and which should be mandatory for further safe operation. Aging aspects will be covered by these inspection requirements.

**References:**

1. PDT 1299: TORNADO Life Extension Process Definition Document
2. PDT 1299 Phase A Report
3. Various reports and presentations of inspection results

# PDT 1299: Life Extension Phase A/B

## Phase A – PANAVIA / NETMA / NATIONS

Compile lists of equipment for each system (from WUC list) → Using original System Safety Assessment Reports → Identify failure modes of system leading to a hazardous situation → Identify equipment contributing to each hazardous situation

→ Prepare a proforma for this equipment → Produce Phase A report → Review conducted -Phase AII decided → Phase AII categories defined

## Phase AII – PANAVIA / NETMA / NATIONS

Each system proformas reviewed → Determine safety relevance category → Update each proforma → Update each system report

## Phase B – NETMA / NATIONS

System Reviews → Equipment Assessment → Decision on which to extend life → Phase B meeting report → TF1/2/3 prepared defining equipment to be funded

# Life Extension Phase C & D for Flight Systems &Equipment

**(Items shown in bold letters indicate customer / operator dependency)**

## Phase C

TF2 prepared

costs defined to equipment level → **Nations consider technical solution and cost effectiveness** → **TF3 issue authorising Phase C activity for chosen items**

→ PANAVIA authorises supplier to commence work → **Operators provide item(s) required** → Supplier conducts assessment and/or calculations / qualification requested → Supplier produces report → DDP for extension issued to PANAVIA

## Phase D

Equipment NSR & 2.5.3 identified → **Interim 4500 FH aircraft Life Extension DDP supplement produced & issued** →

→ Lifed items identified → Items not required to be extended are identified → PANAVIA Lifed Items List to be updated progressively

# Process for identification of Life limited, Safety Relevant PANAVIA Standards