EVOLUTION OF AVIATION ENGINE LIFE MANAGEMENT IN CIS

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ABSTRACT

Evolution of Aviation Engine Life Management in CIS is considered. Condition based maintenance (CBM) has recommended itself as the most reliable and efficient way for aviation engine life monitoring. Some important for successful CDM problems are discussed.

INTRODUCTION

Aviation engine life is one of the most important characteristics of the engine competability and affordability connected with both safety and efficiency of its utilization.

Some different strategies can be used for aviation engine life monitoring [1].

CBM is the concept at which an engine is allowed to operate without shop visit for an unlimited time, according to its condition. It is the most economically efficient way of life time management for expensive and complex equipment. But it is important to keep critical engine parts and components which defects can lead to hazardous effects in safe life limits. So for such engine parts hard (fixed) time maintenance must be used. For minor components which defects do not lead to any significant losses in safety and efficiency (including readiness) operation up to a defect may be used. Airliner can also use some additional approaches – reliability monitoring (to keep fleet reliability in some acceptable limits), opportunity monitoring (simultaneous maintenance of different engines from the same aircraft or different parts of the same engine), monitoring for repair cost reduction, etc.

So speaking about CBM for aviation engine in practice we mean the combination of mentioned approaches which bases on CBM for the engine as a whole and must provide safety and optimized balance between the engine life time and other characteristics – reliability, maintenance (including repair) cost, engine price, etc.

The engine life management has been changed along with development of new engines generations with increased life and reliability as well as with changes in economic conditions and more sharp competition.

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Engines of the first generation were developed for the short life, which could be increased after successful life tests and elimination of the defects appeared during tests and operation. Life tests were performed as flight tests of leaders or engine rig tests using service cycles (in actual time).

In USSR from the beginning of 70-th engines were developed for the full (high) life. Nevertheless for a long time engine maintenance was performed according to hard time between overhauls (TBO). The allowed service life was confirmed by accelerated mission tests (AMT) of the engine and its critical parts. Critical parts lives could be confirmed by engine tests or by tests at laboratory facilities. However the scope of engine tests remained relatively high. Engine must be removed from the wing independently from its condition. Such approach ensured safety but was not economically effective.

So at the beginning of the 90-th when economy in the former Soviet Union was moved to a market the methodology of aviation engine life management was significantly changed and it was reflected in airworthiness regulations and other regulatory documents. It was done for providing more complete utilization of the engine life capabilities, achievement of competable engine and its critical parts lives at the engine entry into service, reliable estimation of possible life at the early stage of engine or its part development, decrease of expenses on engine life tests, harmonization of the national and foreign regulations. Now existing in CIS regulations permit to maintain engines according to hard TBO as well as their CBM in the safe limits of engine critical parts lives.

For efficient CBM it is important to do the best to exclude the main reasons of the engines removals-limitations in lives of critical and non-critical engine parts and components, defects of kit components, foreign objects damages, improper operation of monitoring and diagnostic system, bearing defects, gas path wear, hot part damages. So for successful CBM an engine must meet some requirements including confirmed lives of critical parts and components, reliability, inspectability, exhaust gas temperature (EGT) margin, possibility to use life saving maintenance (take off at the reduced rating), modular design to use soft time approach at overhaul, etc. May be the most difficult problem is to use CBM for aging engines.

Engine management plan (EMP) must be developed and approved by authority to realize CBM of a particular engine type. EMP must include on-wing and in-shop maintenance activities, critical and some other parts and components life extension plans, progressive life release control plan, testing and sampling parts and components after running time in service, feed-back from airliner to OEM, etc. EMP requirements must be specified for every operator. Internet can be very useful for EMP realization.

Some aspects important for successful CBM are discussed below.

RISK ANALYSIS

It has been known that making decisions on the basis of risk analysis is considered to be one of possible and sometimes also the most effective approaches used for taking solutions under complicated conditions.

When considering tasks of using the admissible risk to determine a certain value on which this risk depends, for instance, to determine the safe life of engine components, the procedure of making decisions may be divided in three stages [2].

At the first stage, based on comparison with similar situations in other fields of activity or in other technology areas the admissible total risks are defined. As an example, the maximum admissible risk for a fatal accident situation directly connected with aircraft design and manufacturing defects is defined as 10^{-7} per flight hour (in future this requirement must be met not for flight hour but for a flight).

At the second stage, based on analysis of an actual situation (using the prediction for changing this situation), the total risk is distributed by "contributions" of separate constituents into it. So based upon steady regularity one can establish that about 1/3 of all fatal accidents due to design and manufacturing causes is connected with a power plant. Respectively, based on fixed total risk of fatal accident situation due to design and manufacturing defects for an aircraft $R_{aircraft\ category} \leq 10^{-7}$ one can obtain that the admissible risk of fatal accident situation caused by power plant failures may be approximately determined as $3 \cdot 10^{-8}$ per flight hour. Furthermore the distribution of risks by the lower system levels is performed. It is expedient to use conditional probabilities of the highest level events in a case of lower level event (in a "fault tree").

Based on the Airworthiness Regulations one can take that the conditional probability of fatal accident situation in case of uncontained engine failure at any flight leg cannot exceed 1/10 (with design and manufacture corresponding to the stipulated standards). Hence it follows that even for the biggest rotor fragments (for instance, disk pieces) the maximum admissible failure risk can be determined as 10^{-8} (but not 10^{-9} as it is sometimes claimed).

The maximum admissible risk of blades failure is also determined based on the risk of upper level event but here it is necessary to speak about the risk of two engines in-flight shutdown. It results in $R_{blade\ failure} \leq 10^{-6}$ per flight (considering the necessity of meeting ETOPS requirements).

The results of usage of the first two stages of the above-described procedure are presented in Fig.1.

At the third stage using the admissible risk level the safe engine component life can be determined.

As at the first stage the determination of the initial overall risk cannot be algorithmized, as at the final stage, the criterion for result reliability (confidence probability, or maximum likelihood of estimation or maximum impartiality when selecting the adequate distributions, etc.) is selected but not algorithmized.

Since the admissible risks specified by the Airworthiness Regulations are determined as statistical mean values that correspond to the confidence coefficient

$\gamma \approx 0{,}5$ value at the life determination, then in further estimations it is often worthwhile to take $\gamma \approx 0{,}5$, and only in separate, specific cases to take a pessimistic life estimation (at $\gamma \approx 0{,}8$ and 0,9-0,95).

The example of calculations of margins for critical components safe lives confirmation is shown in Fig.2.

When a risk is used not as an intermediate "link" to determine some value (for instance, life) but to select a possible way of action, the risk values are often determined as expected losses (expenses because of undesirable events).

The example is shown in Fig.3. The relationship $\frac{k_{ur}}{k_{r1}}$ of engine overhaul rate because of unscheduled removals (failures or prefailure conditions) k_{ur} and overhaul rate because of life expiration K_1 is plotted on the X-axis. The sum of these rates (at 1000-hour running time) is equal to the shop visit rate:

$$k_{sv}=k_{ur}+k_{k1} \tag{1}$$

The relationship $\frac{R_{ur}}{R_1}$ of the value R_{ur} of expenses at the improvement of the unit of mean time between failures and the value R_1 of expenses at the increase of the unit of engine life (minimum life of non-replaceable elements) is plotted on the Y-axis.

The curve divides the regions corresponding to economic efficiency of the urgent expenditure on life increase or reliability improvement. The curve is plotted based on solving the task of minimizing expenses R on the unit of the decrease of engine on-wing replacement summation:

$$R = \frac{C_{ur}\Delta\lambda + C_1\Delta h_1}{\Delta\lambda + \Delta h_1}, \tag{2}$$

here λ - failure intensity;

$h_1 = \frac{\lambda e^{-\lambda\tau}}{1 - e^{-\lambda\tau}}$ - mean rate of engine on-wing replacements because of the expiration of life expressed in hours or cycles;

C_{ur} - mean expenses on the unit of engine failure decrease;

C_1 - mean expenses on the unit of the decrease of engine on-wing replacements because of life limitations.

PREVENTON OF FAILURES WITH HAZARDOUS EFFECTS

The prevention of failures with hazardous effects must be confirmed at the engine certification. A fail-safe property is a link between reliability and safety. If a defect is critical and the time of its propagation to a possible catastrophe is not enough for a proper pilot action it is impossible to speak about indication for the crew or about predictive diagnostic. The fail-safe design permits to reduce fracture criticality and number of critical parts and components.

For example results of analysis of main possible reasons of turbine wheels over-speed are shown in Fig.4. Of course, it is necessary to eliminate all these reasons.

Some possible ways are shown in Fig.5. But it is also possible to prevent inadmissible turbine over-speed using blades and nozzle vanes meshing after turbine axial displacement (to provide wheel braking owing to friction between rotor and stator), rational distribution of disk-blade strength margins according to size (to get disk braking owing to blades releasing), electronic or mechanical system for fuel cut-off or surge speeding up or combination of these solutions (Fig.5). In this case a shaft fracture will not lead to hazardous effects and a shaft can be excluded from the list of critical parts. The failure-safe design is also applicable for some other parts including combustion chamber cases; engine mounts; reverses parts and sometimes even for disks.

The safe life of a critical part must be confirmed using AMT or materials structural strength database (Fig.6). For AMT it is important to take into account the above described probabilistic requirements for parts integrity. For a known spread of durability characteristics it is possible to combine results of various tests - finite tests to failure and failure-free non-finite tests. Example of such calculations is shown in Fig.7. The problem of critical components life extension using non-finite fatigue test results was also discussed in a recently published paper [3].

Fracture mechanics must be also used for conservative lives estimations of casted or welded parts or parts made of brittle materials or materials with possible pores or inclusions as well as for the determination of periods between inspections. In the last case possible in service damages must be taken into account and this work can be done for both critical and noncritical parts and components.

Airborne recording of real missions can be used for more complete utilization of possible life taking into account real damage in service conditions.

INCREASING ENGINE ON-WING LIFE AT CBM

1. Exhaust gas temperature (EGT) margin and life saving maintenance.

The EGT margin has a direct relationship with the on-wing engine life: the bigger the EGT margin the longer the on-wing engine life to loose its performance [4]. The EGT margin is the difference between the maximum admissible exhaust gas temperature (so-called red line value) and the new engine exhaust gas temperature at ICA take off trust application. The first of these two values mostly depends on THE engine hot part materials and hot part cooling. The second one depends on the engine core size and gas dynamic efficiency. Engine capabilities at red line conditions must be confirmed at the certification. The EGT margin value must be chosen taking into account desired on-wing time, rate of engine deterioration, necessity to ensure taking off at hot day conditions when one engine shut down and inaccuracy of the engine monitoring system. It is clear that the provision of higher EGT margin leads to a higher engine price. The engine repair cost is connected with an EGT margin monitoring program in service conditions [4].

Take-off ratings and the flight lengths/airport location determine the severity of engine utilization. It is not accidentally that CBM usage began from long distance aircrafts. Usage of take-off at reduced rating is very important for life saving. The engine installation with the thrust margin (excluding an emergency mode) and limitation of the maximum rating in comparison with a certified value at the beginning of new engine type utilization are also useful for increasing engine on-wing life.

2. Bearings life.

The bearing defect is one the most frequent reasons of engines unscheduled removals. The rational approach for the gas turbine engine main bearings lives substantiation is shown in Fig.8. The life extension is based on a conservative design life calculation. The slippage absence must be additionally checked for low loaded bearings. If the calculated life is not enough but the service experience is positive it is possible to provide special tests to confirm life extension. The special attention must be paid to diagnostic for in-flight shutdown prevention and requirements for overhaul bearing checking for their repeat usage.

3. Prevention of compressor gas path abrasive erosion.

Different kinds of wear can lead to engine removals. In particular, gas path abrasive erosion can result in decreasing engine on-wing time and increasing maintenance costs as a result of EGT margin reduction, possible surge or high cycle fatigue fracture. This problem is especially important for helicopter engines.

So requirements for erosion resistance coatings were developed, different kinds of coatings were investigated (Fig.9). The investigations results of technological parameters effect on reactive ion coatings properties are also shown in Fig.9. The optimized titanium nitride coatings were successfully used for different helicopter engines.

COMPLEX DIAGNOSTICS

Diagnostics is one of the basic tools for engine CBM. The efficiency and reliability of the condition monitoring is provided by a complex diagnostics (Fig. 10). The main features of complex diagnostics is:

- application of equipment, based on a various physical principles;
- software integration on the basis of diagnostic data base;
- decisions according to the complex of diagnostic signs.

The new theoretical model for complex diagnostics is developed in CIAM.

1. Diagnostic decisions

The working out of an algorithm of a diagnostic decision without complete and reliable initial data on the process is the most complicated task.

In general view this problem is formalized as a selection of a condition of an object (operable or inoperable). These conditions can be depicted by two noncolinear vectors in the measurement space and by two intersecting (in general case) regions of discrete points – in the space of diagnostic signs.

The process of a diagnostic decision is formalized by the procedure of plotting a hyperplane placed at the equal distance from the mentioned vectors or regions (without taking into consideration different risk costs because of a diagnostic error).

The proper choice of a algorithm for the calculation of these distance of functions of diagnostic signs is a decisive factor for a reliable diagnostics. In a case of a limited number of measurements for diagnostic signs (as a rule it is an usual practice at the evaluation of the condition of machines during operation) it is of special importance.

It will be shown below that the introduced function of an information distance has significant advantages compared to the other functions known from the literature. First of all these advantages show themselves at coming to a decision of tasks associated with the case of limited prior data on the condition of the object as well as when the initial data are the specialists' estimations expressed by confidences of events.

2. Function of generalized information distance

Suppose that there is an object to be diagnosed that in an operable condition is characterized by a **N** - dimensioned vector **A** of diagnostic signs. At the change into an inoperable condition the vector **A** is transformed into a vector $\bar{\mathbf{A}}$**.** Let's designate a square matrix by **D** the elements of which at the principal diagonal are the elements of the vector $\bar{\mathbf{A}}$ and others – their weight coefficients that characterize the cost of losses due to errors at the evaluation of corresponding diagnostic sign values. In the simplest case the elements beyond the diagonal are taken equal to 1. The method of the estimation of a distance or proximity criterion between **A** and $\bar{\mathbf{A}}$ consists of the determination of a function **Hs** that has a defined list of prior specified properties. Considering in diagnostic tasks the function of distance **Hs** must have the following properties given below:

1. 0<**Hs**<1;
2. at **Hs**=0 the properties of **A** and $\bar{\mathbf{A}}$ do not absolutely coincide;
3. at **Hs**=1 the properties of **A** and $\bar{\mathbf{A}}$ absolutely coincide;
4. if $\mathbf{Hs}^1 > \mathbf{Hs}^2$, $\mathbf{A}^1$ and $\bar{\mathbf{A}}^1$ are more close compared to $\mathbf{A}^2$ and $\mathbf{D}^2$ according to their properties;
5. if $\mathbf{Hs}^1 > \mathbf{Hs}^2$ and $\mathbf{Hs}^2 > \mathbf{Hs}^3$, $\mathbf{Hs}^1 > \mathbf{Hs}^3$.

At the formation of the distance function let's use an approach based on concepts of conditional and unconditional entropy.

The function of the generalized information distance **Hs** can be expressed by the following equation:

$$Hs_m := (Ha)_m - (Ho)_m$$

Where $\mathbf{Ha_m}$ – entropy function that characterizes a level of a prior indeterminacy (complexity) of the object to be diagnosed by the range of selected diagnostic signs $\mathbf{a_{i,m}}$ that are the elements of the matrix **A** (here and further a subscript **m** defines a current value of corresponding diagnostic signs).

$\mathbf{Ho_m}$ – function of condition entropy that characterizes the change of indeterminacy of the object at the transition from one condition to another (from operable to inoperable condition).

The equations for calculation of the above mentioned characteristics are derived from the known equations for the entropy and mutual entropy of condition as well as from Bayes' equation for conditional probabilities.

$$Ha_m := -0.5 \cdot \left[\sum_{i=0}^{N-1} \left(P_{i,m} \cdot \frac{\ln(P_{i,m})}{\ln(2)} \right) \right],$$

where

$$P_{i,m} := \frac{\alpha_{i,m}}{\left(\sum_{i=0}^{N-1} \alpha_{i,m} \right)},$$

here:

$$\alpha_{i,m} := \begin{cases} a_{i,m} & \text{if } i \le N-1 \\ a_{(i-N-1),m} & \text{if } i > N-1 \end{cases},$$

N – dimension of a generalized distance (number of objects for which the dimension is to be established).

$$Ho_m := -1 \cdot \left[\sum_{i=0}^{N-1} \sum_{j=0}^{L-1} \left[P_{i,m} \cdot \left| \frac{d_{i,j}}{2 \cdot L \cdot \alpha_{i,m}} + \frac{k_{i,j}}{2 \cdot N} \right| \cdot \frac{\ln \left[P_{i,m} \cdot \frac{\left| \frac{k_{i,j}}{2 \cdot L} + \frac{d_{i,j}}{2 \cdot L \cdot u_{i,m}} \right|}{\sum_{i=0}^{N-1} \left(P_{i,m} \cdot \left| \frac{d_{i,j}}{2 \cdot L \cdot u_{i,m}} + \frac{k_{i,j}}{2 \cdot L} \right| \right)} \right]}{\ln(2)} \right] \right],$$

here

$$u_{i,m} := \begin{cases} 1 & \text{if } \alpha_{i,m} = 0 \\ \alpha_{i,m} & \text{if } \alpha_{i,m} \ne 0 \end{cases},$$

$$k_{i,j} := \begin{cases} (-1) & \text{if } i \le N-1 \\ 1 & \text{if } i > N-1 \end{cases}.$$

L – dimension of a square matrix **D** with the elements $\mathbf{d_{i,j}}$ that characterize the cost of losses at diagnosing (in our simplest case **L** = **N**).

It is easy to show that the derived function has all five specified properties.

The graphic image of the surface of the generalized distance function is given in Fig.11(a) depending on values of diagnostic signs for two objects, one of which is characterized by an unit matrix **D**. The curves of equal levels of information distance for these objects are shown in Fig.11 (b). The similar curves for the classic Euclid are given in Fig.11(c) to reveal the peculiarities of the generalized information distance.

One can see from the graphs that there is some difference of principle in the characteristics of these functions. The main peculiarity of information distance is the following: it takes into account the parameter interaction to a considerable extent. For a pair of parameters close in relative values and for a pair of parameters one of which is essentially less than the other one the information distances are equal. This property plays an important role in using the information distance for a diagnostic decision in case of significant indeterminacy. It depicts an objective necessity of diagnosing according to a set of signs to improve monitoring confidence.

The most obvious example of using generalized information distance to solve a task of sign ranking will be considered below.

3. Task of diagnostic sign ranking

For example, there is an aviation engine, four parameters of which are monitored for routine airborne diagnostics (vibration, particles in oil, turbine outlet temperature and oil inlet pressure). These parameters are ranked by several experts according to the priority of appealing to them for a decision at the engine failure. The priority is set by a higher value (the highest value – 4, the lowest –1). Using several ranks it is necessary to find the one that is most of all in conformity with the opinions of all the experts.

In general case 24 different combinations of ranking can exist for four characteristics of the object. The possible ranking and corresponding values of generalized information and Euclid distance between the initial and subsequent ranking are shown in Table 1.

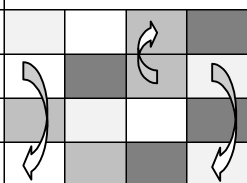
Table 1.

№№	Ranking	Information Distance	Euclid Distance	
1	2	3	4	
1	Initial 1234	1,000	0	0
2	1243	0,721	√2	1,414
3	1324	0,708	√2	1,414
4	2134	0,696	√2	1,414
5	1432	0,549	2√2	2,828
6	3214	0,527	2√2	2,828
7	1342	0,495	√6	2,449
8	1423	0,484	√6	2,449
9	2314	0,470	√6	2,449
10	3124	0,461	√6	2,449
11	2143	0,418	2	2

1	2	3	4	
12	4231	0,409	$3\sqrt{2}$	4,242
13	3241	0,338	$\sqrt{14}$	3,741
14	2431	0,336	$\sqrt{14}$	3,741
15	4213	0,318	$\sqrt{14}$	3,741
16	4132	0,318	3	3
17	2341	0,283	$2\sqrt{3}$	3,464
18	4123	0,252	$2\sqrt{3}$	3,464
19	3142	0,247	$\sqrt{10}$	3,162
20	2413	0,147	$\sqrt{10}$	3,162
21	4321	0,117	$2\sqrt{5}$	4,472
22	3421	0,101	$3\sqrt{2}$	4,242
23	4312	0,092	$3\sqrt{2}$	4,242
24	3412	0,076	4	4

The comparative analysis of the data shown in table 1 demonstrates that the generalized information distance has 24 different gradations (all 24 available). The Euclid distance has only 12 different gradations: it affirms the difference essential in the resolutions of the two distance functions. This can result in an error of the estimate of the experts' agreed opinion. For example, if four experts indicate the ranking given in table 2, the agreed ranking should be a ranking given by the expert 2 (based on the calculation by a mean value of information distance). At the calculation by a mean Euclid distance the ranking given by the expert 4 will be agreed.

Table 2.

	№№ Position in the Table 1	Rankings	Schematic Interpretation	Generalized Information Distance	Euclid Distance
Expert 1	4	2134		0,696	1,414
Expert 2	5	1432		0,549	2,828
Expert 3	6	3214		0,527	2,828
Expert 4	7	1342		0,495	2,449
Mean Value				0,566	2,379

The schematic interpretation shows that the ranking of the expert 2 is a single one (out of four) for which three positions coincide with the three positions indicated by the other experts. It affirms the proper choice of the agreed ranking have derived using information distance.

CONCLUSION

The experience has shown that CBM is the most efficient strategy for aviation engine life monitoring. For successful CBM it is necessary to solve a lot of problems connected with risk analysis, prevention of failures with hazardous effects, engine on-wing life increase, complex diagnostics development, quality system improvement.

Advantages at CBM application for aging engines are not so high as for new engines; nevertheless this method is successfully used CIS for some engines (PS 90A, D18T, etc.).

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RANKING THE CIVIL AVIATION GAS-TURBINE ENGINE COMPONENTS BY THE "R" ADMISSIBLE RISK OF FAILURE FOR THE PROBABILISTICALLY SUBSTANTIATED LIFE ESTABLISHMENT

For components of I & II groups:

$$R_{\text{accident/i-component failure}} \leq 10^{-9}\ ;\ R_{i-comp.unc.\ fail._{\max.admis.}} = \frac{10^{-9}}{R_{accident}/_{i-component\ \ failure}}$$

Группа элементов	$R_{unc.}/_{i-comp.\ fail.}$	$R_{acc.}/_{i-comp.unc.\ fail.}$	$R_{acc.}/_{i-comp.\ fail.}$	$R_{i-comp.unc.\ fail._{\max.admis}}$
I. Shafts, disks, ...	0.2÷1	0.05÷0.1	≤ 0.1	10^{-8}
II. Fan blades, ...	0.1÷0.2	0.025÷0.05	≤ 0.01	10^{-7}
III. Turbocompressor blades, ...	≤ 0.1	≈ 0.01	≈ 0.001	10^{-6}

Fig.1

Required running time margin-confirmed life relation with different "R" failure risks

γ=0.5, z=2

γ - confidence coefficient; z- number of tested parts

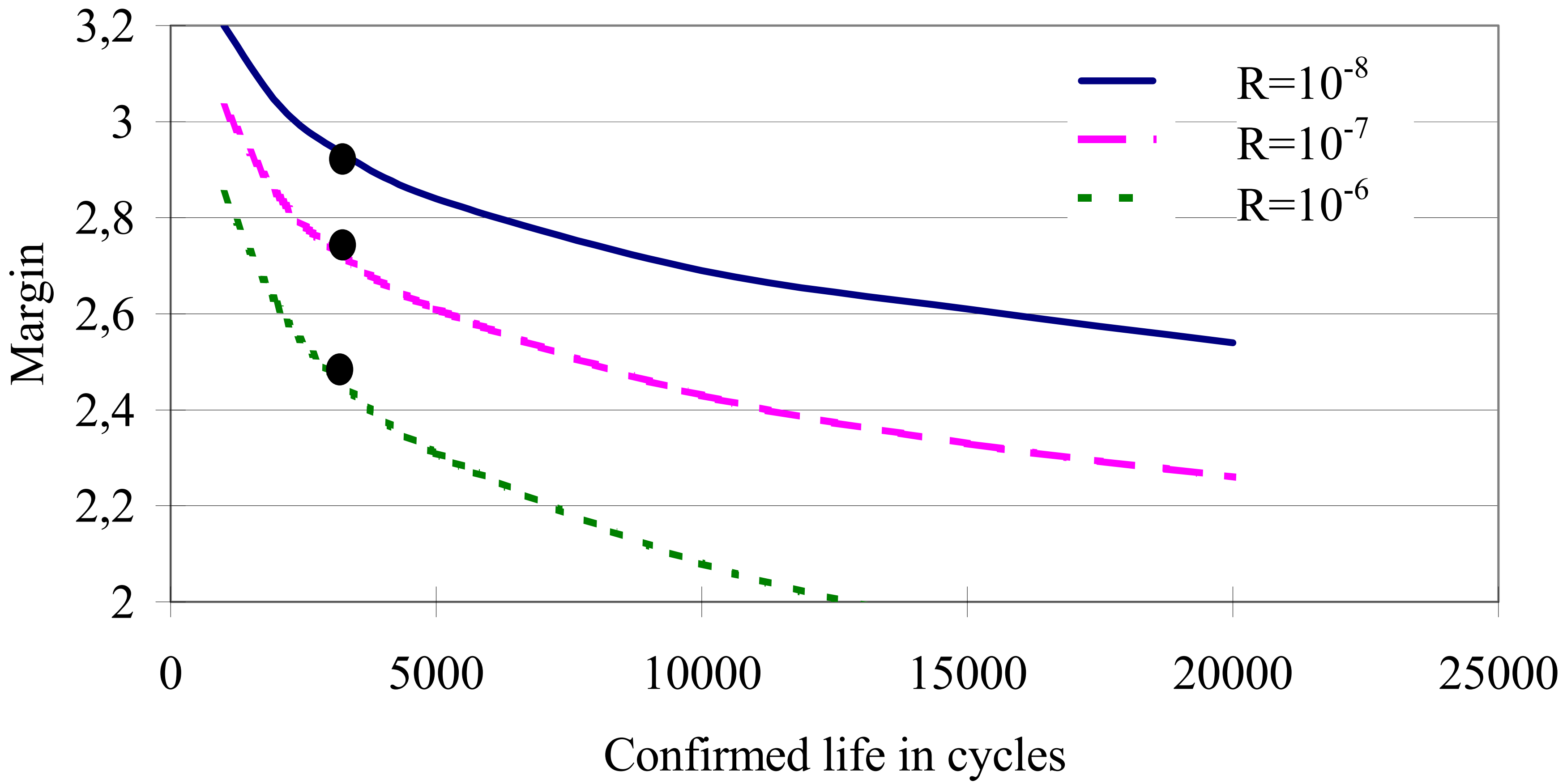
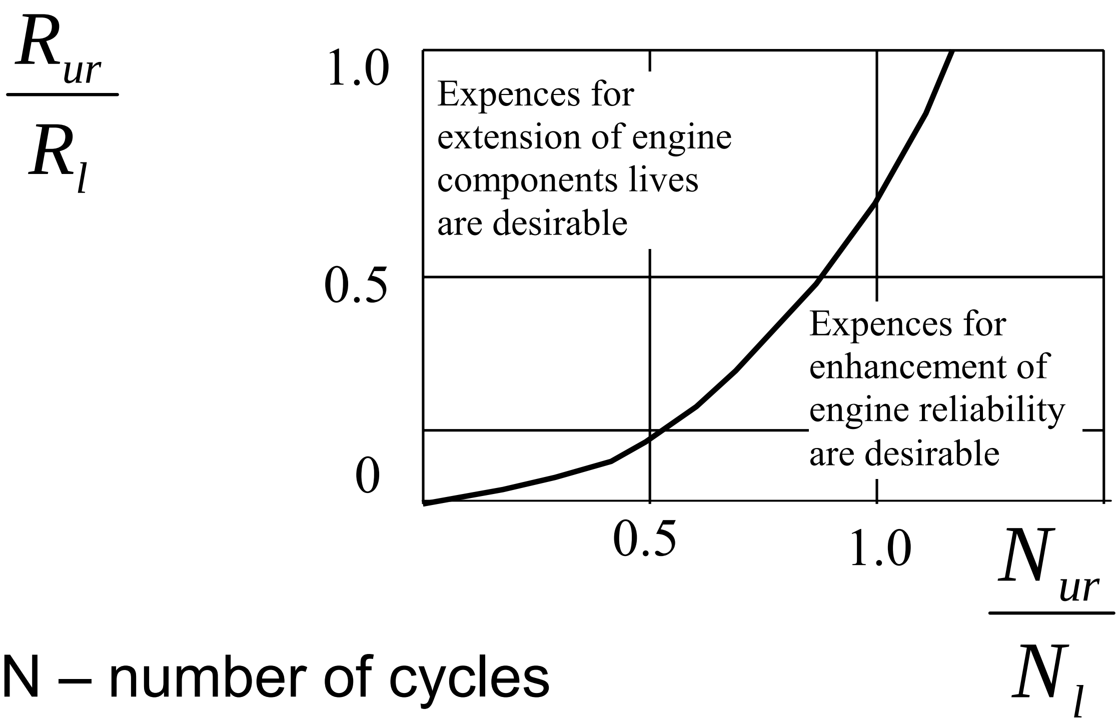


Fig.2

MINIMIZATION OF AVERAGE ECONOMIC RISK BY MEANS OF RATIONAL DISTRIBUTION OF EXPENSES FOR ENHANCEMENT OF ENGINE RELIABILITY OPERATION AND EXTENSION OF MINIMUM ENGINE COMPONENT LIFE



N – number of cycles

Fig.3

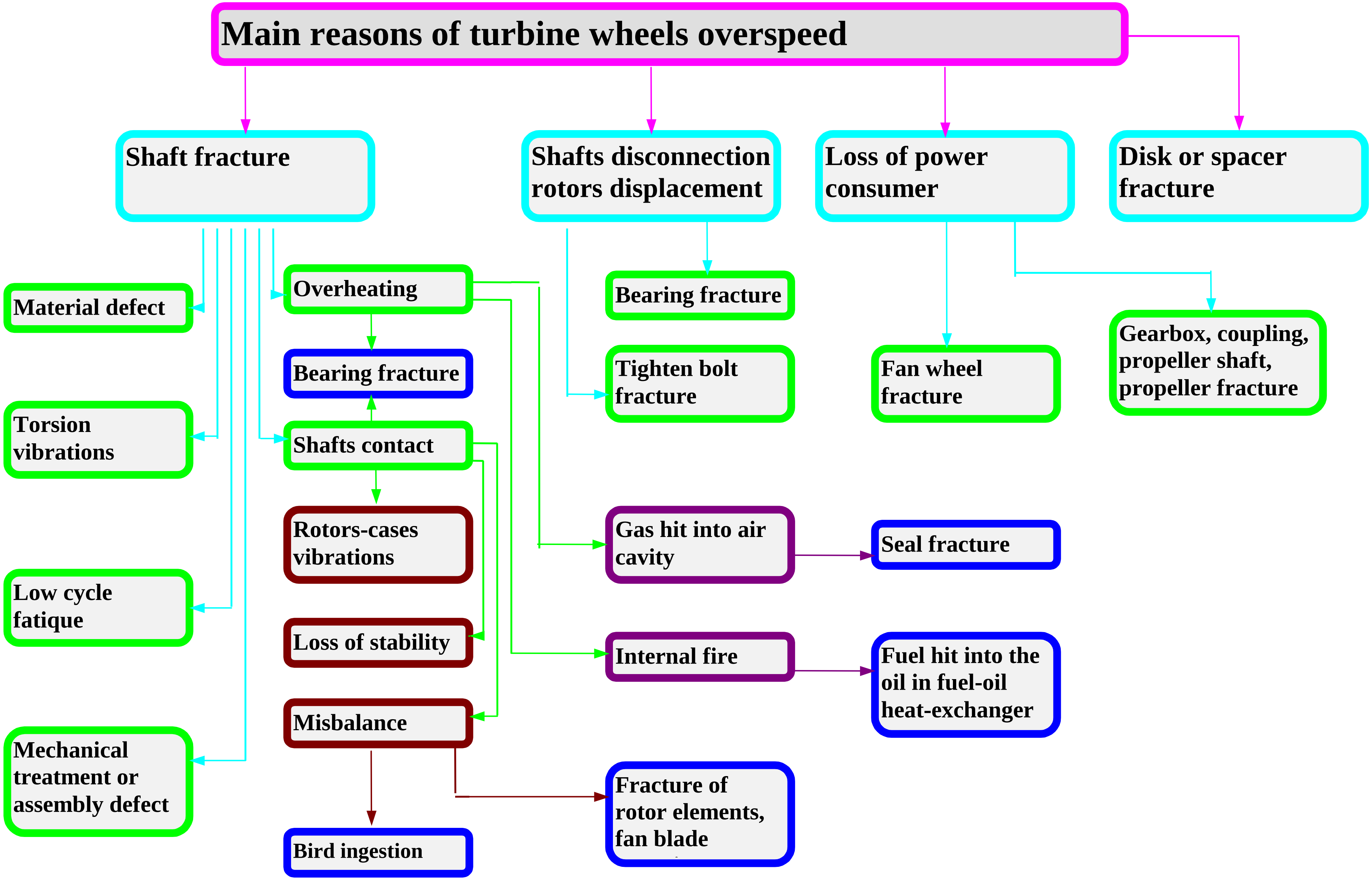
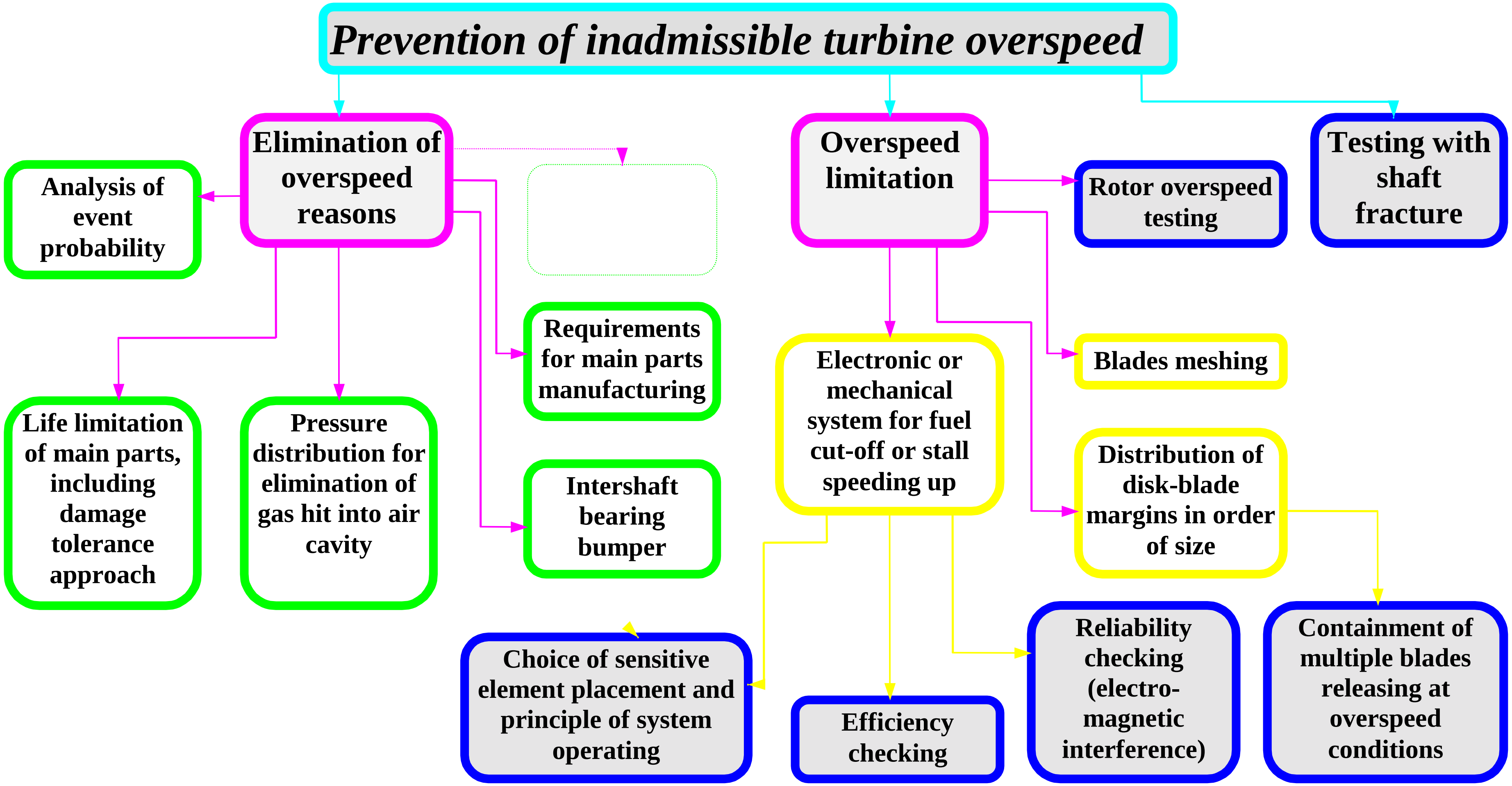

Main reasons of turbine wheels overspeed
Shaft fracture
Shafts disconnection rotors displacement
Loss of power consumer
Disk or spacer fracture
Material defect
Overheating
Bearing fracture
Torsion vibrations
Bearing fracture
Tighten bolt fracture
Fan wheel fracture
Gearbox, coupling, propeller shaft, propeller fracture
Shafts contact
Rotors-cases vibrations
Gas hit into air cavity
Seal fracture
Low cycle fatique
Loss of stability
Internal fire
Fuel hit into the oil in fuel-oil heat-exchanger
Misbalance
Mechanical treatment or assembly defect
Fracture of rotor elements, fan blade
Bird ingestion

Fig.4



Additional problems.

1.Analysis of shaft fracture consequence taking into account the place of fracture relatively ball bearing.
2.Retention of fan rotor in case of axial displacement.
3.Windmilling of large thrust engine (ETOPS requirements: 180 min after fan blade releasing).

CIAM Procedure of the engine main parts safe life determination

Fig.3

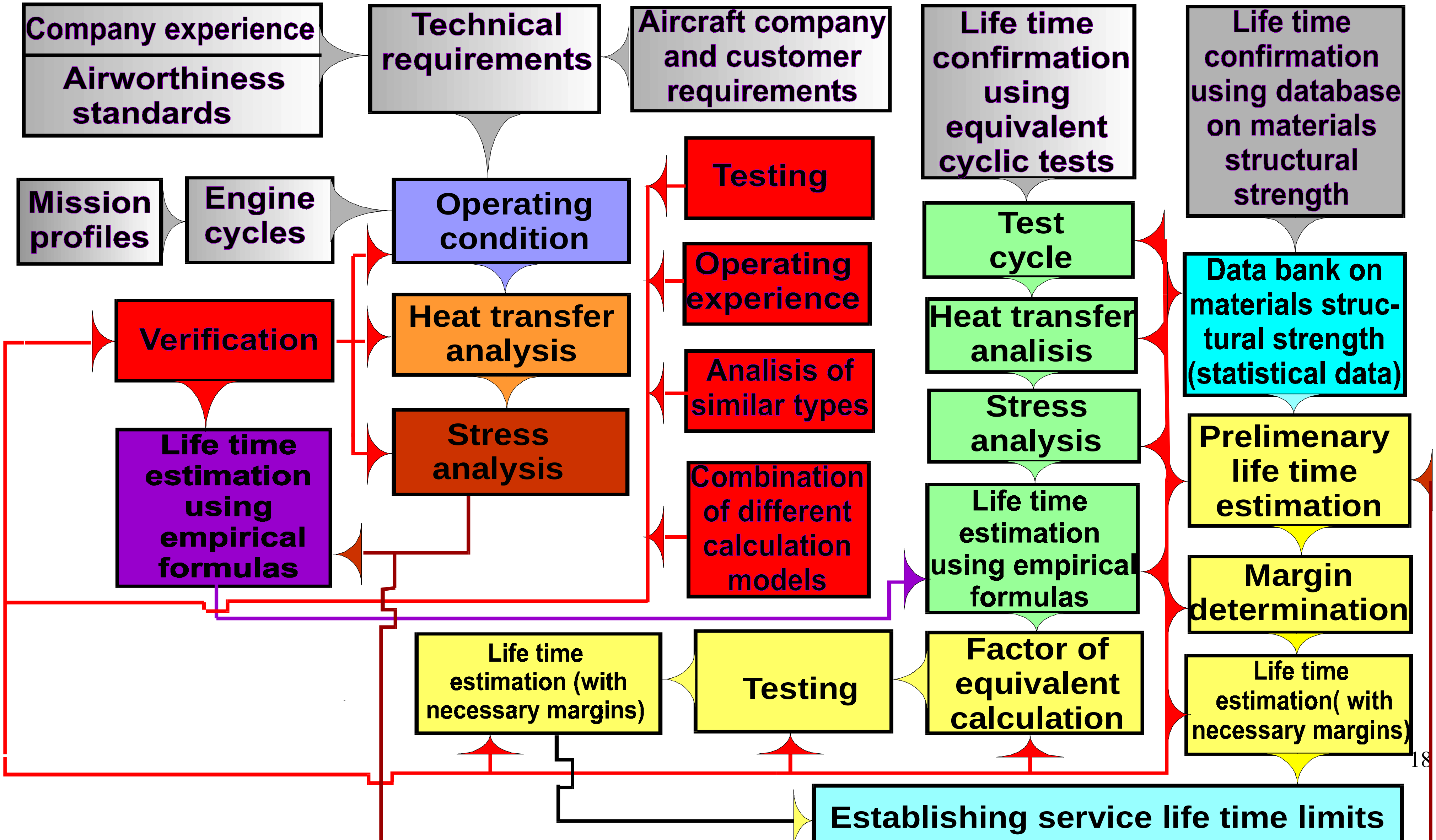


Fig.6

ESTABLISHMENT OF THE SAFE CYCLIC LIFE FOR THE CIVIL AVIATION GAS-TURBINE ENGINE COMPONENTS USING THE ADMISSIBLE RISK VALUE R

Tests without failure
9000; 18000; 27000 cycles

Number of cycles

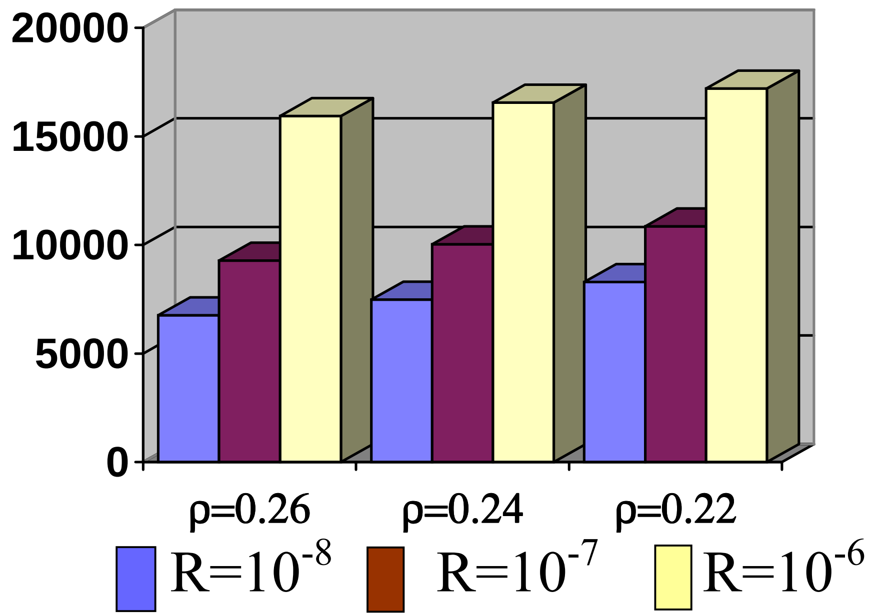
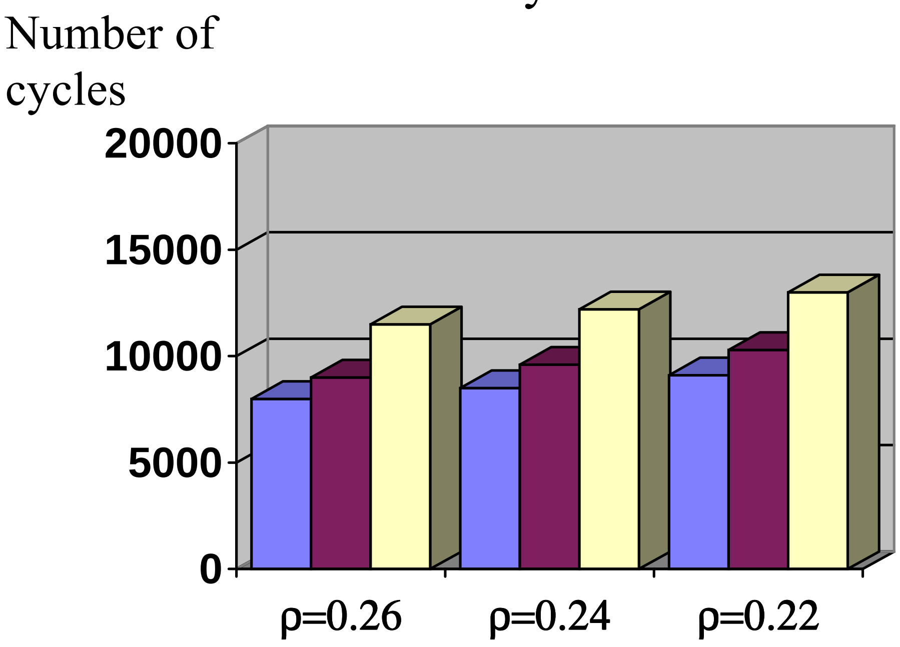


Fig.7

Tests without failure 9000, 18000 cycles
Tests without failure
27000 cycles



ρ – coefficient of variation

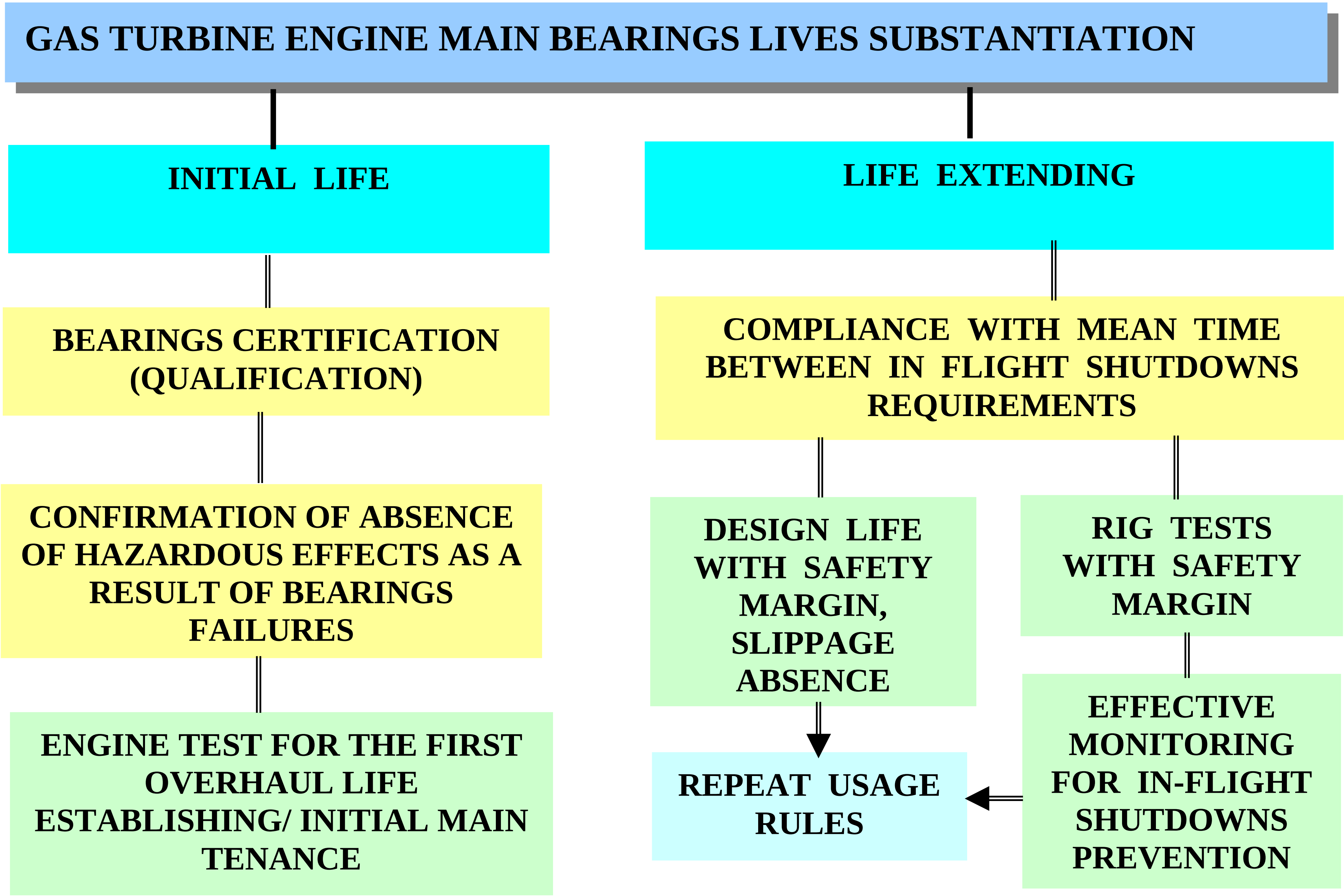
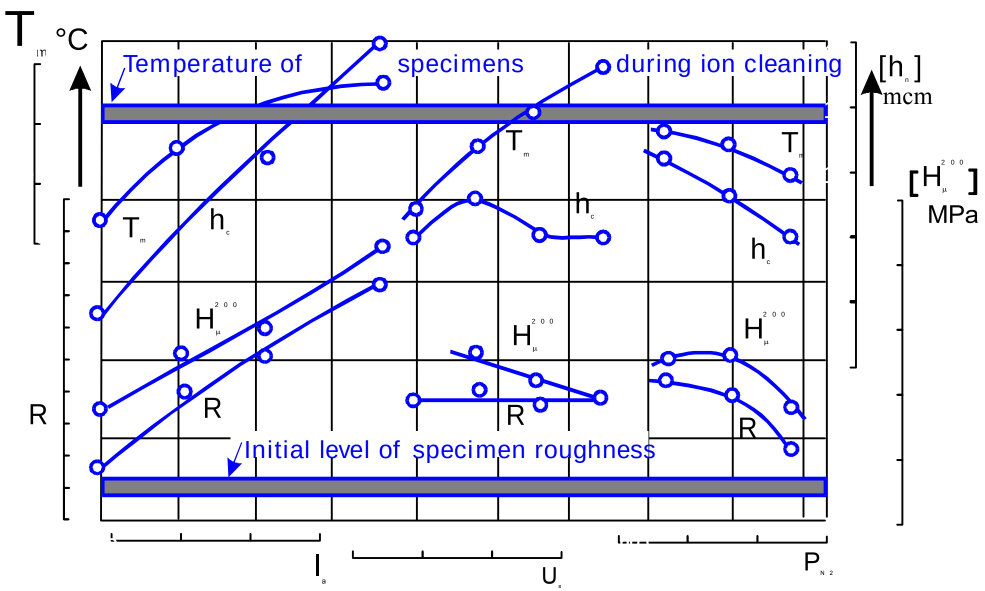

GAS TURBINE ENGINE MAIN BEARINGS LIVES SUBSTANTIATION
INITIAL LIFE
LIFE EXTENDING
BEARINGS CERTIFICATION (QUALIFICATION)
COMPLIANCE WITH MEAN TIME BETWEEN IN FLIGHT SHUTDOWNS REQUIREMENTS
CONFIRMATION OF ABSENCE OF HAZARDOUS EFFECTS AS A RESULT OF BEARINGS FAILURES
DESIGN LIFE WITH SAFETY MARGIN, SLIPPAGE ABSENCE
RIG TESTS WITH SAFETY MARGIN
ENGINE TEST FOR THE FIRST OVERHAUL LIFE ESTABLISHING/ INITIAL MAIN TENANCE
REPEAT USAGE RULES
EFFECTIVE MONITORING FOR IN-FLIGHT SHUTDOWNS PREVENTION

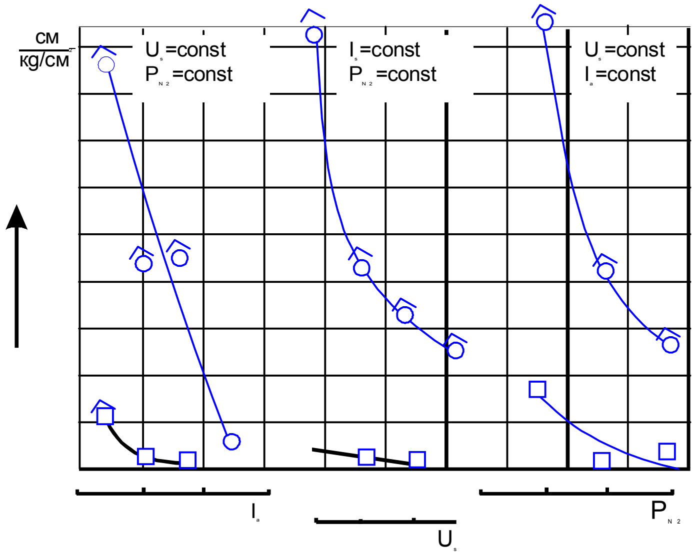
Fig.8

Erosion resistance coatings

High-hardness (metallic, based on refractory compounds)	Blend composition (metallic binder-hard particles)	Elastic
Required: material hardness>abrasive hardness with exclusion of brittle fracture	Required: high volume content of hard particles, high binder wear resistance	Required: high impact energy loss rate; low dynamic modulus of elasticity with exclusion of brittle fracture
Main possible limitations: $\alpha<\alpha_{lim}$, $V_p<V_{p\,lim}$, $h_{min}<h_{coat}<h_{max}$	$\frac{\varepsilon}{E_{sp}} \rightarrow min$	Main possible limitations: $\alpha<\alpha_{lim}$, $V_p<V_{p\,lim}$, $T<T_{lim}$, $h_{coat}>h_{min}$, $I_p=I_p(h_{coat}, G_{p.sp})$

ε-energy portion received by material, E_{sp} - energy required for removing volume unit, h_{coat} - coating thickness, T-temperature, V_p-speed of particles, $G_{p.sp}$-specific consumption of abrasive particles, α-angle of attack, I_h-wearing intensity



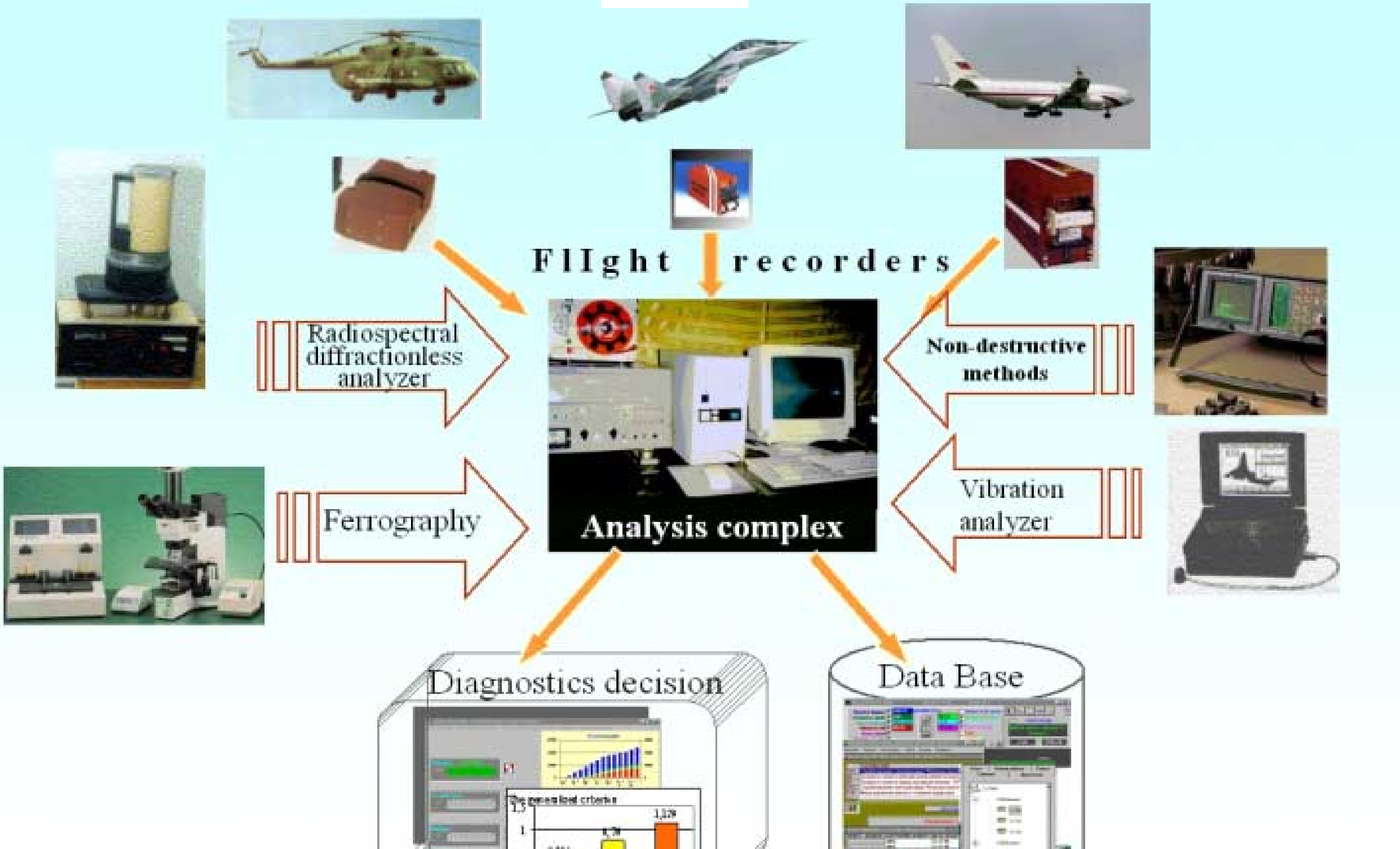


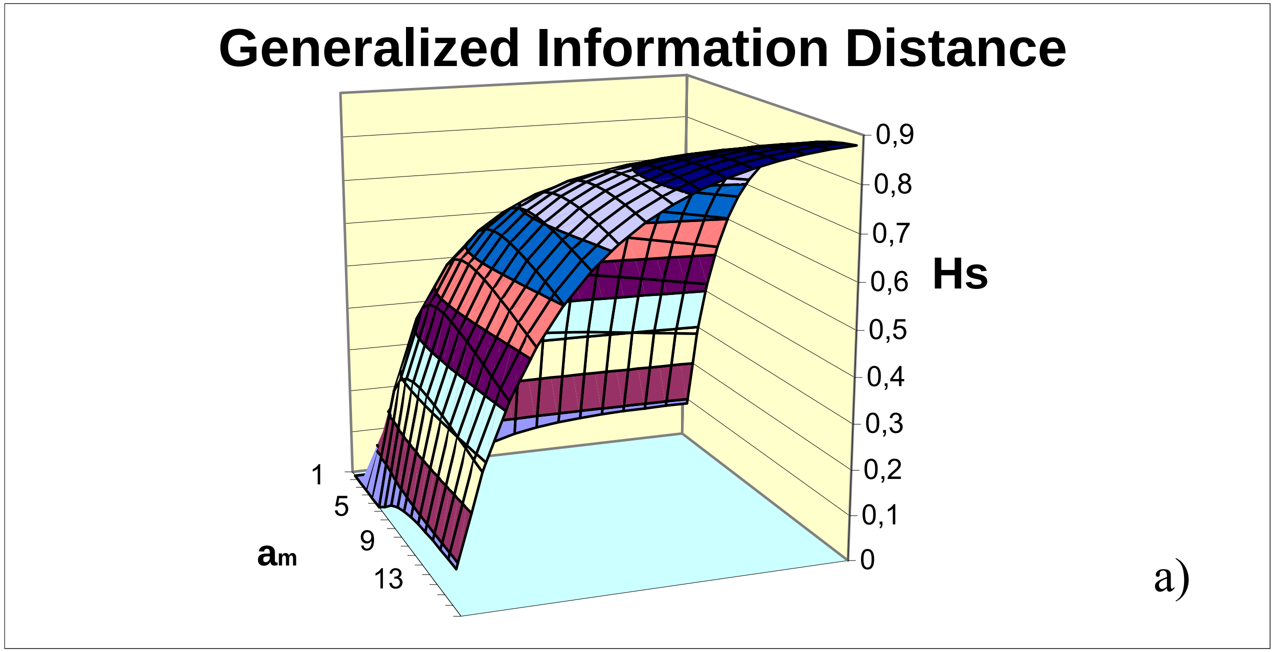
Effect of technological parameters on characteristics of Ion-reactive TiN coating on VT-6C alloy when blasting by particles of size up to 70 mcm (□) and up to 300 mcm (o). Angle of attack is 70°, flow speed is 200 m/s, h_c-coating thickness, T_m -temperature of substrate when applying coating, Hμ-microhardness, R-rougness I_a-arc current, U_s-absolute value of potentials difference at substrate, P_{N2}-nitrogen pressure in chamber

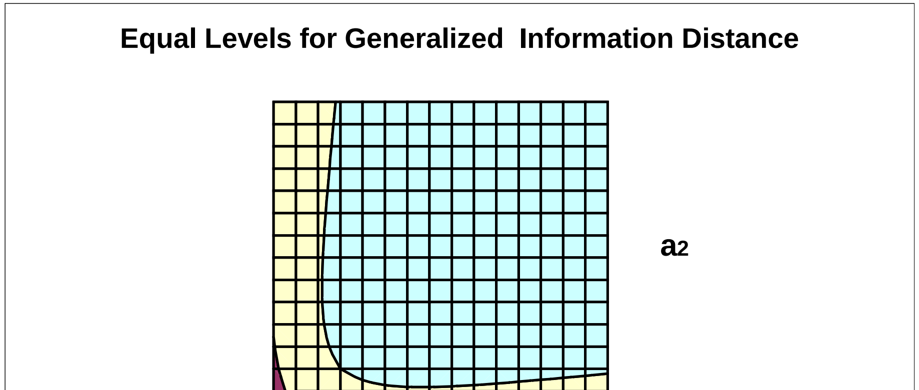
Reactive ion coatings were successfuly tested on TV3-117 product and introducted in TV2-117 (during overhaul) and TV7-117 product

ENGINE COMPLEX DITION MONITORING

Fig.9




Generalized Information Distance
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
Hs
1
5
9
13
am
a)


Equal Levels for Generalized Information Distance
a2

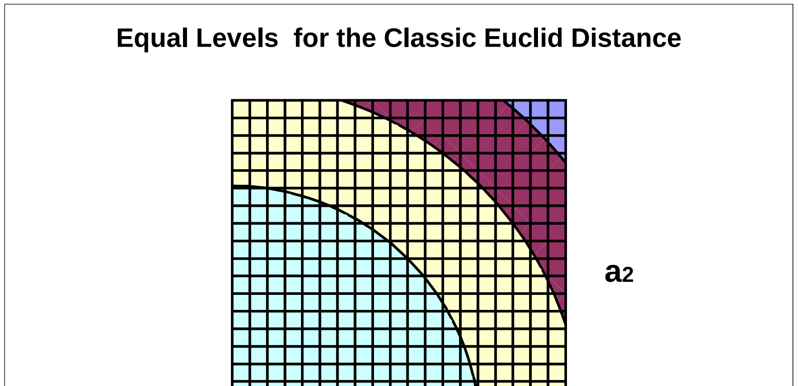

Equal Levels for the Classic Euclid Distance
a2

Fig.11