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SAND INGESTION TESTS ON THE MTR390 TURBOSHAFT ENGINE

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The MTR390 specification requires satisfactory engine operation in certain sandy conditions, with and without sand filter. In both cases it is important for the engine manufacturer to know which engine components show damage after sand ingestion and how engine performance deteriorates after a certain running time. To be able to answer these questions comprehensive sand ingestion tests were carried out. The test case with sand filter represented flight under sand storm conditions, whilst the case without filter simulated take-offs and landings in sandy areas.

In addition to accurate performance analysis of the test data thorough inspection of the engine components was necessary. The results of the performance analysis and the findings of the inspection reveal that the MTR390 engine fulfills the specification requirements. In this paper the test bed configuration and the sand test procedures are described. Furthermore the effects of sand on the performance of the engine components and on the engine parts' integrity are presented.

NOMENCLATURE AND INDICES

N	rotational speed
P	total pressure
PW	shaft power (corrected to standard day)
Re	Reynolds number
s	tip clearance
S	static pressure
SFC	specific fuel consumption (corrected to standard day)
T	total temperature
TIT	gas gener. turbine inlet temperature (corrected to standard day)
TRQ	torque
W	air/gas mass flow
WF	fuel consumption
β	compressor map parameter
Δ	relative change
$\Delta h/T$	reduced specific turbine work
κ	isentropic coefficient
η	efficiency
π	pressure ratio
0	ambient condition
1	engine plane; inlet
3	compressor exit
31	combustion chamber inlet
44	gas generator turbine exit
45	engine plane; power turbine inlet
88	exhaust diffuser exit
m	measurement
M	map
r	reduced value
PT	power turbine

TEST OBJECT AND TEST PURPOSE

The test object was the MTR390 turboshaft engine of the 1000 kW category for application in the German/French military helicopter Tiger and in other helicopters with a take-off weight of 5.5 to 6.0 tons. As shown in figure 1, the engine mainly consists of:

- Two-stage centrifugal compressor
- Reverse-flow annular combustion chamber
- Single-stage gas generator turbine with inter-turbine duct
- Two-stage power turbine with exhaust diffuser (for the test bed)
- Gearbox
- Digital control and monitoring unit.

A more detailed description of the MTR390 engine can be found, for example, in [1] and [2].

According to the specification, two engines have been prepared to pass two different sand ingestion tests: one with sand filter, the other without sand filter.

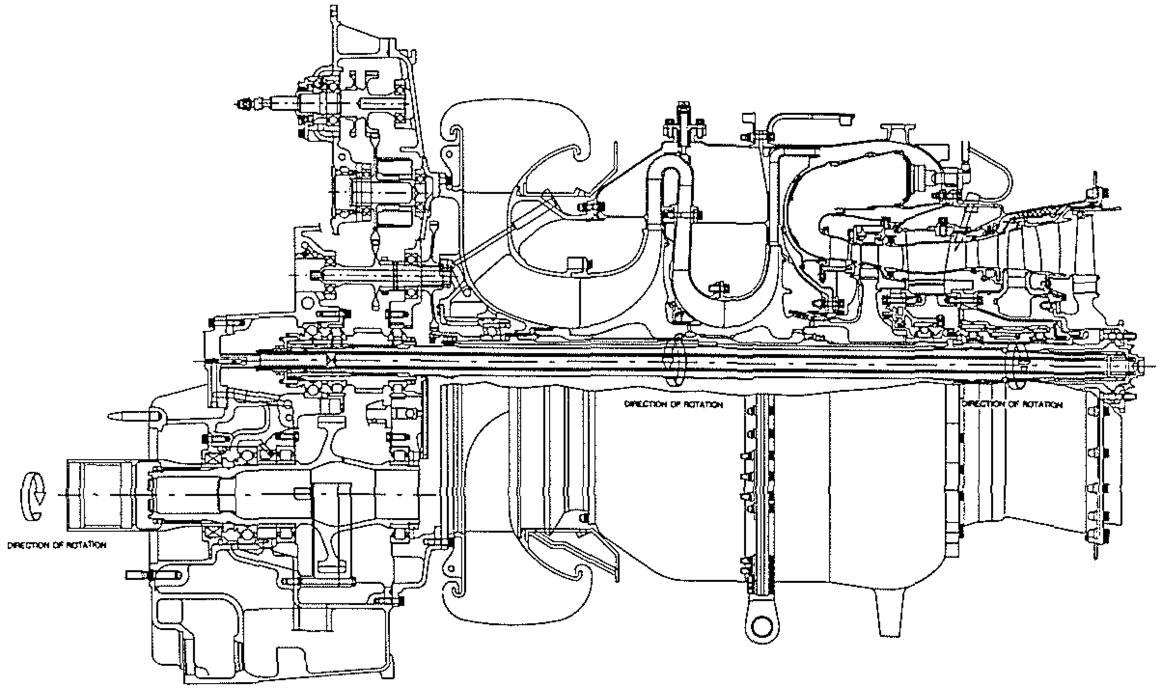

Figure 1: The MTR390 engine cross section

Particle size [µm]	Content [% by weight]
0-5	12
5-10	12
10-20	14
20-40	23
40-80	30
80-200	9

Table 1: Sand grain size and concentration for the test with filter

The purpose of the first test was to find out if the engine could resist a sand storm or whirling-up of sand for 10 hours without deteriorating by more than 5 % in terms of shaft power and specific fuel consumption. For this test, coarse sand that meets the specification SAE J 726 was used. Accordingly the sand had a maximum particle size of 0.2 mm, as shown in table 1. Such a fine grained sand can be described as dust. During the test a sand concentration of 1.5 g/m³ of engine inlet air was achieved.

The second test was intended to simulate take-offs and landings in areas where sand can be whirled up, and to find out after what time a performance deterioration of 5 % occurs. The sand used for the test met the MIL-E-8593A standard requirement. It was a coarse grained quartz with a maximum grain size of 1 mm. The prescribed sand concentration amounted to 0.053 g/m^3 of engine inlet air, with a particle size distribution as shown in table 2.

Apart from the influence of sand ingestion on the overall engine performance, it was also of particular interest to know the effect of sand on the engine components with regard to their performance parameters and their mechanical resistance.

Particle size [µm]	Content [% by weight]
0-75	5
75-125	15
125-200	28
200-400	36
400-600	11
600-900	4
900-1000	1

Table 2: Sand grain size and concentration for the test without filter

TEST FACILITIES

According to the above mentioned requirements special facilities rather than the standard engine test bed were necessary. These comprised a sand feeding system with metering equipment and sand supply system. For the sand ingestion test with filter an engine sand filter with a scavenge system was additionally required, as figure 2 shows schematically.

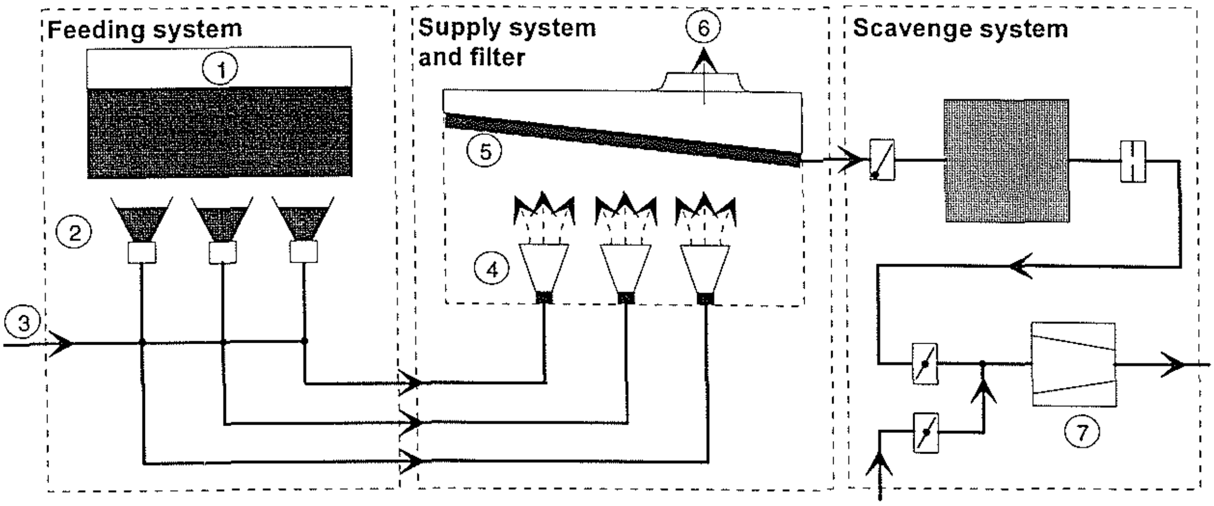

Figure 2: The sand test facilities

From the storage tank (1) the sand went at a constant rate through several vibrators (2) and after being mixed with compressed air (3) to the nozzles (4) of the supply system. These nozzles were to ensure a uniform sand distribution in the air at the front of the filter (5) or directly at the inlet of the engine (6). The filter consisted of a multitude of small centrifugal separators connected to the scavenge system. This filter was a prototype intended for use in the Tiger helicopter. The sand particles separated by the filter were sucked by the blower (7) of the scavenge system at a rate equivalent to that in the Tiger.

Pretests were carried out to determine and adjust the sand distribution in the air at the engine inlet using a lattice painted with varnish. It was mounted in the engine inlet system at the plane of the compressor 1st stage rotor entry.

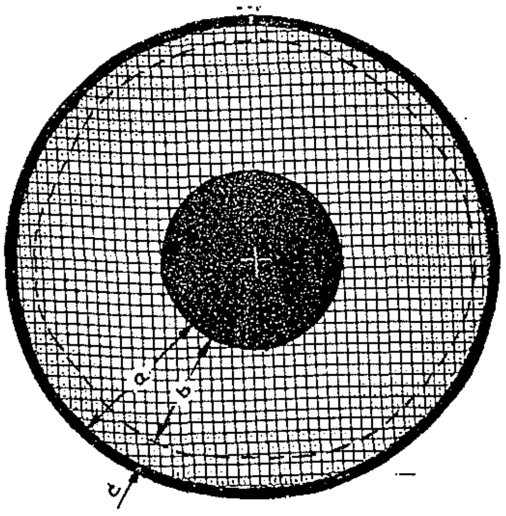

Figure 3: A painted lattice showing the sand distribution; **a:** channel height; **b:** area of uniform erosion traces; **c:** area without erosion

For these pretests only the inlet system without the engine was needed, with the engine air mass flow being simulated by an exhaust fan. The degree of erosion of the varnish was used as a measure for determination of the sand distribution in the air. The results of the pretests are shown in figure 3. It was as expected: a uniform distribution in circumferential direction but a lower concentration in tip direction. This guarantees that the sand test will be representative of actual conditions.

TEST PROCEDURE AND MEASURED PARAMETERS

As usual calibration tests were first conducted to adjust the necessary test parameters of all the test facilities. The programs for the main tests with and without sand filter were basically identical. The sequence of the test program is shown in figure 4. Before and after the sand ingestion test performance calibrations were carried out, where the engine run with an airmeter installed to measure the air mass flow, as this was needed for calculation of the performance parameters.

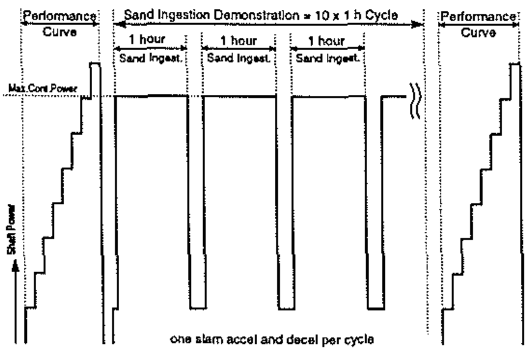

Figure 4: The sequence of the sand ingestion test

During the sand ingestion test the performance was checked at fixed intervals but without airmeter as the sand supply system was installed instead. In this case, the performance parameters were calculated by using correlations.

	Without filter	With sand filter at entry of	
		filter	engine
Sand/air [g/m3]	0.053	1.5	0.08
Sand/hour [kg/h]	0.48	15.4	0.77
Total quantity [kg]	0.48	154	7.7

Table 3: Sand quantities used in the ingestion tests

For the execution of the test it was necessary to dry the sand by heating it up for some time to avoid lumping. The sand needed per engine running hour was weighed before being fed to the engine continuously. In the tests with and without sand filter the sand fed per hour amounted to 15.4 kg and 0.48 kg, respectively. In table 3 the sand quantities used for the tests are compared. During the sand test the engine ran at maximum continuous power. In addition, slam decelerations and re-accelerations were carried out after each running hour to achieve realistic sand depositions.

The test cycle of one hour each was repeated until a total running time of 10 hours was reached or, in the case of the test without filter, a performance deterioration of 5 % occurred.

During the sand ingestion test with filter, it was also of interest to measure the sand quantities retained in the filter thus being able to determine the filter efficiency. For this purpose the scavenge air of the sand filter was routed through a separate fine filter. The retained sand was carefully collected, and its amount was compared with the total sand quantity delivered by the supply system.

Ambient conditions	P_0, T_0
Engine inlet	P_1, T_1, W_1
Compressor exit	S_{31}, T_3
Gas generator exit	S_{44}
Power turbine exit	S_{88}
Gas generator speed	N
Power turbine speed	N_{PT}
Shaft delivery torque	TRQ
Fuel consumption	WF

Table 4: Analysis-relevant measurements

For the analysis of the engine overall performance and the performance of the components only the performance curves before and after the sand ingestion are of interest. The test parameters necessary for the analysis are listed in table 4.

TEST RESULTS

The deterioration in performance during the test series with sand filter was small despite the larger amount of the sand. After completion of 10 hours of sand ingestion the shaft power decrease amounted to 3.5 % which was within the allowed 5 %. According to the analysis carried out at MTU, the comparison of the whole amount of sand used for the test with the amount that went through the scavenge system showed a filter efficiency in the order of 95 %. This means that due to the very efficient separation only 5 % of the 154 kg of sand ingested through the filter entered the engine. The particles found in the engine had a maximum grain size of 0.02 mm, which was smaller than the sand upstream of the sand filter by a factor of ten. The bigger particles had been perfectly separated by the filter.

After the scheduled half an hour of sand ingestion test without sand filter the performance deterioration of the engine was still less than the limit of 5 %. So the engine was run for another half hour. The subsequent performance curve, i.e. after a full hour, revealed that the test purpose, the demonstration of 5 % performance deterioration was fulfilled. The engine hardware was without major detriments, Thus the test without sand filter was terminated successfully.

PERFORMANCE ANALYSIS METHOD

After terminating the sand ingestion tests, the next task was the performance analysis.

A method of the performance analysis based on a synthesis model for engine operating behavior was used. Such a model includes the characteristics of the engine components, and the conservation rules of the physics for concatenating these characteristics, as well as the caloric relationships of the working media. A description of such synthesis models can be found, for example, in [3].

The model used here represents the components of the MTR390 engine. The performance curve of the test engine before the sand ingestion test was used to calibrate the model. In the following, the calibration is demonstrated using the compressor as an example. It is representative for all other engine components.

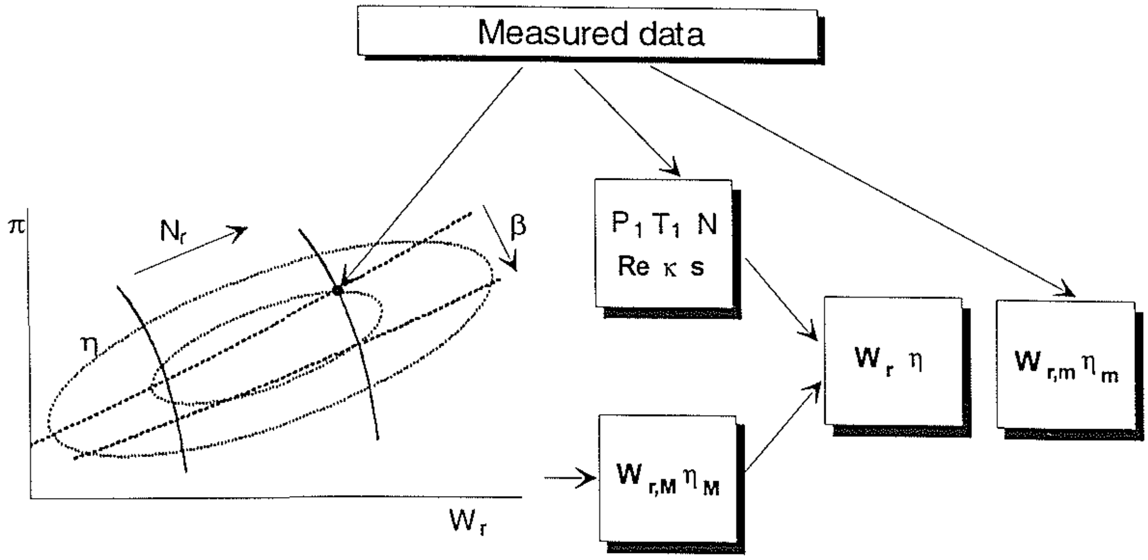

Figure 5: Principle of the test data analysis method

The usual way is to read the reduced air flow $W_{r,M}$ and the efficiency η_M from the compressor map of the synthesis model using the reduced speed N_r and the map parameter β, as shown in figure 5. From the pressure P_1 and the temperature T_1 measurements at the engine inlet as well as the gas generator speed N the Reynolds number Re and the tip clearance s between casing and rotor are calculated.

The effects of Re and the gas properties, symbolized by κ, on the engine component characteristics are dealt with, for example, in [4] and [5]. During the development phase of the MTR390 the influence of Re, gas properties and s was determined by using rig and altitude test data. According to the changes of these parameters versus the reference values for the map $W_{r,M}$ and η_M are corrected. The corrected map values W_r and η are compared with the $W_{r,m}$ and η_m values determined from the measurements. If this results in a deviation, the map of the synthesis model has to be corrected accordingly to obtain a representative model for the test engine. This model is then used to analyze every measured engine condition during the sand test and to detect every deviation from the initial condition.

Depending on the number of the measurements shown in table 4 a specific number of component characteristics from those shown in table 5 can be analyzed at the same time. The effects on the performance of the combustion chamber and on the pressure loss in the inter-turbine duct as well as in the exhaust diffuser were considered negligible. Therefore, only the characteristics of the compressor, gas generator turbine and the power turbine were analyzed.

Engine components	**Characteristics**
Compressor: capacity, efficiency	W_r, η
Combustion chamber: press. loss, efficiency	$\Delta\pi$, η
Gas generator turbine: capacity, efficiency	W_r, η
Inter-turbine duct: pressure loss	$\Delta\pi$
Power turbine: capacity, efficiency	W_r, η
Exhaust diffuser: pressure loss	$\Delta\pi$

Table 5: Characteristics of the engine components

PERFORMANCE ANALYSIS RESULTS

Shaft power, gas generator turbine inlet temperature and specific fuel consumption are the usual parameters to judge the overall performance of the engine. With sand filter the engine deterioration is insignificant, especially at higher loads. At take-off (958 kW) the TIT increases by 5 K and the SFC by 0.4 %. Towards part load the deterioration augments, as shown in figure 6 and 7. This change of the overall performance parameters is explained by the analysis results for the engine components shown in figure 8. The compressor characteristics plot shows a slight decrease in flow capacity and efficiency by less than 0.5 %. The increasing deterioration towards part load can be attributed to the degradation of the gas generator turbine efficiency. The plot on the right-hand side of figure 8 shows the power turbine characteristics. Their change has a less important impact on overall performance.

In the case of the sand ingestion test without sand filter the engine deterioration is more pronounced. As can be seen from figure 9 and 10 the TIT and SFC increase at take-off power (958 kW) by about 30 K and 2 %, respectively. In this case, too, the engine degradation at part load is more severe than at full load.

The plot of the compressor characteristics in figure 11 indicates that flow capacity and efficiency decrease by about 2 % and 1.7 % points, respectively. The efficiency of the gas generator turbine decreases by 1 % point at part load, whilst the flow capacity, as well as the flow capacity and the efficiency of the power turbine remain nearly unchanged.

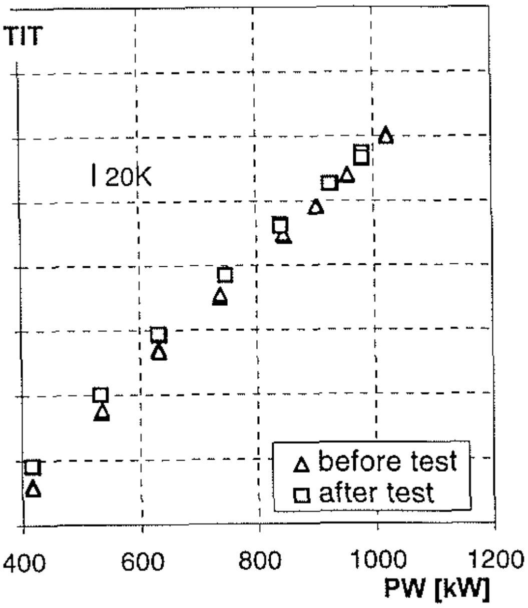

Figure 6: TIT versus shaft power; test engine with sand filter

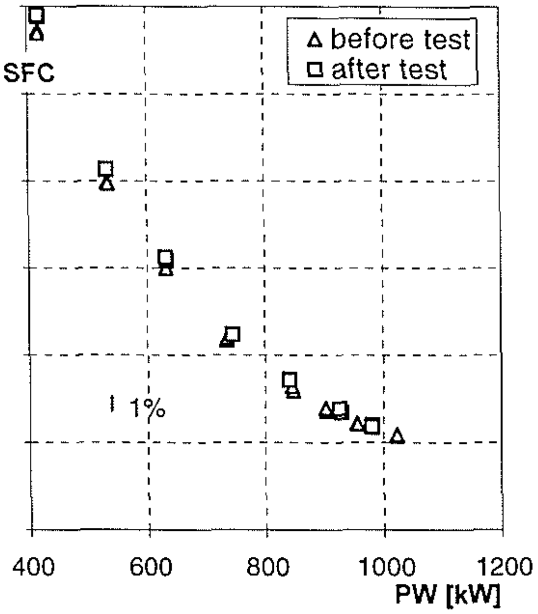

Figure 7: SFC versus shaft power; test engine with sand filter

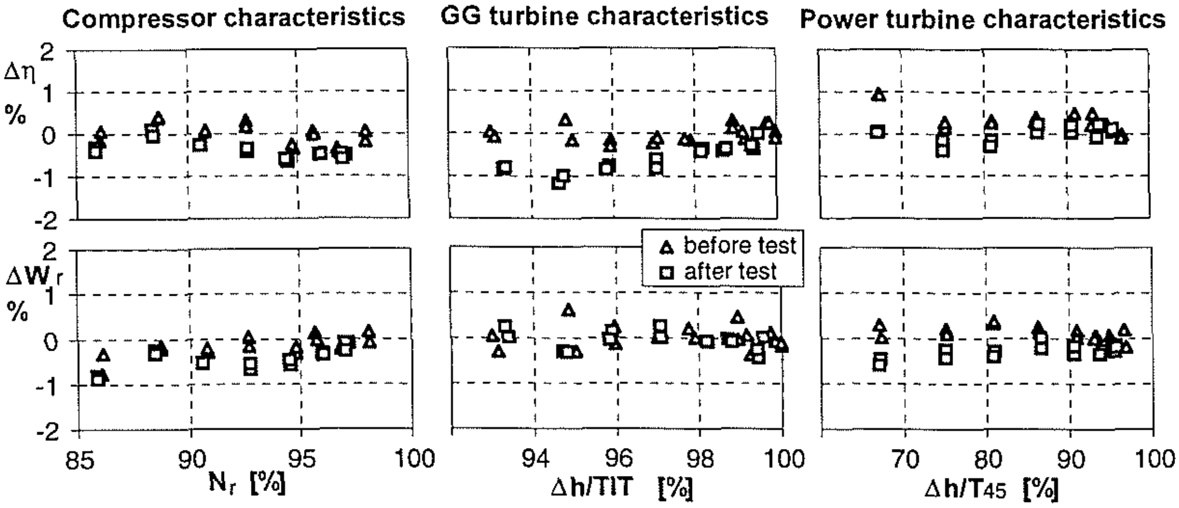

Figure 8: Analysis results for the engine components; test engine with sand filter

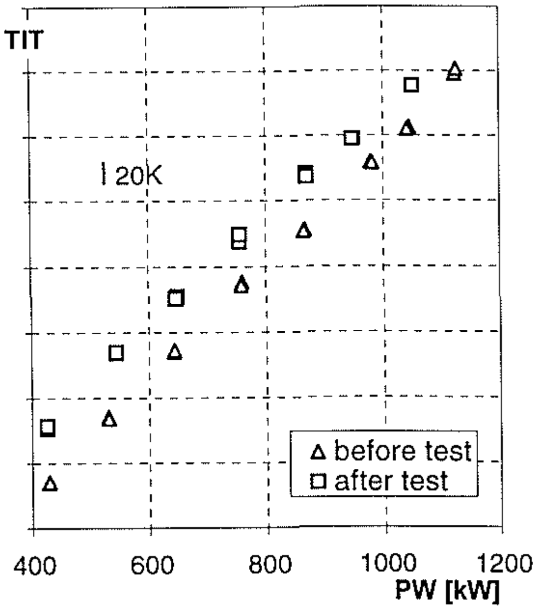

Figure 9: TIT versus shaft power; test engine without sand filter

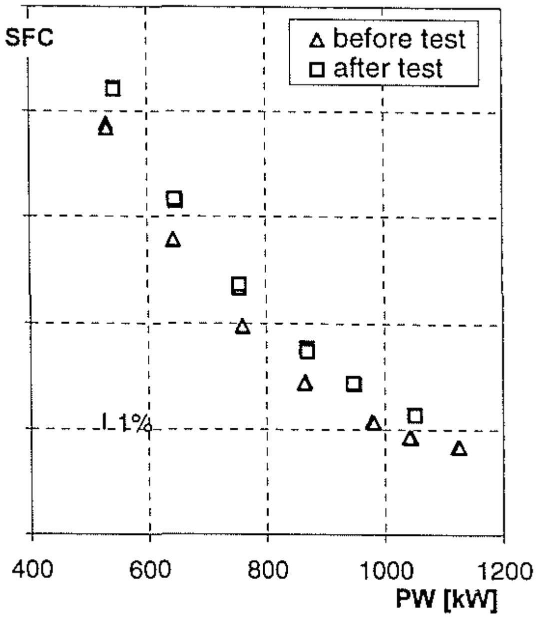

Figure 10: SFC versus shaft power; test engine without sand filter

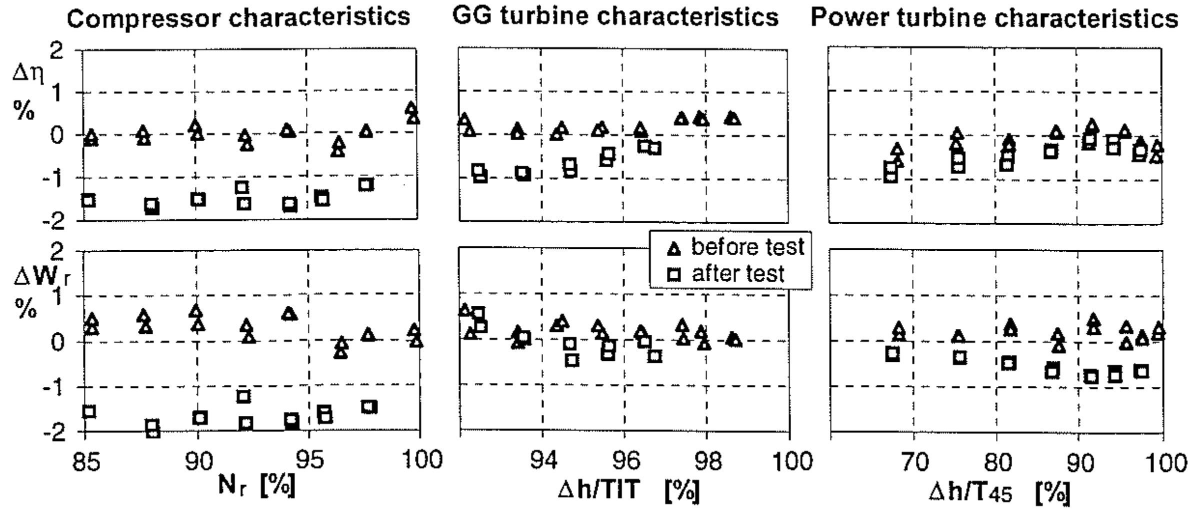

Figure 11: Analysis results for the engine components; test engine without sand filter

ENGINE FINDINGS

The main result of the sand tests is the engine parts condition. After the test without sand filter, traces of erosion were found especially on the compressor blades, which caused a slight increase of the tip clearances. On all the parts in the flow path deposits of fine sand were found. However, the secondary air system and especially the cooling holes in the blades and vanes were found to be free of sand particles.

During the test with sand filter, all particles larger than 0.02 mm were separated by the filter, and from the 154 kg sand ingested by the engine only 7.7 kg of fine dust passed through the sand filter into the engine. These very small particles caused slight erosion on the compressor and gas generator turbine blades and increased the tip clearances of the compressor rotors.

In the combustion chamber a lot of deposits was found, but all the cooling and dilution holes were free and no hot spots were visible.

Although the secondary air system with its sealing and bleed air is designed in such a way that only small quantities of fine sand can penetrate into it, the extremely high sand concentration caused a partial blockage of the cooling channels, as figure 12 indicates. The cooling air flow in the gas generator turbine vanes and blades was reduced by up to 50 %.

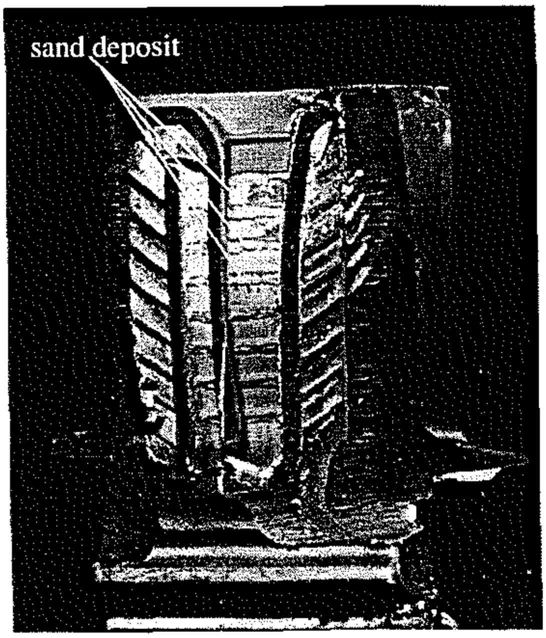

Figure 12: Sand deposit in cooling channel

Figure 13: The 1st stage rotor of the compressor with sand deposit

The gas generator turbine blades showed no signs of material overheating, but slight traces of erosion at the leading edges and on the discharge side of the trailing edges. The gas generator turbine vanes, however, had some local hot spots on the suction side with molten base material in the areas where the decrease in cooling air flow reached a maximum. This became apparent from an additional investigation carried out subsequent to the sand test, which included, among others, testing at maximum contingency power, where extremely high metal temperatures were reached. These high temperatures caused local melting of the vane material, but did not affect the integrity of the vanes.

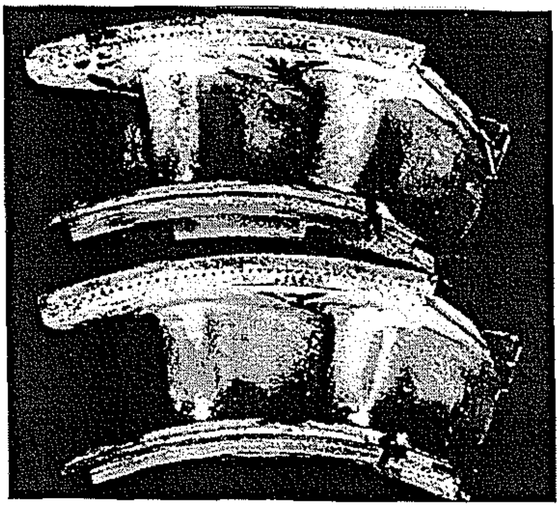

Figure 14: The nozzle of the gas generator turbine with sand deposit

The flow path as well as the vanes and blades showed a thin deposit in the areas with lower flow speeds, see figures 13 and 14. Glazing of the sand did not occur. That is to say the sand could be removed by brushing or by blowing off with compressed air. The tip clearance of the gas generator turbine was unchanged and, therefore, the slight change in efficiency was not caused by the tip clearance.

The inter-turbine duct and the power turbine also showed slight dust deposits in the smoothed flow areas, which had no effect on the engine parts and the secondary air system. The abradable linings and thermal barrier coatings were in good condition and showed only minimal traces of erosion. The function of the labyrinth seals and that of the secondary air system was not impaired.

A very small quantity of sand residues was also found in the oil system. This had no effect on the bearings and the gearbox. The accessories, like oil pumps, oil cooler and temperature probes were likewise not affected by the sand, neither mechanically nor functionally.

On the whole, the engines were found in a very good mechanical condition after the sand ingestion tests, and all their parts as well as their accessories could be used for further operation after simple cleaning.

SUMMARY

As expected the mechanical deterioration of the engine parts was significantly higher with the coarse sand despite of the smaller amount of sand. The sand of the one-hour test without sand filter caused a more severe engine deterioration than the complete test series with sand filter. This difference in engine behavior is mainly due to the grain size of the sand particles that entered the engine.

The analysis of the test data revealed that in the case of the test with sand filter the performance deterioration of the engine components, despite a running time of 10 hours, was negligibly small. The same applies to the overall performance. Without sand filter, a performance deterioration of 5 % was measured after a running time of about one hour. The performance deterioration without sand filter mainly resulted from erosion in the compressor area. Sand deposits in the gas flow path on vanes and blades also played a role. The more severe deterioration towards part load is attributable to the gas generator turbine.

As the integrity of the engine parts and the accessories and their functionality was not affected, the engines could be further used after being cleaned from sand deposits.

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