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MAIN GEARBOX WITH HIGHER SURVIVABILITY AND RELIABILITY

BY

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Abstract

In the scope of helicopter performance enhancement, the gearbox safety and reliability aspects are one of the main areas of concern.
It is in these sectors that both the commercial and the military customers demand the most stringent improvements, with a particular interest for operational capacities after a total loss of lubricant.
A few years ago, in order to improve gearbox survivability in case of loss of lubrication, an exploratory development programme called "tolerant MGB", based on the TIGER helicopter's MGB, was initiated with assistance from the French SPAé authority ("Service Pour les Armées").

This paper describes the technical solutions adopted for the tolerant MGB, on the one hand:
- reduction of the friction coefficients by means of coating,
- maintained lubrication on critical points thanks to scoop systems,
- spray cooling,

and on the other hand, the tests performed in the scope of this programme as well as their results.
The tolerant MGB operated without failure for over six hours after a total loss of lubricant.

1 - CONTEXT

The economical requirements associated with market difficulties both dictated cost savings and manufacturing cycle reductions, as well as increased performance levels and reliabilities, made even more stringent by stricter and stricter regulatory requirements.

In the scope of this ongoing improvement scheme, gearbox operation makes up one of the main areas of concern, especially in the aspects involving flight safety.

In fact, it is in this and in the reliability domain that both the commercial and military customers require the most significant improvements, with a particular interest for operating capacities after a total loss of lubrication likely to arise further gearbox casing piercing, either by an ammunition round in the case of a military aircraft, or to the failure of a pipe or the oil cooler in general...

Furthermore, as regards regulations, the requirements are changing notably with the enforcement of amendment 26 to the FAR/JAR 29.927(c) rules, now dictating "maintained flight in safety for a period of 30 minutes after detection by crew of the loss of lubricant, followed by landing".

This required survivability for heavy aircraft is all the more difficult to achieve as the power levels transmitted in the gearboxes of these types of machines are high.

Although the 30-minute requirement seems to meet the expectations of the military operating on land, as it would probably allow them to stand off the hazardous zone in case of combat, conversely, the "seamen" tend to claim for 1 hour in order to avoid ditching in all cases.

For the same reason, civil aircraft operators of the off-shore sector in the North sea require up to 2 hours.

To meet this general demand for survivability improvement and reinforced reliability, a research programme called "tolerant MGB" exploratory development was implemented in order to test on an actual gearbox many new concepts likely to increase survivability after loss of lubrication.

Based on a recent operating test experiment after oil loss, the Tiger helicopter's MGB was selected as scope of work, therefore allowing the precise assessment of the improvements brought by the specific devices under study, and also providing good comparison elements.

Furthermore, the architecture and technologies implemented for the Tiger helicopter and optimised to achieve high survivability are particularly suitable for this exploratory study. One hour and six minutes of operation after total loss of lubricant, simulating a landing every thirty minutes, was demonstrated in test, which was deemed very satisfactory for the power level transmitted in the gearbox, ca. 1,400 kW.

Therefore, derived from the Tiger helicopter's MGB, the operating objective for the tolerant MGB after loss of oil was to double the operating time achieved on the Tiger.

To reach this objective, the specific devices were oriented towards three targets:

- reducing the calories generated by friction factor reduction, by means of coating
- keeping an oil film between the contact parts, by maintaining lubrication on critical by scoop systems
- limiting overheating by cooling fluid spraying.

2 - TESTED SOLUTIONS

2.1 Tiger technology

The tolerant MGB reuses the Tiger MGB technology, which is suitable for operation after loss of oil:

- nitrided gears,
- bearing races integrated to the gears,
- bearings in M50 or M50 NIL,

as well as its architecture (figure 1):

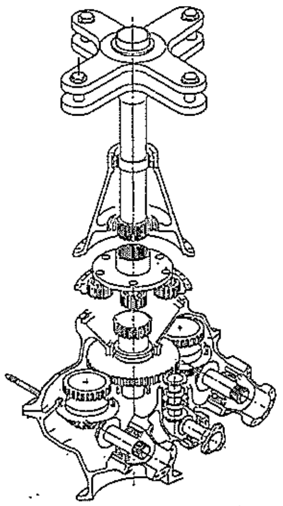

figure 1: TIGER MGB architecture

2.2 Reducing friction coefficients

Nearly the entire power generated in a gearbox operating after a loss of lubricant is due to phenomena close to friction. The friction coefficient reduction between 2 contact elements allows the generated power to be reduced.

Although in "normal" operation, this reduction results in a negligible mechanical efficiency improvement, the effect is fundamental after a loss of lubricant. In the absence of oil, the calories are no longer drained, which results in a gradual overheating of the gearbox components therefore causing successive degradation, until the loss of the functions ensured by the gearbox. Thus, with a lower friction coefficient, the operating time can be extended.

Inserting a coating between 2 contact parts is one of the most efficient methods to reduce the friction coefficient value. Two coating were selected in the scope of the tolerant MGB study:

- **Balinit C**

"balinit C" coating (developed by the BALZERS company in SWITZERLAND) are comprised of alternated overlayers of carbon and tungsten carbide, obtained by ionic bombardment spraying.

The coating thickness obtained by the industrial process ranges from 1 to 4 microns.
This type of coating features the advantage of a very low friction coefficient (ca. 5 times lower than the friction coefficient of nitrided steel), without however causing very different hardness values for the base metal which could cause cohesion problems.

Furthermore, the coating spraying technology, at temperatures of less than 250°C, allows the treatment of most materials previously submitted to thermo-chemical treatments, without derating the characteristics of the material. This coating also improves corrosion resistance in the treated areas.

The "Balinit C" process was selected further to the results from tests of "wear on rollers " type performed on various types of coating. "Balinit C" proved the most efficient coating.

"Balinit C" coating were essentially applied to gear tooth levels (figure 2) and to integrated bearing races in the tolerant MGB.

figure 2: Balinit C coating

- **Silver plating**

Unlike the "balinit C" solution, the improvement of friction coefficients through silver plating is a well-known practice in the aerospace industry. Most steel bearing cages are protected by a silver layer in order to improve friction with rolling elements and the centering ring. Silver plating has also been tested on gear teeth but, as silver is highly ductile, the coating is rapidly eliminated from the pitch meshing zone.

The power transmission bearing races non treated with balinit "C" were silver-plated.

2.3 Scoop devices

A scoop device which recycles the running oil allows a sufficient oil quantity to be maintained for a certain time in order to ensure minimum lubrication of gears and bearings in the critical zones of the main gearbox.

The remaining oil quantity does not permit calory draining to the external skin of the casing or to a cooling unit; however, it limits heat generation by reducing friction coefficients by contact lubrication.

EUROCOPTER's experience with functional tests after loss of lubrication shows that the epicyclic trains are one of the most critical items in the gearbox. This criticality is due to the high density of heat sources, difficult to evacuate, and to high transmitted torque values.

Although the epicyclic stage of the Tiger MGB behaves correctly during the test after loss of oil, in the scope of the tolerant MGB it was necessary to further improve lubrication in this zone to achieve a successful survivability improvement, as the degradations which occur during this type of test are sudden and hardly predictable.

The technical solution ensuring this standby lubrication function is comprised of (figure 3):

- a tank created in the part, and recovering the running oil underneath the epicyclic stage,

- one scoop per planet gear which, under the effect of dynamic pressure created by planet holder rotation, raises part of the oil present in the tank towards the planet gear bearings.

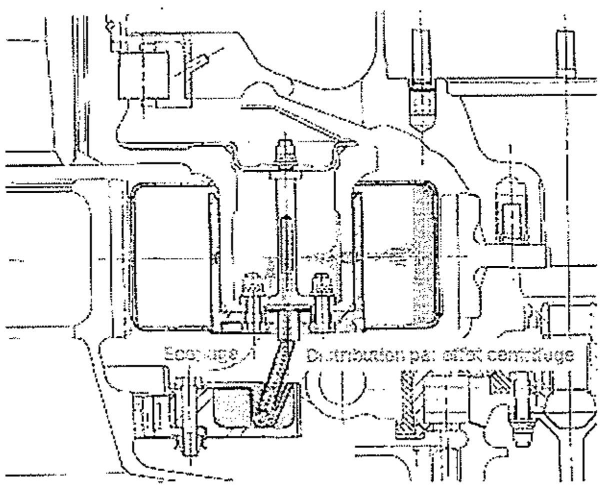

figure 3: epicyclic train scoop system

Similarly, a scoop device was implemented at the gearbox sump in order to recycle the running oil (figure 4).

The dynamic effect is created by driving the oil tank in rotation through links with the addition wheel (figure 1). The tank features fins which improve oil driving. The scoop is comprised of a fixed pipe.

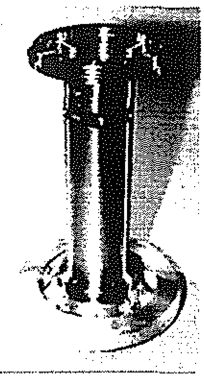

figure 4: scoop system in MGB sump

The oil scooped from the turning tank at MGB sump is reinjected to the various MGB oil jets through lubrication systems integrated in the MGB casing.
The oil jets are suitable for the scooping dynamic pressure. Equilibrium between flow and pressure is obtained from the pressure drop which, in this case, directly depends on the drilling diameter of the oil jet holes.

2.4 Spray cooling

In the study of various systems permitting MGB overheating limitation in case of operation after loss of lubricant, the technical choice is dictated by the weight, efficiency, and ease of implementation.

Liquid spraying on "hot" zones was deemed preferable compared to other solutions such as:

- cooling fins on the casing (drawback: remote from the zones which generate the most heat);

- internal gearbox ventilation (drawback: higher risks of leakage in normal operation, and favours the elimination of residual oil after loss of lubrication).

The spraying system was judged efficient in relation to the overheating reduction aspect, and thanks to its flexibility of implementation in case of series-production application on aircraft: this system can be envisioned as an optional device, triggered by the pilot when certain degradations or certain temperature thresholds are reached, or can be triggered automatically.

In the scope of the tolerant MGB, the spray cooling system is planned to be tested either on completion of the loss of the lubrication test, or in case of detection of divergent phenomena (abrupt increase in the consumed power, or abrupt rise of a temperature parameter), with the possibility to intermittently inject a lubricant volume in order to keep temperature low.

The external part of the MGB comprised of pipes and of a pressurised tank is dealt with as a bench tooling, in order to facilitate the tests. This offers the advantage of a possible selection, in the course of the test, of the injection points best suitable for the desired effect, in accordance with the evolution of various temperature parameters.

The internal part is comprised of pipes, routed from the inlet port in the gearbox to the spray points and the spray jets (nozzles), capable of creating a lubrication mist while ensuring a suitable flow (figures 5 et 6).

figure 5: spray nozzle diagram

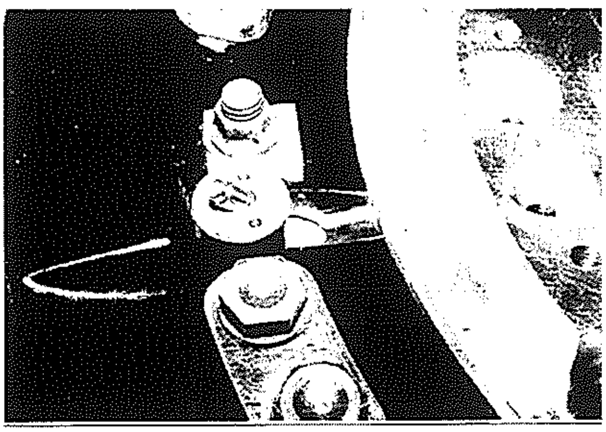

figure 6: spray nozzle location

The spraying product must feature both a high calorific capacity and good characteristics in terms of resistance to seizing in the absence of lubrication.
A product based on glycol and water was selected after laboratory testing.

3 - TEST AFTER LOSS OF LUBRICANT

3.1 Preliminary phase

The tolerant MGB test programme breaks down into two main parts:

- a new system adjustment phase, followed by a minimum endurance test permitting the various coating to be run in;
- the loss of lubrication test itself, with an endurance objective of at least two hours.

The flowrates were evaluated, and the presence of satisfactory lubrication was checked (sufficient pressure) in the scoop systems at MGB sump and at the epicyclic train, during this laboratory adjustment phase.
This step also permitted the spray nozzles to be characterised: type of spraying, evaluation of the mist cone angle, spray range and sprayed surface, associated flow.

Once this adjustment was completed, the MGB was mounted on the test bench for endurance testing. The purpose of the test was to run in the various coating (silver plating, Balinit C) so as to obtain, for the test after loss of oil, an MGB representative of the mechanical system in operation, and so as to particularly check that the coating are still in an acceptable state in relation to the function that they must ensure.
A 33-hour endurance test with a power spectrum and sequences similar to the endurance test carried out on the Tiger helicopter was performed on a “back to back” power bench.

An analysis of the various MGB modules was conducted after this test in order to determine a reference point before the loss of lubrication test.

3.2 Test and measurement device

The test after loss of oil is conducted on a “back to back” power bench (figure 7), equipped with the Tiger helicopter’s cooling unit (fan and cooler).

A device ensures supply and metering to each individual spray nozzle, which permits the test device to be controlled during testing by varying the spray time and frequency (figure 8).

A valve mounted in lieu of the MGB sump magnetic plug permits fast gearbox draining triggering in order to simulate the loss of oil.

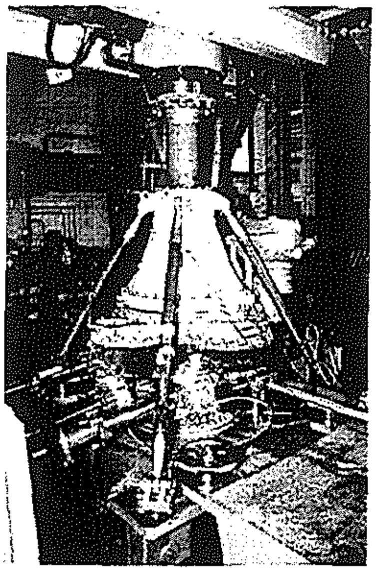

figure 7: test bench

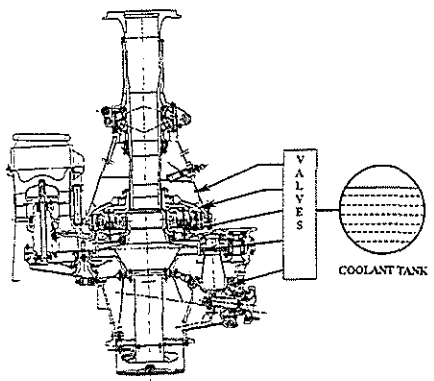

figure 8: spray system

The parameters to be monitored and recorded are essentially:

- internal ambient temperatures in the MGB,
- local temperatures: bearings, teeth, casings,
- oil pressures in the various systems (scoop),
- rotation torques and speeds.

3.3 Test programme

The test must be carried out by comparison to the test performed in the scope of Tiger MGB qualification.

A *first test sequence at maximum continuous power* (i.e. 710 kW) on each input until temperature stabilisation is intended to establish a reference for each measurement point.

The test begins by a normal operation phase (with lubrication) in order to stabilise the temperature and pressure at maximum power.

The loss of lubrication is triggered by MGB sump valve opening.
When the "low pressure" alarm for the main system comes on, the stop watch is triggered and the power level is reduced to the fall-back flight power (i.e. 360 kW on each input), for a period of 1 hour on completion of which a landing manoeuvre is simulated. If MGB operation is satisfactory, the same sequence is simulated again (figure 9).

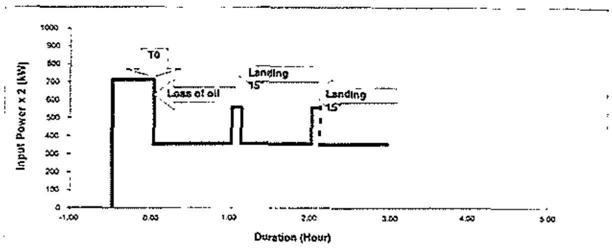

figure 9: test power spectrum

The spray triggering decision criteria are of three types:

- temperature threshold for one or more sensors
- divergence in the evolution rate of a temperature parameter
- beyond a determined period, in order to evaluate efficiency.

3.4 Test sequence

The tolerant MGB was operated for six hours and 15 minutes after total loss of lubricant without failure, which is well beyond the assigned objectives.

The test was conducted as follows: after oil temperature stabilisation at 80°C at maximum power, the opening of the gearbox sump valve caused draining beginning. As soon as the low pressure alarm came on, the T0 test time was counted and the power reduction procedure (to fall-back power) was carried out in compliance with the test programme.
Power was kept at this level. Landing manoeuvres were simulated after one hour, then 2 hours.
On completion of each simulation, return to fall-back power was carried out. The test was then resumed until T0+ 5 hours at fall-back power.

Taking into account the correct behaviour, the test proceeded as follows:

- 1/4 hour at landing power
- then, 1 hour at maximum continuous power.

On completion of these 6h15, after noting temperature stabilisation, the test was interrupted in order to obtain an MGB in good condition for the analysis. The MGB did not feature any hard running point.

In order to anticipate overheating due to excess power transmitted during the landing phases, spraying at input levels was initiated immediately before each simulated landing.

Spraying was also triggered locally when a strong temperature divergence was recorded on one element.

From T0 + 2 hours 45 minutes of test until the power increase (T0 + 5 hours), no injection was necessary, as the temperatures were generally stabilised. At this point of the test, only 2.85 litres of coolant had been used.

The main part of the coolant was used during the first half hour of testing at maximum power (last phase).
In total, a volume of 7.8 litres of coolant was used during the test, less than 3 litres of which during the first 5 hours.

The diagram in figure 10 summarises the test sequence.

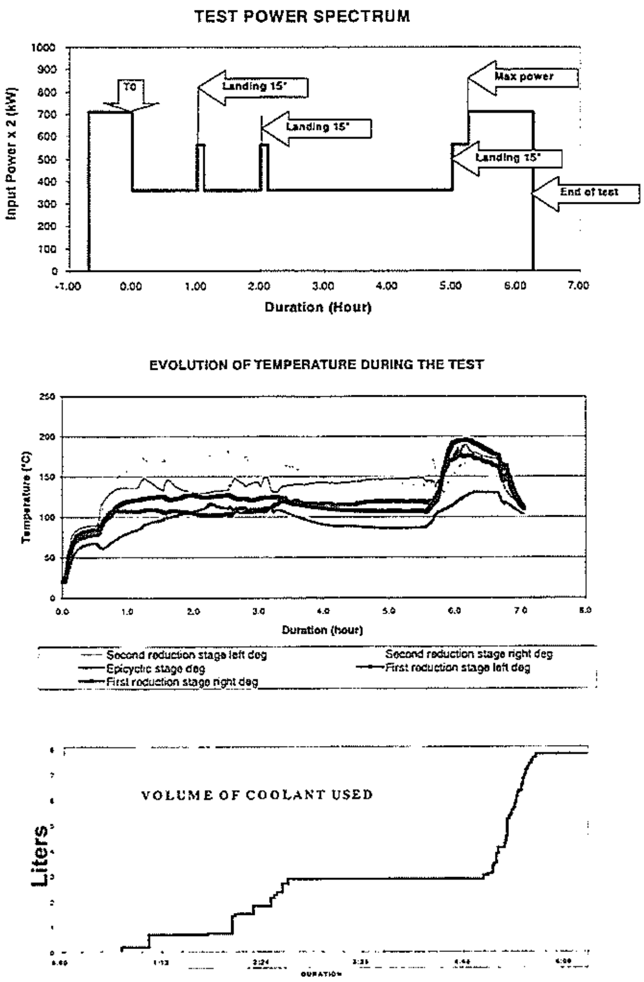

figure 10: test sequence

4 - ANALYSIS AFTER TESTING

4.1 General condition

On completion of the test, no hard running point or seizing in rotation was reported.

After removal, the oil was found burnt and the epoxy varnish of the casing degraded in its internal part (figure 11).

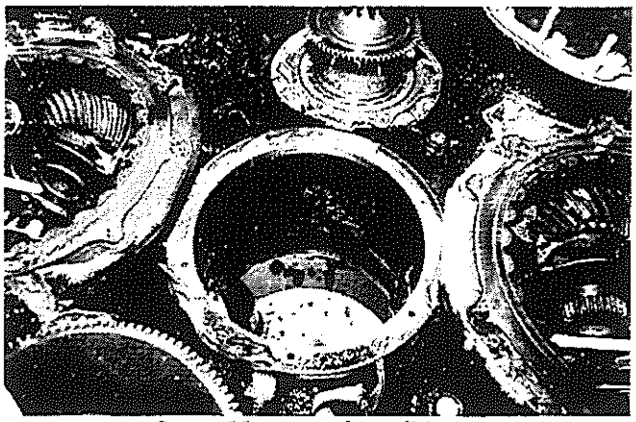

figure 11: general condition

To the contrary, the parts did not feature any particular deformation or degradation. The gears and bearings were found in good general condition.

Oil was found in the scoop system tank of the epicyclic train, which demonstrates the correct operation of this system during the entire test.

4.2 Tooth analysis

The gears were found in good general condition, not featuring any significant damage.
However, on spiral bevel input teeth, a degradation of the balinit C coating was found, as well as beginning scratching (figure 12).

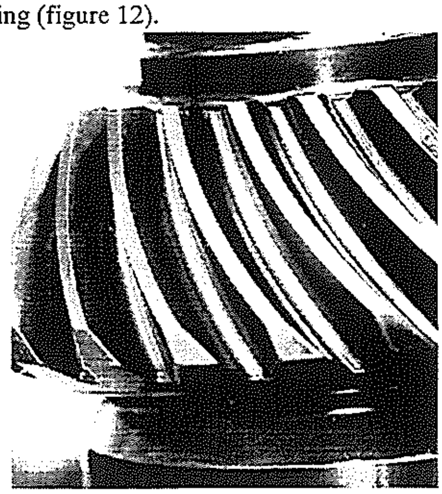

figure 12: spiral bevel input teeth

On certain teeth, beginning of pitting as well as a slight degradation of the balinit coating were also visible.

However, this damage remains moderate and does not compare to those generally obtained after this type of test (figure 13).

figure 13: state of planet gear teeth

The general state reported demonstrates the good behaviour of meshing gears in the course of the test and shows the efficiency of the balinit coating.

4.3 Bearing analysis

Again, the visual state demonstrates the good behaviour of the assembly during testing.

On certain bearing races, a local degradation of the balinit coating is reported, but with no trace of pitting or seizing (figure 14).

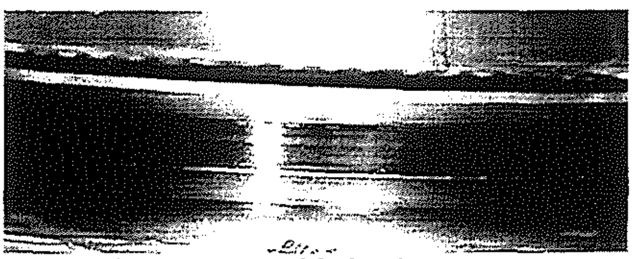

figure 14: state of the bearing races

To the contrary, this silver plating was eliminated. However, no particular degradation is reported.

5 - RESULT ANALYSIS

The behaviour of the tolerant MGB *during testing after* loss of oil is compared to that of the Tiger helicopter's MGB in the same test conditions.
The MGB behaviour is analysed through temperature measurements.

It is remarkable to note the behaviour similarity between both gearboxes, with a lower general temperature in the case of the tolerant MGB (figure 15). This difference is explained by the contribution from both systems: coating and scooping.

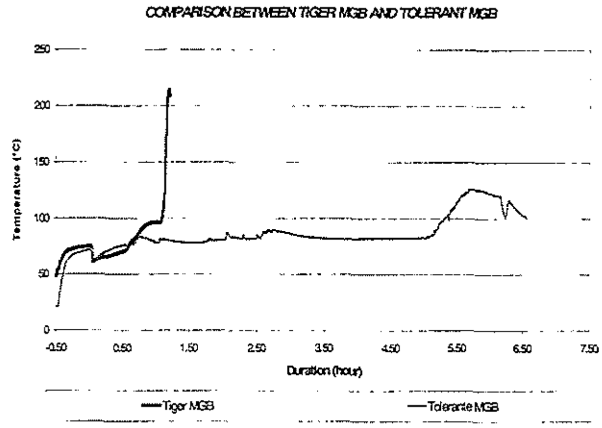

figure 15: temperature evolution

A clear change in the temperature gradient is reported further to the landing manoeuvre in the case of the Tiger, whereas in the case of the tolerant MGB, the *temperature gradient remains* unchanged. The reduction in the friction coefficients, thanks to the coating, accounts for this behaviour difference.

The *gain introduced* by *cooling fluid spraying is* particularly significant in the course of the last part of the test, during the maximum power phase.

For reference, the injection points were *multiplied to* avoid the need to identify the locations which required cooling.

Even though all spray nozzles were used, 56 % of the volume was injected by means of 2 spray nozzles, and over 90% by only one half of the available spray nozzles.

Less than 8 litres were sprayed intermittently, which corresponds to a weight of less than 8 kilograms.

6 – APPLICATIONS ON HELICOPTER

6.1 coating

The results demonstrated the improved operational endurance after loss of oil, introduced by the Balinit C coating. This coating is particularly suitable for teeth which generate calories: high speed stages, heavily loaded teeth...
However, from the economical standpoint, the studies demonstrate that a "Balinit C" coating introduces a significant overcost, estimated at 15 % of the price of the part.

The advantage of silver plating essentially lies in the fact that the process has been in use for many years (bearing cages, bolt protection, etc.), and that many companies are therefore equipped and approved for its application. The cost of silver plating depends on the size of the area to be treated and, above all, the necessary masking for local treatment. The overcost can be estimated between 300 and 500 French Francs per part in accordance with the area to be treated and the thickness to be obtained, for parts of medium sizes.

6.2 Scoop system

This device, if integrated to the gearbox from the design phase, does not introduce any particular manufacturing difficulty or overcost. However, as the weight and reliability penalty is high, the choice will probably be oriented towards kits to be installed for specific missions or conditions. In this case, the study of capability (by minimising weight and reliability penalties) and the integration of the kits as optional items will introduce:

- a price increase for the mechanical assembly (not including kits) which will however remain less than 1 %
- a kit price essentially determined by the detail definition of the kits.

6.3 Spray system

The results obtained illustrate the considerable interest of this device.

From the economical standpoint, the "mechanical" part of the spray system will not be particularly costly, provided its installation is planned as soon as the gearbox design phase (installed in the basic version, or allowances made for optional installation). The price of the injected product is equivalent to that of the lubrication oil.

The costly part of the device relates to the triggering control. In fact, the reliability of the device detection and control systems must be very high in order to ensure efficiency in case of necessary use. Furthermore, a control device capable of injecting the cooling fluid intermittently in order to extend the effect of the coolant is necessarily more complex and costly than a system triggering from a defined threshold.

However, the interest of this type of device is such that it should be embodied very shortly on series-production applications.

Various solutions are feasible and specific kits can be envisioned, treated as optional items, which would meet certain military or commercial customers' requirements for an increased authorised flying time after loss of lubrication detection.

7 - CONCLUSION

These R&D works allow us to analyse new technologies with sufficient advance with respect to application needs on aircraft. This will help us minimise the risks of future developments and enable us to propose matured solutions in the scope of future aircraft development efforts.

The specific solutions proposed in the scope of the "tolerant MGB" exploratory development phase (coating, scoop systems, spray systems) were analysed in order to demonstrate their technical and economical feasibility on the future products. This allowed us to largely exceed the assigned objectives of endurance after loss of oil.

Thanks to the particularly impressive results achieved, this type of devices should very shortly be integrated on series-production applications with minimum complementary development work.