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DESIGN TRENDS FOR GEARBOXES

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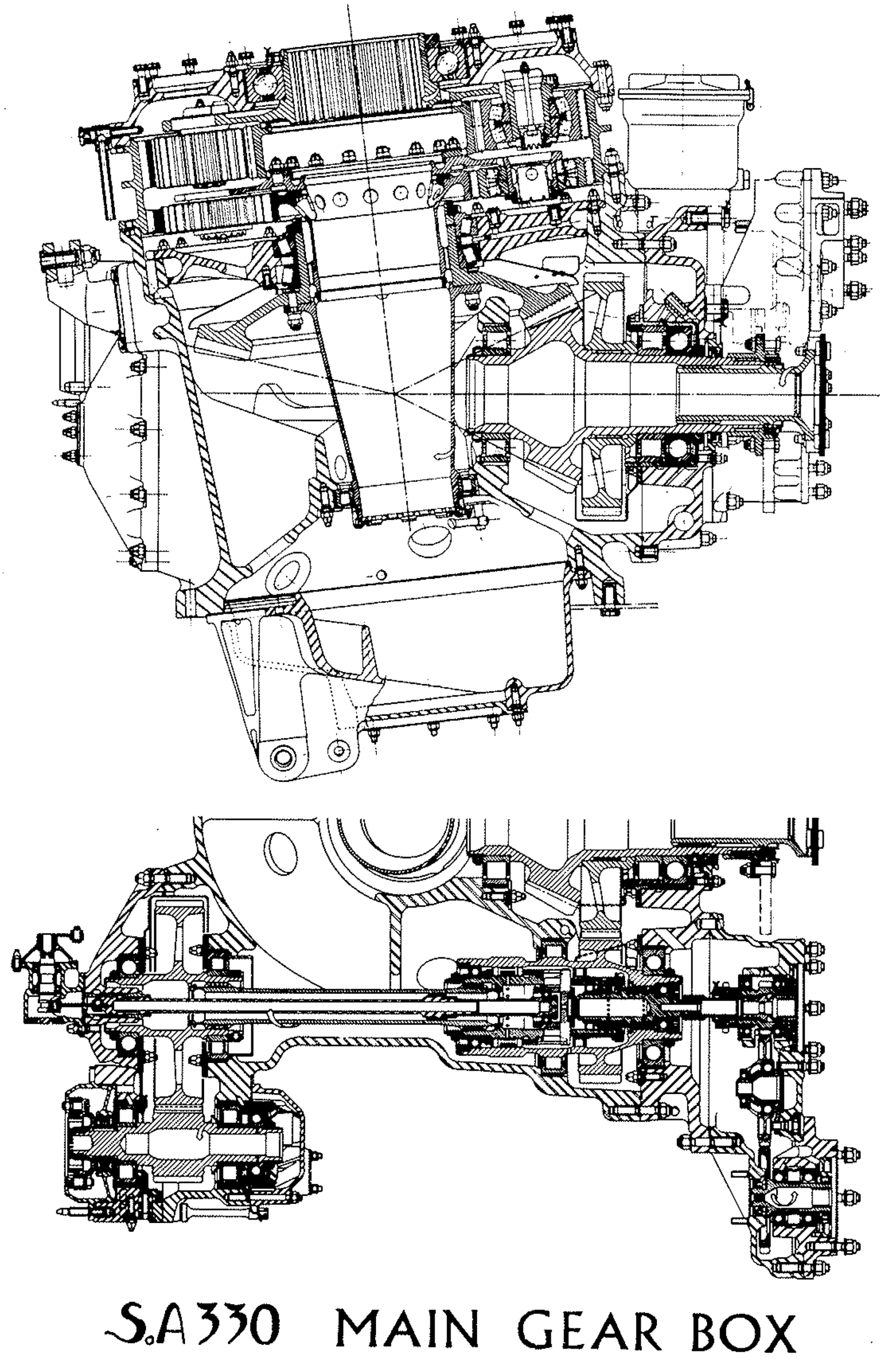


S.A330 MAIN GEAR BOX

FIGURE 1

1. INTRODUCTION

The main gearbox in the helicopter (fig. 1) fulfils several functions :

- transmission of power and reduction of rotational speed between engines and rotors.
- transmission of the reaction torque from the main rotor to the structure.
- provision for a fixed anchoring for the flight servo-controls.
- driving various accessories such as lubrication and hydraulic pumps, alternators, tachometer generators, cooling fans, brake disc.

In addition, freewheels and torquemeters may be incorporated in the main gearbox.

As the main gearbox represents an important part of the helicopter empty weight (6 to 10 %) it has always been designed with the lowest possible weight/power ratio as a primary goal.

In most cases, this requirement has resulted in the design of gearboxes including at least 3 reduction stages of which 2 epicyclic reduction stages with a large number of planet gears.

If a graph (fig. 2) shows the weight versus the maximum output torque for several conventional gearboxes, it can be seen that there is little scatter around the mean curve.

When the main gearbox of the newly born Aerospatiale helicopter (The Ecureuil or Astar) is plotted on this curve, it may be seen that the relevant point is clearly above the average curve.

Can it be concluded that this gearbox is too heavy ?
Not at all. This means simply that when designing this assembly, it was not sought to obtain the lowest possible weight but the optimum one taking into account some other requirements which were given priority.

These requirements are of 3 kinds :

- Economical requirements
  - . low manufacturing cost
  - . low operating cost
- Safety requirements
- Comfort requirements.

In the following, these requirements will be detailed and we will pay a closer attention to the means used to meet them.

2. LOW MANUFACTURING COST

The reduction in the manufacturing cost may be obtained in different ways.

- The most obvious and most spectacular way consists in simplifying the design through the reduction of the number of items and assemblies. A good example in applying this principle is the gearbox designed for the AS 350 helicopter.

  Figures 3 and 4 compare the number of components for this gearbox and that of the Alouette. This demonstration is self-evident and need not further comment.

- Other means to reduce manufacturing costs are :

  . simplified shapes

  . selection of economical materials and manufacturing processes

  . adaptation of the design to economical manufacturing facilities

  . relaxation of pointless close tolerances.

These theoretical examples may be illustrated with precise examples :

- Figure 5 shows how the internal machining of a bevel pinion may be simplified.

- Figure 6 shows how the relaxation of a surface roughness tolerance and a special study of the protuberance (root radius) allows the cancellation of a costly grinding operation from the manufacturing process. Obviously, this was only adopted after full substantiation of the part by fatigue testing.

- Figure 7 shows how some saving can be made in increasing the number of bolts for the attachment of a bevel gear onto its shaft. It appears that the increased number of bolts allows transmitting the torque by friction between the bevel gear and the shaft instead of a shearing effect through the bolts. It is therefore possible to replace close tolerance bolts and jig-bored holes by standard ones fitted in holes having wide dimension and position tolerances. So, the machining may be made on a conventional machine-tool using simple fixtures.

- It can be added to the wide range of cost reduction measures, the use of mass-produced standard components sometimes made for the automotive industry. These components are most of the time accessories, such as a filter, a sump, a warning light or a valve.

  As far as bearings are concerned, perfectly standard items are sometimes used with, however, the addition of a special individual inspection.

However, the use of a standard bearing in a main gearbox casing may lead to such compulsions that it is more economical to design a special bearing. It can be seen on Fig. 8 that the machining and installation costs for the liner and the locking parts result in a total cost (purchase price + manufacturing cost) of the solution with the standard bearing 30 % more expensive than the solution with a special bearing.

The example above clearly shows the need of knowing the manufacturing times right from the design stage.

This requires a close cooperation between Design and Production Departments during preliminary project and design stages.

We think that the team work achieved in making the value analysis for all the components of the AS 350 helicopter (Ecureuil/Astar) has contributed to a large extent to the growing interest met by this helicopter on the world market.

3. LOW OPERATING COST

The operating cost of a main gearbox contributes to the DIRECT OPERATING COST (D.O.C.) of the helicopter through maintenance schedules and particularly through removal actions and overhaul costs.

The improved reliability of the equipment is the best answer to reduced operating costs.

Again let us consider the example of the AS 350 main gearbox (Fig. 9).

As the overall reliability of an assembly is equal to the product of the reliability of all its components, it goes without saying that reducing the number of gears, bearings and assemblies brings about a significant gain in reliability.

Then the choice of proven solutions enables the achievement of the required reliability level while avoiding chipping, pitting, fretting corrosion, wear or leakage problems.

The gears are widely sized both for bending stress, which guard against any fatigue failure and for contact stress.

The selection of a limit of 90 hb for "sungear/planet gear" meshing and of a nitriding steel for the sungear contributes to the elimination of any surface damage despite the use of synthetic oil.

The risks of fretting corrosion in the splined couplings have been eliminated by hardening the surface of the splines and an efficient lubrication.

As to the bearings, their life L 10 was selected so that the expected reliability of the whole gearbox would be very high.

Fig. 10 shows, on a Weibull's curve, the calculated reliability of the AS 350 main gearbox and that of the Alouette 319.

It may be reminded that this law versus time is exponential with 2 parameters of the form $R(t) = e^{-\left(\frac{t}{\theta}\right)^{\beta}}$ which may be represented under the form of a straight line when the time is plotted on a logarithm scale and the reliability on a log-log scale.

If it is considered as the limiting Time Between Overhaul (T.B.O.), the time at which 50 % of the assemblies are prematurely removed, it can be seen on this curve that 1.500 hrs is the T.B.O. for the Alouette gearbox whereas it is 5.000 hrs. for the AS 350 main gearbox.

This high reliability level enables Aerospatiale to propose an initial T.B.O. of 2.000 hrs and as soon as the reliability substantiation operations are completed, to leave the customers with a choice between :

- the "On-Condition" removals provided an increased monitoring is implemented through spectrometric oil analysis and teeth condition checks with borescopes.
- on a very high T.B.O. given to each module in the main gearbox.

In fact, as it can be seen on Fig. 11, the main gearbox is made of three modules interchangeable at the operator's level.
From the maintenance aspect, this enables the operator to return to the factory only the module involved or having reached its T.B.O. limit.

4. SAFETY REQUIREMENTS

The flight safety is provided on the one hand by the previous demonstration of the component service lines and on the other hand by the knowledge of the equipment condition thanks to the various monitoring facilities.

These facilities may be :

- either permanent : minimum oil pressure and maximum temperature warnings, chip detector with its indicator.
- or periodical : magnetic drain plug, oil filter check, spectrometric oil analysis, borescope inspection.

With the recent United States and European Military Programmes, new mandatory requirements relative to the vulnerability of the helicopter and its components are now in force.

As far as gearboxes are concerned, an important vulnerability factor is the loss of lubrication oil - numerous research tasks have been conducted firstly on the philosophy and the design of emergency lubrication systems and secondly on the dry running capability for a limited period of time. This latter point has resulted in interesting work on materials : case-hardening steels with high tempering temperature, bearings made from M 50 steel ; on surface treatments, on running- in and the self-lubrication of bearings etc... but it is important to note that without any particular treatment, most gearboxes are capable of a dry-run of 15 to 30 minutes, provided the power is reduced to the minimum cruise power as soon as the oil-pressure warning light flashes. This power level is generally about 50 % of take-off power and corresponds to a cruise speed of 120/140 km/hour.

In the case of the AS 350 main gearbox, it has been possible to demonstrate a dry-running period of 1 hour 50 minutes at minimum cruise power, on a test rig including a main rotor. This remarquable results has been obtained with a production gearbox without any modification nor special preparation.

Fig. 12 shows the curves of temperature variation versus time of both points regarded as being the most characteristic : the input bevel bearing and the fixed ring gear.

At the end of the test, which ended by the complete failure of the input bearing, all other items : gears and bearings were in good condition as shown on picture (fig. 13).

Another trend is the study on lubrication of gearboxes with grease. The obvious use, for military purposes, is to avoid the complete loss of oil should the casing be perforated by a bullet or a metal fragment. The experimental results obtained on Gazelle and Alouette tail gearboxes are very encouraging from the reliability, stabilisation of temperatures and detection of failure aspects.
It is thought that this technique could be applied also to civil aircraft to cure once for all the oil leakage problem.

However, grease lubrication calls for a special design or a modification of current gearboxes and the incorporation of such a modification to a main gearbox would raise heat rejection problems.

5. COMFORT REQUIREMENTS

Under the term COMFORT REQUIREMENTS, it is understood : reduction of noise produced by gearboxes with a view to improve the passengers' comfort. In fact, the noise spectrum of a gearbox generally includes several bands produced by gear meshing and their frequencies are a nuisance for the ear of the human being.

It is possible to filter or attenuate these frequencies by a special treatment of the airframe but the sound-proofing is in most cases very heavy and it would be preferable from the design stage to do one's best to reduce firstly the excitation and secondly the noise amplification produced by gears.

The reduction of excitation as such should consist in providing the best possible meshing continuity. To achieve this, the parameters have to be optimized : pressure angle, helix or spiral angle, module, whole depth and face width in order to achieve the highest possible contact ratio and face contact ratio (see NOTE 1), while ensuring that bending stress, contact stress and bearing lives remain acceptable.

Note 1

- contact ratio $= \dfrac{\text{contact length}}{\text{base pitch}}$

  This ratio is featured by one pair of teeth in engagement until the following pair is out of engagement.

- face contact ratio $= \dfrac{b \operatorname{tg} \beta}{\pi\, ma}$

  where b = face width

  β = helix angle

  ma = transverse module

  This ratio is featured by the increased number of teeth under simultaneous load versus the helix angle.

This optimization which represented numerous working weeks in the past, is now done very quickly thanks to the computer both for spur and spiral bevel gears.

The contact ratio and the face contact ratio being selected, the profile and barreling corrections together with the machining accuracy are to be defined with a view of reducing the impact on meshing.

It goes without saying that the machining accuracy has some influence over the manufacturing cost. The choice of this accuracy results from a compromise.

As to the amplification of noise, it comes from the resonance of the main gearbox components with a meshing frequency or harmonic. This may be a torsional or a flexural resonance in the shafts, webs or in the casing.

A theoretical analysis may enable, from the early design stage, the avoidance of some shaft resonances by playing on weight and stiffness features, but the casing natural frequencies are numerous and can hardly be assessed at the design stage. This is the reason why the casing resonance problems are dealt with afterwards i.e. after the prototype gearboxes are manufactured. To illustrate this, let us take again the AS 350 main gearbox.

The tooth shape for this gearbox has been studied as regards noise reduction. The probability of experiencing resonance problems was further reduced, taking into account the small number of items and meshing parts.

The results turned out to be excellent as the noise level recorded into the cabin with a light soundproofing was 79 dB S.I.L. in forward flight and 73 dB S.I.L. in hover.

6. CONCLUSIONS

The example of the AS 350 main gearbox is properly illustrating how a sensible weight penalty may largely be compensated by advantages relative to cost, reliability, safety and noise reduction problems.

We have mainly spoken of the present and the near future ; by way of conclusion we could try and imagine what will be tomorrow's gearboxes.

Our impression may be summarised in three points :

- The current trends regarding cost, reliability, safety and noise aspects will persist and will be intensified.

- The conventional involute profile is far from being replaced by another technology.

- Novelties will stem from current research programs and will bear on material and lubricant improvements.
  The use of high temperature tempering steels for gears and high speed steels for bearings could lead to the deletion of heavy, expensive, vulnerable cooling systems.

Lubrication could be achieved with grease. Housings could be made of high performance or internal damping light alloy.

If an actual revolution was noted in the field of helicopter rotors over the past years, we think that a comparable phenomenon will not be found for transmission components. The evolution is more progressive but has the same objectives, among which the promotion of the helicopter for civil purposes comes first in making it more competitive relative to other means of transport.

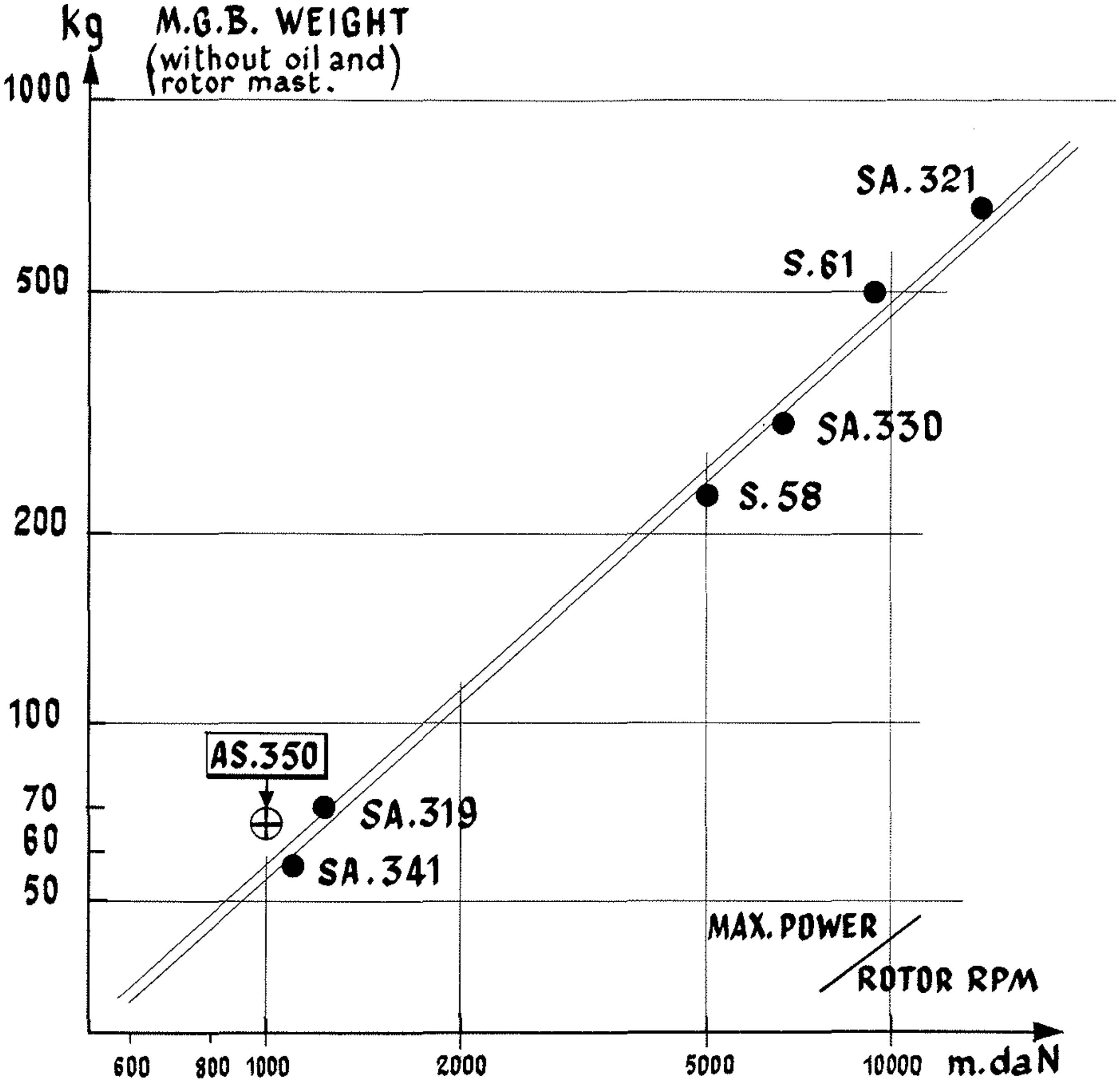
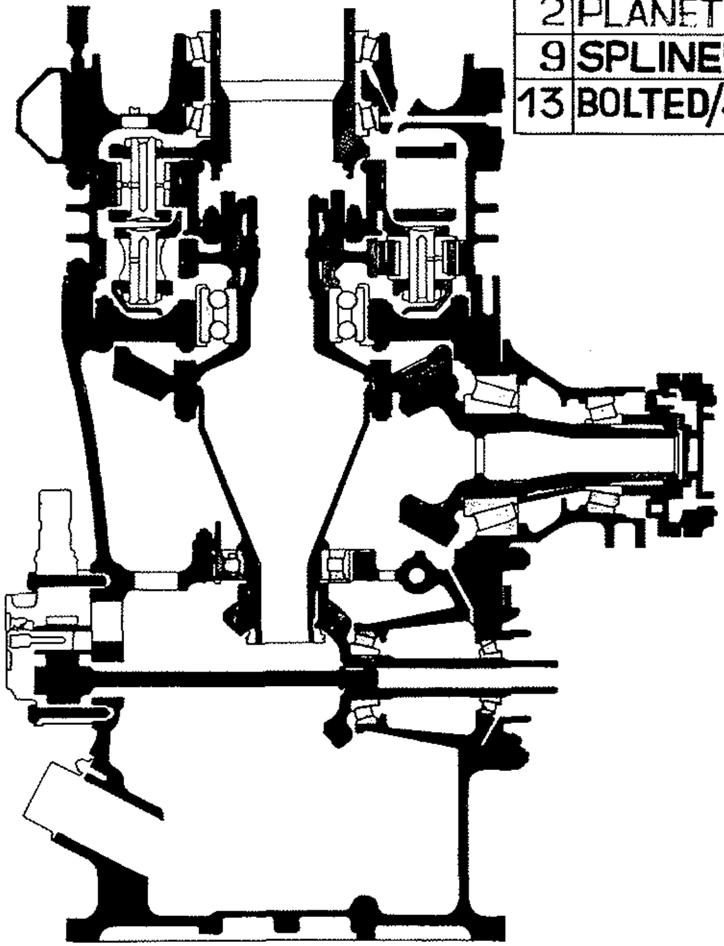

Kg
M.G.B. WEIGHT
(without oil and
rotor mast.)
1000
500
200
100
70
60
50
SA.321
S.61
SA.330
S.58
AS.350
SA.319
SA.341
MAX. POWER
ROTOR RPM
600
800
1000
2000
5000
10000
m.daN

FIGURE 2

AS350 MAIN GEAR BOX - NUMBER OF MAIN COMPONENTS

22	GEARS	9
23	BEARINGS	9
2	PLANET GEAR HOLDERS	1
9	SPLINED ASSIES.	3
13	BOLTED/STUD ASSIES.	5

ALOUETTE - 318



ECONOMICAL MAIN GEAR BOX

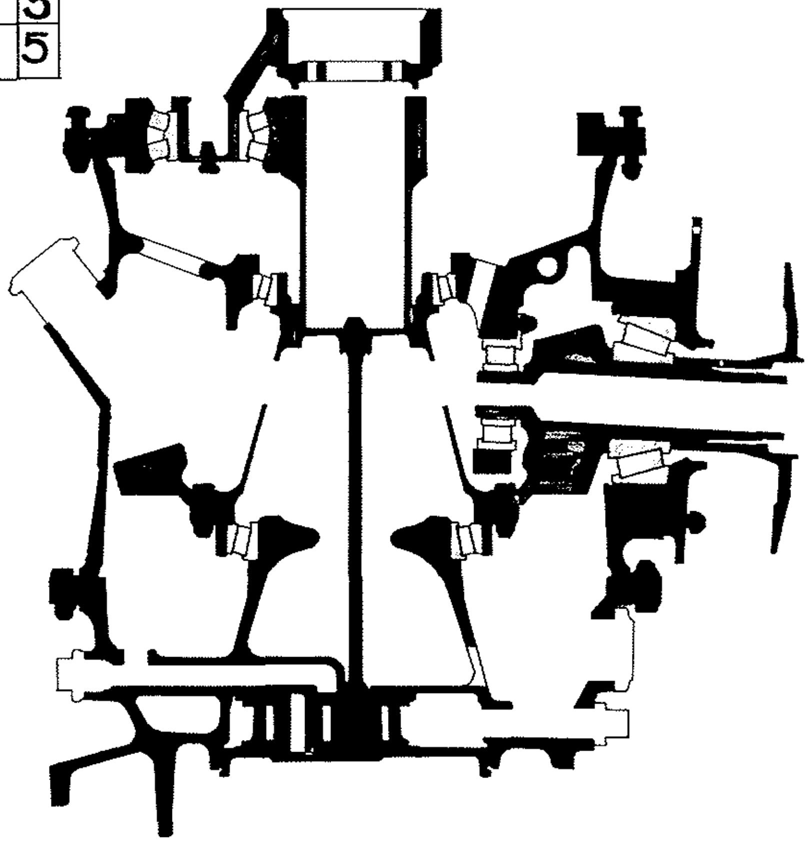
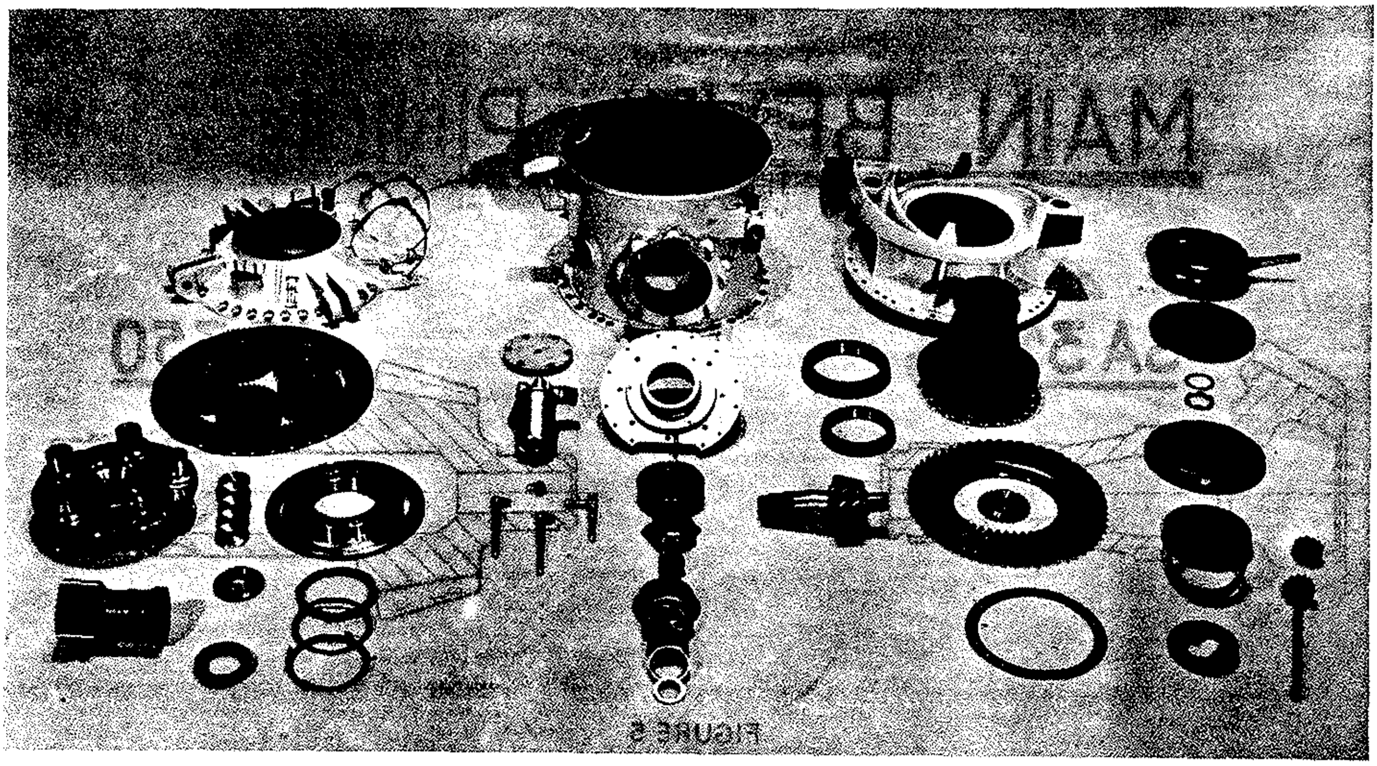


FIGURE 3



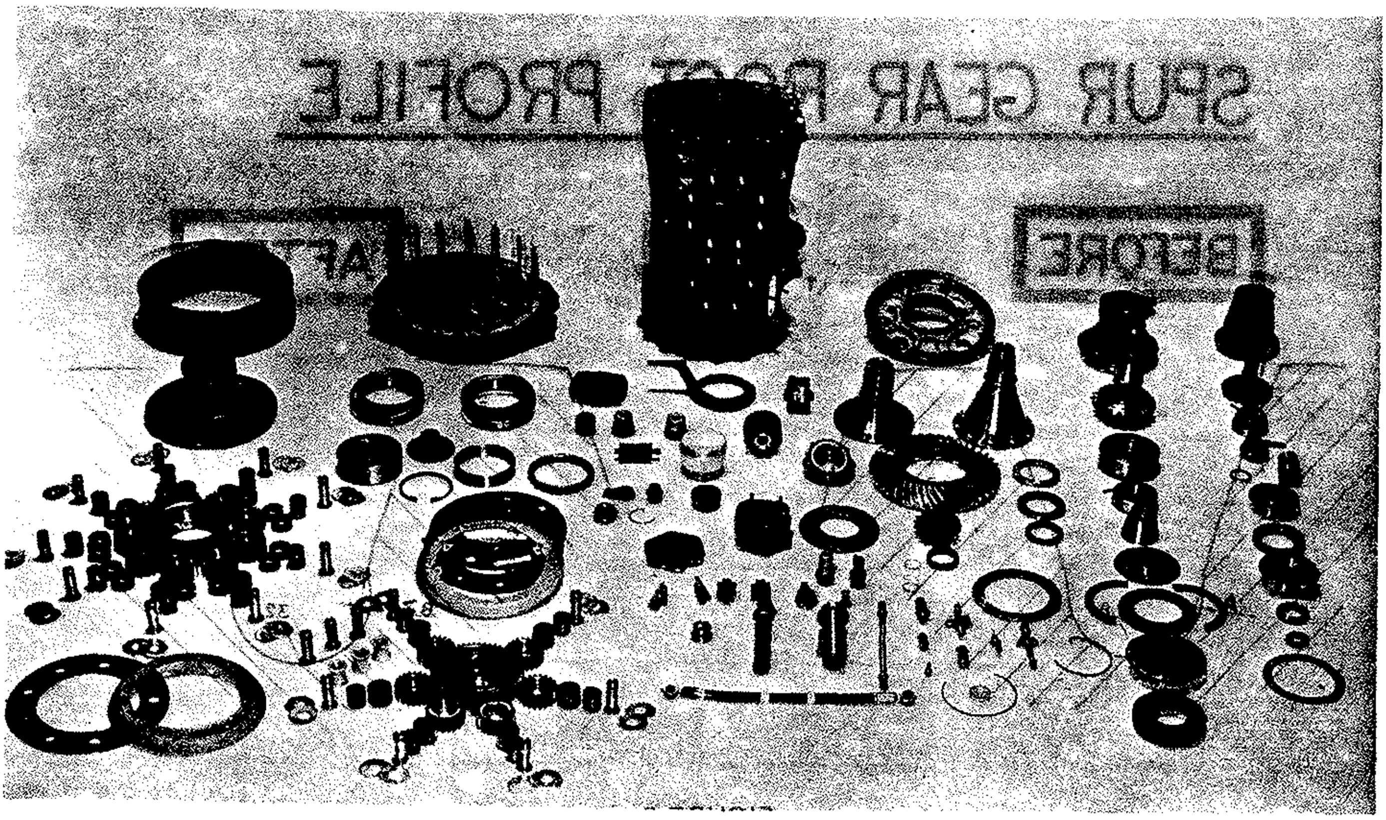


FIGURE 4

MAIN BEVEL PINION

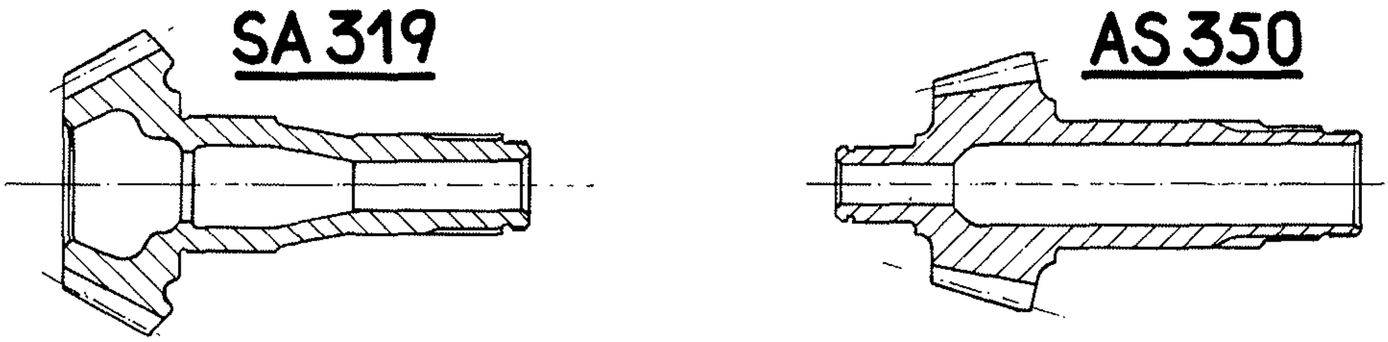


FIGURE 5

SPUR GEAR ROOT PROFILE

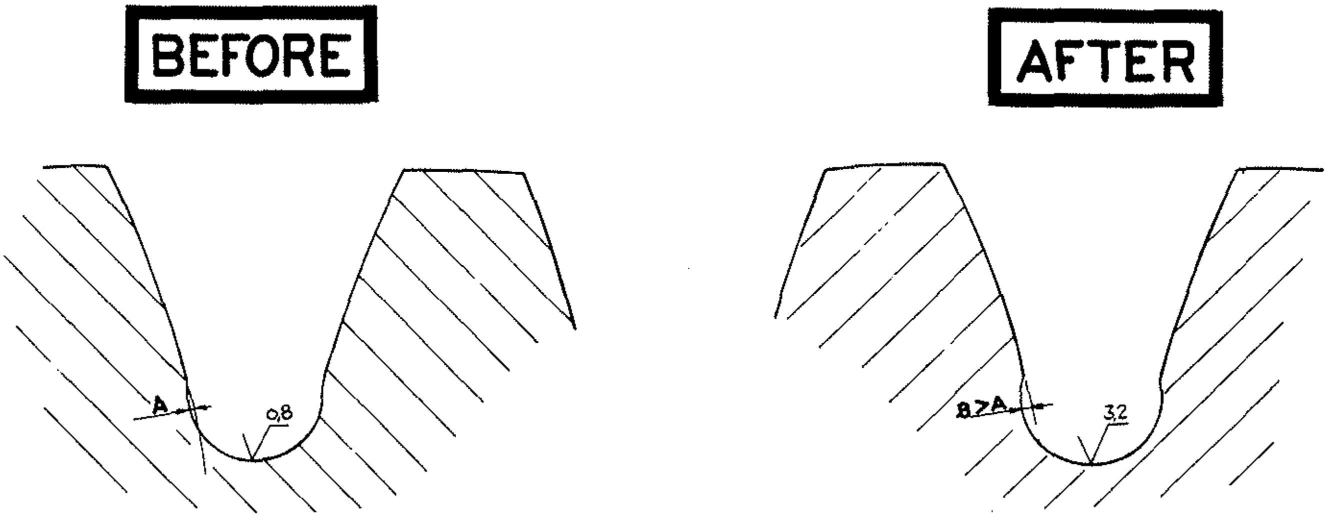
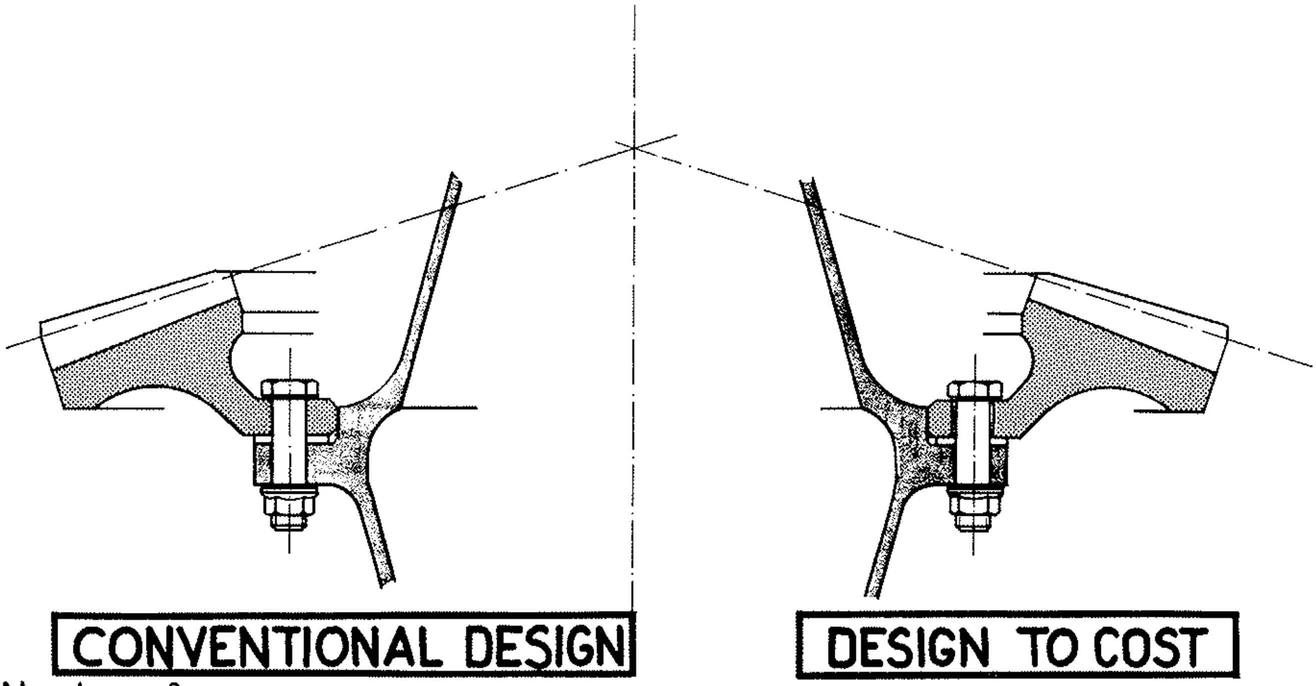
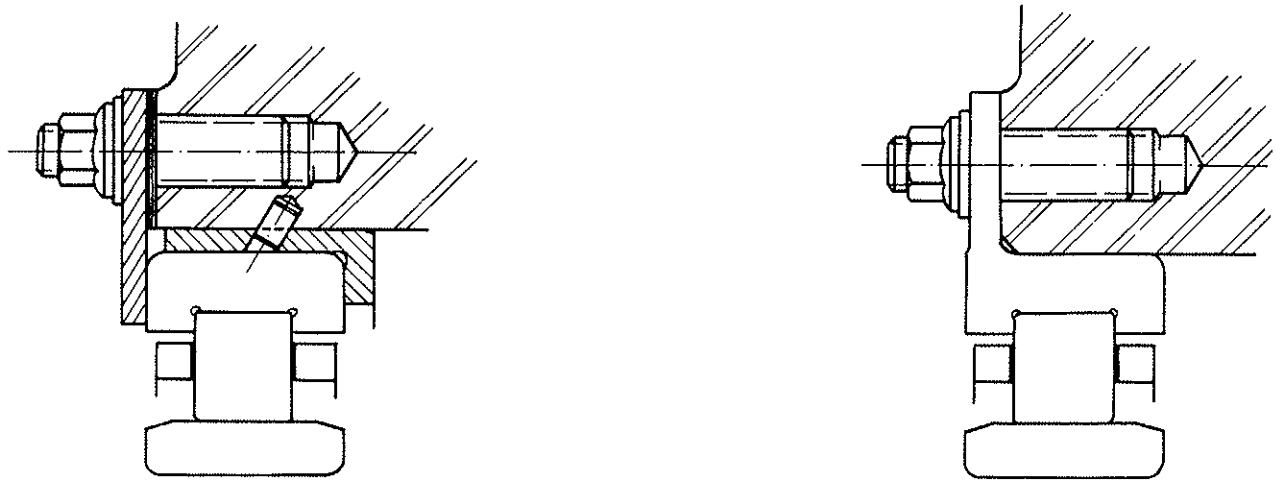


FIGURE 6



Number of Bolts	12	18
Gap in holes	.01mm .02mm	.2mm
Holes position accuracy	.01mm	.1mm

FIGURE 7



STANDARD BEARING **SPECIAL BEARING**

FIGURE 8

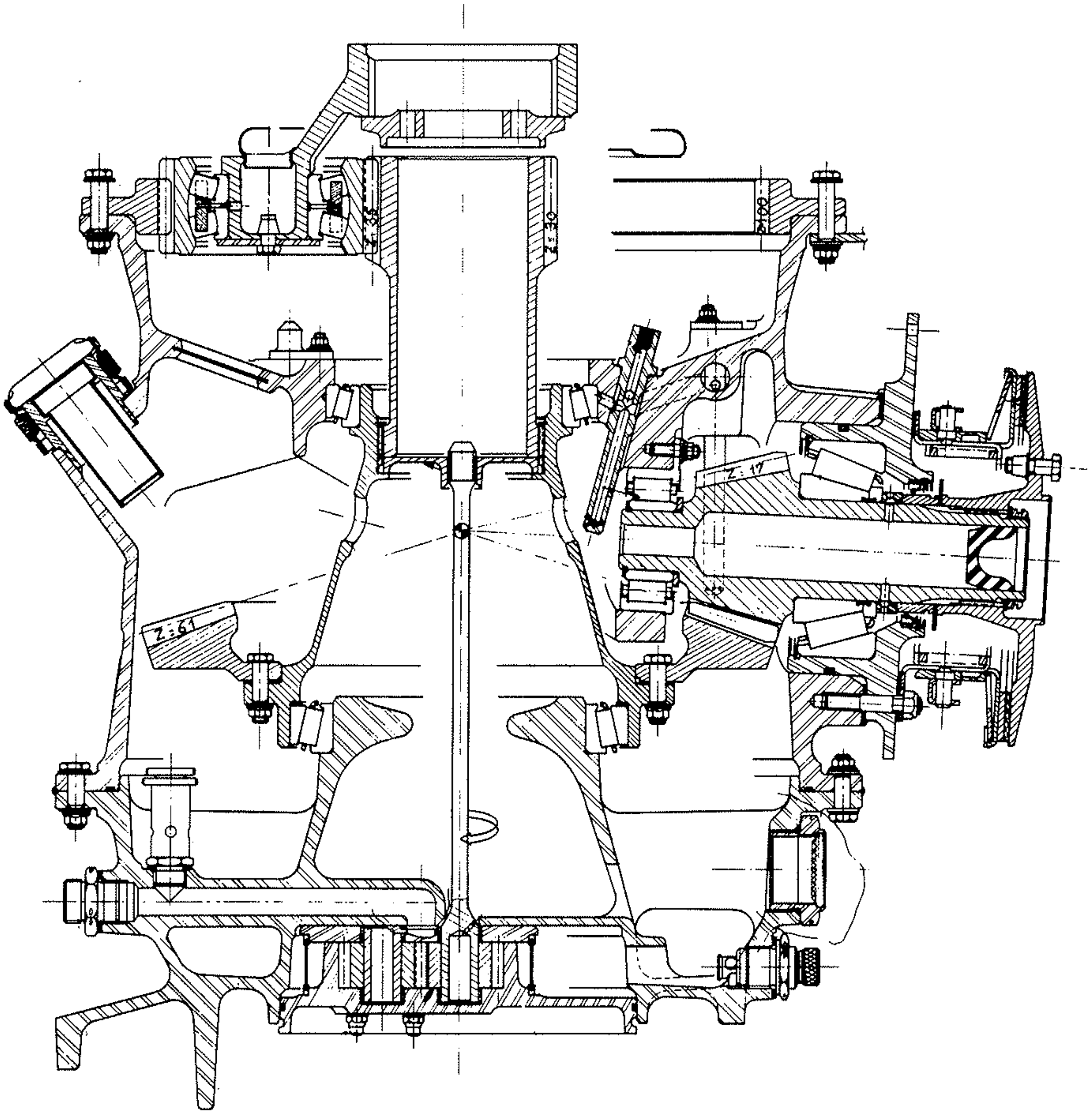


FIGURE 9

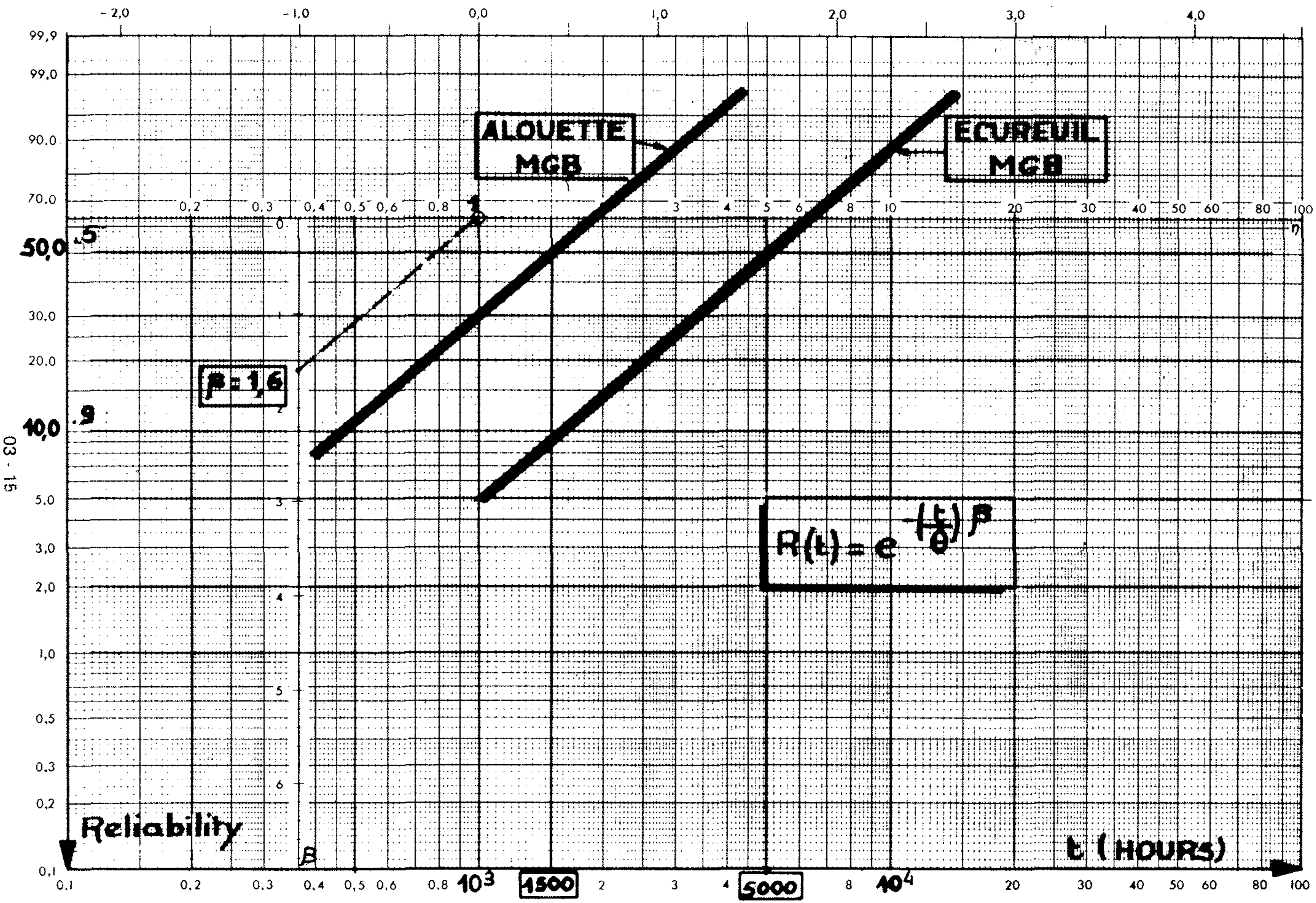

-2,0
-1,0
0,0
1,0
2,0
3,0
4,0
99,9
99,0
90,0
70,0
50,0
30,0
20,0
10,0
5,0
3,0
2,0
1,0
0,5
0,3
0,2
0,1
.5
.9
ALOUETTE MGB
ECUREUIL MGB
β = 1,6
$R(t) = e^{-\left(\frac{t}{\theta}\right)^{\beta}}$
Reliability
t (HOURS)
β
η
0
1
2
3
4
5
6
0,1
0,2
0,3
0,4
0,5
0,6
0,8
10^3
1500
2
3
4
5000
8
10^4
20
30
40
50
60
80
100

FIGURE 10

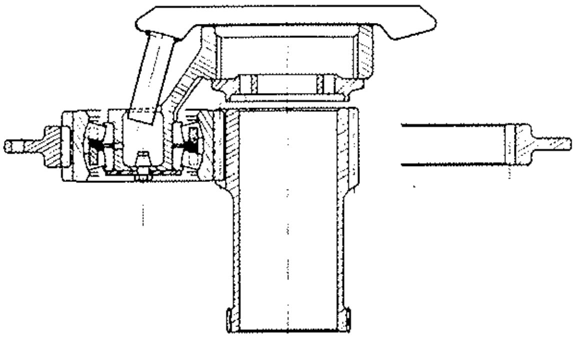
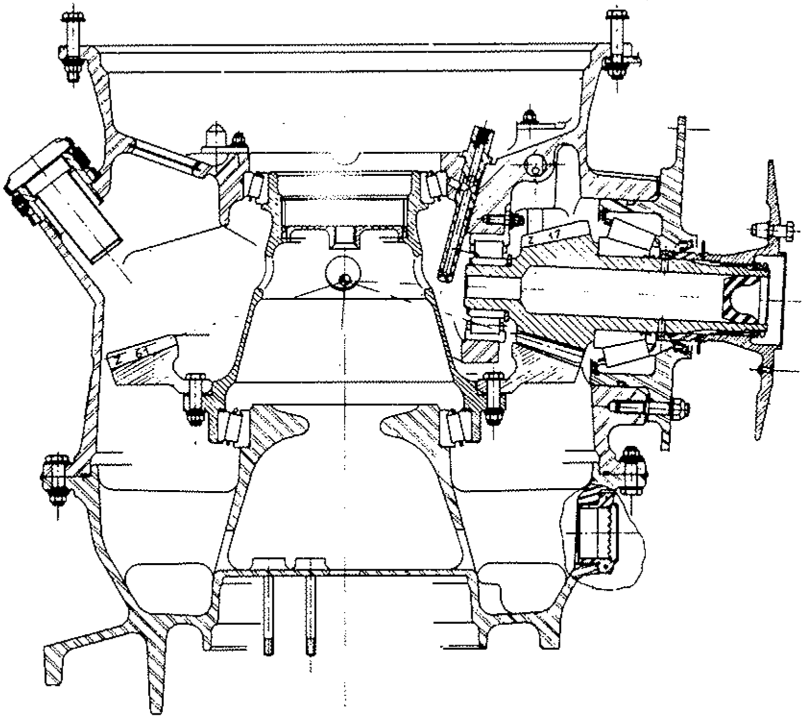
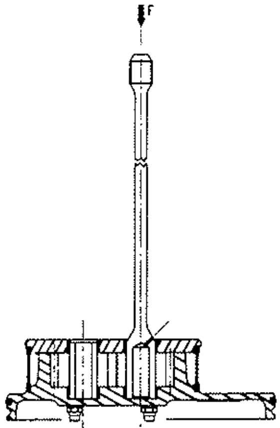
MGB MODULES	TBO
	5000 h
	7000 h
	7000 h

FIGURE 11

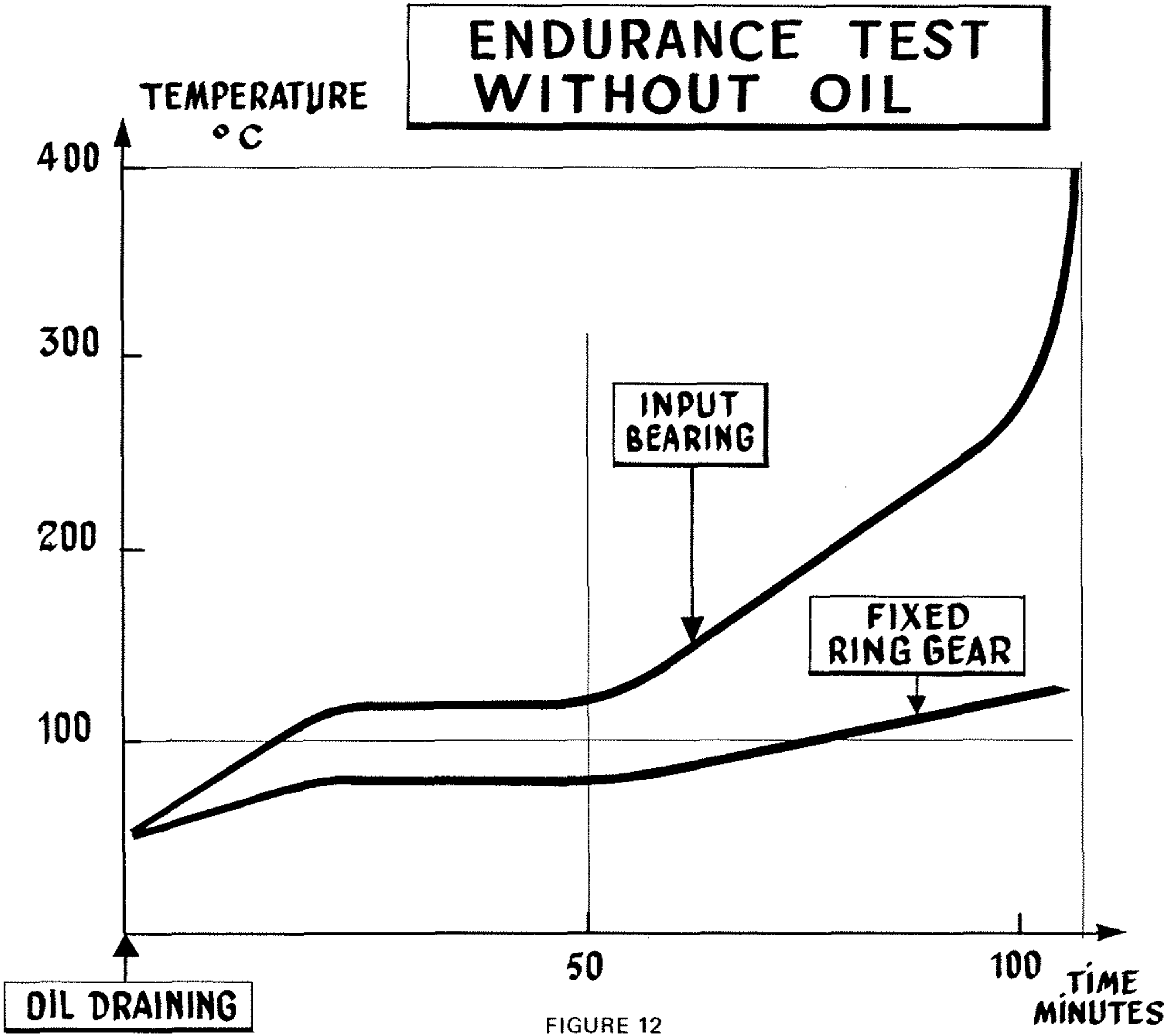

ENDURANCE TEST WITHOUT OIL
TEMPERATURE °C
400
300
200
100
50
100
TIME MINUTES
INPUT BEARING
FIXED RING GEAR
OIL DRAINING

FIGURE 12

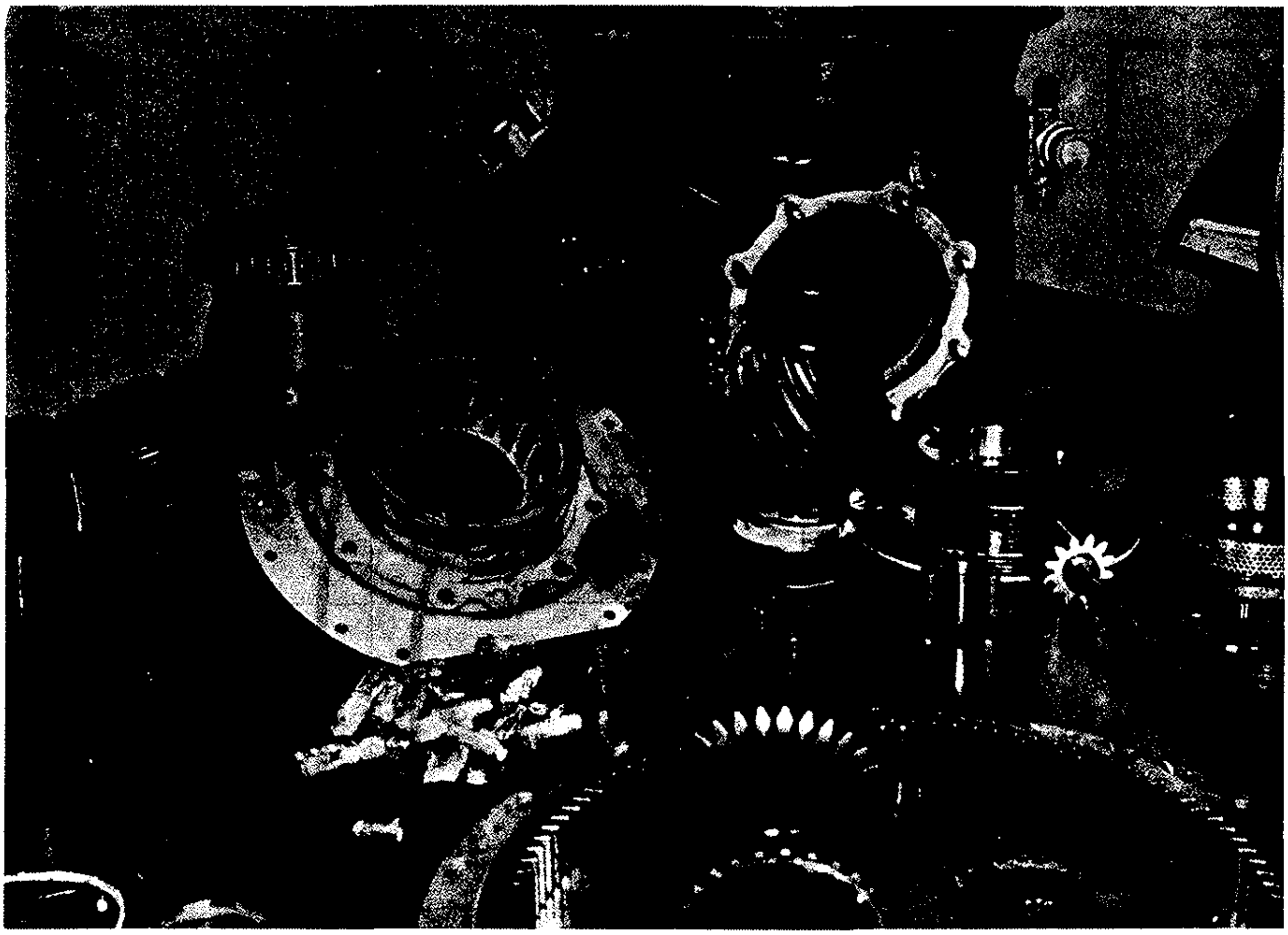


FIGURE 13