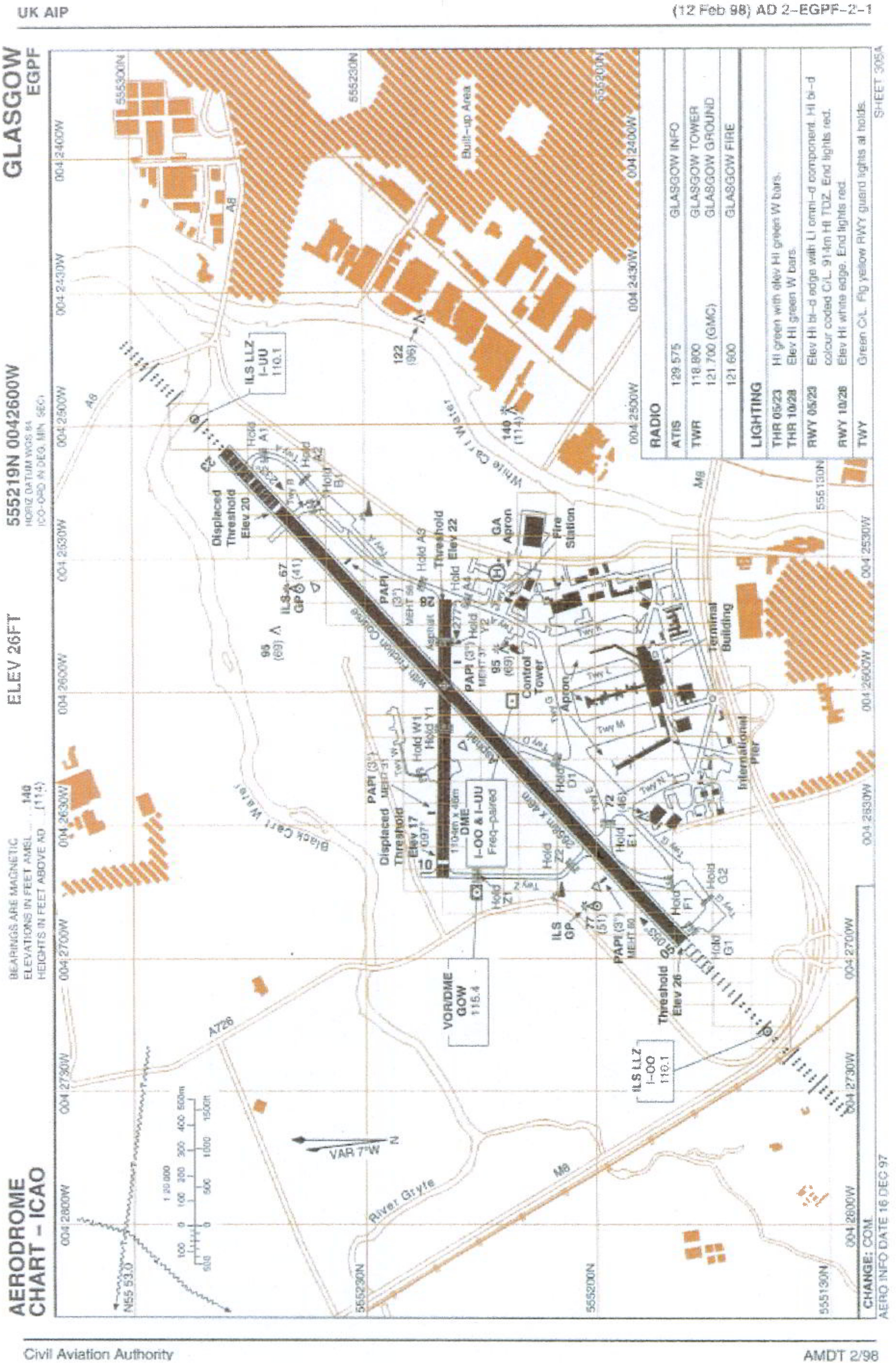
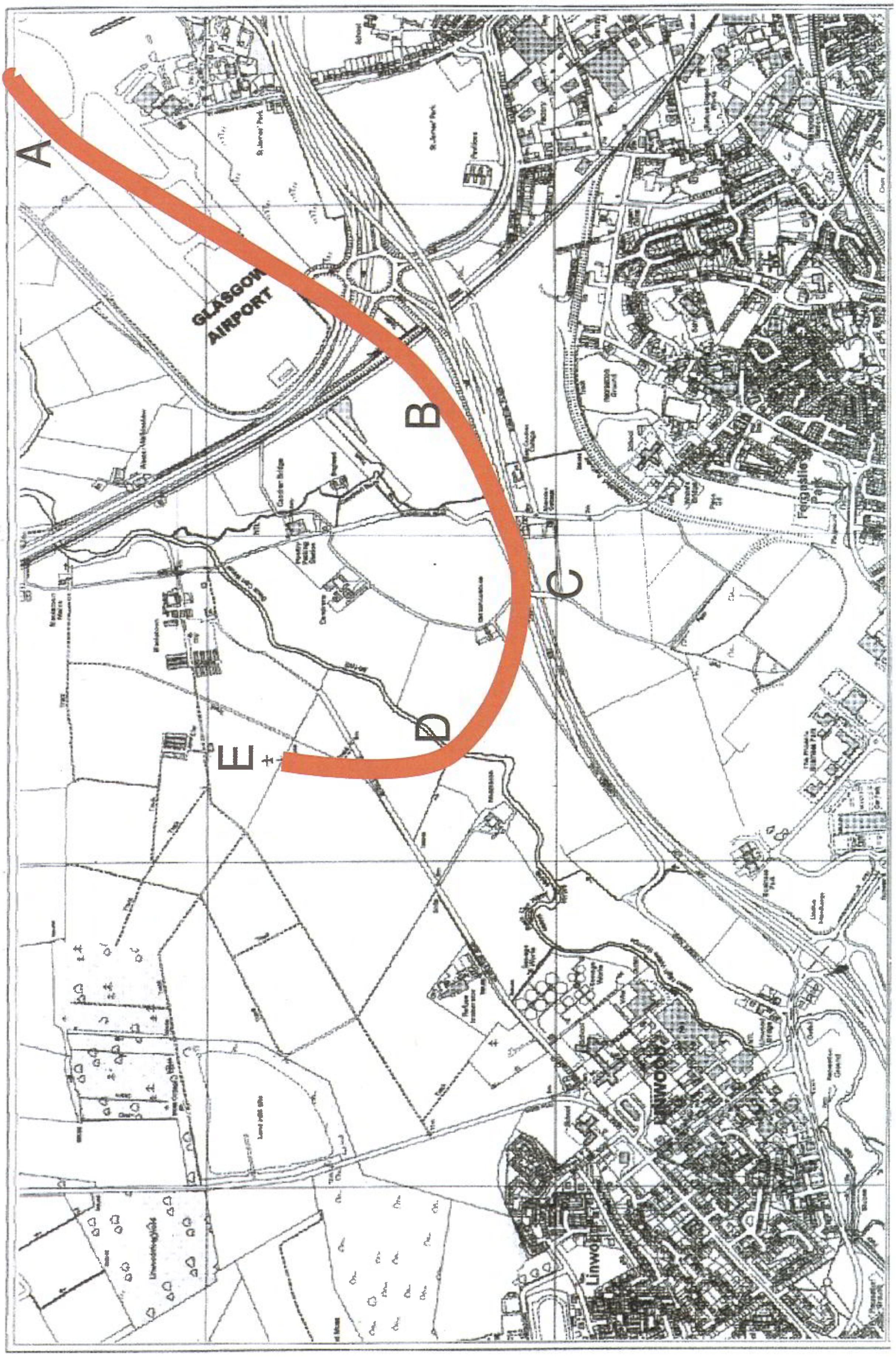
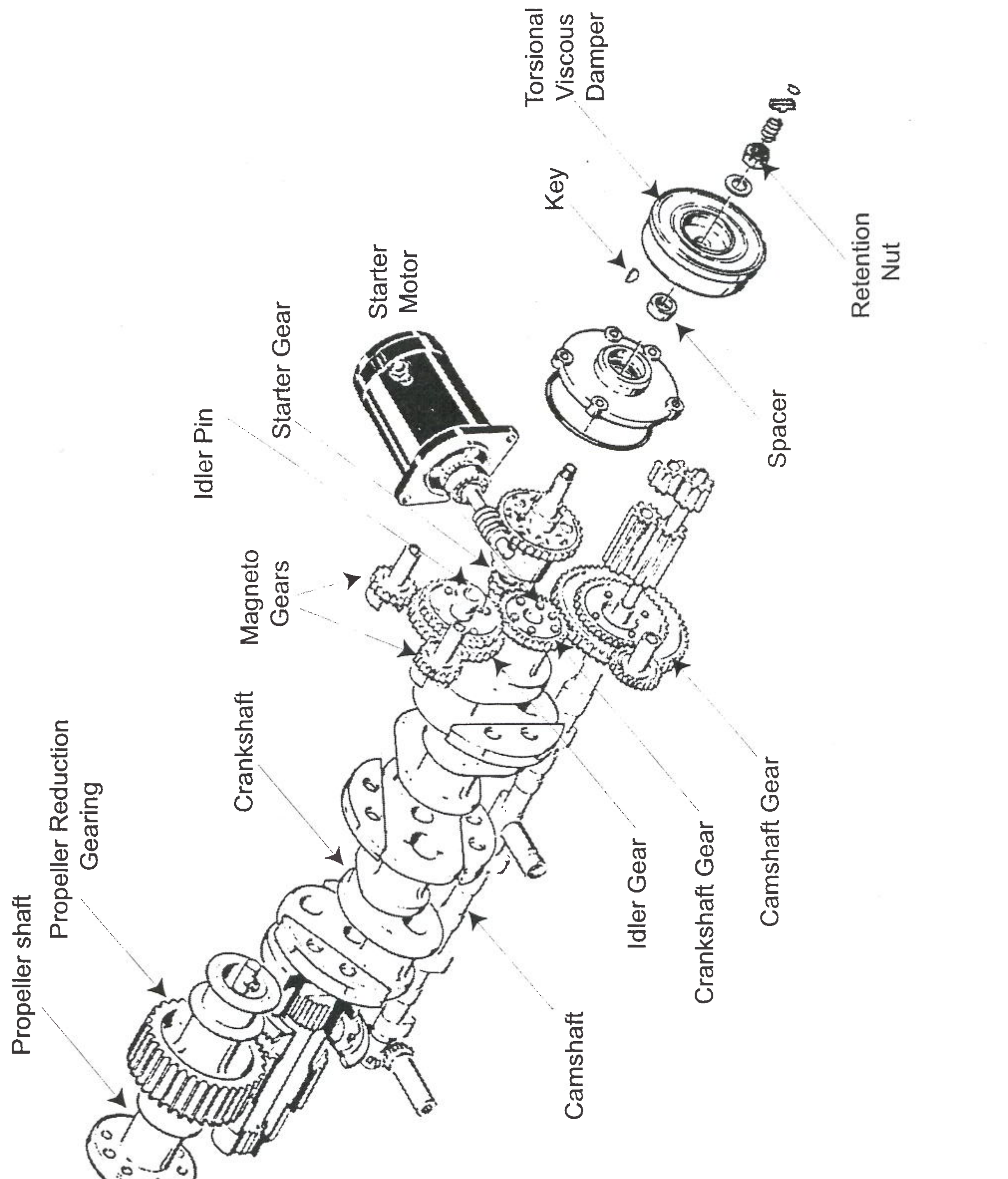
GLASGOW AIRPORT CHART



MOST PROBABLE FLIGHT PATH

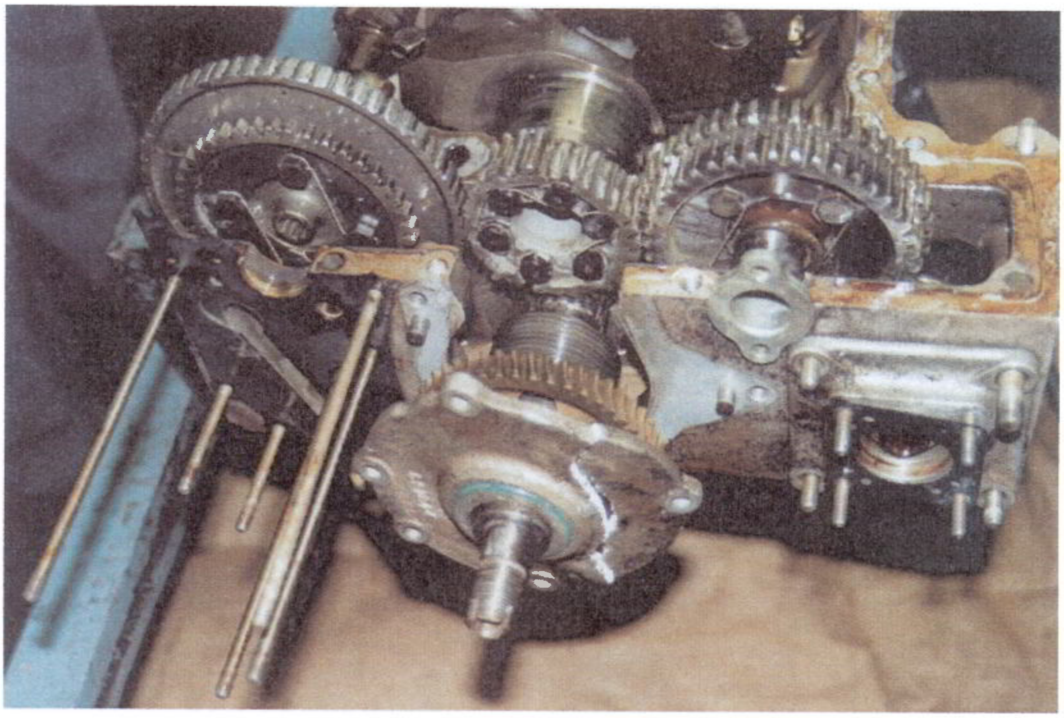


APPENDIX B



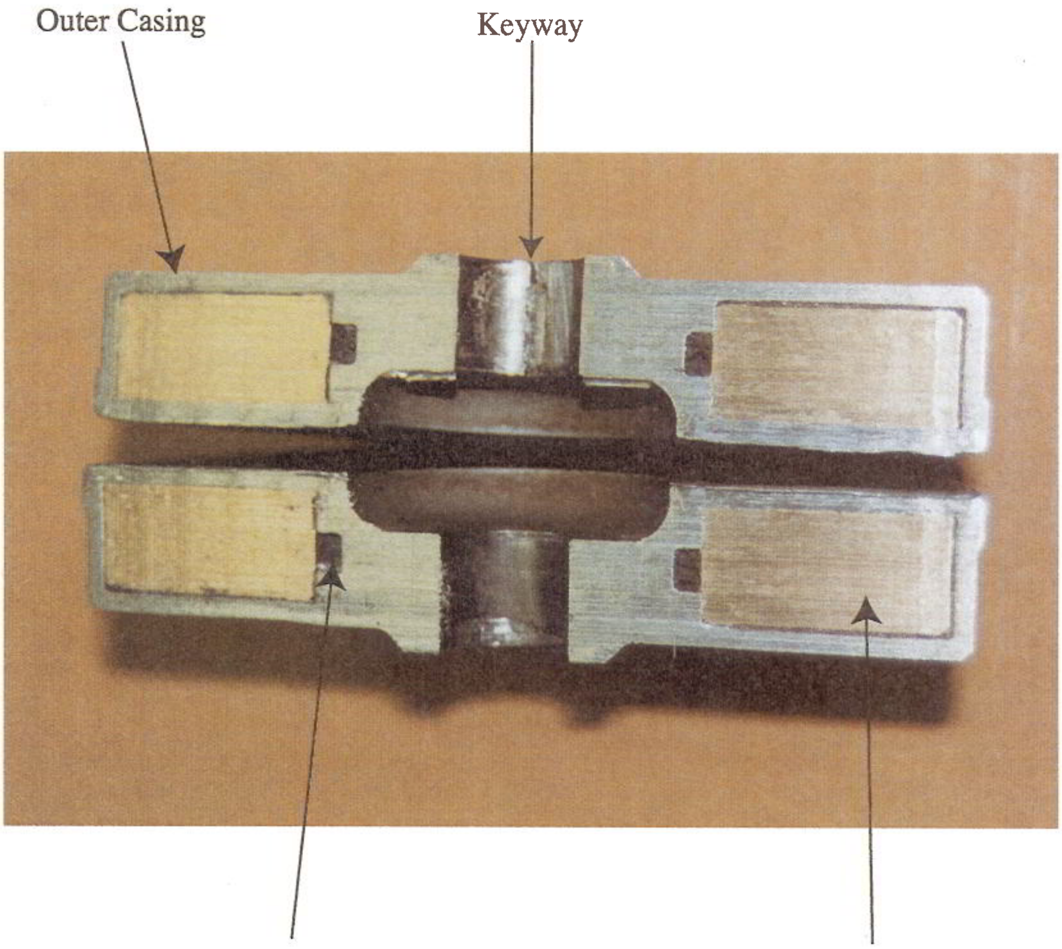
Propeller shaft
Propeller Reduction Gearing
Crankshaft
Magneto Gears
Idler Pin
Starter Gear
Starter Motor
Key
Torsional Viscous Damper
Retention Nut
Spacer
Camshaft Gear
Crankshaft Gear
Idler Gear
Camshaft

PHOTOGRAPH OF DAMAGED ACCESSORY GEARS - LEFT ENGINE



CLOSE-UP OF CRANKSHAFT GEAR - LEFT ENGINE

TORSIONAL VISCOUS DAMPER FROM LEFT ENGINE AS SECTIONED



Detailed examination of the left engine accessory gears

As the left engine and propeller was windmilling at impact and had continued to rotate after the initial failures, damage was caused to these components which tended to obscure the nature of the initial damage.

The starter gear (Part number 653712C) had been stripped of all its teeth and only four survived in recognisable state in the debris recovered from the sump. The one tooth of the starter gear, which was considered to be the first to fail, contained multiple fatigue sites. No material or manufacturing defects were identified and it appeared, therefore, that fatigue had developed due to high cyclic loading conditions. The gear tooth flanks showed evidence of heavy wear, being indented, polished and pitted and this, also, was an indication that the gear had been subjected to damaging loads. This wear was distinct from the coarse damage seen on the flanks of the other teeth and was taken to represent the condition of the gear before its break-up had begun and was therefore the result of a longer term wear process.

The crankshaft gear (Part Number 653580C) had lost 17 of its 30 teeth. All the tooth fractures were in overload. The 13 still in place showed bruising and impact damage from running out of mesh with the starter gear, the camshaft gear and the idler gear. Damage from the starter gear could be distinguished because its teeth were broader than those of the other two gears. The gear teeth flanks (both sides) also showed evidence of longer term wear. The teeth which had detached from the crankshaft gear and were found in the sump showed less damage from their contacts with the other gears but all showed heavy wear.

All the teeth on the camshaft gear had been removed and only the smeared roots of the teeth remained. No camshaft gear teeth were identified in the sump debris.

The idler gear was less damaged than the other gears described above. The crowns of the teeth were damaged but the teeth were not wiped out down to the roots as on the camshaft gear. One tooth had broken off at the root in overload and was recovered from the sump. One flank was highly polished, slightly dished at mid height (just perceptible) and there were two pits near one end. These features were indicative of wear rather than traumatic damage. On its crown and other flank the tooth showed evidence of having been sheared out by crown to crown impact with another gear tooth. The tooth's crown was almost undamaged but near its trailing edge (relative to direction of travel) material has been sheared downwards along a straight spanwise line. One half of the tooth was sheared downwards against the other, splitting the tooth from crown to root. This had forced the other half of the tooth backwards against direction of rotation shearing it off at the root. The two halves of the tooth appeared to be welded together along the mid-tooth shear fracture. The trailing face of the tooth was smeared and indented. The shape of the indentation fitted with it being made by the crown of another tooth normally aligned.

Thus it appeared that it was crown to crown contact with a crankshaft gear tooth that sheared this tooth out rather than loose debris. (The conflicting gear is identified as the crankshaft gear as the magneto gears do not engage with the idler gear over full flank width.) From the condition of the crown and one flank it appeared that this happened before the idler gear tooth had suffered any other sort of traumatic damage. For crown to crown contact to be made with the crankshaft gear the crankshaft gear must already have lost a tooth to allow correct meshing to be lost. Such damage could only have come from conflict with the starter gear, which has teeth of the same width as the crankshaft gear.

The force on the idler gear associated with loss of the idler gear tooth evidently caused the rupture of the idler pin's inner support and that of the magneto drive. These two ruptures had not left the idler gear and magneto drive completely unsupported and, after the initial event, they would have disengaged to some extent but not fully. There was coarse damage on the flanks of the idler gear teeth and the crowns had been removed. This suggested that its disengagement had been progressive. The remaining support for the idler pin would be from its external flange clamped to the rear wall of the crankcase and also from its fit in the hole in the back (exterior) wall of the crankcase. The pin's support would be less stiff but it would be able to react loads from the gear as it evidently did when the tooth crowns were being destroyed. The failure of the idler pin's securing studs would have introduced a step reduction in support. Also the hole in the crankcase aft wall became ovalised through the vertical movement of the pin and gave less support.

The disengagement of the idler gear would appear to have been progressive. Some synchronisation of the magnetos may have been lost initially but they could have continued to operate.

The teeth on the camshaft gear appear to have been progressively destroyed, only shards of debris from them were recovered from the sump and, although drive from the crankshaft the to the camshaft was eventually lost, it may be that early in the process, the drive and synchronisation was lost only progressively.

The sequence of loss of magneto and valve timing and function cannot be proved conclusively but it does appear possible these events were not sudden and that the loss of power from the left engine was progressive.

Four metallic fragments were found in the sump which, from their deformation, had clearly passed between gear teeth. Their origin and characteristics could not be fully accounted for but metallurgical examination suggested that they were most likely to have been fragments of starter gear tooth. If any one of them had passed between the crankshaft and idler gears then it could have caused the rupture of the idler support but it is considered more likely, as described above, that the idler gear support rupture was caused by out of mesh contact. It is possible that these fragments passed between the crankshaft and starter gears and these, more strongly supported, could have caused the observed deformation and suffered corresponding tooth damage.

Analysis of the rupture of the idler pin support

The circumstances of the rupture of idler pin's inner support and the failure of its retention studs were examined as possibly containing the initiation of the accessory gear damage. The engine manufacturer reported two cases where it was determined that loss of nut torque on the pin studs had led to gear damage similar to that seen here.

The idler pin's inner support, a bore in the inner wall of the accessory gear housing, had ruptured and the pin had burst out of the bore in a vertical direction. The direction of the excess load on the pin coincided with the weakest area of support, which was the 'roof' of the bore. The detached roof material was recovered from the sump. The damage sustained by the bore, including the detached fragments, indicated that the pin was engaged to its full depth in the hole when the roof was torn off. There was no sign of the roof being lifted at its outboard end by a partially engaged pin. There were tensile fractures along both sides of the bore (for a distance equivalent to the full length of the pin boss) and smeared shear failures at the inboard end. The smearing at the inboard end contained imprints of the end face of the pin. This indicated that the pin was still fully engaged and had not migrated out along the studs when the inner support housing ruptured.

The retaining studs were found to have failed in fatigue. The outboard ends of the studs and the nuts were not found. The fatigue in both studs was in reverse bending and had developed in a low strain mode (indicating relatively low fatiguing loads). The very small residual overload part of the fractures across the horizontal diameters of the studs also indicated low fatiguing loads. From a small area in one of the fatigue cracks where striations were discernible the metallurgist estimated a minimum of 2,080 cycles to failure.

Once the inner support had ruptured the pin would have been able to move vertically at its inner end and this would have subjected the retention studs to bending loads but only in one direction, not reverse bending. As described in paragraph 1.6.4.2 the idler gear axle is offset vertically from the pin axis. A side load on the gear would therefore produce a torque on the pin. Side loads would be generated on the axle if material passed between the idler and crankshaft gears or the teeth collided out of mesh. Initially, any interference between teeth or from debris passing between the teeth would occur on the 'upstream' side of the line joining the two gear centres. The very large radial force generated by such interference would be at an angle to the line joining the gear centres and this would create a side component on the idler axle as well as the separating load which ruptured the inner support. As the gears rotated and the point of interference passed between the gears the direction of the radial load would change giving a side load at the gear axle in the opposite direction as it emerged on the other side of the gears.

Evidence that the pin was being rotated was provided by contacts made between the pin flange and the flanges of both magneto support housings. The corners of these two flanges showed small areas of hammering damage at the points at which they would be contacted by the pin flange. This damage showed that after the studs failed, the pin was oscillating in rotation and its flange had hammered against both magneto bearing housings. Before the studs failed they would have been being subjected to the reverse bending stresses corresponding to this oscillation and this was, therefore, the source of the loads which failed the studs in reverse bending fatigue. The hammering marks on the magneto support flanges also showed that the pin flange was very close to its normal clamped position against the crankcase when it was released by the failure of the studs and the nuts, therefore, had not backed off significantly on the studs. There was some evidence that the nuts may have been loose on the studs at some time but the loosening of the nuts may have been the result of the rotational loads on the pin and flange described above.

Without the pin being sufficiently disengaged from its inner support bore to reduce the support that the axle was giving to the idler gear, it was unclear how damage could have been caused to the gears merely by the loosening of the securing nuts. This possibility was dismissed as a source of the initiation of gear break-up.

It was further considered whether the stud fatigue failures could have occurred within the time-span of the flight. The estimated flight time between the first untoward event during the flight, the reported 'bang' heard by the survivors, and the crash was between 47 and 72 seconds. The left engine continued to rotate, at least windmilling, to impact. Assuming a probable windmilling propeller speed of 1,500 RPM, the idler gear's speed would be 1,467 RPM. All 46 teeth on the idler gear were severely damaged and each damaged tooth represents a load per revolution applied to the idler gear and its axle. It is most likely, therefore, that the repetitive fatigue loads were caused by the interference between the gears and was applied at the passing frequency of the idler gear teeth for at least part of the time available. Within the 47 to 72 second time period there would be a maximum possible number of load cycles of between, 52,860 and 81,000 and it would be quite feasible for the stud fatigue development to have occurred within that time-span during the accident flight and after the bang' heard by the survivors. In this case, at the very minimum, the number of load cycles could have been applied in about 2 seconds. At the other extreme, if the fatiguing loads were generated by a phenomenon which repeated at only once per revolution, then a minimum of 85 seconds would be required but the fact that all the idler gear teeth had suffered multiple impacts makes the higher frequency case appear more likely.

The above analysis places the idler pin stud fatigue failures as secondary to the occurrence of gear damage within the engine and capable of being sustained within the time-span of the flight following the 'bang' heard by the survivors.

Investigations into torsional viscous damper's and accessory gears

FLIGHT-TESTS TO MEASURE THE TEMPERATURE OF THE VISCOUS DAMPER AND ITS ENVIRONMENT IN FLIGHT.

The aircraft manufacturer carried out two tests using a Model 404 aircraft with equipment installed to measure the temperature of the viscous damper and its environment in flight. The flights were carried out to an FAA engine cooling test protocol on two days in ambient temperatures of 98°F and 100°F on the ground so minimal theoretical adjustment was required to correct the data to the datum ambient of 100°F. At all times, including post-flight heat soakage, the temperatures within the environment of the damper remained below 210°F and the damper surface temperature did not exceed 230°F.

INITIAL EXAMINATION OF GEARS AND DAMPERS RETURNED FROM SERVICE

Unfortunately, the information on engine history received with the engines including reasons for their return from service and operating hours achieved, was incomplete and some of the information, particularly engine operating hours was probably unreliable. Furthermore, without detailed engine history it could not be assumed in any individual case that components had not been changed or that the engine operating hours applied also to components such as the damper, starter gear and crankshaft gear. No simple causal relationship could be demonstrated from this data between damper behaviour and gear deterioration. However, useful information on the behaviour of the gears and damper in service was obtained.

At manufacture each damper is tested on a torsion bar rig. The bar, with the damper fitted at its free end, is given a pre-set twist and released. The damper's performance is assessed by the decay rate of the resultant oscillations, expressed as the time required for a specified reduction in amplitude. The production pass-off limits are 1.7 to 3.0 seconds. In the post-service results 11 dampers (37% of 30 tested) still performed within the pass-off limits, but 63% were above the maximum of the these limits, and 20% were outside the expanded limits (maximum of 10 seconds) given in TCM bulletin M85-11. The longest damping time measured was 15 seconds.

The engine manufacturer presented the information on the engines returned from service as qualitative assessments with photographs of gear condition together with information on any other anomalies seen. From an AAIB examination of the photographs of the gears, it appeared that up to 84% of the gears would fail the criteria contained in CSB 94-4A. Almost 60% of these gears exhibited significant spalling. Three sets of gears, representing 10% of the sample, showed actual gear failure. At least 20% of gears were showing pitting or spalling damage while their related dampers were found to perform within the original production limits. There was a small but identifiable tendency for the starter gears to exhibit worse damage than the crankshaft gears. This was not surprising, as the starter gear is smaller and each tooth experiences twice as many load cycles as a crankshaft gear tooth from their mutual engagement (the crankshaft gear also meshes with other accessory gears, but tooth surface condition showed that wear took place predominantly between the crankshaft and starter gears). In two cases, where both gears had broken teeth, the key on the damper shaft was sheared. This was also seen in the left engine from G–ILGW. There were some irregularities evident in that there were 3 sets where there appeared to be a mixture of modified and unmodified gears and in another 3 sets there were starter gears of the wrong applicability (Gear 643257, which has GTSIO 520-N applicability, being installed in -L and -M engines).

There were 6 gear sets composed of the unmodified gears (Pre-CSB94-4A and Kit EQ 6642) and 18 composed of the modified standard. In a comparison of wear and damage between modified and unmodified gears the modified gears actually showed a slightly worse condition than the unmodified gears. This confirmed information obtained by the AAIB from the anecdotal maintenance organisations and that, following implementation of CSB 94-4A and kit EQ 6642, gear wear and damage was still being seen.

EXAMINATION OF DAMPERS RETURNED FROM SERVICE

The engine manufacturer made available a time-expired engine to be instrumented and run on a test bed with some of the ex-service dampers discussed above. A new starter adapter was fitted; the crankshaft gear was inspected, found to be in good condition and retained. A load cell was fitted on the propeller shaft to measure vibratory torque within the engine and the engine was run with a test (fixed pitch) propeller.

A vibration survey was run over the normal operating range with the new damper that was already fitted to the starter adapter. A second run with this damper was performed later in the series of test as a check on repeatability. Test runs were then performed with 5 dampers returned from service and finally the first (new) damper was fitted again but with low torque (100 ft lb.) on its securing nut. From the dampers returned from service two were chosen which were associated with the worst gear damage seen, two which were associated with light or average gear damage but which had shown poor damping performance on the production test rig and one which had performed within the production test limits.

A qualitative assessment of the damping fluid from each of the dampers placed the material in the four categories shown below based on its appearance and ability or inability to behave like a liquid. The condition of much of the material was such that a measurement of its viscosity was not practicable. The silicone fluid used is translucent when new.

Categories: -

1. Viscous clear fluid with some black contamination.
2. Little tendency to flow but surface, when settled, became glossy brown.
3. No tendency to flow, sticky, grey/brown.
4. Dry, broke into fragments when disturbed, brown.

Analysis of the fluid allowed other characterisations of its condition, which are also tabulated below with the engine test results. Analysis was carried out for the AAIB by DERA Pyestock and DERA Bridgewater and, for the damper manufacturer, by Exponent Failure Analysis Associates. DERA reported that the fluid contained metal particles from the casing and flywheel which were present in a range of sizes from very fine wear product (order of microns) to coarser, millimetre sized particles. When silicone fluid was removed from the samples by a solvent, silicon was still present in non-soluble form and was in the largest quantities in the samples with high metal content as large solid agglomerations with metallic debris.

Analysis by Gel-Permeation Chromatography (GPC) carried out for the damper manufacturer showed that the silicone in fluid form in damper Nos. 1269, 1239 and 733 had undergone very similar changes resulting in fractions being present with shorter molecular lengths (lower viscosity). The fluid from Nos. 001, 250 and the damper from G-ILGW showed molecular change in a similar direction but to a lesser extent (half in rough terms). DERA Pyestock, in its original analysis of silicone extracted from G-ILGW's left engine damper, had found little difference between it and a reference sample (from an available used damper) which was still fluid in its behaviour and had contained much less contamination. Exponent, in comparing extracted silicone from G-ILGW's damper with new fluid, found some molecular changes representing the presence of lower molecular lengths (lower viscosity), but these were more akin to the results from damper Nos. 001 and 250, than to those from the dampers with highest metal contamination, Nos. 733, 1239, and 1269.

GPC analysis carried out on samples from these dampers by DERA Pyestock covered a smaller range of molecular lengths and the results differed in some respects from those obtained by

Exponent. This may have been due to differences in equipment and technique or variations in the sample material. The DERA analysis appeared to show increased variation in molecular length in the basic fluid with some overall decrease. It did not cover the range where separate fractions were identified in the Exponent report. Damper Nos. 1269 and 733 again showed the most change relative to the others but the difference was less marked. In the sample from damper No. 250 there was an indication of the presence of fluid with distinctly higher molecular length.

DERA Bridgewater produced estimates of the level of metal contamination in the samples and these are included in the tabulation below. These estimates were made from semi-quantitative x-ray Fluorescence analysis with a correction to allow for those elements in the silicone which could not be directly detected (carbon, hydrogen and oxygen) but which would be present in predictable quantities with silicon.

All the fluids showed signs of decreased viscosity with use. The indications were strongest in damper Nos. 1269, 1239 and 733 which had the highest metal particulate contamination. (There was some evidence that No. 250 contained a higher viscosity fraction.) The damper fluid from G-ILGW, while showing a lesser indication of any decrease in viscosity was in the highest category of metal congestion.

To summarise the vibratory behaviour of the engine with the different dampers fitted; vibratory torque is tabulated below at three conditions; at 1,850 RPM (propeller), just within the normal operating range, at 1,950 RPM, within the cautionary range, and at maximum take-off, 2235 RPM. These conditions are somewhat arbitrary but they serve to illustrate the principal features of the results.

Damper Serial No.	Test Rig Damping Time Sec	Fluid Condition *See note	Vib. Torque - 1,800 RPM	Vib. Torque -1,950 RPM	Vib. Torque - 2,235 RPM	Gear Condition
298	New	New	5,000	5,000	6,000	
001	2.9	1/7%	5,000	5,000	5,500	Average
250	15	2/ 8%	5,500	5,500	6,000	Good/Ave .
1269	13.6	3/49% SS	6,500	9,000	5,500	Average
1239	8.1	3/ 48% SS	10,500	10,000	6,500	Destroyed
733	12.6	4/48% SS	10,500	10,000	7,000	Destroyed

298 (50% nut torque)	New	New	5,500	5,500	6,000	
0035 (ex G-ILGW	Not Known	4/50%	Not Known	Not Known	Not Known	Destroyed

*Note: Three fluid condition criteria are listed; visual assessment as described above, metal content as a percentage by mass and presence of solid particles containing Silicon (SS).

The tests featuring the two dampers (Nos. 733 and 1239) which were associated with the worst gear damage produced the highest vibratory torque levels and they did so over an extensive range of RPM. Significantly, this covered the whole of the normal (green) operating range and represented an increase of about 100% over operation with a new damper. The engine manufacturer presented some previous engine test results, which showed that, without a damper, vibratory torque was high in the yellow range, with a peak of ±30,000 in lb. at 2,135 RPM. All of the dampers tested removed that resonance and vibratory torque was generally low at the take-off condition.

The dampers' performance in controlling vibratory torque, tabulated above, did not appear to correlate consistently with the post-service test results on the production test rig. This was not investigated further and it can only be surmised that the differences in environment and the degree of excitation between rig and the test engine had variable effects on the worn dampers.

There appeared to be some correlation between damping effectiveness on the engine and the assessments of damper fluid condition. The three dampers, whose contaminated fluid showed no propensity to flow, all allowed relatively high vibratory torque (±9,000 in lb. or more). However, damper 1269, while containing fluid which was identical in condition to that in 1239 and producing poorer damping performance on the test rig, allowed high vibratory torque over only a limited RPM range. High vibratory torque with a maximum of ±9,000 in lb. was measured only in a RPM range occupying the lower half of the yellow sector. The gear wear associated with this damper was unexceptional.

These tests showed that, in the engines returned from service, there was some correlation between damper condition, engine vibratory torque and gear damage, but only in gross terms. The variability in the results was probably due to influences and parameters that were not being taken into account. It can be surmised that these could include the manner of use of each engine, the rate at which damper behaviour had changed in service or whether there had been any short term events e.g. rough running, which might have affected the damper or the gears.

The increase in vibratory torque in the normal running (green) range appears particularly significant as the largest number of load cycles during an engine's operating life would be accrued in that range i.e. cruise. The gear loads resulting from the levels of vibratory torque seen in these tests could not be quantified from the work done during this investigation.

All 31 dampers were examined in the areas involved in their attachment to, and their security on, the starter shaft. Most showed no damage to the keyway and only light fretting in the bore with slight smearing of the pressure faces loaded by the securing nut. However, the three dampers which were associated with the most heavily damaged gears (i.e. loss of teeth) contained wear and damage to the keyway and other surfaces which were similar to, though less severe than, the effects seen on the damper from the left engine of G-ILGW.