AN ALTERNATIVE APPROACH TO ENGINE RATING STRUCTURES USING MONITORING SYSTEMS

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Abstract

Optimising the engine size to the multi-engine helicopter's needs is a difficult process which has traditionally been carried out through the mechanism of the engine rating structure. However, the rating structure has many limitations and does not allow the best potential use of the engine to be realised in service. The introduction of the micro-processor based Engine Monitoring System permits a re-evaluation of the rating structure and also the presentation of limitations to the pilots. By using EMS it should be possible to achieve a better relationship between the demonstrated capability of the engine as shown in the Qualification Programme and the authorised release for in-service use. This may be regarded as a first step to be followed later by a change of the qualification test to a more representative form with the EMS giving a more tangible link between bench test and customer operation. This should allow better use of the engine to be made for the short time/high power requirement thereby allowing a more efficient engine performance at cruise conditions.

One of the most vexing problems continually faced by the engineers in the helicopter industry is how to optimise the match of the engine (and hence the power capability) to the multi-engine helicopters needs.

The technically elegant way of achieving this is to fit a larger number of smaller engines but there are good reasons why this way is not being followed such as increases in cost, weight and maintenance demands. It is likely that the optimum number of engines for most helicopters will remain at two with three being used only occasionally.

Whilst it is as well in discussing a subject such as this to avoid any direct association between what it is right to do and the methods by which it is achieved, nevertheless it may be that the time is right to consider an alternative approach to the traditional engine rating structure for helicopter power plants now that we have the Engine Monitoring System as a viable weapon in our armoury.

It is proposed in this paper to examine this subject in 5 sections:-

1. The rating structure and its purpose
2. The disadvantages of the traditional rating structure
3. Consideration of the difficulties in changing the rating structure approach
4. The integrity of engine monitoring systems
5. An alternative approach

The Rating Structure and its Purpose

The objective of a rating structure is to define a set of power/time limits which enable the helicopter to achieve its optimum role performance and, at the same time, ensure an acceptable level of airworthiness and safety.

It has been long established practice to test engines to specific ratings which are mandatory limits on the pilot for time of operation at specific power levels. These form a practical but approximate method of limiting the rate of cumulative damage to the engine in order to achieve acceptable lives. The format of the testing required goes back to the piston engine era and has been modified but not fundamentally revised since the early days of gas turbines.

The rating structure in use by the British Ministry of Defence is shown in fig. 1 and is a typical example with minor variations of that employed by all the leading Aviation Authorities, both military and Civil, throughout the world.

A.	TWIN ENGINE OPERATION		
	Maximum Continuous	-	The highest rating of the engine which may be used continuously in flight
	Maximum 5 minutes	-	The maximum rating of the engine which may be used for a duration limited to 5 minutes per flight
B.	SINGLE ENGINE OPERATION		
	Maximum Contingency	-	The maximum rating of the engine which may be used for a duration limited to 2½ minutes during take off and landing
	Intermediate Contingency	-	The maximum rating of the engine which may be used for a duration of 1 hour during an en-route failure of the other engine.

Fig. 1 Rating structure terminology. Twin engine rotor craft.

For any engine, its ratings are validated by a series of tests carried out to strictly defined rules laid down by the authorities. This is called the Certification, Qualification or Type Approval Process.

Unfortunately the conditions specified do not always equate with the needs of a helicopter and authorised variations have to be built into the processes with the result that it becomes irrevocably linked with the particular installation.

The Disadvantages of the Traditional Rating Structure

The gas turbine power/life characteristics are basically incompatible with the balance of the various modes of power requirements of the twin engine helicopter.

Some of the particular aspects are described as follows:-

Power requirements - The power demand of a rotary wing aircraft varies typically with air-speed as shown in fig. 2.

As well as requiring to be low cost, light weight, economical and reliable, the engine has to provide over a range of ambient conditions, levels of:-

	Power factor
i) Efficient cruise power	100
ii) High power for take-off and landing	170
iii) Higher power for en-route flight after loss of one engine	200
iv) Higher power for transient to forward speed and climb after loss of one engine in the hover	300
v) Higher power to maintain height in the hover after loss of one engine	340

The dilemma that faces the designer trying to cover this widespread of power is all too obvious and if he decides to provide enough power within the traditional rating structure to meet (v) then the engine suffers from being too heavy and having a too high fuel consumption to be optimum at (i).

Operational environment - The certification programme has to cover the wide operational envelope in terms of ambient pressure, temperature, humidity, air cleanliness etc.

The resulting effects on engine speeds, temperatures, pressures, vibrations and life are expected to be evaluated in a programme which is already disproportionately expensive compared to that of the helicopter.

The programme has to cover the full corners of the envelope demonstration, i.e. on the hottest day, at the highest altitude with the most inept pilot handling a low performance engine, made in the worst material, to the biggest tolerances with the most inaccurate instruments; and of course, it is assumed that all these factors can be present at the same time - a probability that would be regarded as extremely remote in most walks of life.

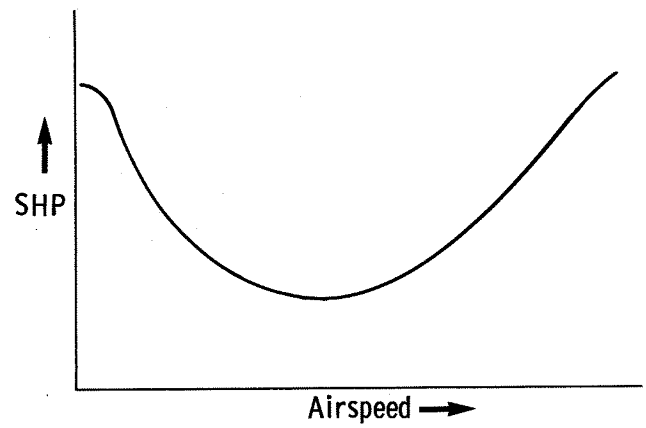

Fig. 2 Typical helicopter power requirement

The power requirements for a specific operation with respect to day temperature are shown on fig. 3. It can be seen that the power requirement on a helicopter rises slowly with AIT whereas the power available falls sharply over the same range.

This is another basic incompatibility which has to be catered for in the approval programme.

The dilemma that results is, if the engine is tested at high ambient temperatures, it does not produce the power to test the transmission. If the engine is tested to the cold day power level it is not exposed to its maximum turbine temperatures. As usual it is a compromise between the two with auxiliary tests being run to make up the short falls where necessary.

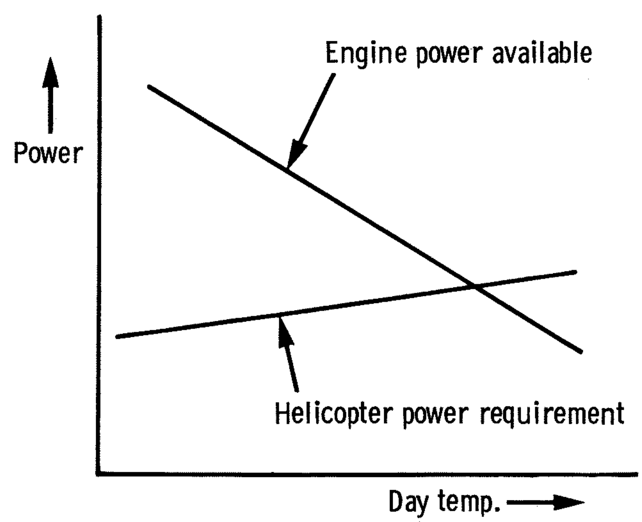

Fig. 3 Typical helicopter vs engine power

Additionally, there are the installational aspects which override some of the engine limitations and by impinging on the supplementary approval tests as they do, start to make the approval programme specific to a particular type of aircraft.

Emergencies - The concept of a rating is a "power" level usage associated with a time which enables helicopter performance to be scheduled in a flight manual and checked by flight test.

This assumes that all operation is normal - i.e. that the helicopter does not enter the "avoid areas" where it will be unable to fly on one engine. Hence in the UK the use of the word "contingency" rather than "emergency". What the contingency rating does is to reduce the avoid areas, but it does not unfortunately, eliminate them. It now seems that helicopter designers are becoming interested in eliminating the avoid areas altogether by calling for higher power levels to deal with the true emergency.

If we are going to provide for the ability to cover emergencies then it has to be ascertained that the engine is capable of doing so. It is worthwhile quoting here from the Civil Aviation Authorities "Bible" in these matters - the BCAR.

"Definitions of power/thrust in terms of usage and duration (and the use of these to form the basis of certain flight manual limitations) are not intended to remove the pilots right to judge whether and to what extent such limitations may be ignored in emergency conditions."

It seems to us, as engine designers, that with the better tools we now have at our disposal we ought to be able to ease the interpretation of "emergency conditions" by the pilot and allow him to devote his energies entirely to making safe manoeuvres without the worry of what is happening to the engines in the process.

Applications - One of the major problems faced by the Technical Departments of Aero Engine Companies is how to cater for the wide variety of rating structures that current operators and potential customers are seeking.

This range has been extended recently by the proposal to insist on full category A capability for all medium twin engined helicopters.

The range covers such diverse items as:

i) Anti submarine warfare operation, requiring long period hover ratings for sonar dunking and an emergency power level for fly away following single engine failure.
ii) Armed attack warfare with high speed dash capability and nap of the earth power fluctuations.
iii) Recovery and ferry of aircraft with single engine failures from difficult take-off sites such as oil rig platforms or the surface of the sea.
iv) High altitude surveillance in mountain ranges with ability to elude sniper fire-arms by agile manoeuvrability.

These are just some examples of the latest proposed uses of the ever expanding role of the helicopter and they all, in their turn, produce small variations in the qualification requirements for the engine. These can generally result in a repeat type approval test unless one is extremely lucky and has covered the requirements inadvertently during earlier programmes.

Pilot observance of limitations - With the traditional rating structure the "red lines" on the cockpit instrumentation for engine temperature and speed can usually number four.

Four red lines on a cockpit instrument may sound acceptable but it should be remembered that engine instruments are not primary flying devices and are, therefore, restricted to a small size with a small scale for a large range. The actual observance of these limitations by the pilot is very difficult and the suspicion exists that the discipline employed in the observance of engine limitations may leave something to be desired.

Since the clearance of the engine limitations forms a significant base of the engine approval programme, the disparity between the effort that is put into selecting and clearing these limitations and the way this information is displayed and may be observed by the pilot is extremely frustrating to engine designers.

General - Whilst the five specific subjects dealt with above constitute anomalies and irritants which emanate from the rating structure, the general problem which swamps all of them is the disproportionate hot section factor damage which the current rating approval process accumulates in relation to other factors such as low cycle fatigue counting. The seriousness of this problem manifests itself not in some unreliability in service effect (such as would be the case if the LCF programme had been of poor quality) but in the far more fundamental form of the engine being basically the wrong size for its applications and it is this subject that is dealt with in more detail in the next section.

Consideration of the Difficulties in Changing the Rating Structure Approach

The clearance of a rating structure is achieved by what is called the type test in Britain and the model qualification test in the US. It is 150 hours long and has been in existence since at least the 1950's. It is beloved of Airworthiness Authorities and bears absolutely no resemblance to actual customer use.

On the other hand, it is regarded as a very sound and dependable yard-stick as to the measure of an engine's suitability to enter service and any suggestion to alter it is usually met by trenchant resistance.

As stated at the end of the previous section, its unrepresentativeness is mainly concerned with its high use of hot section damage, be it of a conventional creep usage form with solid turbine blades or of a more thermal fatigue bias for cooled blades and static nozzle vanes. For the purpose of this argument the hot section factor damage will generally be referred to as creep.

What could be changed initially is not the type test itself but the relationship between the demonstrated creep capability during type test and the authorised release life/power figures which come from it. This certainly ought to be a short term target with perhaps a slow change to a more representative type test to follow. Any change to the type test structure would probably require a doubling up of new and old styles for a period to demonstrate consistency of standard and while this is happening, programme costs would probably increase.

The long term returns, however, should be very beneficial in relation to reduced cost of ownership in service and a more efficient use of some of the world's dwindling oil supplies.

The most obvious change that could be made to the type test is to impose the condition of a torque limitation for the normal temperate conditions under which the helicopter will operate. As was said earlier there is no recognition of this in the regulations and if it were employed it would allow a greater proportion of the creep usage in the test to be devoted to the tropical operation and thereby allow a higher engine temperature to be cleared for that part of the helicopters use. Fig. 4 illustrates this point simply.

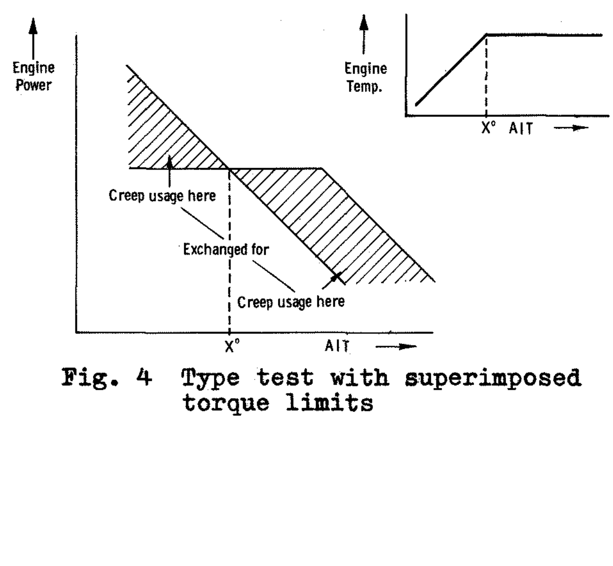

Fig. 4 Type test with superimposed torque limits

The problem here is the accurate recording and re-allocation of the creep capability and hence we come to the Engine Monitoring System. If the proposed system with its programme algorithms for hot end usage (as well as other functions) is run on all the endurance testing during the development programme, then a sound basis of demonstrated creep capability is established which allows a degree of flexibility to be used in the type of release which the qualified engine can be given for potential customer use. In other words by compiling a data bank of the hot section damage capability for the engine, a new application with its power requirements can be evaluated against it to see that the new rate of damage and top power requirements are not incompatible with what has already been demonstrated.

It is interesting to consider what happens today when a rating is exceeded, say on an en-route failure either in duration or temperature. The pilot reports it (let's be kind!) and the operator's engineers consult the maintenance manual. Invariably there are no clear instructions on what to do, so they ask the manufacturers. The manufacturer's Service Department ask the Stress Engineers who generally say it's acceptable. (There are, after all, no definite rules to say how many times an OEI rating may be used in an aircraft life). The engine stays in service and the aircraft flies on.

If it happens another eight times, say, the answer may be different but this stems from two reasons - one, the incidents have been recorded and two, the Stress Engineers have knowledge on the strength of materials.

Recording and storing knowledge are things that computers can do so why can't this process be dehumanised and put on to a computer?

The above function should be taken in context with the other necessary tasks undertaken in an EMS. These are limit exceedence, rotative LCF counting and thermal fatigue monitoring. All are a measure of the usage of the engine and become more cost effective if integrated in one unit. Additionally the pure health monitoring aspects of performance trending, vibration data analysis and lubrication system status can be added to provide a comprehensive monitoring system.

LCF counting is not covered extensively in this paper as it is already a practiced art-form in the industry. The full EMS does allow, however, a higher degree of sophistication to be adopted on this subject and an illustration of the possible benefits is shown on fig. 5. The three lines show the progression in authorised, hourly life possible from a demonstrated cycle fatigue programme:-

i) The lowest line represents the traditional approach with little or no knowledge of the type of operation the customer is using. e.g. Mission spectrum and/or typical ambient conditions:-

ii) The middle line represents the modern military approach where a mission profile with severity factors applied is defined at the onset of a qualification programme to form the basis of the component lifing philosophy.

iii) The upper line represents the release life possible from actual recording of service type operation at temperature sea level conditions.

It can be seen there is a three-fold advantage gained in the actual release life possible (the figures incidentally are real from a current Rolls-Royce programme).

From the fatigue point of view then, the rating structure and the type test are almost irrelevant and the cyclic qualification programme stands on its own. It is fundamentally hot section usage, limit exceedance and pilot observance that this argument is about.

The Integrity of Engine Monitoring Systems

For engine monitoring systems to become group 1 equipment, (in other words, the release life and hence the airworthiness of the engine is dependent upon the results which the EMS provides,) the integrity of these systems will have become very high and this will take some-time to achieve. Initially it seems reasonable that they should be fitted to aircraft in group 2 equipment role, the engine released to traditional methods and the EMS monitored to ensure that it is producing valid data bearing at least some resemblance to the estimated life usage produced by manual methods.

We should certainly quote our own experience to date. Rolls-Royce has a helicopter operation in its flight test facility and an EMS has been under evaluation on this helicopter for a period of 5 years. This system was MOD furnished equipment to Rolls-Royce and was one of a number of projects supported by MOD during this period. The others were all direct service trials and the benefits accrued are available for examination. The system is a fairly simple first generation device comprising multiplexing Data Acquisition Units and Cassette Recorders. All computation is carried out off-line at ground replay stations. With this equipment we have shown that good valid data can be acquired in the harsh environment of a helicopter. We have also shown that such equipment needs intensive development if it is to become totally reliable.

Computer programmes for LCF, creep, performance trending and vibration monitoring have been developed and proven and some details of the configuration and the results are shown in the following figures:-

Fig. 6 shows the equipment configuration in the helicopter.
Fig. 7 shows the flow chart for LCF usage calculation.
Fig. 8 shows the flow chart for creep usage calculation.
Fig. 9 shows the recording of temperature versus time over a 400 hour flight programme.
Fig. 10 shows the recording of torque versus time over this 400 hour flight programme.
Fig. 11 shows the distribution of creep usage over different types of flying carried out during the 400 hour flight programme.

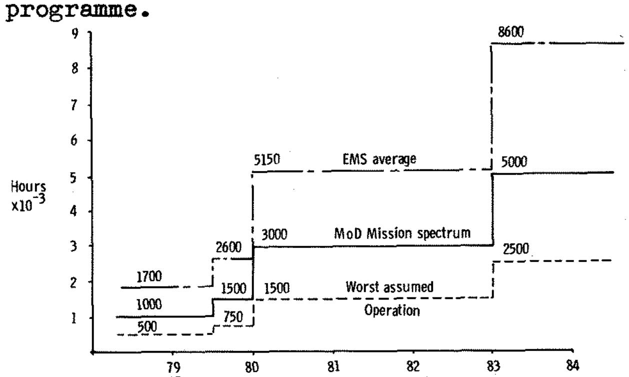

Fig. 5 Benefits to LCF using EMS

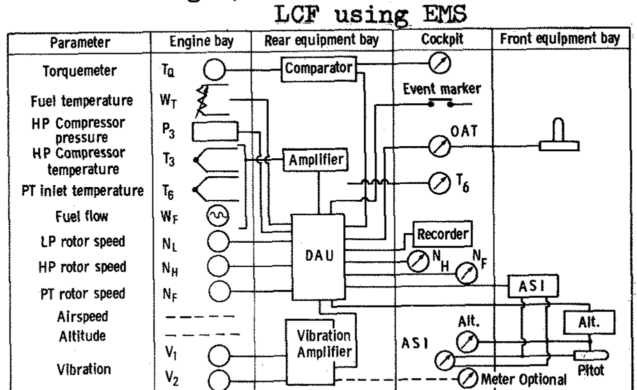

Fig. 6 Early engine monitoring system

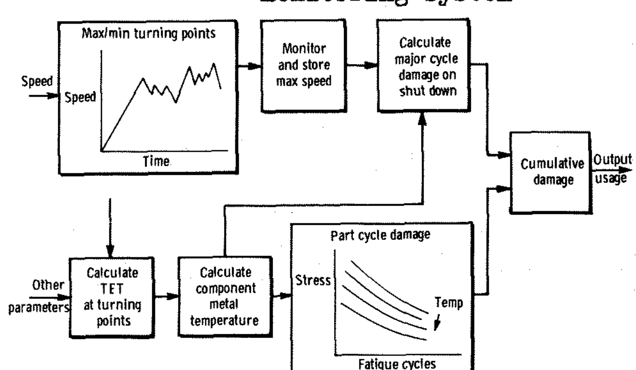

Fig. 7 Low cycle fatigue. Calculation of cumulative damage.

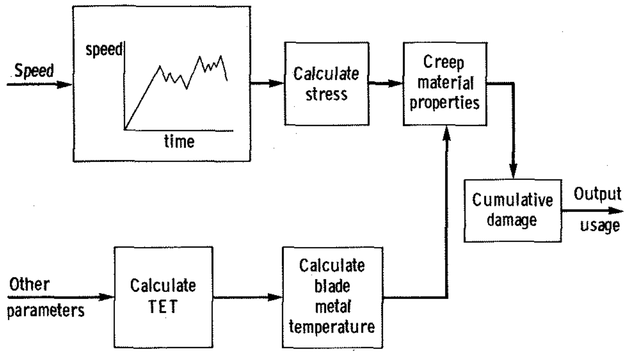

Fig. 8 Turbine blade creep.
Calculation of cumulative damage.

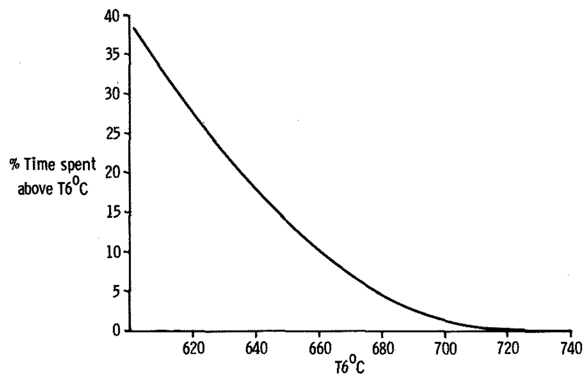

Fig. 9 Typical time temperature analysis

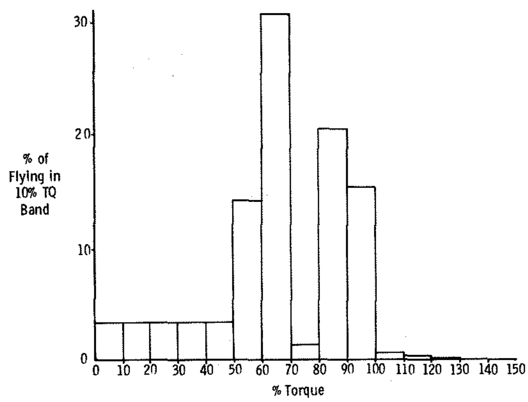

Fig. 10 Typical time torque analysis

Flight Description	No. of Flights	Flight Hours	% Creep Used
Mission	40	72.4	0.239
Development	29	40.6	0.246
Crew training	2	3.1	0.004
Ground run	18	8.7	0.003
Air test	2	1.2	0.020
Tracking	5	4.1	-
Miscellaneous	48	80.2	0.725
Total	144	210.2	1.237

Fig. 11 Typical blade creep usage (200 hrs.)

Some of the surprising aspects were:-

i) The smoothness of the time temperature curve.
ii) The discontinuity in the time torque curve.
iii) The wide variation in creep usage for different types of flying, e.g. if only the prescribed mission was flown then 50% creep usage would allow 15000 hours flying of this type. However, the rate is three times this for "miscellaneous", but as the programme was flown by test pilots, we believe we can still afford to be relaxed on the subject.

Based on the experience described above, together with Rolls-Royce's experience on electronic control systems over 20 years and the fact that the industry is apparently poised to change over to digital electronic control systems en-masse, there is now a general feeling that the integrity question concerning monitoring systems can be faced with confidence and that only extensive field experience can progress the state-of-the-art from this point onwards.

An Alternative Approach

The basis for an alternative is a long held belief that much greater utilisation of engine components could be achieved if a more accurate count of hot end damage occurring in actual engine usage is made.

Another factor forming the basis of this proposal is that when the pilot is in a critical situation, the last thing he wants to be bothered with is engine limitations. He is there first and foremost to fly the machine and his eyes should be "out" as much as possible not "in".

The approach is, therefore, two-fold; maximising economics and minimising workload.

The proposal is set as a bold step representing an ultimate position with the express purpose of challenge, stimulation and discussion rather than dwelling on a tortuous path of how actually to get there.

Qualification - The programme should be aimed at establishing a temperature/time cumulative damage bank for the engine components compiled from actual engine running. There must be dedicated creep and/or thermal fatigue evaluation testing using components of known strength from known batch manufacture. This testing will be exhaustive and must result in failures to be effective. (Some engines actually experience component creep failure during normal running but Rolls-Royce engines are not normally in this favourable position!) The new temperature measurement techniques such as radiation pyrometry will be employed. Two milestones will be achieved by this testing. Firstly, the critical part of the creep curve will be established for the real environment of the engine and secondly it will be demonstrated consistently that the failures are "soft". The by-product will be that the early warning failure detection systems will be tested and developed for real. The creep usage meter will be monitoring all the testing and a good relationship will be established.

This testing will be supported by the currently employed thermal shock and simulated mission tests to establish the degree of inter-action of creep and fatigue. We must demonstrate clearly to the authorities that we have a sound knowledge of the creep capability of the engine - this is the only way to be able to reduce the severity of the safety factors currently employed and start to achieve the objectives.

The qualification test itself will be changed to a mission based schedule and will take into account a likely aircraft torque limit over the lower ambient temperatures. The test will be of longer duration than the current one, probably 3 or 400 hours and will be aimed at using at least $\frac{3}{4}$ of the potential life of the hot components. The engine temperatures will be chosen to achieve this figure over a spectrum or air inlet temperatures. This spectrum should cover ISA to ISA+25°C SL in four equal steps, the engine temperature being at maximum for the top two AIT's and reduced according to the engine torque limit for the others.

The composition of the mission will be based primarily on twin engine power levels but at intervals to be agreed, simulated single engine power levels will be incorporated varying according to engine failure, occurring at different points in the mission. The frequency of the single engine cycles should be commensurate with typical figures for engines in their infancy in service.

The test would continue with normal problems and failures being repaired as in service but with major failures of Design or Quality rendering the test void.

Allowance for performance deterioration would be built in by raising the temperatures in the torque limited stages accordingly.

At the end of the qualification test and the supplementary endurance testing, the creep accumulation will be evaluated and a case presented to the authorities for an agreed initial creep release to service. If things have gone well, then approximately 2/3 hot section life could be claimed. It might be argued, however, that if too high a factor is achieved then the estimates were too low in the first place, but that is just one of the frustrating vagaries of this business!

For further supporting evidence it is believed that the qualification test engine should be run on to failure, in an accelerated form if necessary to minimise the cost.

The last point about qualification is the establishment of the absolute maximum temperatures and speeds at which the engine can safely operate. These should then be protected by the automatic limiters of the engine control system and the resulting power should be available to the pilot in an emergency. As long as the damage is being recorded, the appropriate maintenance action can be taken after emergency power levels have been used.

Certification - The engine will be certificated with a carpet of characteristics (obviously on a card deck) showing the relationship of power versus percentage creep life usage per hour for all ambient conditions. It is believed that this is really all the aircraft designer needs to know to select an engine in order to compose his flight manual around it.

Operation - The pilot will be relieved of any need to observe the engine temperature and speed instruments. He will need to be warned of the fact that he is employing a high rate of hot end usage and this warning needs to be progressive. The computer can be programmed to do this but how it is presented is not for us to say. Pilots tend to have strong views on this matter!

The onus of monitoring the usage should be on maintenance personnel. The amount could be displayed in the cockpit to be read at appropriate intervals or more likely in Civil operation, to be fed out on to a ground printer.

If the computer fails in flight, advisory procedures for safe operation need to be spelled out in the flight manual but it should not be regarded in any sense as a serious problem and there should be no need to abort the mission unless it is of a highly critical nature.

A full "on-condition" maintenance approach is compatible with this system and that concept is now gaining wide acceptance in the industry.

The engine is withdrawn for appropriate action when the authorised hot section factor is achieved.

Hardware - For military machines some aircraft contractors envisage a full integration of the EMS with the main computer system as shown in fig. 12. A visual display unit with interrogation capability is available to the pilot in flight and to Maintenance during servicing periods.

For Civil machines the system should be a stand alone unit primarily to provide option for fitment to the customer.

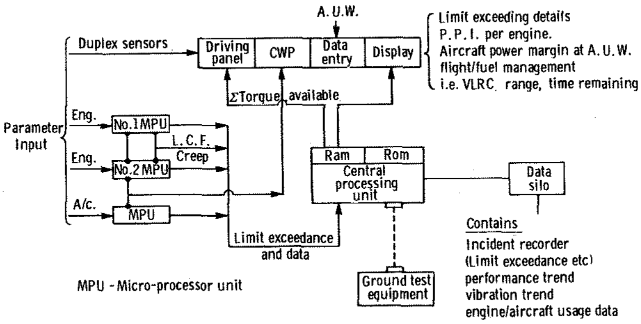

Fig. 12 Integrated helicopter monitoring system

Conclusion

This paper is aimed at basically trying to achieve a better use and hence return for money of todays costly engines.

It is believed that it is the certification test that sets the size of an engine for a helicopter application under the current rules and that the disparity between this and the need to have efficient fuel usage in service needs to be constantly questioned, always within the broad envelope of safety that is termed "airworthiness".

There should not be a tacit acceptance that the present rating structure and philosophy is sacrosanct for ever-more. It is one of the engineers basic functions to always question the status quo to see if it can be improved and this paper is offered against a pursuance of that function.

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