THE SCIENCE OF EQUIPMENT USAGE

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INTRODUCTION

To those engaged in the manufacture of aircraft and equipment the day of the delivery flight is rightly one for rejoicing. On the receiving end the operator watches the arrival of his brand new aircraft with mixed feelings. The first landing is the first of some 20,000 landings which the aircraft will make in the next 30,000 flying hours, averaging about eight hours of flying a day over the next ten years.

Today's typical four-engine jet aircraft consumes about $1,000 of direct operating cost in each flying hour, of which about $300 per hour is spent on fuel and $160 on maintenance (Fig. 1). Applied to a fleet of 50 jet aircraft about $440,000,000 will be spent on fuel and $230,000,000 on maintenance of this fleet over the next ten years. Where an operator can prevent his costs from increasing by 10 per cent, or can decrease costs by 10 per cent, he will, even in the maintenance field alone, obtain a direct saving of over $2 million a year.

Apart from these direct dollar considerations, it is basic to airline operation that equipment must be maintained at a safe level, and that the aircraft should be on time. The inherent design capabilities of the equipment, the level of its development, the standard of in-service monitoring and control regulate the pattern of Equipment Behaviour and therefore determine the degree of safety, reliability, and economy achieved.

As the demands for better understanding and control of Equipment Behaviour have increased, new methods and refinements in the interlocked loop of Equipment Analysis-Forecasting-Specification and Development are providing the foundation stones for the Science of Equipment Usage.

It is the purpose of this paper to briefly outline some specific examples and thoughts, based on airline operation, in the hope that these will encourage further applications and developments in this rapidly growing and rewarding field.

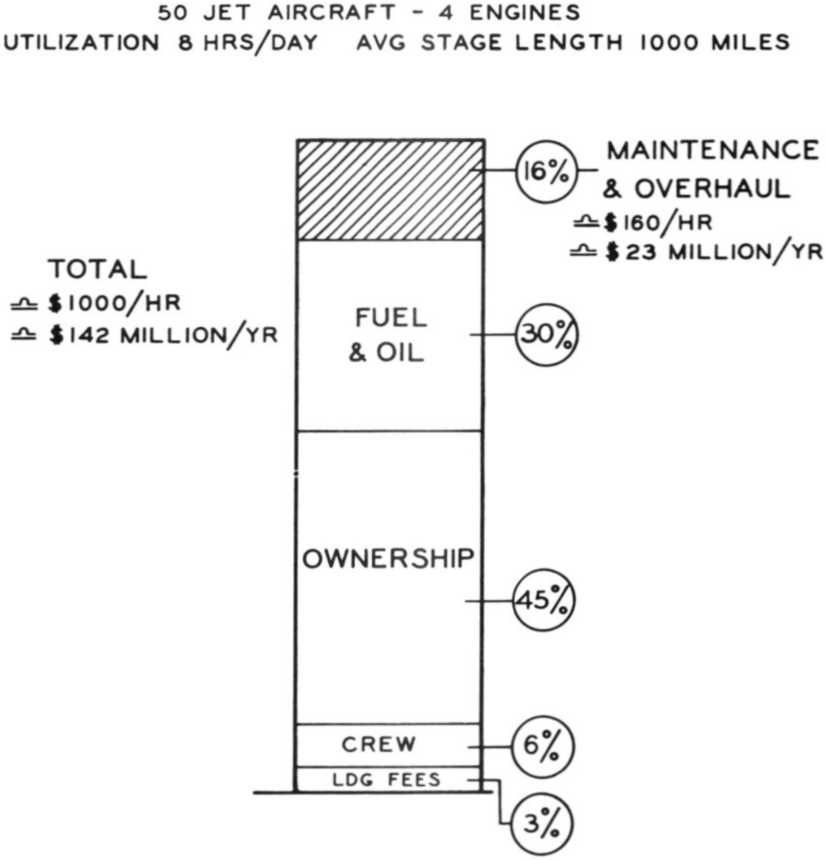


Figure 1. Direct operating cost.

OBJECTIVES AND SPECIFICATIONS

In the area of equipment usage a clear objective is before us:

> To fulfill the required operating plan to attractive standards with the minimum usage of equipment and manpower.

It is not enough for the operator to organize and work towards this objective, it must just as firmly belong to the manufacturers' philosophy of design and development of airline equipment. Good design of individual components to give long, trouble-free life is undoubtedly the most important foundation on which the manufacturer should build.

Experience shows that a large number of operating failures do not occur at the inherent design life being achieved. Causes such as material variances, manufacturing differences, and differences in exposure and handling contribute heavily to the problem. It must therefore be fully accepted that equipment will fail.

As the design and development of equipment proceeds a detailed failure analysis must be made to assess all feasible modes of failure, as well as secondary failure effects. The assessment of individual component life and failure should be substantiated by adequate rig testing, and continuously used to pinpoint unacceptable levels of performance.

Even at the initial design stage the basic layout of systems has to be assessed from an operating viewpoint. Surprise is the worst enemy of smooth airline operation. The ability to test for failure trends, and to give early warning of impending failures, has to be analysed and designed into the equipment. Systems which are essential for continuous operation must be reviewed to assess the wisdom of incorporating redundancy, to permit the operation to continue until maintenance action can be performed without disruption.

A thorough analytical study of equipment stress levels, under simulated extremes of operating environment, should be performed at the development stage to ensure that when in-service problems arise the manufacturer has a wealth of stress information to fall back on so that problems can quickly be solved. Speed in providing the right problem solution is essential to the reduction of wastage.

The observation of equipment behaviour during rig testing, development running and operation has to be translated into usable data (Figs. 2 and 3). Data collected from the manufacturer, other airlines' operation and one's own is the bloodstream of the equipment organization. Such data must be used as the basis for optimizing the total operation. Efficient airline operation requires the presence of the right amount of:

Material
Manpower
Skills
Facilities

at the right place, at the right time (Fig. 4).

A correct amount of money has to be allocated at the right time to procure the above.

The behaviour of the operating equipment determines the above requirements. This equipment is never static, but is continuously changing in its margins of operational effectiveness with usage, age, modification and repair. The program of plans, budgets and arrangements is therefore also never static but requires continuous readjustment with each new event and experience.

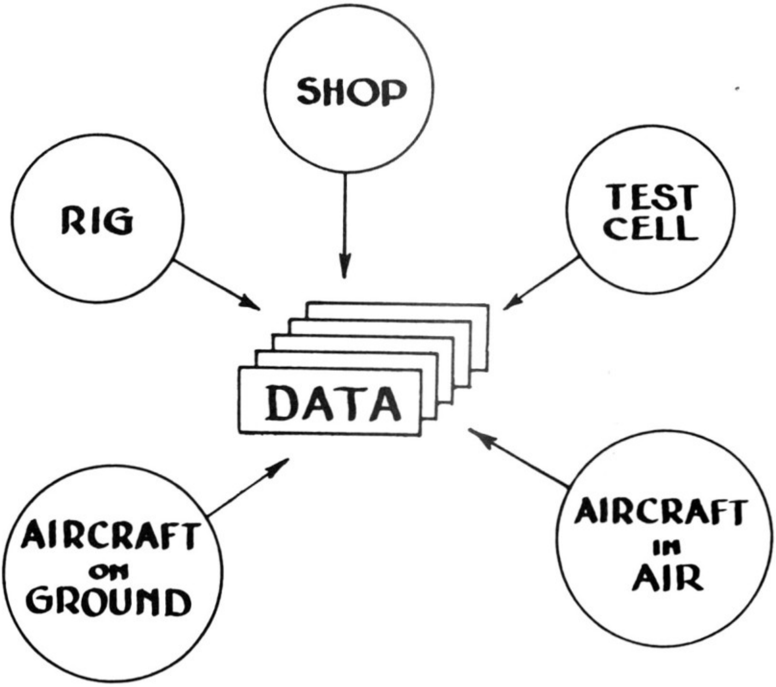


Figure 2.

The process of assessment has to start in the initial design phase and can never stop throughout the life of the aircraft (Fig. 5).

Good continuous analysis and forecasting of equipment behaviour is a fundamental prerequisite to the effective planning, purchasing and implementation of the required equipment support program.

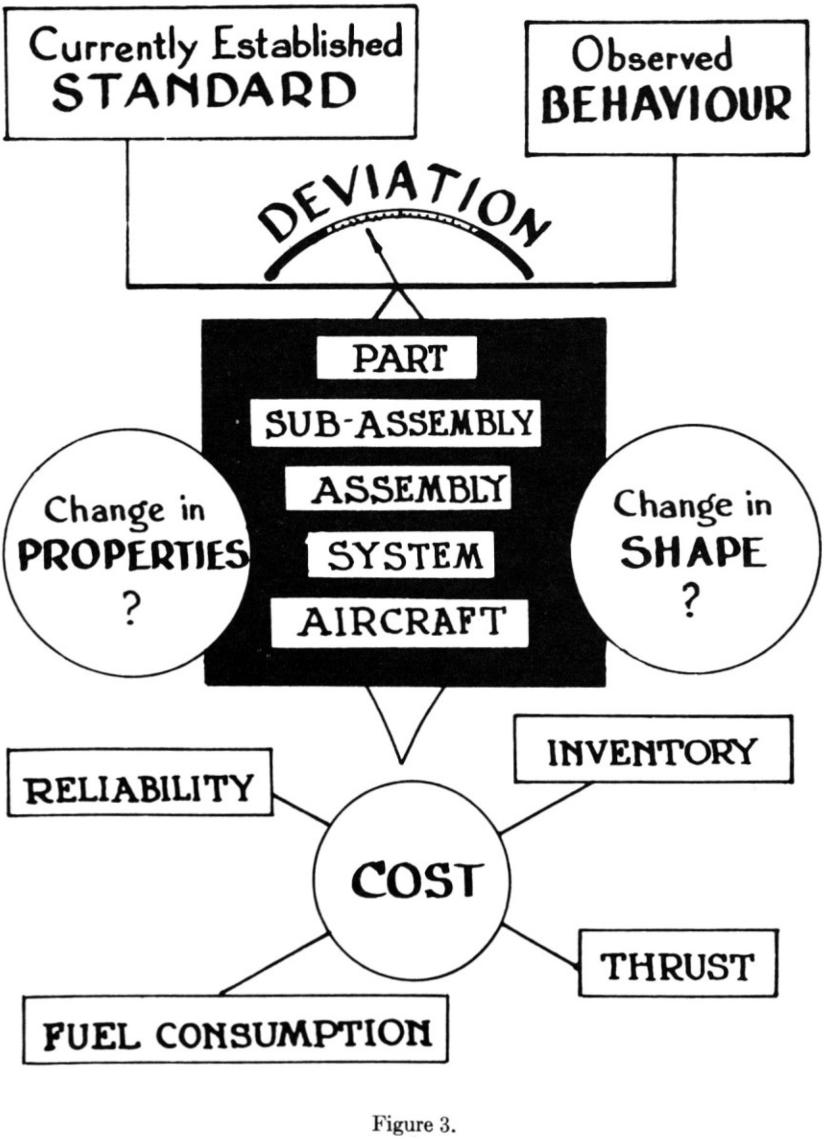


Figure 3.

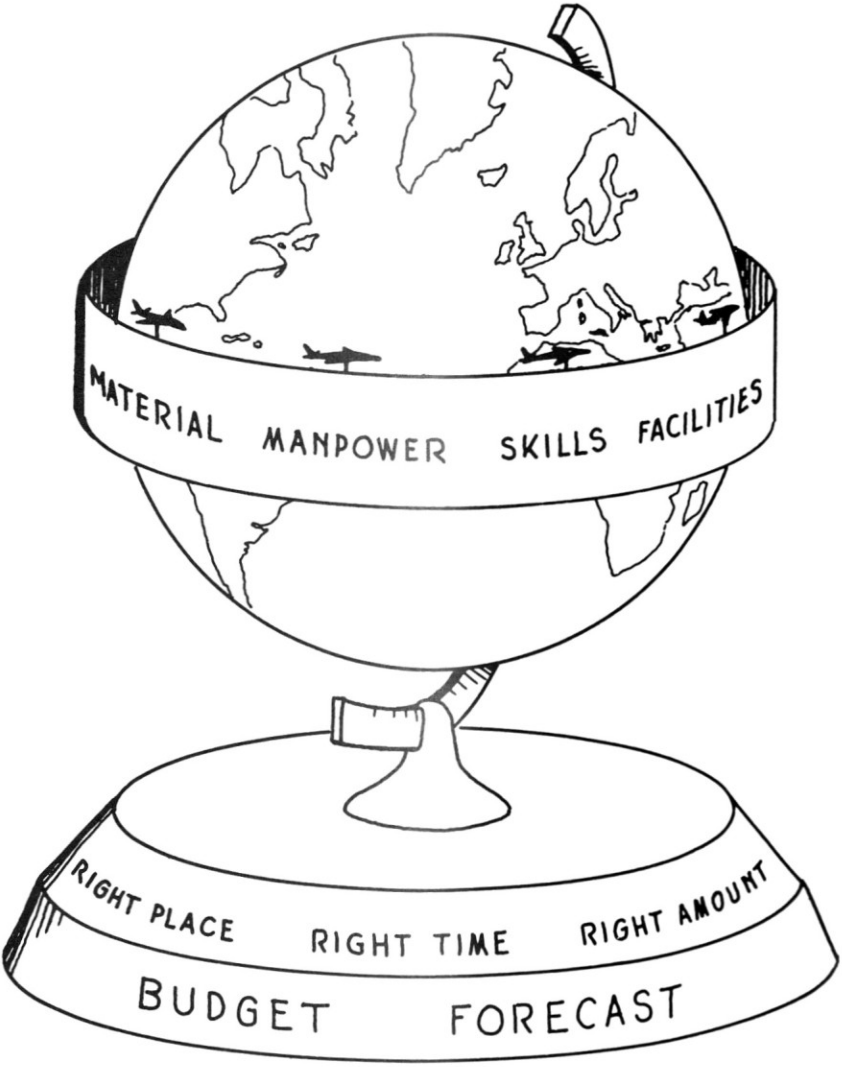
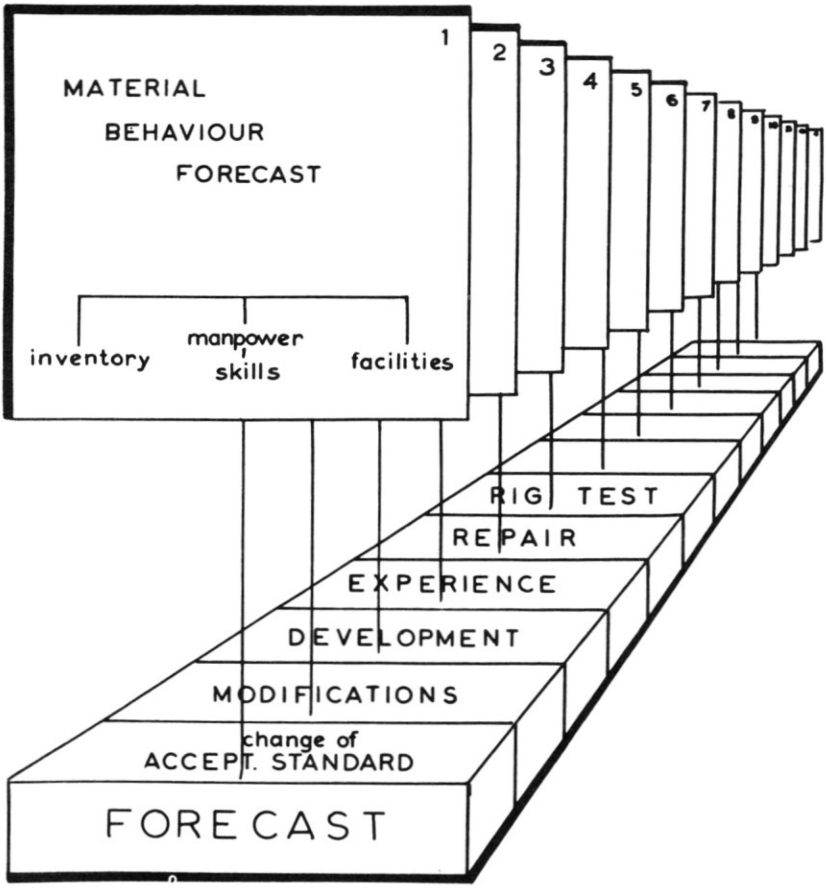

MATERIAL
MANPOWER
SKILLS
FACILITIES
RIGHT PLACE
RIGHT TIME
RIGHT AMOUNT
BUDGET
FORECAST

Figure 4.


1
2
3
4
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6
7
8
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10
MATERIAL
BEHAVIOUR
FORECAST
inventory
manpower
skills
facilities
RIG TEST
REPAIR
EXPERIENCE
DEVELOPMENT
MODIFICATIONS
change of
ACCEPT. STANDARD
FORECAST

Figure 5.

EXAMPLES

EXAMPLE 1

Figure 6 illustrates the effectiveness of performing a reliability study of system layout at an early stage. Even allowing for the latest improvements in fire-detection systems, a single system could be expected to give one false warning in about 20,000 one-hour flights, which represents about one false warning every two months in a fleet of 50 aircraft. A dual system, in conjunction with the principle of only shutting down if both systems give a warning, is expected to give a false warning in about one billion one-hour flights or about one warning in 9,000 years in a 50-aircraft fleet. Although the resulting figures may not be accurate, the order of the results certainly shows that a dual system is very much better than a single system.

The above analysis has led to the standardization of a dual fire-detection system on the DC-9 aircraft.

EXAMPLE 2

Thorough development testing by the manufacturer prior to the delivery of equipment is essential. Figure 7*a* represents the typical condition of flame tubes from new engines in airline operation after 320 hours of running. As a result, the manufacturer started a vigorous program of development which very quickly led him to produce a modified flame tube. Figure 7*b* represents a typical condition of the modified flame tube as seen at 3,200 hours. If the homework had been done more thoroughly prior to airline operation, both the manufacturer and the airline would have gained.

EXAMPLE 3

Modifications do not always have to be complicated. Figure 8*a* shows the condition of inlet guide vanes in a jet engine at 2,500 hours. In an attempt to overcome platform wear silastic compound was applied between the platforms. Figure 8*b* shows a set with silastic as seen after 4,800 hours of operation. This serious problem was completely eliminated by this simple procedure.

EXAMPLE 4

To overcome operational problems in the best manner, detailed information is required. Figure 9 shows a cross section of an anti-iced intake and bearing support vane. A large number of cases of vane cracking occurred.

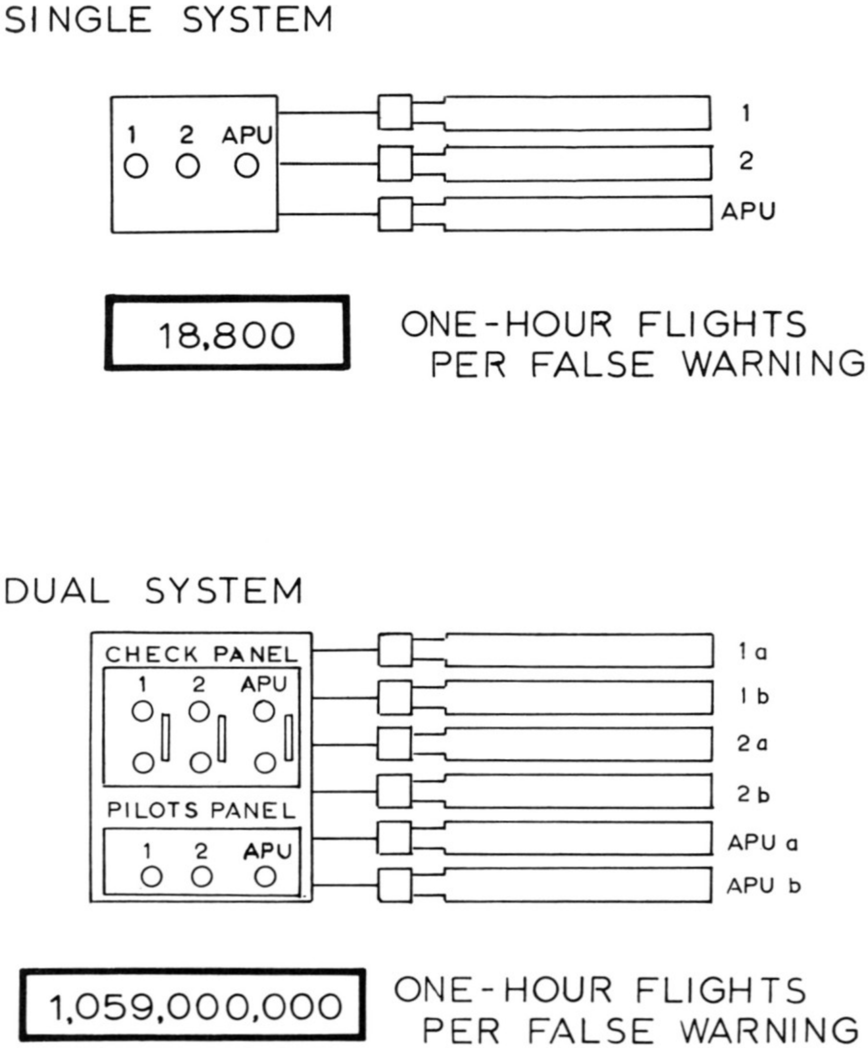


Figure 6. Fire-detection system design comparison.

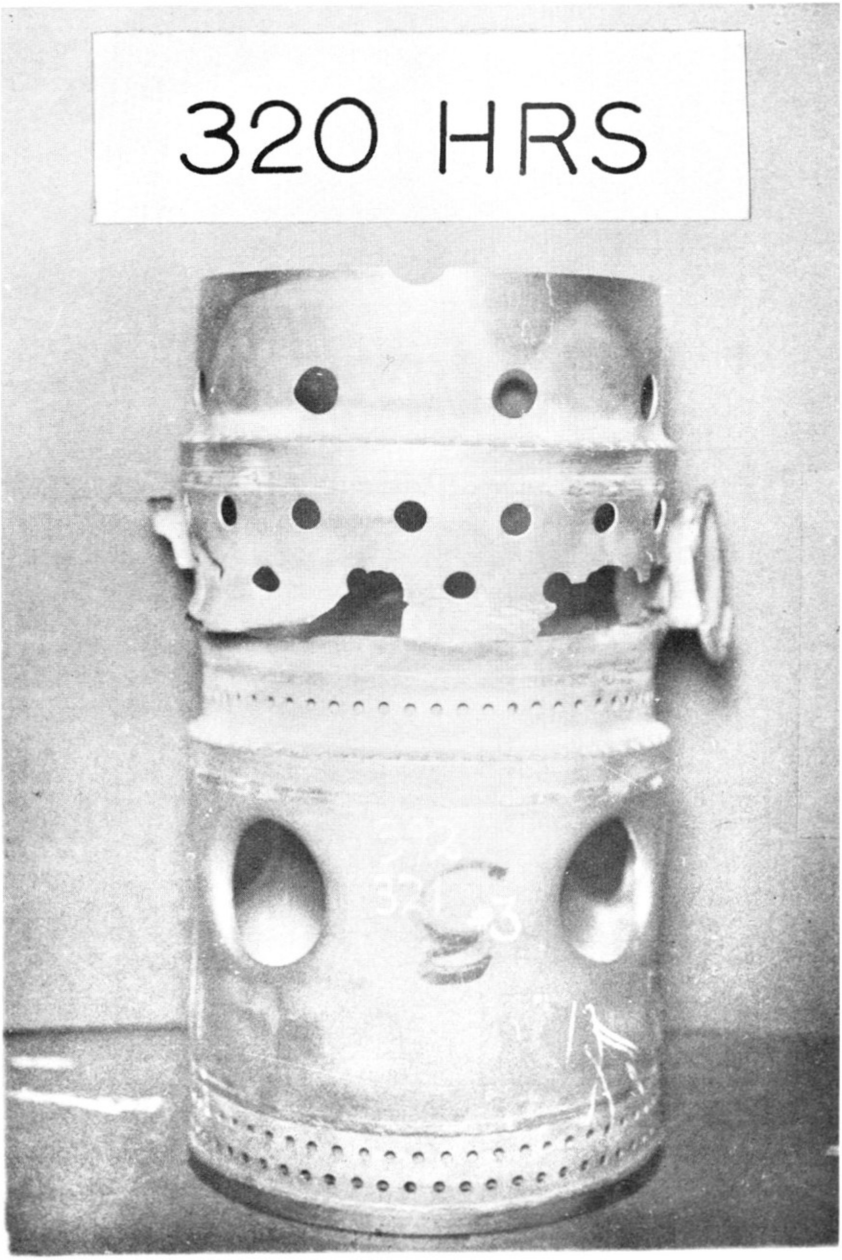


Figure 7*a*.

Figure 7*b*.

Figure 8a.

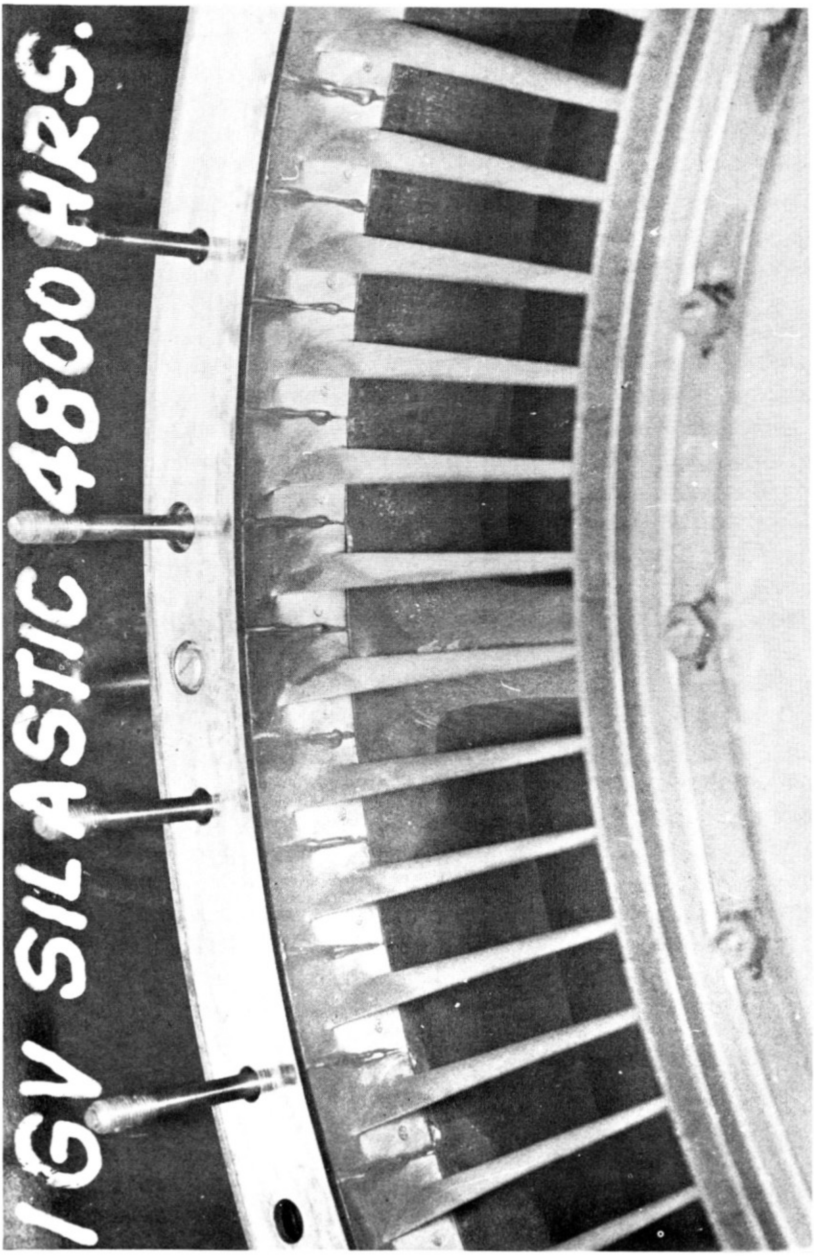


Figure 8b.

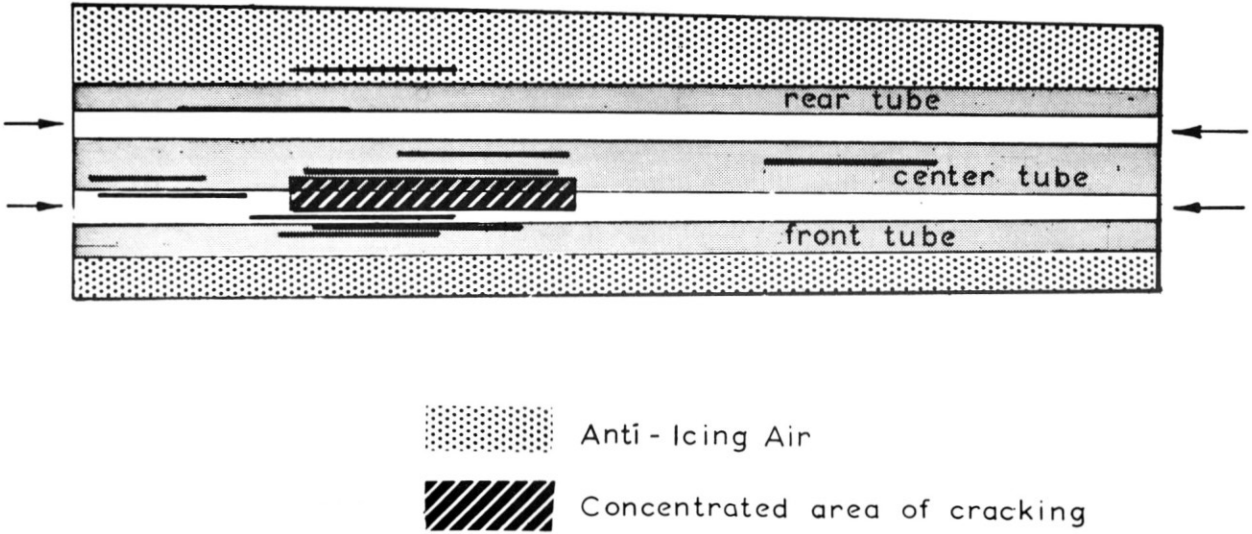


Figure 9. Cracking of housing vanes.

By collecting and recording the exact location of each crack a pattern of cracking was established corresponding to that which could be expected from vane resonance. By filling the empty spaces, as indicated by the arrows, with rubber material the resonance and the cracking were eliminated without affecting the anti-icing characteristics.

In each case of operational problems the more scientific and detailed the information the better the solution.

EXAMPLE 5

By collecting and using life and performance data on components and parts the right decisions on life control can be taken. Figures 10*a* and *b* show the percentage survival in different time zones of two different bearings. In both cases about 20 per cent of the bearings had failed by a certain time, however, in the case of Fig. 10*a* the failure rate was increased with bearing age, whereas in Fig. 10*b* older bearings were better than young bearings. The curves drawn from the statistics show that the action required for bearing *A* is different from that required for bearing *B*.

EXAMPLE 6

Can we determine whether an assembly is deteriorating with age? With the right data available the answer can be continuously presented. Figures 11*a* and *b* show the risk of shutdown and unscheduled removal respectively for a certain period of operation of a jet engine. The data has been plotted on semilogarithmic paper, on which constant failure rate plots as a straight line. The slope of the calculated reliability curve can then easily be compared to the line representing constant risk of failure with age. It will be seen that in both the case of total shutdown and total removal the risk, if anything, is slightly greater in the first 2,000 hours than in the next 2,000 hours. In this example the overall performance is certainly not deteriorating with life, and overhauling the assembly at short intervals would in fact produce a worse performance.

The same method of analysis can, of course, be applied to all parts, assemblies, and systems of the aircraft.

EXAMPLE 7

Can we forecast the behaviour of parts, or assemblies? Figure 12 attempts to forecast Conway Engine unscheduled removal behaviour, and by this means lead to the forecast of the number of engines which would come into

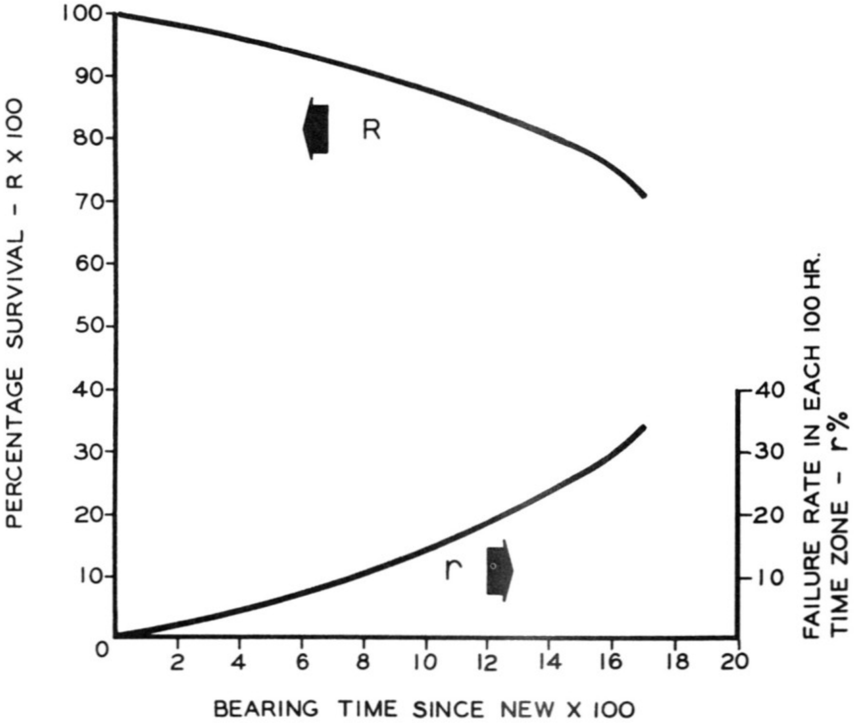


Figure 10*a*. Front compressor bearing—tyne engine reliability function.

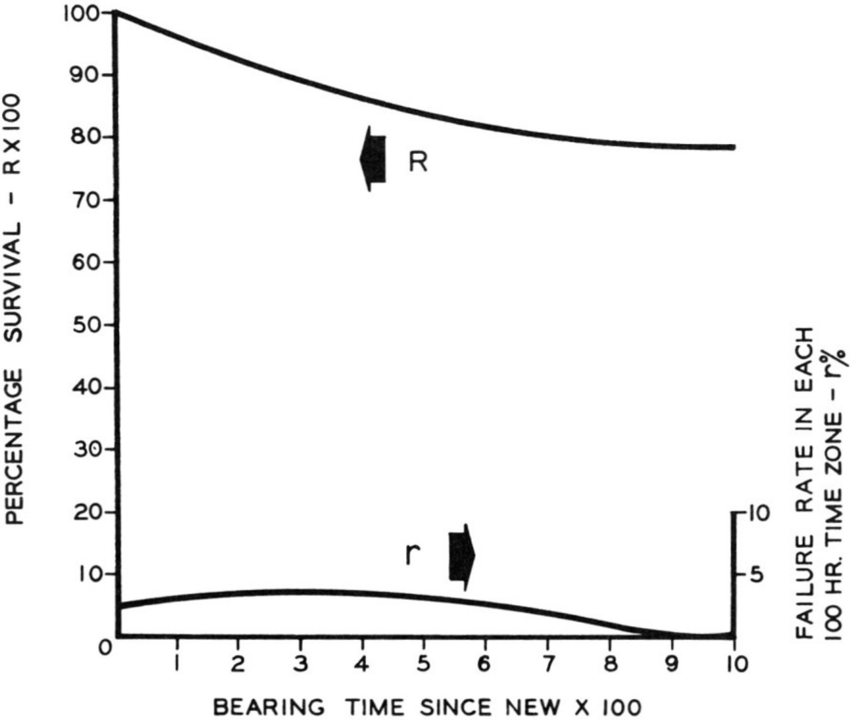


Figure 10*b*. H.P. turbine bearing—tyne engine reliability function.

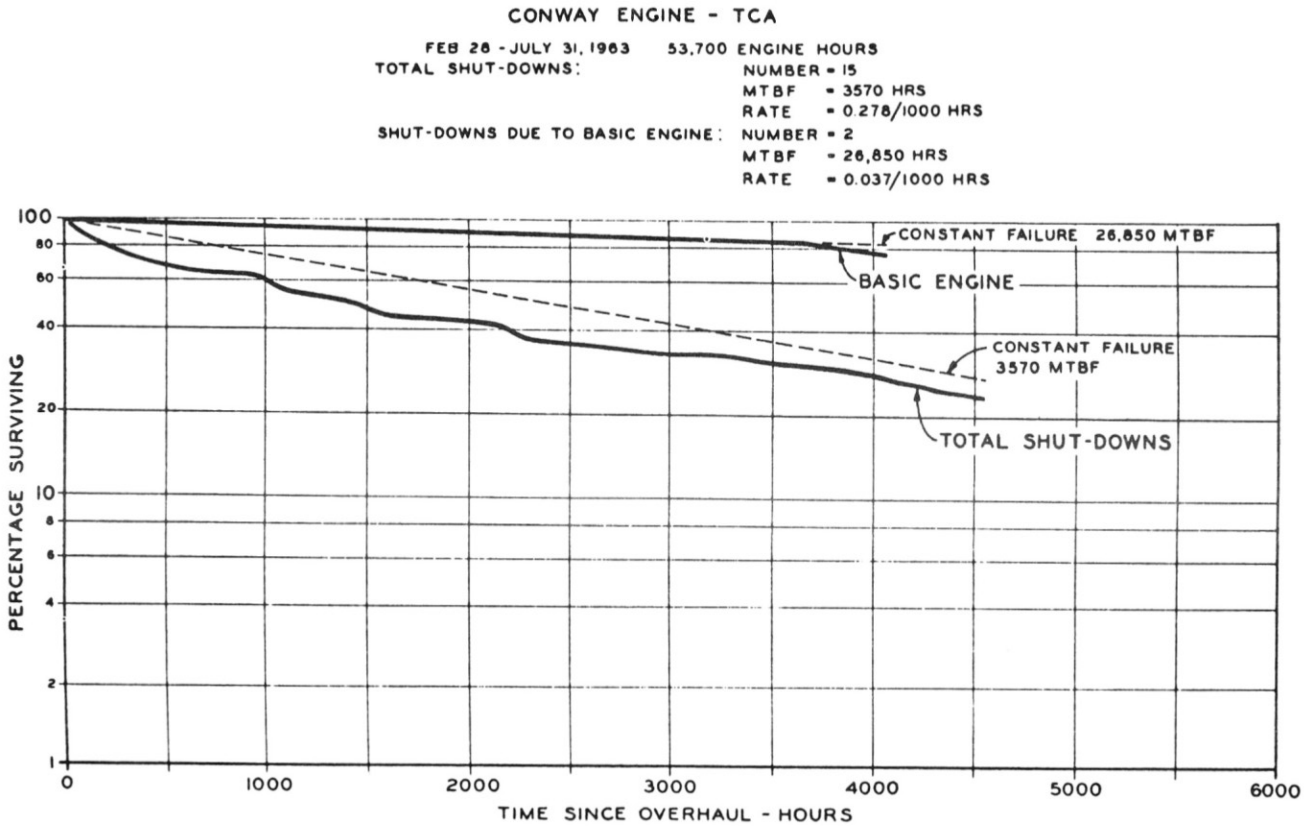


Figure 11*a*. Reliability function—in-flight shutdowns.

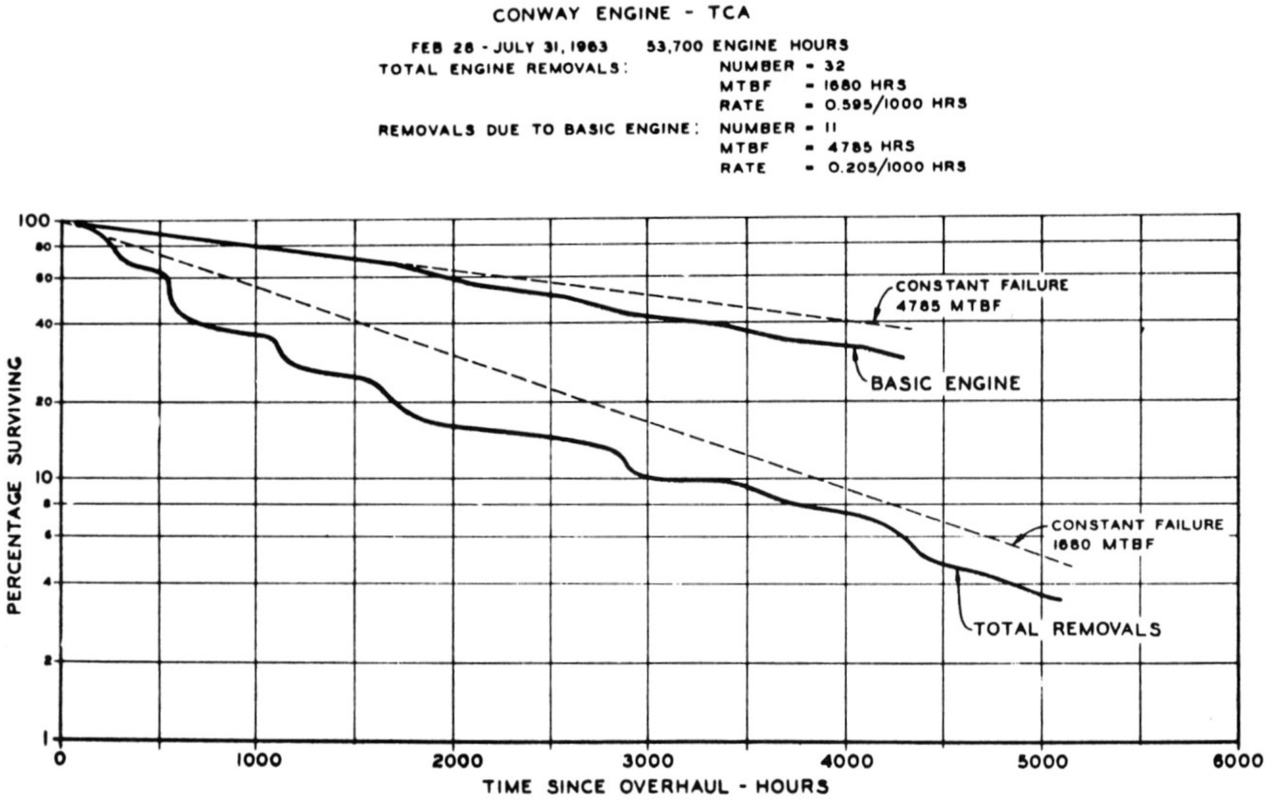


Figure 11*b*. Reliability function—unscheduled removals.

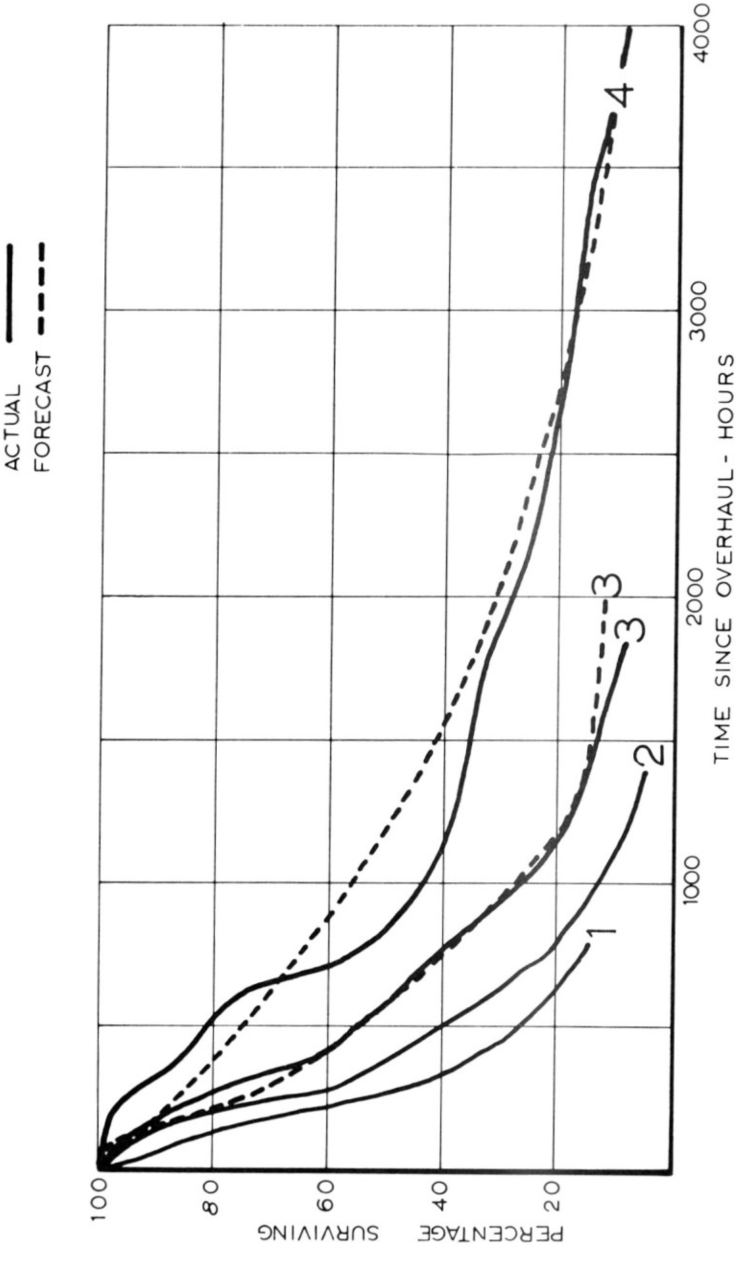


Figure 12. Conway engine unscheduled removals—actual and forecast.

the shop at a given time. Curve 1 shows the actual experience during the first six months of operation. Curve 2 shows the somewhat improved experience during the next six months. At that time a forecast, taking into account the expected availability of modifications—and the expected rate of incorporation, was made for the next six months.

This forecast is shown as the broken line 3. The actual results of this pattern come extremely close to the forecast as shown by the solid line 3. At the end of period 3 a forecast was made for period 4, and again was realistic.

The method can be applied to all parts, units or systems of an aircraft. Forecasting has its inherent problems but this rational method of approach can undoubtedly, with repeated use and experience, give good results.

EXAMPLE 8

Assessing the effectiveness of modifications is an important aspect of equipment operation. It is important to know as soon as possible to what degree the modification has been effective, if at all.

Figure 13 shows the development of a unit in which a needle bearing was failing. Initially 80 per cent of the units would have failed for this cause by 1,000 hours. Following a design analysis and development running by the manufacturer, a modification was introduced which was supposed to prevent these failures. Looking at the operation an improvement was felt, but when the available data was plotted it was seen that no improvement had in fact occurred. Whereas Curve 1 represents over 30 failures, Curve 2 was drawn following 10 failures, and illustrates that proper use of even limited experience can lead to sound conclusions.

As a result of seeing that no improvement had resulted, further work was undertaken leading to a new modification. Curve 3 shows that instead of 80 per cent, 40 per cent of the units would now be expected to fail by 1,000 hours. Although the results were disappointing it showed that the modification was in the right direction. Further refinements to the modification have produced an operation where less than 10 per cent of the units would be expected to fail by 1,000 hours, and with the knowledge gained further refinements should now eliminate the failures.

Apart from providing a check on the effectiveness of the modifications, this method of presentation can also be used to forecast the probable failures at different times since overhaul for a fleet with mixed modification standards, and appropriate action can be taken. In this case, for example, a decision to limit the risk to 20 per cent failures, a life limitation of 500 hours would be required on Standards 1 and 2, 750 hours on Standard 3, and over 1,500 hours on Standard 4.

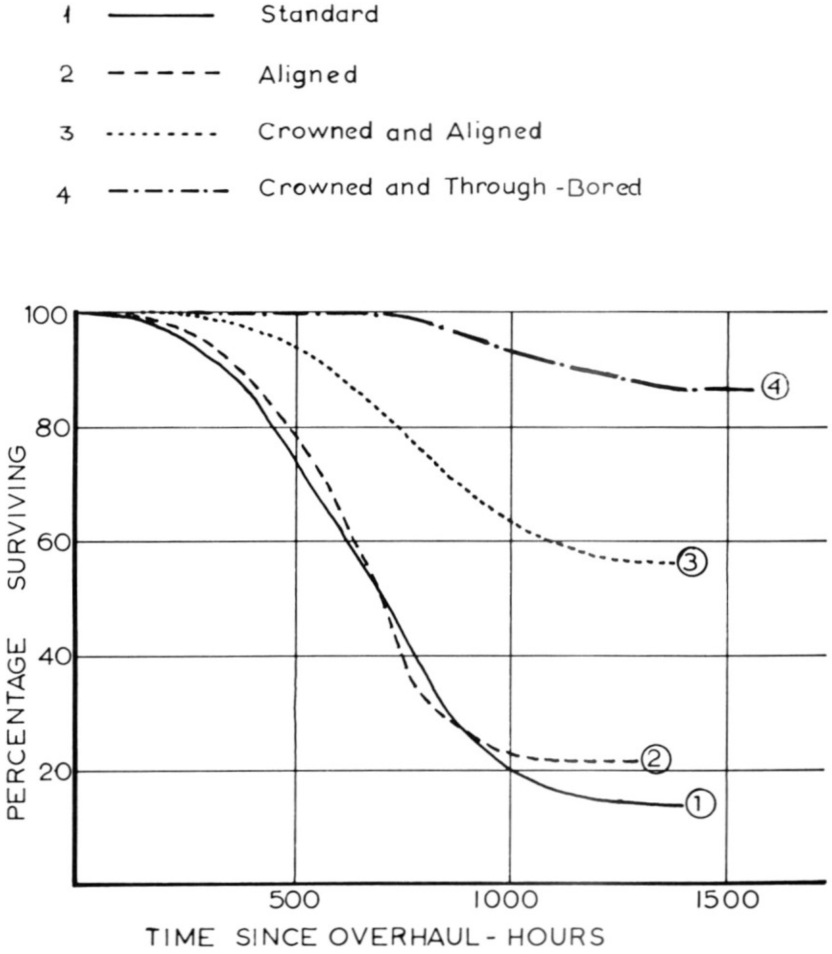


Figure 13. Propeller control unit.

EXAMPLE 9

The material cost of the engine for every hour flown is generally about equal to the material cost of all the units on the aircraft. Figure 14 shows the material cost distribution for all aircraft units representing an input of about 14,000 units. The cumulative percentage of total cost contributed by the various types of units has been plotted. This shows that the most expensive unit type contributed about 15 per cent of the total cost, the two most expensive unit types cumulatively contributed 20 per cent, etc.

Firstly, it will be seen that placed on semilogarithmic paper the distribution of unit costs shows a clear exponential pattern, giving results that fall amazingly close to a straight line. It can be concluded that as long as this relationship holds it would be sufficient to accurately establish the cumulative percentage of the first three or four most expensive units, and then by extrapolation conclude how many units represent, for example, 80 per cent of the cost.

Secondly, it is seen that the first ten types of highest cost units accounted for 55 per cent of the total material expenditure on all units, that the first forty types of most expensive units accounted for 80 per cent, and that one hundred types of units accounted for 95 per cent, leaving 676 unit types accounting for the remaining 5 per cent of the material cost.

These observations are generally found to apply not only to different types of units, but also to the material cost distribution of parts within assemblies. It is felt that such observations can be put to good use in forecasting, as well as the general field of performance and cost control, and more work in this area is required.

EXAMPLE 10

In the operation of two modern aircraft it has been observed that five or six units were removed unscheduled per aircraft hour. This represented a shop input of about 14,000 units during a one-year operation of this fleet. Out of these a total of 4,800 units or 33 per cent were declared serviceable during the subsequent shop inspection, and were therefore defined as unsubstantiated removals as shown in Fig. 15.

Classifying the units by systems, Fig. 16 shows that the areas of communications, navigation and autopilot produce the largest number of unit removals, and also have the highest percentage of unsubstantiated removals. The responsibility of unsubstantiated removals can be very easily placed on the maintenance man's shoulders, however,the true prime cause is a lack of design recognition of system checkout. If the designer gave due consideration to these problems at the initial design stage, and

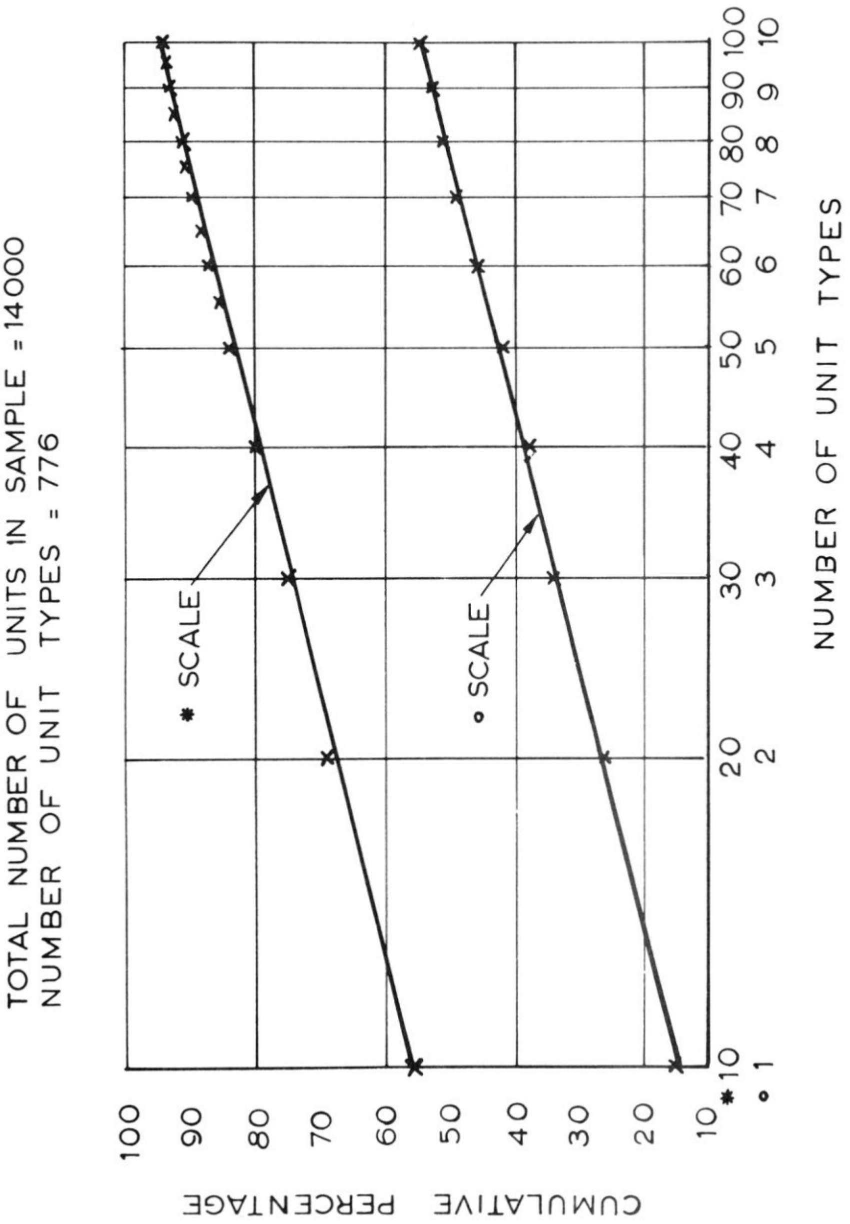


Figure 14. Material cost of accessory units.

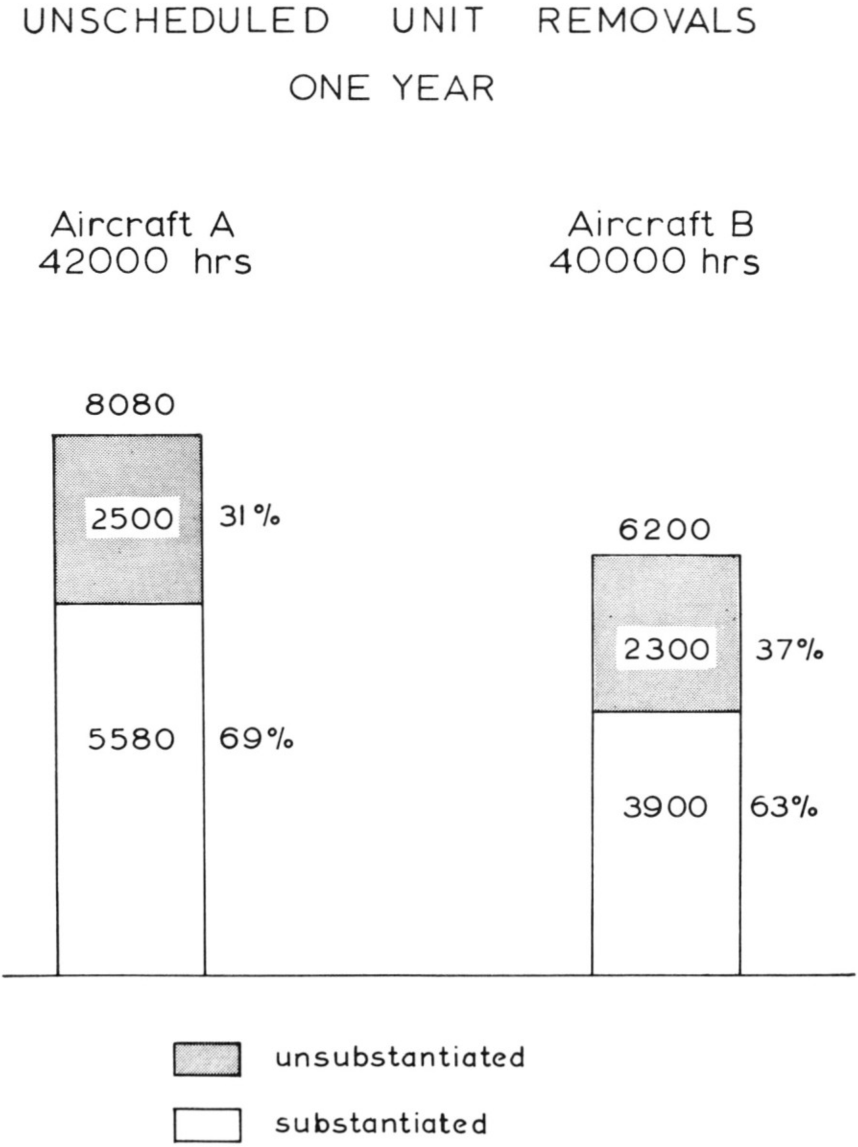


Figure 15. Unscheduled unit removals—one year.

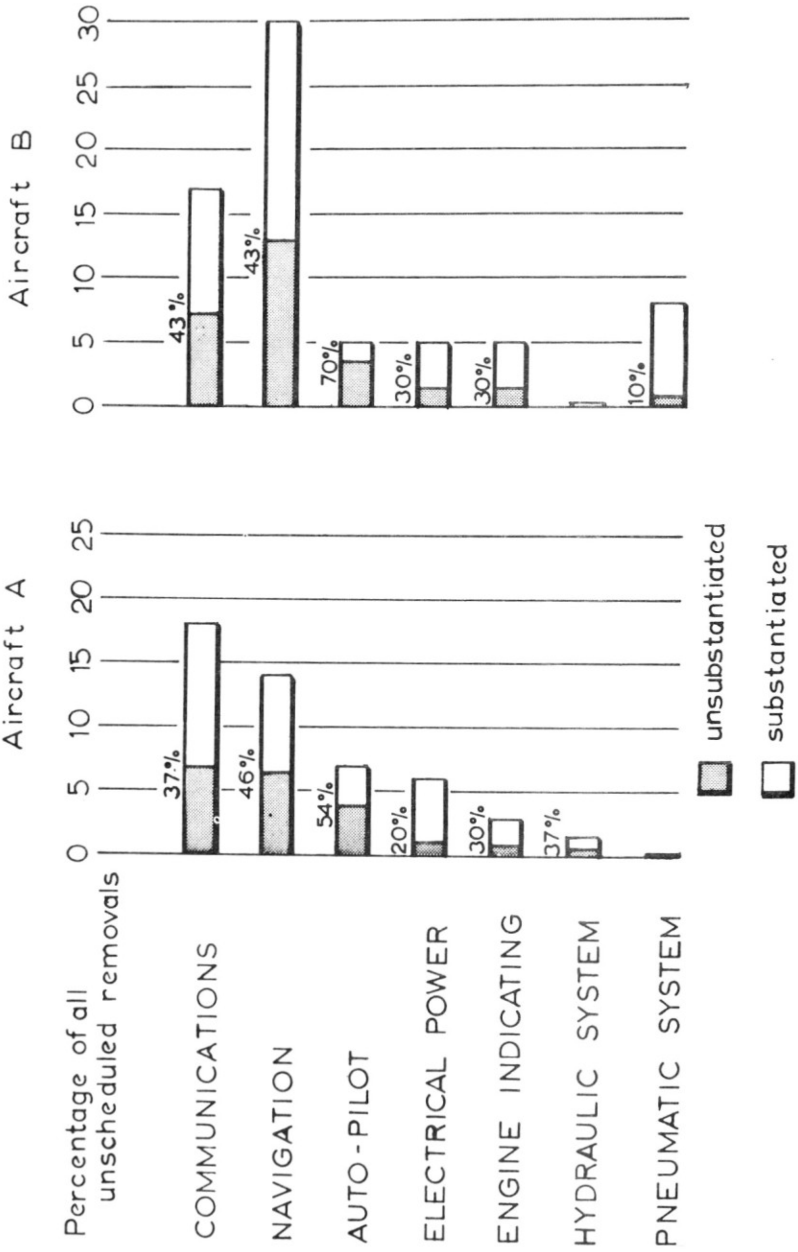


Figure 16. Unsubstantiated unit removals.

if the question of checkout, including the necessary recording and testing equipment, was an inherent part of the design, these efforts would be reflected in an immediate reduction of about one-third of all unit removals.

EXAMPLE 11

If sufficient data are available they can be used to make economic assessments of the required action. Figure 17 illustrates the case of component repair. A cost of X, as well as $2X$, has been used to illustrate that depending on the cost of a component and the relation between prime cost, repair cost and labour cost, different action should be taken.

To assess the economics of repair of this component, good information on the percentage of components falling into categories of serviceable, repairable, scrap, and scrapped during the repair process is required. Good information on the life expectancy under different inspection cycles is also needed.

Where such information is only available to the operator from his own operation he is limited to the size of his own sample. If this information was collected from all the units in operation, with all operators, better answers would be available much sooner.

In this example, the curves of cost of operation per hour show that in the case of the more expensive vane a repair cycle would produce savings. In the case of the less expensive vane, running the vanes as long as possible without repair, and then scrapping them would give the best results.

EXAMPLE 12

The effect of available test equipment to check out aircraft systems is illustrated in Fig. 18. In this case, a complicated and troublesome propeller synchrophasing system was the cause of a large number of pilot reports. The effects of bad synchrophasing showed themselves in flight by a high noise level which can not be checked during ground maintenance work. The requirement of system test equipment was not considered during the design stages, and no equipment was available at the start of operation.

A long period of operational flying in service took place before a test rig was designed. Figure 18 shows that following the introduction of this hanger test rig, system malfunctions as reported by pilots rapidly halved.

At the same time the number of unit removals, most of which had been found unsubstantiated, was drastically reduced: positive proof that checkout and testing of units and systems must be a continuous design consideration.

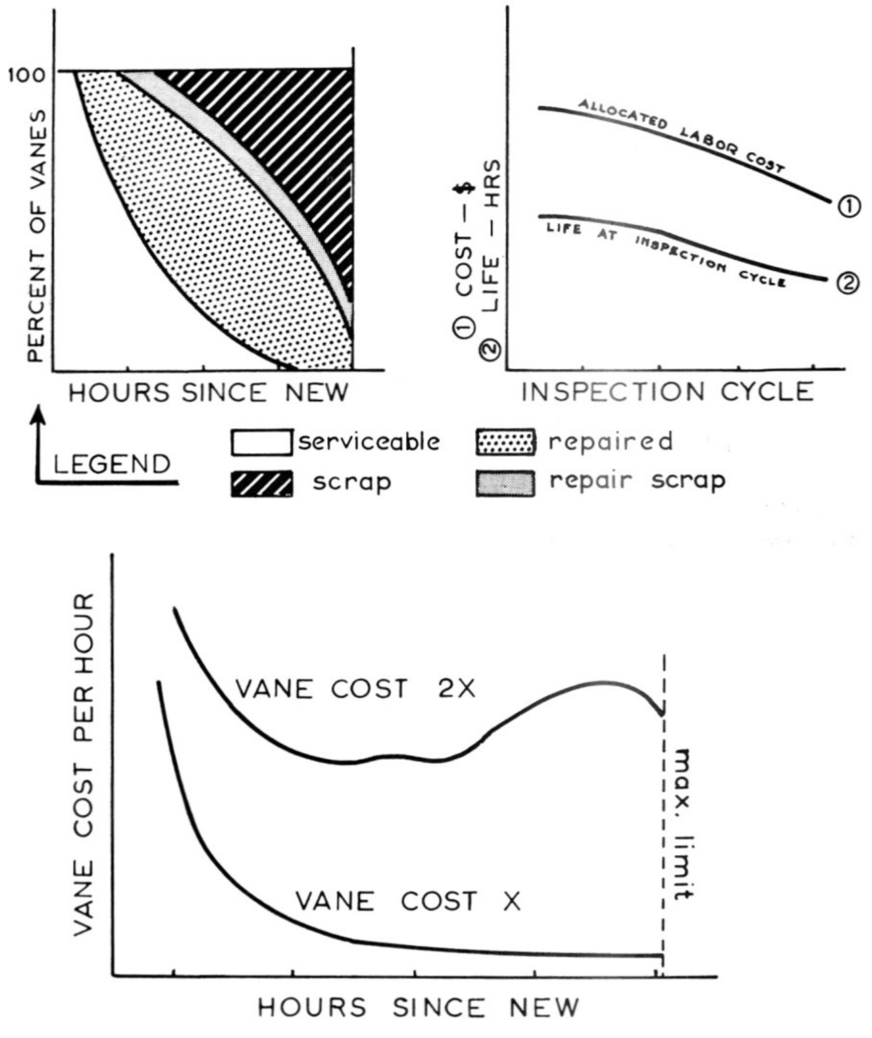


Figure 17. Economics of repair.

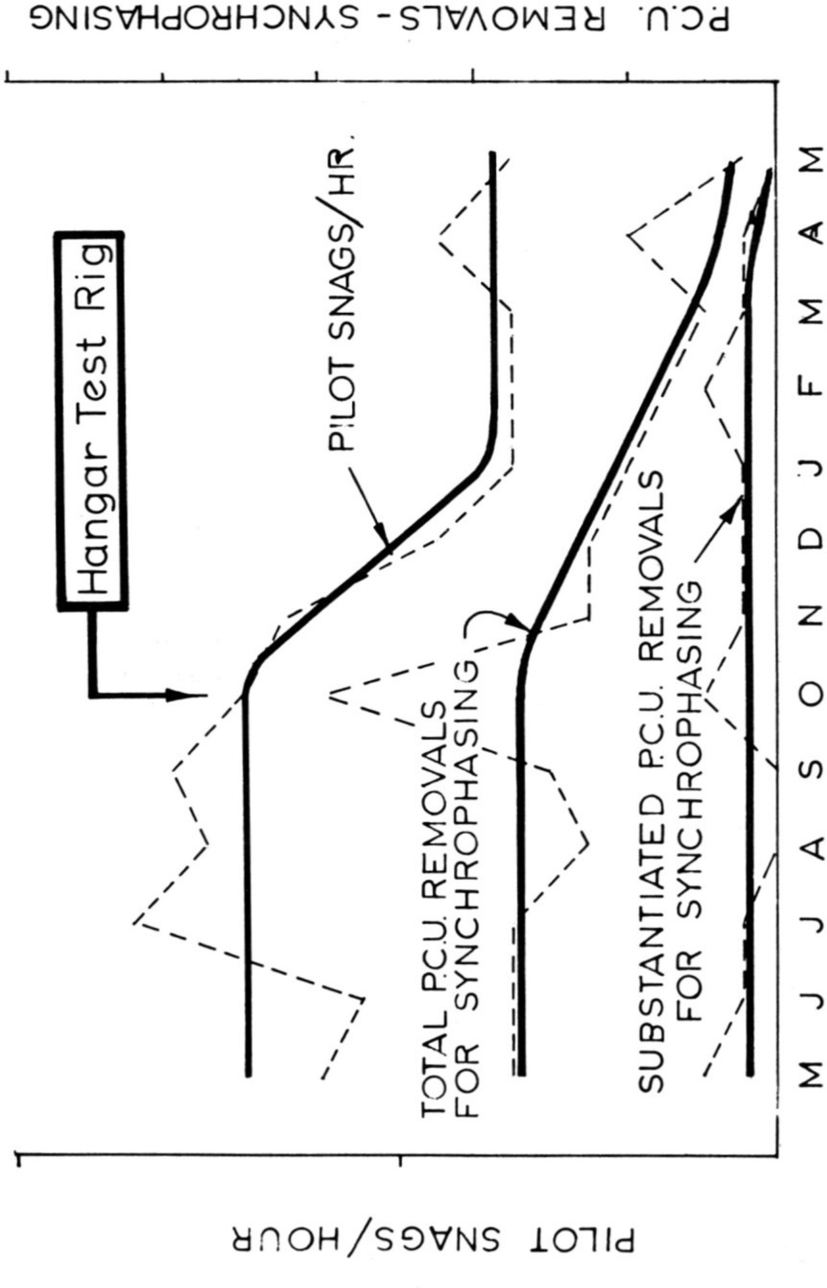


Figure 18. System checkout/synchrophasing.

EXAMPLE 13

A detailed failure analysis should be performed by the manufacturer as design and development proceeds. This failure analysis should pinpoint the areas requiring further design improvement and development running. In conjunction with the inherent design capabilities the designer has to ask himself how the failure of the part, or the system, would be detected at an early stage. There is a great difference in operation between being prewarned of a failure, as compared to only knowing when the full extent of the failure actually occurs. The level of early available failure detection directly influences the standard of operational delay, and also has a great effect on material cost. A number of modern techniques are available such as X-ray, better detection of metal in fluid systems, vibration monitoring, and automatic recording.

Figure 19*a* shows an X-ray picture of a flame tube which was found to be cracked. This picture was taken without taking the engine out of the aircraft. Figure 19*b* shows an X-ray picture of a serviceable flame tube. The method of X-ray of these flame tubes had to be developed by the operator. The question of early detection of flame-tube failure had not been considered by the manufacturer during the design of the engine. If this aspect had been considered, much better accessibility would have been provided. With proof of the effectiveness of X-raying now available, manufacturers should design with X-raying of certain inaccessible components in mind. An engine should have had an X-ray survey made, from front to back, during the development stage to determine which areas and what types of failures lend themselves to this technique. If necessary redesigns should be made to permit detection to take place.

Figures 20*a* and *b* show metal particles collected on magnetic plugs in the oil system, and the corresponding incipient bearing failures. Again the method of particle detection in fluid systems should be an inherent part of the design and development of the components and systems.

The above are only examples of two specific techniques of early detection. The greatest contribution at this stage, in this field, would come from a systematic analysis of the detection ability of each given design.

The following formula provides an approach to such a systematic study.

$$\boxed{P_{OF} = p_F\,(1 - P_{ED})}$$

where P_{OF} = probability of operational failure
p_F = probability of component failure
P_{ED} = probability of Early Failure Detection (sufficiently early to avoid disruption to scheduled service)

Figure 19a.

Figure 19b.

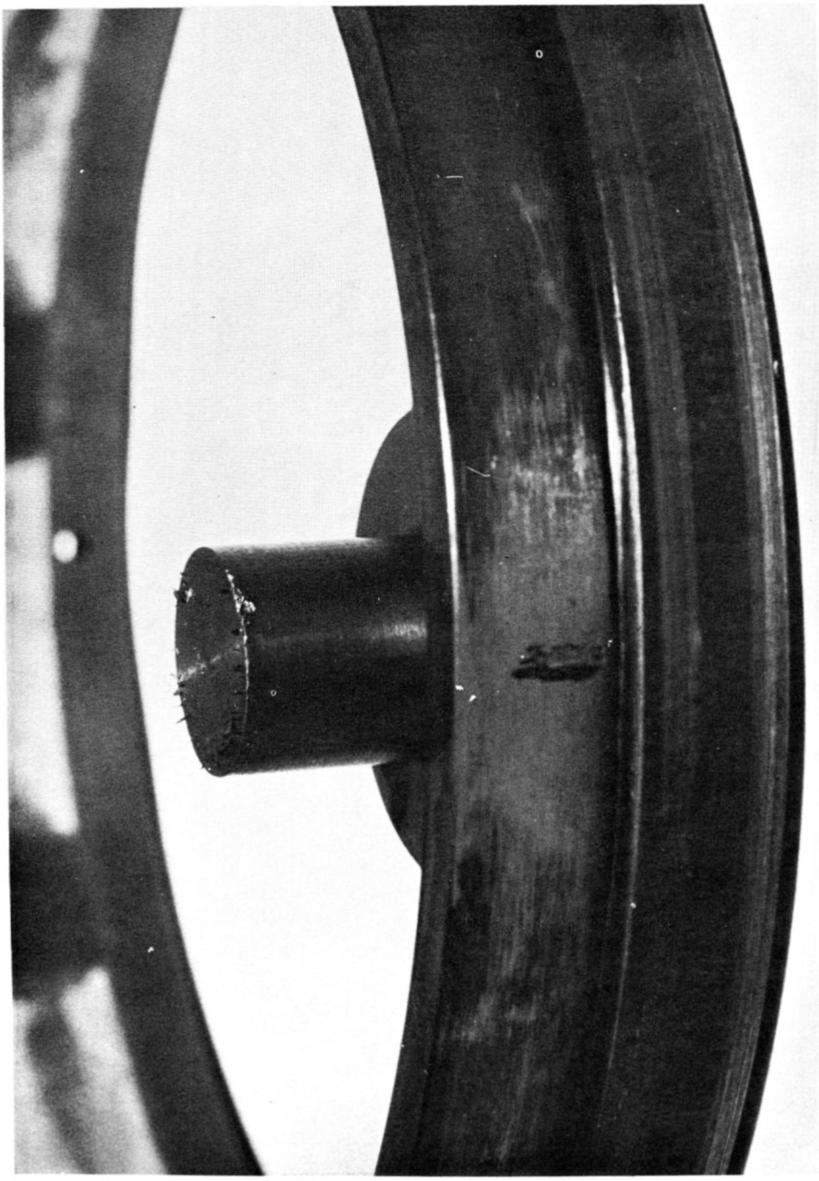


Figure 20*a*.

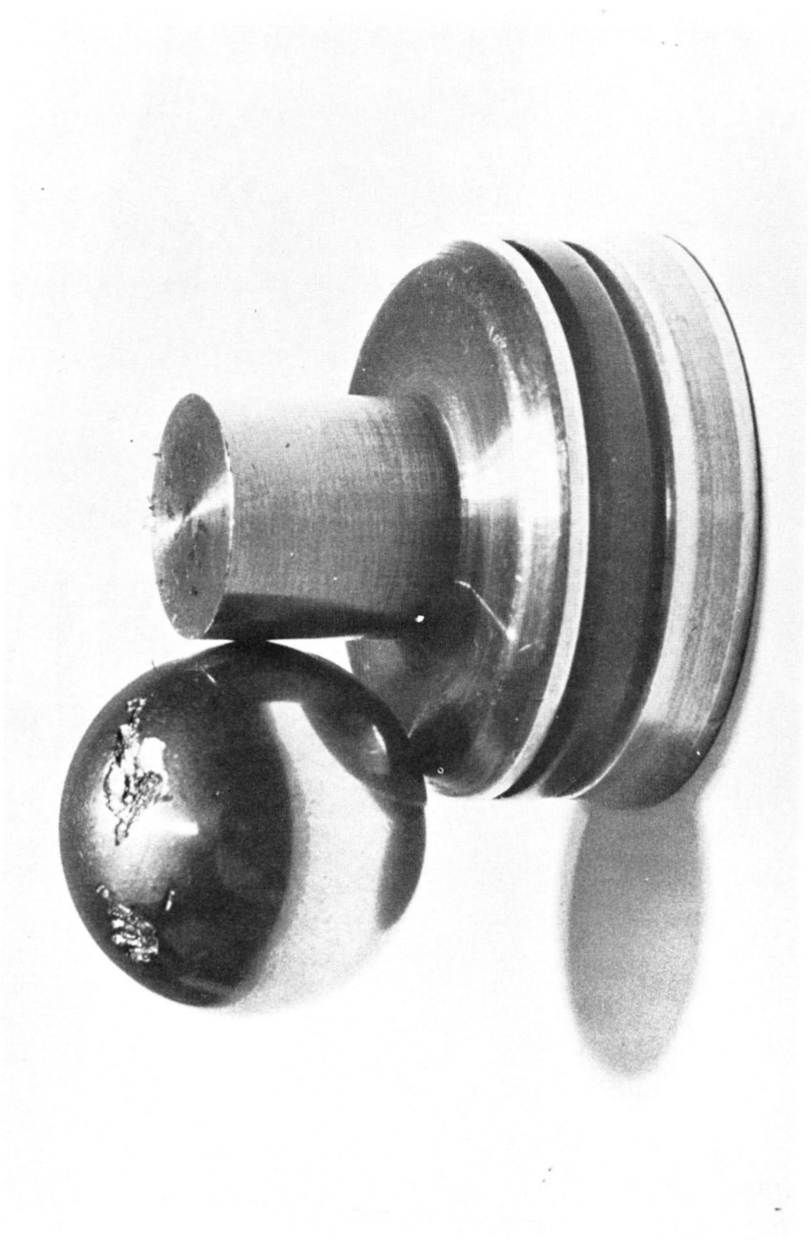
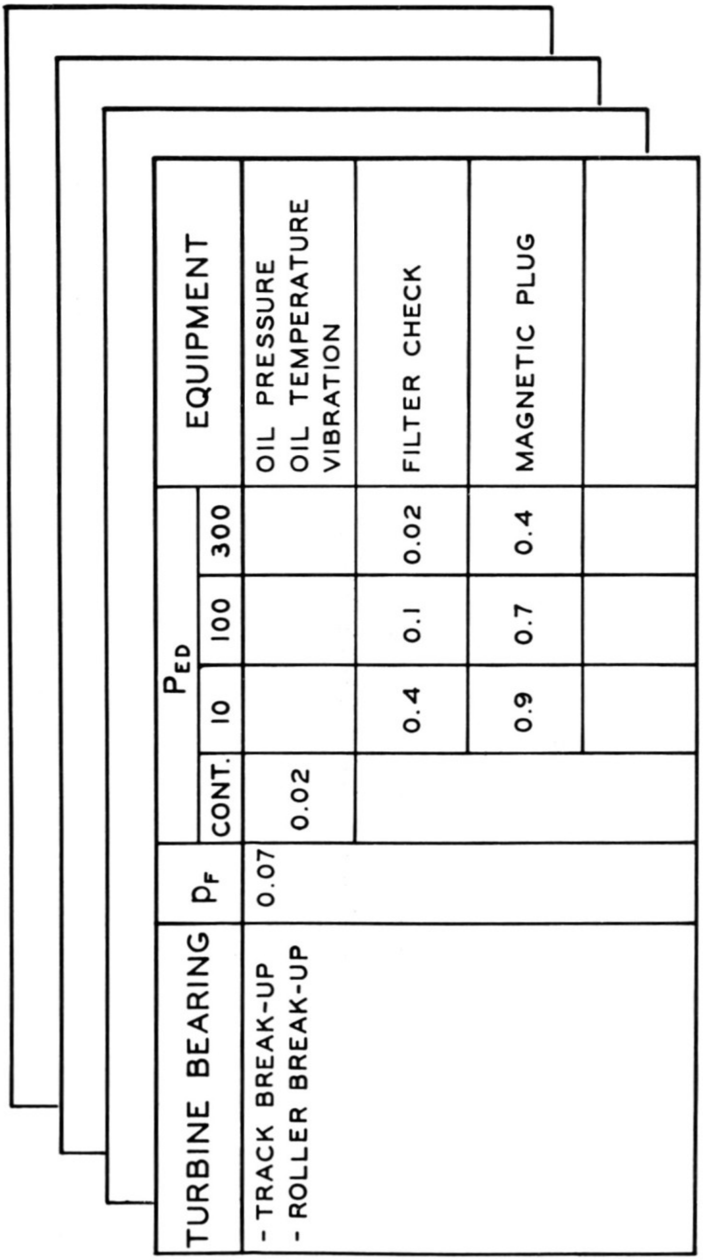


Figure 20b.



TURBINE BEARING	P_F	P_{ED}				EQUIPMENT
		CONT.	10	100	300	
- TRACK BREAK-UP - ROLLER BREAK-UP	0.07	0.02				OIL PRESSURE OIL TEMPERATURE VIBRATION
			0.4	0.1	0.02	FILTER CHECK
			0.9	0.7	0.4	MAGNETIC PLUG

Figure 21. EFD analysis.

The above formula shows that the probability of early detection in a refined design is as significant as the probability of failure, and must therefore receive equal consideration. Figure 21 illustrates the breakdown which could be used for a component and systems analysis. If performed soon enough during the design, this would again bring out those areas needing further attention at a time when changes can be easily implemented, and thus lead to a much better product than may be obtained by leaving these considerations to chance.

CONCLUSIONS

A number of examples gathered from operational experience have been given. Although these have been specific the problems, developments and techniques outlined apply equally to all the parts and systems of an aircraft. To grow and mature the Science of Equipment Usage has to be recognized as a field of activity and endeavour which offers to give great direct return. Concentrated education of scientists and engineers is required to give a number of individuals the specialized background required, and both manufacturing and airline organizations have to be changed and refined to provide better and earlier application of these rewarding functions.

As a result of the many breakthroughs in the technologies of aircraft design, development and manufacture, fifty years of air transportation have shrunk the world, helping to bridge many gulfs and cement many relations. In its ardent desire to be the pioneer in the field of human progress and understanding the young airline industry perhaps ran a little before it could walk.

By developing and using the Science of Equipment Usage in the Design, Development and Operation of Airline Equipment we shall strengthen the foundations of economic self-sufficiency on which every industry, to be truly healthy, has to be built.