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REVIEW PAPER

Quality Engineering in Aerospace Technologies - A Review

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ABSTRACT

Quality assurance and reliability have assumed paramount importance in aerospace technologies due to stringent requirement of weight-to-strength considerations and the need for highly reliable systems. The techniques of inspection and testing have given way to the use of sophisticated reliability engineering, failure mode effects & criticality analysis, design of experiments and total quality management concepts. The role of failure analysis to improve the quality on a continuous basis has been realised by all engaged in aerospace technologies. The number of simulation runs help to build up quality in design and development phase and obviate the need for extensive hardware testing. The techniques of metrology and nondestructive testing have been upgraded considerably during the last decade. Most of the manufacturing techniques, now being computer-aided, give consistent production and better quality.

1. INTRODUCTION

With the opening up of economy, the products and services conforming to global quality standards have started flowing freely into the country. Overseas goods designed, manufactured, marketed and sold using state-of-the-art quality practices are finding entry into India. European and American manufacturers are using tools of business process re-engineering, bench marking, etc in their operations to attain quality leadership. Indian companies have to evolve a formidable strategy to survive and grow in the wake of this severe competition[1].

In the context of aerospace, the quality function assumes even greater significance. There is no mechanism for rectification/replacement of defective parts in mid-space and hence it is imperative that an aircraft or a launch vehicle performs reliably as per the design. Secondly, the structural weight of the airborne system must be as low as possible, i.e., in engineering terms, materials of construction must have high strength-to-weight ratio and they must be used at levels close to their maximum capability. Alternatively, the margin of safety used in the design and the realisation of the system has to be as close to unity as possible. For example, a factor of safety as low as 1.15 on the yield strength or 1.5 on the ultimate strength is used

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in the design of vehicles launched into space. When compared with the factor of safety of 4 or more in engineering applications, the need for assuring quality and reliability from design to manufacture and testing can be appreciated[1].

Human activities and accomplishments have all along been driven by the insatiable thirst for excellence displayed over the generations. Aeronautics and aerospace sciences are no exception, though the levels of excellence aimed at might be much higher in view of the society's concerns about the consequences of imperfection in these fields. The assurance that the required level of perfection has been achieved is the prime objective of airworthiness and certification[2].

Though certification is the culmination of a series of analytical and validation activities, the essential ingredients are seeded right from conceptual stage, through the development, and the activity even spills over to the usage phase. The problems faced at each of these phases, ranging from technology issues to formal regulations and procedures, are taken note of. Management and control of airworthiness assurance and certification system are matters that get evolved over a period of time, and the experiences gained in our country over the last three decades are briefly touched upon here. The need for flexibility in approach to cater to the wide spectrum of activities ranging from indigenous development to ensure continued airworthiness of bought-out systems, is highlighted. The relevance of the initial experience with transferred technology continued updation of expertise and the need to sustain a motivated cadre capable of reacting to any difficult situation, are emphasised[2].

The experience over the years, during which the technology was constantly upgraded, is discussed from the airworthiness perspective. Pleasures and pains in evolving and meeting the requirements of digital fly-by-wire controls, composite structures, high temperature-capability materials, full authority digital engine (or electronic) control (FADECS) etc are delineated, indicating that the approach need to be specifically tailored, depending upon the merit of each case. The only essential ingredient for the successful development of an airworthy system is the harmony and transparency among the designers, the manufacturers, the users and the airworthiness certifying personnel[2].

2. FACTORS INFLUENCING QUALITY

The factors which influence the quality of engineering products are:

* Product volume influences quality inspection (QI)
* High component density *vs* defect rates
* Superior first-pass *vs* lower defect rates
* New organisational structure *vs* product improvement, and
* Improvement in one product *vs* quality assurance.

3. QUALITY ASSURANCE IN DESIGN

It is imperative that quality assurance is a paramount activity for any successful weapon system which is required to perform satisfactorily when deployed under adverse environmental conditions. Today, quality and technology go side by side in achieving product excellence. This, in turn, reminds that unless quality is concurrently engineered right from the conceptual stage, it would be impracticable to realise a satisfactory and cost-effective product. More so, in the multidisciplinary and complex systems like those of light combat aircraft (LCA), the task of building the quality becomes exceedingly complex and needs systematic and concerted efforts[3] (Fig. 1).

4. DESIGN & QUALIFICATION AUDIT

Qualification audit in design assesses the effectiveness of implementation of the quality system and determines the degree upto which the system objectives are being achieved. The audit is system-oriented rather than product-oriented. It is not explicitly hardware-oriented, except where the hardware may contribute to the assessment of the overall system[4].

Design auditing is a major area of total quality management (TQM) and should take place according to a thoroughly structured programme which includes all key activities of designing.

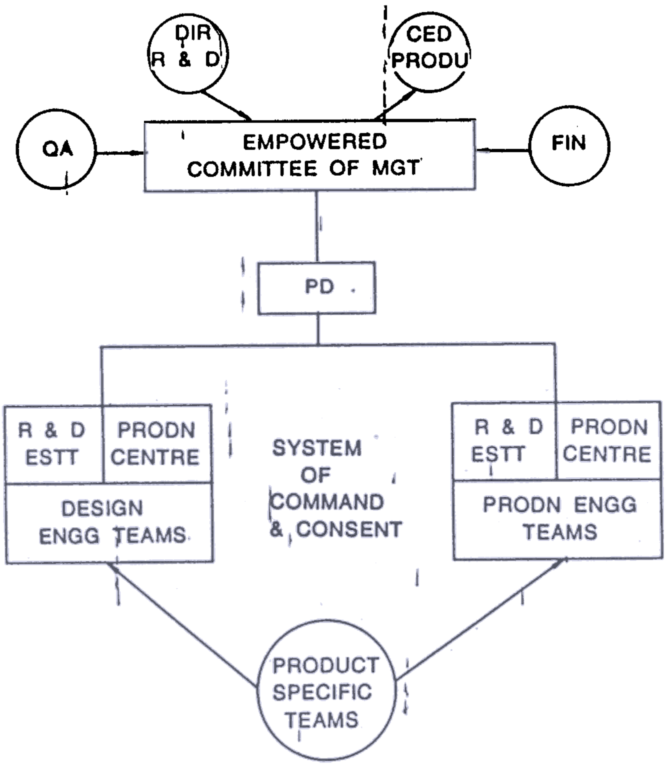

Figure 1. Structuring the process of mutual adjustment design bureau concept.

Audit reports are formally documented and reported to top management and all key individuals and groups. Areas, especially of implementation weaknesses, are thoroughly identified, corrective action steps are established and improvement responsibilities proposed. Follow-up audit in necessary areas is an integral part of the system audit programme to ensure that necessary improvements have taken place.

It is important that qualification audit examines only a small proportion of the work being done, so that it cannot be treated as an executive function. Work examined should be looked at, in-depth, but the sample should be kept small. For example, only a small number of drawings for a particular design should be audited thoroughly. Dr Juran's 'Pareto' principle - to concentrate on the vital few and discount the trivial many - is of particular importance here. Therefore, the auditor needs to exercise considerable skill, judgement and understanding of the organisation in selecting areas for audit.

Use of computers in quality audit of design could result in quicker checks of vital areas, especially of calculations. An approach to audit linked to computer-aided design (CAD) and computer-aided manufacturing (CAM) would result in an automated sequence (Fig. 2). Standardisation of design could be verified through audit checks. This would result in time and cost savings. Finally, it must be very clear that the aim of qualification audit in design is not to curb the talents of initiative of designers. The aim is to set a boundry around any design so that inputs and outputs are controlled. Such a control leads to better designs which in turn ensures that the product designed meets the users requirements during its entire service life.

5. QUALIFICATION OF AEROSPACE MATERIALS

Sea-change in design philosophy for aircraft and space vehicles resulted in increasing demands of extreme quality materials with integrity, and low scatter in short-term and long-term (both static and dynamic) properties. Further, lower but just adequate factor of safety used for aerospace component design pushed material engineers and technologists to have utmost chemistry control and use highly sophisticated manufacturing and processing equipment. Materials so produced have specific advantages over general engineering materials obtained employing similar alloy chemistry. This gave rise to separate series of specifications for aerospace materials.

Current aerospace materials are superior[5] in their environmental capabilities, higher resistance to low cycle fatigue, greater fracture toughness and slower crack growth with minimum scatter as compared to their counterparts used for general engineering applications. These improvements resulted in reliability of crack detection intime, for corrective measures, essential in 'fail safe' and 'damage tolerant' designs adopted for aircraft and aeroengines. Whereas, acceptance of material for infinite life design criteria adopted for general engineering product continues to be based on

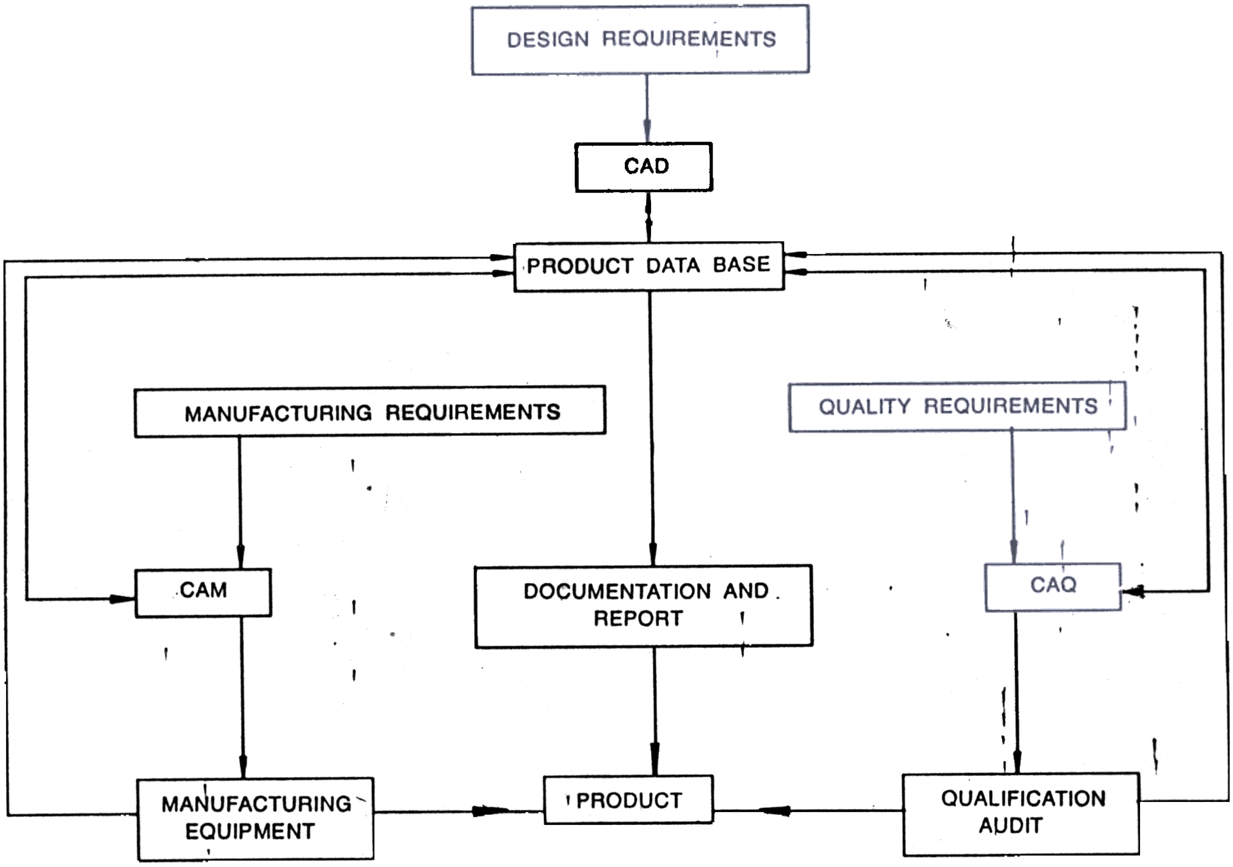

Figure 2. Design requirements

tensile property, and rejection of non-compliance comes only at the final stage. For the aerospace materials, during regular production, existing company/national specifications are the only checkpoints for procurement from already approved source.

Approval of source for aerospace material manufacturer is first assessed through quality audit. Subsequent type evaluation of each material/product is carried out by evaluating zero time. Material manufacturer, on satisfactory completion of evaluation, gets a certificate for the type developed (type certification). Adoption of the same route for series production of material/product is mandatory. No deviation in any parameter, that may significantly affect the product, is allowed. In addition, trace element control is also ensured by using raw materials from the same source. Periodic checks on the suppliers are conducted to avoid possible deterioration in quality. These controls and their mandatory compliance result in low property scatter and consistent response in service.

Based on change in design philosophy of aerospace vehicles, all the leading countries have adopted separate series of aerospace specifications. Usage of other specifications is mostly based on specific approvals. This provides better control on material properties and overall weight. Further, aerospace specifications are only for acceptance of materials during series production from approved sources. The approval results in usage of fixed sources of the material and fixed route of production.

The use of engineering materials for class I and class II (grade A) components for aeronautical systems as a routine has serious repercussions due to high scatter in dynamic properties which also results in heavy weight penalty. Even for class III (grade B) components, if safety factors are applied in designing the components, the use of aeronautical alloy is preferred to avoid weight penalty. However, if design is such that component thickness and size are merely for regidity to maintain shape, the use of general engineering material is normally allowed.

6. FAILURE ANALYSIS

It is not always that we attain success; there have been some system failures. But the silver lining has been that we are able to learn from these failures for the benefit of posterity. The challenges before us are daunting, viz., airworthiness of aging aircraft and damage-tolerant designs, development of lifting policies for materials which are yet to be adequately characterised, diffusion of the airworthiness concepts into the vendor's systems, etc[2]

Failure-free service from an item is the sweet dream of every client. Failure is an event, or inoperable state, in which any item or part of an item does not, or would not, perform as previously specified. Failure-free service requires that the potential failures are fast located, analysed and fixed. This is achieved through failure analysis, which is a logical and systematic examination of an item for identifying the failure mechanism and its course. Failure mode refers to the manner by which a failure is observed. Failure mechanism refers to a physical, chemical, electrical, thermal or other process which results in failure. Ascertaining failure mechanism and the course of failure mode often requires experimentation and forms a part of failure analysis. The basic purpose of the failure analysis is the isolation of the root cause which ultimately helps in developing an improvement plan.

Failure analysis is to be carried out during the entire life cycle of an item, particularly the early phases. Hence, it is expedient that the process of failure analysis be structured. Fig. 3 shows a failure analysis spiral[6].

As per Advisory Group on Reliability in Electronic Equipment (AGREE), product reliability is the probability of a product performing its intended function over its intended life and under the operating conditions encountered. Thus, it is associated with four facets, namely, probability, performance, life (time of

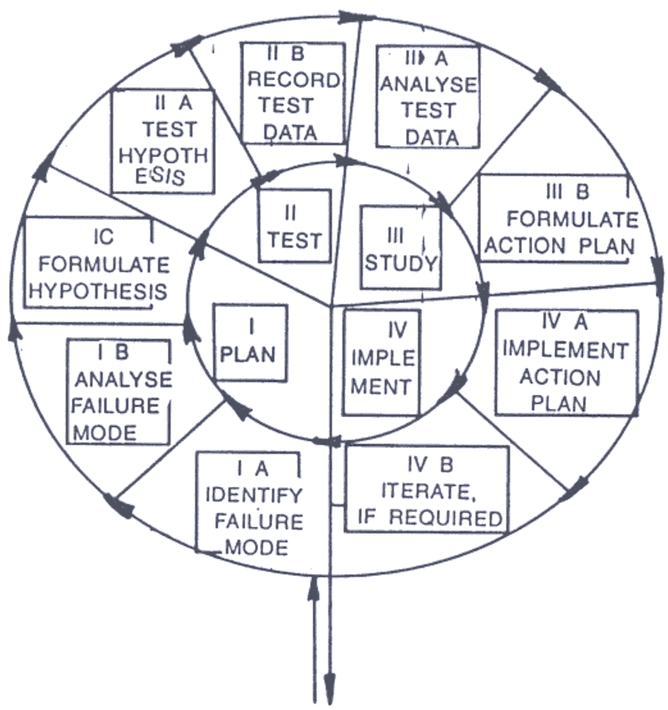

Figure 3. Failure analysis spiral.

operation) and operating conditions (environment). While reliability is the measure of quality in time domain, the term defect relates to item not conforming to the requirements of specification. Thus reliability may be associated with design assurance, while defects are the revelation of manufacturer's quality assurance.

Inspite of the best efforts towards ensuring reliable quality during design, production and maintenance of the aircraft, defects do occur resulting in premature withdrawal of components. These defects could be due to environment and operational factors, cumulative effects of tolerances during manufacturing, chemical actions during the ignition of fuel oil used, etc. To avoid recurrence of such defects, the prematurely withdrawn items are thoroughly investigated to identify the causes and based on that suitable recommendations are made to avoid recurrence of these defects[7]. Figure 4 shows a scheme for defect investigation.

7. QUALITY IMPROVEMENT THROUGH PREVENTIVE ACTION

The old saying 'prevention is better than cure' is virtually applicable to all such types of organisations even today. Generally, the time and cost aspects of assessing the non-conformances are of very high order. Thus non-conformances must be prevented every time.

In most of the organisations, maximum efforts are generally put in to eliminate the existing causes of non-conformity through the corrective action system to prevent their recurrence. Mr. Philip Crosy, a distinguished quality expert has said: 'Quality must be achieved by prevention rather than detection'. Hence, preventive action is more important to eliminate the causes of potential non-conformity and to prevent their occurrence in future. Certain international standards on 'quality systems' like ISO 9001, 9002 and 9003 also specify this requirement as one of the most important requirements[8]. Figure 5 depicts the preventive action system followed at the Defence Research & Development Laboratory (DRDL).

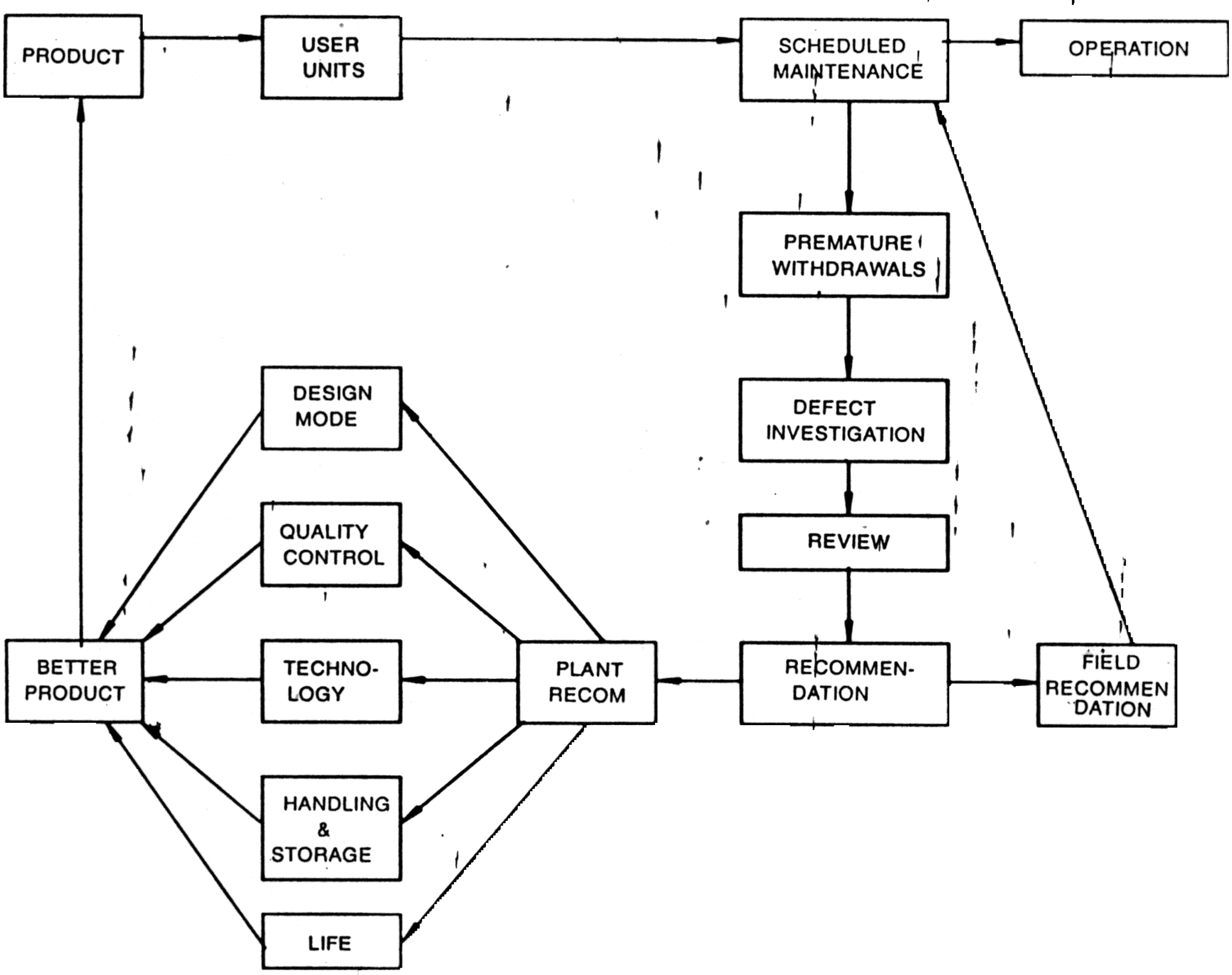

Figure 4. Scheme for defect investigation

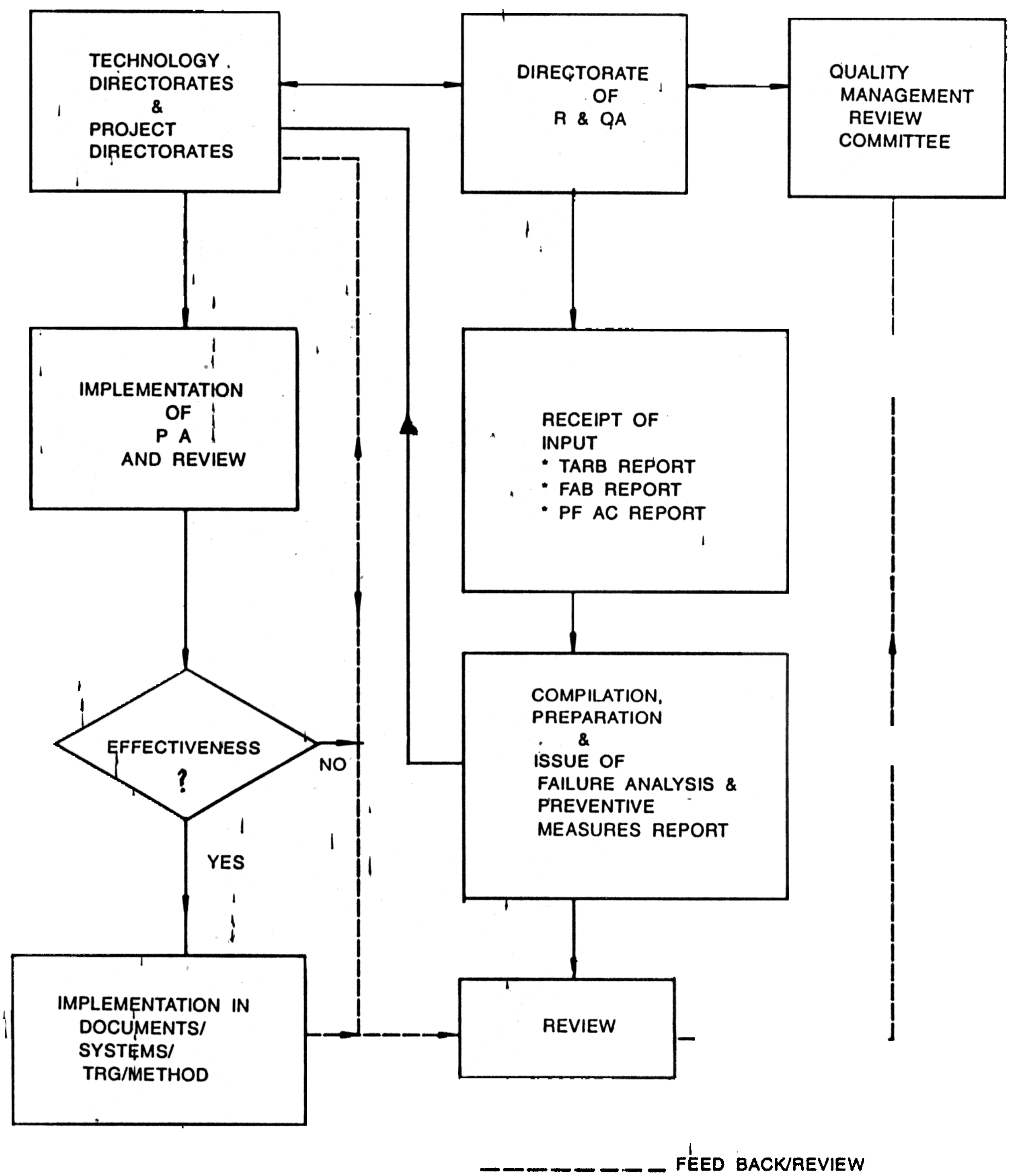

Figure 5. Preventive action system of DRDL

8. FAILURES - HIDDEN TREASURES FOR ACHIEVING TECHNOLOGICAL EXCELLENCE

Failures may be considered as hidden treasures for achieving technological excellence and give an opportunity to learn and update knowledge. Failure may be due to stringent user's requirement or mission requirement. Development is a learning process. Professional enrichment by learning from second Agni test failure was many times more than the first test success. The failure enables the designer to modify the design of the system with the help of design of experiments, collection of appropriate data, interpretation of the data and validation of the result. Secondly, failure is never final. Multidisciplinary, multicentred hi-tech R&D project with uncertainty and ambiguity mix cannot only recover from failure, but can also lead to technological excellence. Failure, at any stage, is a manifestation of quality deficiency[9].

9. RELIABILITY IN AEROSPACE SYSTEMS

Airworthiness management has always realised the need for being dynamic. But 'being dynamic' cannot be construed as losing the sense of priority or direction. Changes in the approach have to be controlled with caution, if the results are not to be catastrophic. The global experience on spurious aircraft general spare parts flooding the markets and Federal Aviation Administration's rethinking on the system of 'Designated Airworthiness Representative' cannot be totally ignored. The significant impact of limited development maturity, lack of inherent system-strength in terms of checks and balances and the cultural ethos on the success, or otherwise, of a dilute technical audit system, needs to be recognised. The fact that failures will not be limited to just hardware, but could also result in shattering the society's confidence in the aerospace endeavours of the country, cannot be lost sight of. Finally, the integrity of 'people-ware' is as significant as hardware integrity or software reliability. In view of the benefits to one and all, the cooperation of all agencies is solicited in ensuring a competent, pro-active and vigilant airworthiness assurance system[2].

With the increasing complexity and automation of systems, reliability has become inextricably linked to all major phases of the genesis and use of commercial, military and space systems and at all levels of design, development, procurement, production, operation and maintenance. An evaluation of system reliability therefore becomes essential to decide whether a system will accomplish its mission successfully[10].

10. RELIABILITY ENGINEERING FOR ELECTRONICS

It is conventional wisdom in defence systems that electronic brains are engaged where much of the present and future weapon system capability is being developed. Electronic hardware advances, particularly in microprocessors, allow highly complex and sophisticated software to provide a high degree of system autonomy, and customisation to mission at hand. Since modern military systems are dependent on the proper functioning of the electronics, the quality and reliability of electronic hardware[11] and software have a profound impact on defensive capability and readiness (Figs 6 and 7). At the hardware level, due to the advances in the microelectronics field, functional capabilities of today's systems have increased. The advances in the hardware have an impact on software also. Nowadays we are able to implement more and more system functions through software rather than going for a pure hardware solution. On the other hand, complexities of the systems are increasing, working energy levels of the systems

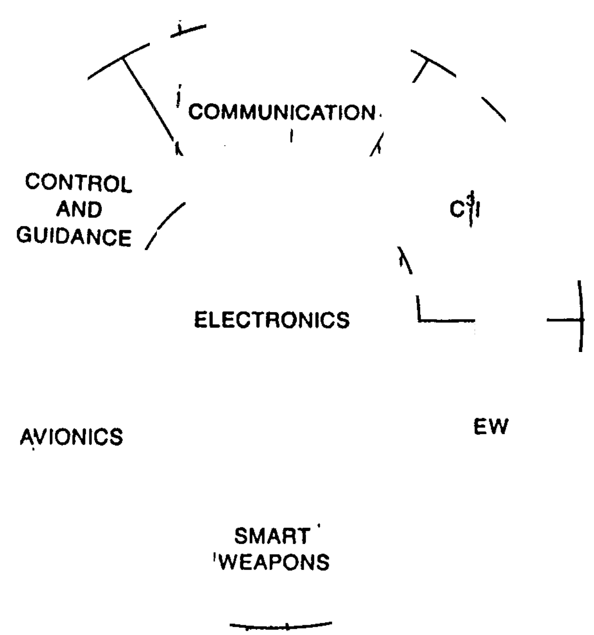

Figure 6. Use of electronics

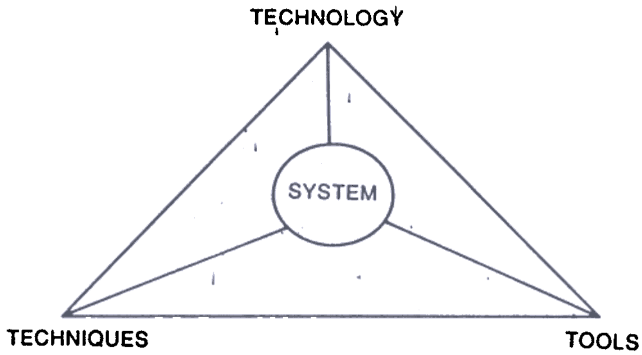

Figure 7. Technological loop

are decreasing and areas of reliability and quality assurance are becoming wider. The test strategy will vary widely from product to product depending upon the system requirements. Also, in an ideal environment, test engineer works side by side with design engineers, software programmers, and hardware design engineers. This permits test features to be incorporated at the time of implementation rather than adding components later that affect other system features[12]

The statistical quality control techniques are useful in monitoring the process behaviour. Attribute control charts are widely used in process control. The selection of sample size, sampling interval and control width of the control chart are important in minimising the 'quality' costs. The control chart parameters like 3σ, control limits and fixed fraction sampling at conveniently selected sampling intervals result in deplorable cost penalties in quality control. The best selection of these parameters depends on several process parameters like frequency of occurrence of a shift in the process, cost of sampling, cost of investigation for finding assignable causes, probability of false alarms, penalty cost of defectives and process correction costs[13]

System reliability[10] is desired both in terms of hardware and software (Fig. 8). A false alarm or an unnoticed problem can cause a massive failure in different perspectives. The source of failure in software is the design faults, while the principal source in hardware has generally been physical deterioration. Once a software (design) defect is properly fixed, it is in general fixed for all times to come, except when the system is exposed to some unforeseen environment which was not tested or developed for. The probability of hardware failure due to wear and other physical causes has usually been much greater than the one due to an unrecognised design problem. Thus hardware reliability has a specific pattern and can be increased or altered with the use of definite redundancy. On the other hand, software reliability is due to the inherent faults that are not visible and are very difficult to assess. Moreover, it also changes or improves the process of development and maintenance. Thus hardware and software reliability follow inverse logic[14]

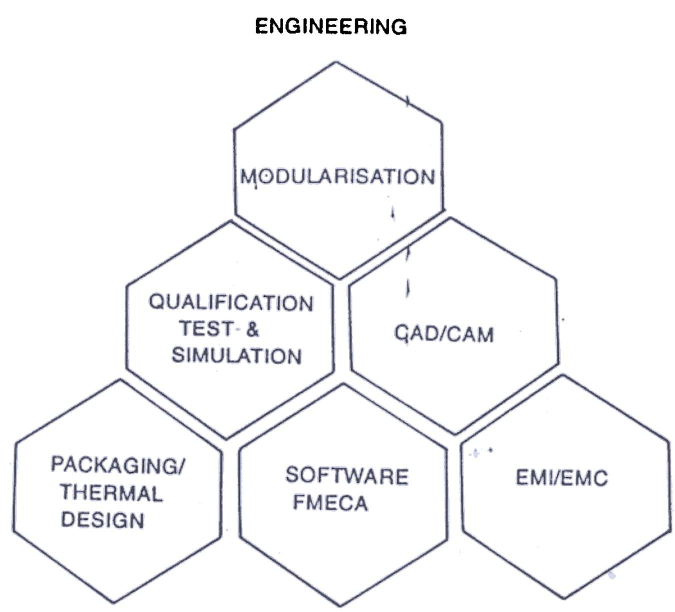

Figure 8. Role of engineering in electronics

11. ADVANCE TESTING TECHNIQUES

Accurate theoretical predictions of the structural behaviour of the composites have been proved critical for the continued commercialisation of composites. Within the last decade, the increased use of composites has paralleled advances in analytical techniques. Aircraft structures fabricated from 'advanced composites' are being utilised for both military and commercial aircraft. The less expensive composites and plastics are experiencing increased usage in the automotive industry. The sporting goods and commercial furniture industries have also experienced increased composite usage[15].

The key to these applications has been the creation of computer-aided engineering tools that permit accurate design and analysis of composite structures. Assessment of their reliability through identification and evaluation of damages in these materials is complicated because of simultaneous existence of different defect modes. Ultrasonic methods are versatile and relatively inexpensive for such a task and they are playing an important role in helping to identify damage mechanisms (in composites) to characterise the role played by them in the final failure process. The most popular among the ultrasonic methods is the C-scan. In recent years, with the availability of high speed analog-to-digitial (A-D) cards, attention has been focussed on automated C-scan through interfacing and control by computers[16]

12. CONCURRENT ENGINEERING

Reduction of product development cycles is one of the important critical factors to gain an edge over rival companies in a competitive environment. Though the conventional sequential engineering model is quite efficient for product development, it falls short of providing a clear advantage in terms of development time. Concurrent engineering on the other hand offers an opportunity to fulfil this requirement. On the negative side, the concurrent engineering has an inherent disadvantage of depending on fine coordination between various functional groups specifically among the designer, the manufacturer and the user. Failing to achieve this fine tuning will only result in protracted product development cycles, mounting quality control, inferior product and obsolescence of the product itself, thus turning an advantage into a disadvantage. Quality assurance during design and development prevents such catastrophy and helps the designer to transform seemingly chaotic and uncoordinated functions into unbelievable achievements. Infact, quality assurance in concurrent engineering successfully ensures that all the customer needs are met during design itself and also assures conformance of the final product with the design during manufacture[17].

13. TRANSFER OF TECHNOLOGY

DRDO has reached a stage where a number of technology transfers have taken place. In this context, it is desirable to look at the successes that have been achieved towards transfer of technology (ToT) as well as the failures and draw out a strategy[18] for its effectiveness. As per Jacques Bagur, 'Technology transfer can be defined as a process by which knowledge concerning the making or doing of useful things within any organisation is brought into use within another organisational context'.

The ToT from development to manufacturing is not so straight-forward as it may appear. In this context, ToT would imply transfer of an organised knowledge from R&D set-up to a commercial/public sector unit for the eventual purpose of producing new or improved products, processes or services. The ToT is possible through one or more of the following modes, i.e. frequent consulting, documentation transfer and collaborative technical work. The success of ToT mainly depends on person to person communication, quality of documentation and other factors.

Smilor and Gibson identified four key elements which are critical in the technology transfer process while working at the Microelectronics and Computer Technology Corporation - a major US R&D consortium. These are communication, motivation, distance and technological equivocality. Figure 9 depicts one type of ToT. However, it is felt that Smilor and Gibson have taken into account one very important factor, i.e. quality. The management can influence, direct and monitor each of these variables including

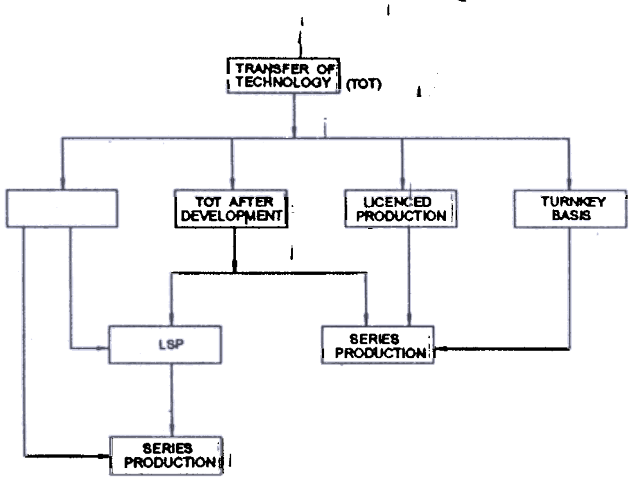

Figure 9. Types of technology transfer

quality. Figure 10 shows quality assurance and the process of technology transfer.

14. TOTAL QUALITY MANAGEMENT

Total quality management (TQM) is a thought revolution in management. If implemented, it can contribute to company's health and character. The TQM is concerned with moving the focus of control from outside the individual to within, the objective being to make everyone accountable for their own performance, and get them committed to attain quality in a highly motivated manner. It is more an attitude of mind, based on pride in the job

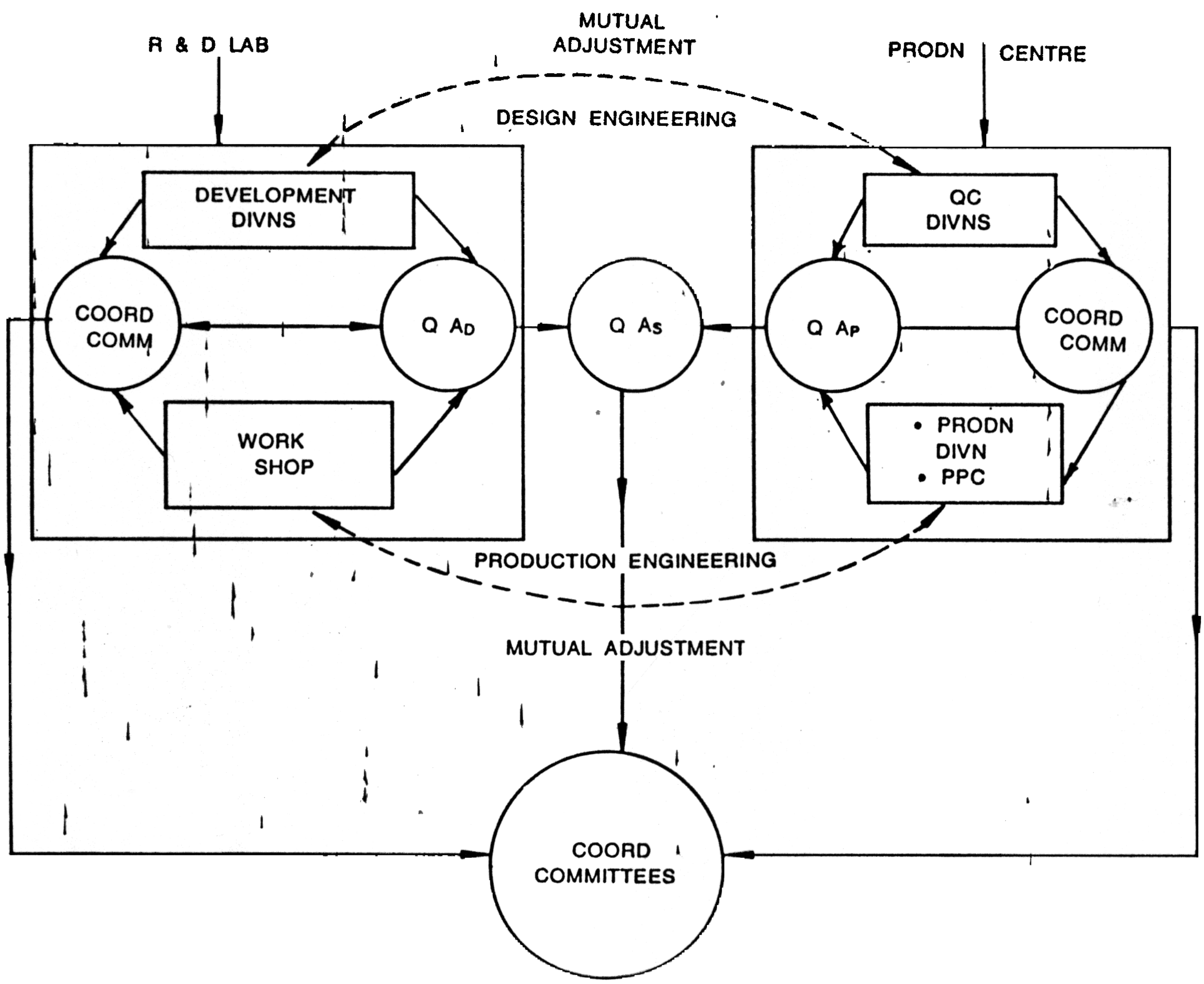

Figure 10. QA and the process of technology transfer

and requiring total commitment from the management which must then be extended to all in the organisation[19].

The TQM is seen as a way to beat the competition and to improve business effectiveness by introducing a degree of flexibility in the company's various activities[11,18]. Be it a service or production, it involves the whole organisation, i.e. every department, every activity, and every individual up to the grass-root level, getting organised (Fig. 11). In fact, ISO 9000 quality system has many TQM ingredients built-up in its system which when followed strictly lead to a road to total quality management. Quality systems are perhaps the single, most powerful tools, which address how a product or service is produced rather than what is produced. This series of standards is now seen as a passport to international trade. Quality being a password for exports in view of the ISO 9000 standards, it is applicable globally to all industries as well as Services. Applicable ISO standards[18] are shown in Fig. 12.

Figure 11. Tree for TQM

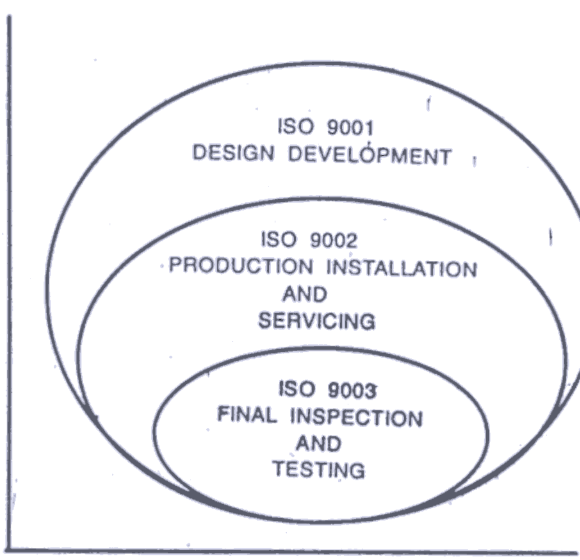

Figure 12. ISO standards for quality

15. CONCLUSIONS

The concept of quality consciousness must start at the top level. The chief executive's sincere support and encouragement is essential to upkeep and reach-out excellence in quality. The commitment of top management to foster quality is essential.

2 The quality process has to start from the specification requirement and must flow down to design reviews, to men, materials and machineries used, to production, inspection and testing process, and to handling and storage.

3 It is essential to focus on 3 Ps - the people, the process and the product. This requires the skills, expertise and continuous training of people to meet the changing demands and technologies. The process calls for well-defined procedures, house keeping and well-documented manuals. The product should meet the required specifications.

4 The software reliability is going to be the key for future systems. It calls for robust software design, low bug design, verification, validation, test and simulation in extreme environment and exercising every branch of software and flaw-less integration with other software.

5 Real-time feedback of failure analysis and corrective action for various systems are essential,

and a culture to analyse the past records/experiences should be brought in.

6. It is now time to shift thinking from MBO (management by objective) to MBQO (management by quality objective).

7. ISO 9000 is the stepping stone along the road to total quality. It is a tool for use in TQM process and should not be seen as an end in itself.

8. The establishment of integrated quality culture involves three prime factors - the quality awareness, the quality control and the continuous quality improvement.

9. The successful implementation of total quality calls for the selection of right people, giving them a refresher course, motivating them, training them and developing them as total quality professionals.

10. Total quality never comes accidently. It is the result of efforts of intelligent people, systematic action, persistent reviews and continuous improvements.

Promoting quality requires quality systems to be setup and certified by an accredited agency and also procuring and deploying certain resources in terms of equipment and manpower. It needs a national body on quality engineering in aerospace technologies which will take up promotional activities like holding seminars/conferences, issuing bulletins, instituting quality awards. Generating a directory of scientists and engineers engaged in quality engineering in aerospace will be a natural evolutionary process.

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