Indian Light Combat Aircraft (LCA) – Lessons Learnt in R&S During Development

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SUMMARY & CONCLUSIONS

The development of advanced fighter aircraft is a highly challenging task and the experience is invaluable and rewarding, especially when the development is made for the first time. The technology development from conceptual stage to final realization is a long journey for the new systems getting matured for integration on the aircraft. The common denominator for any such development is to accomplish reliability and safety requirements. The project complexity demands a planned, systematic and effective approach for R&S assurance during development phase. In case of LCA, more than 100 work centers were involved in the development activity spread over the length and breadth of the country. The integration and testing of complex systems on the aircraft posed lot of teething problems to the team, who accepted the challenge and were finally successful. During the process of development, quite a number of lessons were learnt, which have been summarized in this paper, along with important aspects on R&S assessment.

1. INTRODUCTION

The LCA is a lightweight, multi-role, supersonic aircraft designed to meet the stringent operational requirements of Indian Air force. The aircraft has been designed to provide superior performance, high agility, maneuverability, multi mission capability in all weather - day and night missions, with ability to carry and launch a wide range of conventional / precision-guided weapons and still possess high survivability and maintainability features. LCA is a control configured unstable vehicle with advanced technologies such as fly-by-wire flight control system, advanced digital cockpit, multi mode radar, integrated avionics systems, advanced composite material for primary structure, digital brakes and micro processor based health monitoring for general systems. The performance, maintainability, survivability, reliability and safety features are briefly illustrated in Figure 1.

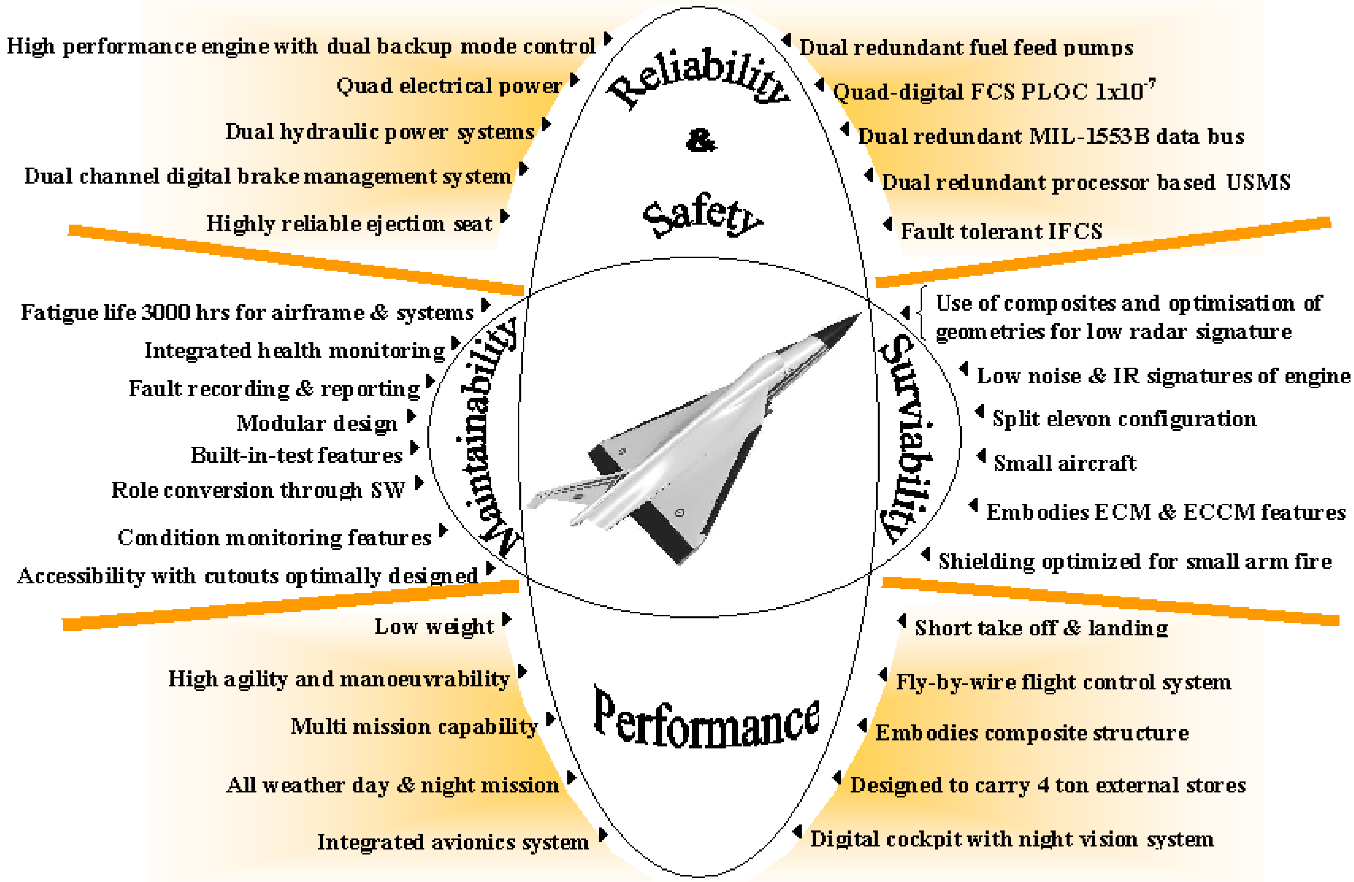
Ever since the first prototype aircraft successfully completed its maiden flight on 4th January 2001, the development program got a boost and marching ahead with series of successful and safe flights by proto vehicles (TD1, TD2).

The prototype vehicles TD1 & TD2 are intended to prove the vehicle technologies, where as subsequent proto variants (PV series), which are in advanced stage of integration, are intended to prove the weapon systems.

It is a quantum jump in technology to develop a modern, state of the art fighter - LCA after the development of a fighter prototype HF-24 "MARUT" which flew way back in 1961. The development of such an aircraft, besides setting up of the entire infrastructure and support system for the technologies, was a challenging task for the program. On the other hand, equally demanding was R&S assurance task, particularly taking into consideration systems / LRUs (i.e. Line replaceable unit) development at multiple work centers. Higher level of complexity and interdependency of systems, weight and volume constraints and use of state of the art technologies made realization far more daunting. The safe and successful flights of LCA is the culmination of dedicated efforts of entire design team with proactive support from Quality Assurance and System Effectiveness (QA&SEG) team, which has spearheaded the tasks related to System safety, Reliability, Maintainability and Survivability studies. This paper summarizes briefly the need for an integrated R&S assessment, the supporting studies and integrated testing, pilot vehicle interface (PVI) assessment and the lessons learnt in the process.

2. INTEGRATED R&S ASSESSMENT

The reliability and safety analysis was carried out right from the inception of project definition phase. Considering the quantum of the tasks, a detailed planning was carried out and priorities were clearly defined. Following are some important aspects relevant to R&S assessment.



FCS-Flight Control System, IFCS-Integrated Flight Control System, PLOC-Probability Of Loss Of Control, USMS-Utility Services Management System,

Figure 1 : Highlights of LCA Performance, Maintainability, Survivability, Reliability and Safety Features

2.1 *Reliability Analysis*

The mission reliability requirement was rationally apportioned to the individual systems taking into account the factors like criticality, complexity, novelty, cost, duty cycle and maintainability features and subsequently it was periodically reviewed to ensure that each system meets its apportioned target. The compliance to the target could be ensured either by one or combination of features like use of high reliable components and incorporating redundancies (both at component and system level). The reliability analysis enabled the required assurance that the aircraft system has attained the inherent capability of meeting the target goal. The LCA reliability assurance programme is shown in figure 2. All the tasks identified in the programme were carried out meticulously at an appropriate phase. However the real challenge remains to safeguard the same during the development. Another important activity in realizing the reliability goal was to define the correct environmental map (taking into consideration the flight envelop of the aircraft and tropical conditions in which aircraft has to operate), as the LRUs and systems were required to get cleared for the specified environmental conditions.

2.2 *Integrated Process Oriented Approach*

An integrated and rational approach was followed for the entire assessment. The objective here is to unearth and analyse all probable / potential hazards associated with aircraft and systems functionality due to failure of LRUs (i.e. inherent, command and secondary failures) or due to common failure causes at the aircraft level. The Safety assessment process followed for LCA is shown in Figure 3.

2.3 *Qualitative Vs Quantitative Analysis*

Both the options have got merits and demerits. The quantitative estimate is always associated with uncertainty, although objective. In contrast, the qualitative analysis is subjective, but still guarantees certain improvement in reliability and safety. In LCA, qualitative analyses were also given due importance along with numerical estimates. Development of 48 fault trees at the system level for the identified potential failure conditions and an aircraft level tree for the top event – ‘Loss of aircraft and crew’, were one of the significant task. Functional Hazard Analysis (FHA) at aircraft and system level, FMECA, Zonal Safety Analysis (ZSA),

Reliability Assurance Program

1. **Reliability Program Plan**
2. **Reliability Requirement**
3. **Reliability Modelling**
4. **Reliability Allocation / Apportionment**
5. **Reliability Predictions**
6. **Reliability Analysis :**
   - **FMECA**
   - **FTA**
7. **Design Review**
8. **Reliability Assurance during testing**
9. **FRACAS, TAAF, RGT**
10. **ESS**
11. **Reliability estimation with field data**

- Reliability feasibility study
- Statement of reliability objectives & requirements

- Reliability apportionment, modelling & prediction
- Redundancy analysis
- Analysis of parts materials & processes
- FMECA & FTA
- Human factors
- Design reviews
- Environmental testing

- Quality conformance verification
- Screening (run-in, bed-in or burn-in) of components & assemblies
- Reliability estimation

- Data collection & feedback
- Redesign / modification

Figure 2 : Overview on LCA Reliability Assurance Program

Common Mode Analysis (CMA), and Cascading Failure Analysis (CFA) were the important tasks carried out in qualitative assessment.

The ZSA, CMA and CFA have been found to be very effective analytical tools for specific failure causes at the aircraft level. As shown in figure 4, ZSA systematically identifies the neighbouring installations (under normal and failure condition) that may influence the functionality of a component in the same zone. In common mode analysis, it was verified whether available redundancy in the systems are influenced by the presence of any common failure cause. The CFA [1] was carried out in a structured way, using matrices and the procedure was found to be very effective for the complex interdependent systems. The functional relationships amongst systems were identified first, using relational matrix and then each system failure effect (in different modes) on other systems were analysed systematically by cascading failure effect matrix as shown in figure 5.

2.4 *Risk Assessment*

Appreciation of associated risks apriori to the intended phase is extremely important not only from the management prospective, but also to ensure certification, to instill the confidence with operating crew and designers, who again are the prime stakeholders in the project. The risk assessment was carried out as per the MIL guidelines. Having identified and categorised the risks as high, medium and low, these were tracked and monitored down to realization during the development.

2.5 *Safety Assessment Review*

In safety assessment review, total stock of the situation is taken, accounting the inputs from the risk assessment, rig tests

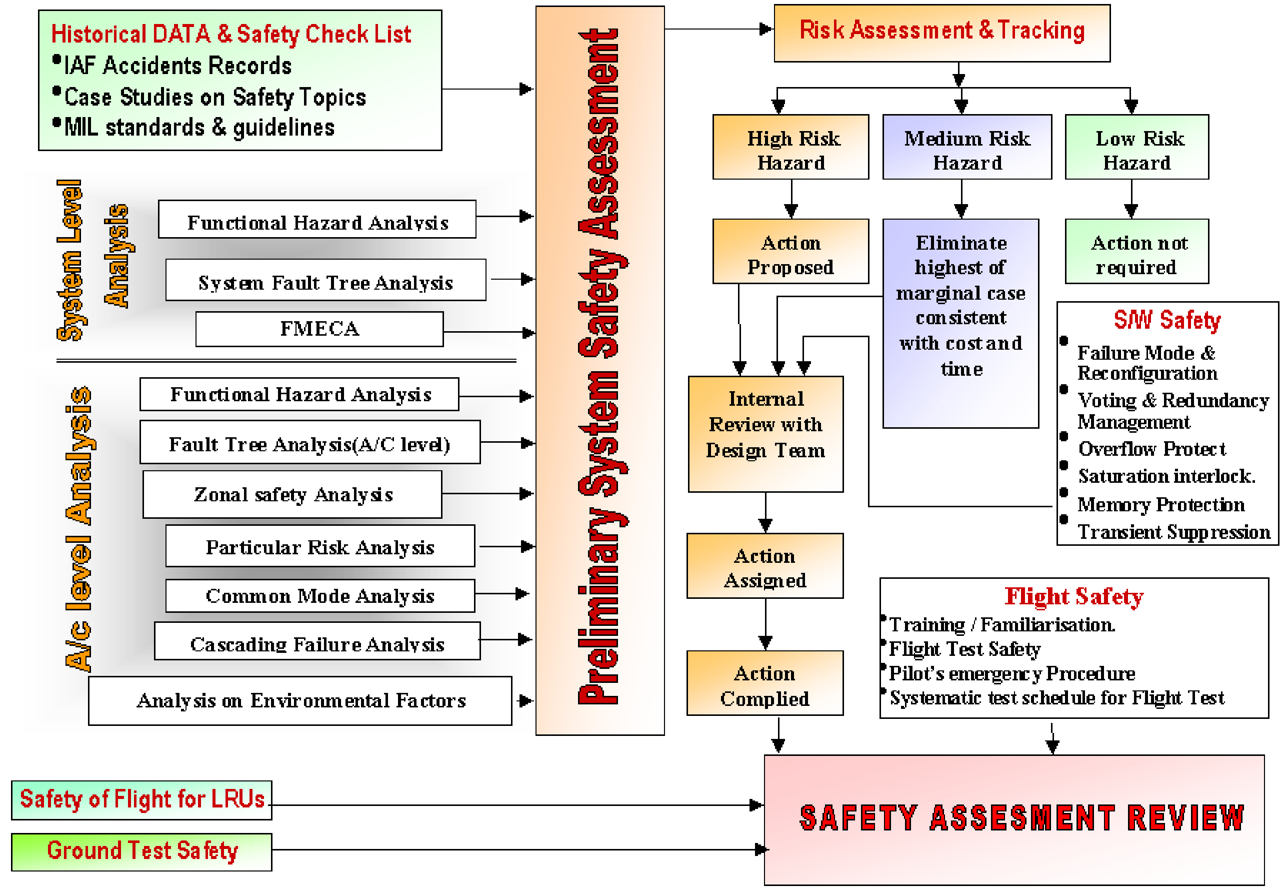


Figure 3 : System Safety Assessment Overview

a) Zonal Safety Analysis

FOD- Foreign object damage

b) Common Mode Analysis

Figure 4 : Common Mode and Zonal Safety Analysis

a) Typical complex interdependent Functional Relationship of systems

b) Relational Matrix

c) Cascading Failure Effect Matrix

Figure 5 : Cascading Failure Analysis [1]

on ground and supportive studies. In safety reviews, along with primary stakeholders, specialists were co-opted. The committee members critically scrutinized the adequacy of available safety provisions and made unbiased assessment on residual risk considering all the relevant inputs and features to safe guard such as periodic ground servicing, operating procedures, interlocks / warnings.

3. SUPPORTIVE STUDIES

Supportive design studies were carried out during appropriate phase of the development that provided useful inputs for the R&S assessment. Finite Element analysis, scale model studies, Vibration analysis and Simulation studies are the typical techniques which provided the required confidence in the design and prediction of behaviour of the aircraft, its systems and LRUs. Subsequently, the predictions were validated by the flight data and found to be accurate. The dedicated software operating on powerful computing machines, are now capable enough to analyse and solve any complex design issue. ELFINI, NASTRAN and ANSYS along with CATIA softwares were used for structural analysis using finite element models. The Real Time Simulator (RTS) has been used extensively to assess the handling qualities of the aircraft, in both normal and failure modes. The R&S requirements for the onboard softwares were ensured by following time tested QA practices and independent verification and validation approach. The proven approach in the software development yielded the desired result, as evidenced from the reliable performance of flight critical software.

4. INTEGRATED TESTS AND SYSTEM VALIDATION

One of the success stories behind LCA development is harnessing the resources, talents and infrastructure from various institutions (government, industry and academic institutes) and close co-ordination between multiple work centers.

In addition to qualification testing at LRU level, the integration tests (on system rigs) and aircraft level tests were given equal importance. Even with qualified LRUs integrated in the system, some hidden issues related to interoperability and interface mismatching figured during testing of some equipment. Validation tests along with system and aircraft level failure analysis both in reactive and proactive way were the means followed for unearthing these hazards. Various test facilities were developed such as Ironbird, wherein different hardware and software tests were successfully carried out in an integrated fashion. All test rigs developed, meet the relevant MIL standards and were approved by independent certification authorities. The availability of dedicated system test rigs has saved the valuable aircraft time, lest much time would have been lost in unearthing a host of anomalies on the aircraft.

Failure Mode Effect Testing (FMET), Fault Free Testing, Limited Qualification Tests (LQT) and Safety of Flight (SOF) tests were deployed, in order to obtain confidence in the reliable performance of the systems. During integration tests, few anomalies were encountered. Analysis of these anomalies provided valuable lessons during the process.

The configuration control activity ensured monitoring of the changes, duly scrutinized and approved, with respect to aircraft, system and LRU configuration.

5. ANALYSES Vs TESTING

Even after carrying out supportive studies and R&S assessment, some failures were encountered at the aircraft level during ground testing. The failures revealed that while R&S assessment could reduce the cycle time for testing, it cannot totally eliminate the need for testing. The variations are primarily due to incorrect definition of requirement, anomaly in assumptions, manufacturing variability / tolerances, assembly imperfections and interface mismatching (hardware & software). Therefore an optimal and rational balance between the analyses and testing could reduce cost and time.

6. MAINTAINABILITY AND BIT OPTIMISATION

As part of maintainability studies, accessibility assessment using human model, collision aspects and studies on assembly and dis-assembly sequences, carried out with the help of Virtual Reality (VR) facility, revealed that due consideration need to be paid to monitor the health of the LRUs / systems in-situ through required provisions. However experience has shown that unutilized test cases might lead to nuisance failures. In order to monitor the health of the important systems, provisions of Built-In-Test (BIT) facility has been incorporated which has significantly enhanced the maintainability feature of the aircraft with respect to safety.

7. PILOT VEHICLE INTERFACE (PVI) AND EVALUATION

Operational reliability of the aircraft depends on the human reliability and it follows how effectively and efficiently crew interface is designed. A rational balance between crew authority vs. automation and engineering foolproof provisions in the ergonomically designed cockpit, are some of the important considerations, that influences the human and system reliability. It is especially true under relatively higher crew workload and stress level conditions in a typical mission. The cockpit environmental facility was developed to study pilot vehicle interface aspects and to enable familiarization of emergency drills.

8. INDEPENDENT EVALUATION

Airworthiness certification has been carried out by third party independent government organizations, which was considered beneficial in ensuring safety and reliability requirements and to uncover inherent risks. These organizations were involved throughout the design and development process.

9. LESSONS LEARNT

Following are some important illustrations on lessons learnt during the development of the aircraft with respect to safety and reliability:

9.1 *First Time Right – Pays Rich Dividend*

Reliability can be enhanced significantly if the stated policy is followed, particularly for those cases where the right approach is known. Following are some of the occasions while snags were observed due to deviation from the correct approach –

- While carrying out direct braking test (anti-skid off) with one of the redundant channel of dual channel digital brake management system, one securing screw of LH brake pedal potentiometer got loose. This in turn resulted in wheel lock, even with application of only 50% LH brake pedal pressure and then resulted in tyre burst. In short an erroneous pedal potentiometer input, which is a feed back signal to processor, has commanded higher hydraulic brake pressure to the LH brake unit.
- Routing of electrical looms in close vicinity to EMI / EMC field, resulted in malfunction of integrated flight control system (IFCS). This anomaly was observed during undercarriage operation checks.
- In one case, insufficient clearance between hydraulic pipelines led to physical contact and rubbing resulting in fuel leak of the system. Even hard titanium alloy pipeline cracked and one of the pipeline started leaking.
- In several cases loose electrical connectors caused intermittency in signal transmission
- Fuel contamination in one of the tank led to blockage of a filter, which chocked the fuel supply to the fuel cooled oil cooler (FCOC).

9.2 *Work Centers Commitment for QR&S*

Whether the work centers involved in the development activities have understood, planned, committed and are making continual effort towards accomplishment of R&S objective of their product? On many occasions, it has been found that R&S objective at aircraft level could not be met due to failure of some LRUs, developed by the work centers, which were sometimes lacking understanding / total commitment for QR&S. Development agency can play a catalytic role by selecting work centers based on their capability and proven commitment to QR&S and wherever, the systems at centers are found deficient, the prime development agency must extend technical support and training to the work center and its personnel.

9.3 *Respect for Standards and Engineering Guidelines*

Overlooking standards and engineering guidelines, even for seemingly insignificant issues, may demand heavy penalty some time later. Minor deviations observed from the stipulated requirements of the standard, during LRU and system level performance check, if not critically reviewed, analyzed and disposed of, may cause significant delays in the program that too at a critical juncture. Also unexpected premature failure of the LRUs may take place, unless the guidelines related to shelf life, preservation, storage and exercising are scrupulously followed.

9.4 *Compromise on Quality Vs Programme Goals*

It is learnt in a hard way that in order to complete the current task within allotted time, no compromise on quality be permitted, otherwise a longer delay due to failures at later stage would set the clock back. Also each failure enhances the probability of occurrence of other LRU failures due to possible disturbances to healthy units co-located in the same zone, while testing and replacement.

9.5 *Development Test are Superior in Value Addition*

Development tests significantly add value to the product, though it is not recognised as a formal test. Equipment are unlikely to fail during formal qualification test, if the product has undergone a planned and effective development test programme, using the concepts such as Test Analyse and Fix (TAAF), Failure Reporting and Corrective Action System (FRACAS), Reliability Growth Testing (RGT). Also Design of Experiments (DOE) and Six Sigma approach may be followed to enhance the effectiveness of the design changes, those are made to meet the performance requirements during the course of development process. It has been observed that some work centres do not give importance to the development tests and encounter failures at a fairly advanced stage of qualification.

9.6 *Review the Analyses, Every Time Failure Encountered*

Some anomalies or failures are not unlikely and these can not be ruled out during the development. Some are due to improper threshold and require only fine-tuning of the system characteristics or minor readjustment in the threshold values. The analyst under such circumstances should review the failure every time a failure occurs. The exceptions could be those, which are covered under valid / justified assumptions. Following are some important considerations for analysis –

- The failure analyses are proactive and need to be carried out at an early stage, much before the system is realized. The recommendations cannot be implemented unless those are made at an appropriate time.
- Over optimism based on numerical estimates may some time prove to be wrong, unless validity of failure data, assumptions and applicable environment considered in the analysis, are ensured.

- The risk assessment is an important activity of the management for appreciation of residual risk. Disposition on identified risk and justifications for acceptance of the same need to be critically checked.
- The analysts should always be careful about objective, scope, and level of analysis including validity of assumptions made. The same analytical tool such as FMECA may be used for LRU reliability improvement or system safety assessment. While carrying out the FMECA at the LRU level, advantage of available system redundancy should not be taken; rather LRU functionality should be addressed. The analyst should also be clear about the strength and weakness of the analytical tool and judicially use the same.
- It is important to analyze and understand the mechanism of failure, once failure modes are identified. Therefore scope of analysis should essentially include physics of failure approach.

9.7 *R&S Enhancement Through Over Testing is a Myth*

Over dependence on analysis and supportive studies may cause surprises, until maturity and confidence is achieved. The grey area is because of subjectiveness involved with qualitative assessment and uncertainty bound around quantitative assessment, such as simulation studies. Unless analytical tools, models and assumptions get validated with the test results with reasonable confidence, simulation studies cannot replace testing, but only complement. At the same time over testing cannot improve the reliability and safety of the aircraft. Thus a judicious balance is the need of the day.

10. CONCLUSION

The first time development of a technologically advanced aircraft is always a challenge. It is not only the development of aircraft perse, but also the development of needed infrastructure, integrated technologies and above all a competent team having the motivation and dedication. The successful accomplishment of the goal is very important within the constraints of time and cost. The entire approach is therefore to build a strong foundation that can be relied upon to accomplish the objective within the constraints and support such technological challenges in future.

The flawless LCA flight test programme conducted so far was the result of extensive and intensive analysis along with rig level and aircraft level testing. The entire R&S assessment process provided the required confidence prior to the test flights and useful input on strengths and weaknesses of various analytical tools. The overall approach was quite effective in enabling safe flight test programme and the lessons learnt in the process were quite rewarding.

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Dr Kota is the President of Aeronautical Society of India, Chairman of Technical Committee of the Aeronautics Research and Development Board, Ministry of Defence. He is the Fellow of Aeronautical Society of India and Indian Academy of Engineering. He was awarded National Aeronautics Prize and FIE Foundation award in 1996. He received SBI-Pragna Pursakar in 2001. In year 2002, he has received Padma Shree award from the President of India for spearheading the design and development of Indian Light Combat Aircraft (LCA), which has been flown successfully

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