

Kaveri in Context: Comparative Lessons from International Fighter Aero-Engine Programmes and the Road to AMCA

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Abstract: India's Kaveri programme, launched in the 1980s to power the LCA Tejas (Light Combat Aircraft, Tejas), may have fallen short of the airframe's wet-thrust requirement, yet throughout its 35-year development, it has created durable assets: a running core, validated dry-engine and maritime derivatives, altitude-test competence, and an emergent private supplier base. This paper interprets Kaveri as unfinished capacity rather than programme failure. Framed by the historical reality that fighter propulsion matures through failure-rich iteration rather than linear research and development, the Kaveri programme's oscillation, vibration, and weight-growth episodes are typical of engines at the technological frontier. The paper argues that fighter aero-engine programmes should be understood as dynamic innovation systems whose outcomes depend more on ecosystem architecture than single-programme performance. Building on this base, we propose a two-lane "Road to AMCA": safeguard airframe schedules with a proven interim core while a time-boxed spiral drives toward a next-generation indigenous engine, funded as a portfolio with explicit reliability gates and process-oriented collaboration. The paper integrates technical evidence and certification lessons to show that programme design across funding continuity, supplier development, certification discipline, and collaboration structure can convert Kaveri's learning into credible Advanced Medium Combat Aircraft (AMCA) power, faster.

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1. Introduction

India's Kaveri programme emerged in the 1980s as the country's first serious attempt to field a fighter-class indigenous turbofan, conceived to power the Light Combat Aircraft (LCA Tejas) and reduce strategic dependence on foreign propulsion. Tejas is the Indian Name given to LCA, and Kaveri to the Indigenous Aero Engine. The stated requirement for Tejas demanded a wet thrust in the 81–85 KN class (Table. 3), whereas the Kaveri prototypes stabilized around ~46–48.5 KN dry and ~70.5 KN with afterburner in high-altitude testing, performance that proved insufficient to produce Tejas variants. [5] Consequently, Tejas Mk.1/Mk.1A adopted GE F404 engines, and Tejas Mk 2 will transition to the GE F414 (Fig. 6), while Kaveri was formally delinked from the LCA programme in 2008, even as technical work continued.[10], [21]

Yet it would be misleading to frame Kaveri's trajectory solely in terms of "success" or "failure." Measured against its original Tejas objective, there is no doubt the engine fell short, but if measured against capability accumulation, the programme generated significant learning and options that matter directly for India's next-generation propulsion needs. Concretely, Kaveri produced spin-offs and derivatives, notably the Kaveri Marine Gas Turbine (KMGT) tested to ~12 MW for naval/industrial use, and a dry Kaveri (~49–52 KN), with no reheat, well-suited to the Ghatak (Indian Name) stealth UCAV (Unmanned Combat Aerial Vehicle), while building national

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competence in materials, high-altitude testing, combustor/augmenter behaviour, and compressor aero-elasticity. The programme's later phases also drew the private sector into engine module manufacturing (e.g., Godrej delivering Kaveri derivative modules), strengthening the industrial base for future power plants.[16].



Figure 1. GTX-35VS Kaveri undergoing testing at GTRE in 2011. [31]

A second reason to resist “failure” language is historical: in advanced combat propulsion, turbulence is the norm. Early U.S. jet programmes progressed through concurrency, serial redesign, and materials-science constraints, with reliability and durability maturing only after extended cycles of bench and flight experience. As Scranton shows, fighter-engine development exemplifies “dynamic innovation”, a failure-rich, iterative process in which attempts to freeze the design are continually upset by new test findings and evolving performance demands. [32] In this lens, Kaveri’s setbacks are characteristic of propulsion development at the technological frontier, not anomalous.[33], [3], [24].

A third reason is comparative: modern airframe programmes frequently out-run domestic engine maturity, prompting near-term reliance on interim imported cores even when indigenous engine work is underway. India’s choice of F404/F414 for Tejas mirrors this pragmatic sequencing; other contemporary fighter programmes (Fig. 7), which will be detailed in subsequent sections, have faced similar propulsion detours, while joint ventures, technology-transfer constraints, and certification frictions have played out over time. In the Indian case, the specific hurdles: thin, stop-start funding relative to global benchmarks; early-stage gaps in Single Crystal Blade/Thermal Barrier Coating (SCB/TBC) metallurgy and CFD/wind-tunnel data; afterburner combustion oscillations and compressor-blade vibration [33],[3]; and the heavy lift of Joint Venture (JV) certification and vendor standardization are all well documented in the open literature and official audits.[11], [22]

This paper makes two contributions. Firstly, it offers an overview of Kaveri’s evolution: what was attempted, what was achieved, what was learned, and why those learning effects still matter for India’s Advanced Medium Combat Aircraft (AMCA) engine roadmap.[26] Secondly, it places Kaveri in a comparative context against the contemporary international experience to extract actionable levers for compressing India’s time-to-capability. The argument in this paper emphasizes that Kaveri is an unfinished capacity rather than a dead-end, a base of knowledge, people, rigs, and suppliers that, if coupled to these levers, can power a realistic spiral to a 90–100 KN indigenous core suitable for AMCA.

In this context, “unfinished capacity” refers to a partially developed but strategically significant technological base that has not yet matured into a fully operational system. It captures the idea that the Kaveri programme generated critical competencies, such as core engine design, materials knowledge, and testing infrastructure, without achieving complete performance readiness. Rather than a failed outcome, it represents an incomplete but valuable stage in long-term capability development that can be built upon for future programmes.



Figure 2. Kaveri Derivative Engine unveiled by GTRE in Bengaluru. [31]

2. Problem Statement

Despite decades of investment, India has not yet achieved a fully operational, indigenous fighter-class aero engine capable of meeting the thrust, durability, and reliability requirements of modern combat aircraft. The experience of the Kaveri program highlights that this shortfall is not merely a consequence of isolated technical deficiencies, but rather the result of deeper systemic limitations in materials capability, testing infrastructure, industrial ecosystem maturity, and program management approaches.[4]

Conventional evaluations of such programs have largely relied on binary success-failure metrics tied to predefined performance targets, overlooking the cumulative development of national technological capacity. This has constrained both policy learning and strategic planning. At the same time, global evidence indicates that advanced aero-engine development is inherently iterative, capital-intensive, and ecosystem-dependent, raising critical questions about how India can restructure its development model to achieve long-term propulsion sovereignty while managing near-term operational requirements.[6], [9], [29].

3. Research Gaps

The Systematic Literature Review identified the critical technological, industrial, and institutional gaps and their implications. The research gaps and their rationale are given below.[3], [4], [18], [24], [33].

Table 1. Research Gaps with Rationale [24]

Research Gaps	Rationale
Absence of Ecosystem-Level Analysis	Existing studies predominantly assess aero-engine programs at the level of individual performance outcomes, with insufficient attention to the broader industrial, technological, and institutional ecosystem required for sustained engine development.
Limited Comparative Benchmarking	There is a lack of systematic comparison between India's aero-engine development trajectory and those of other nations (e.g., the United States, United Kingdom, France, Russia, and China), particularly in terms of funding models, development timelines, and failure-recovery mechanisms.
Inadequate Focus on Process Knowledge	Prior research emphasized technology acquisition and hardware outcomes, while underexploring the role of tacit process knowledge, such as testing protocols, certification practices, and reliability growth methodologies, in achieving mature propulsion systems.
Neglect of Temporal Risk Management Strategies	The strategic value of decoupling airframe and engine development timelines (e.g., through dual-track or "two-lane" approaches) has not been sufficiently examined in the Indian context.

Fragmented Understanding of Technology-Performance Linkages	While individual technological gaps (e.g., single-crystal blades, blisks, thermal barrier coatings) are well documented, there is limited integrated analysis of how these deficiencies collectively influence thrust, efficiency, durability, and overall engine viability.
Insufficient Integration of Policy and Engineering Perspectives	The intersection between technical challenges and defence industrial policy, particularly funding continuity, public-private collaboration, and certification frameworks, remains underexplored.

4. Research Objectives

- a) To evaluate the Kaveri aero-engine programme in terms of technological performance, development challenges, and outcomes.
- b) To compare India's aero-engine development trajectory with leading and emerging global engine-producing nations.
- c) To analyze the impact of key technological gaps (materials, TET, T/W ratio, manufacturing, testing) on engine performance and reliability.
- d) To assess the role of industrial ecosystem and policy frameworks in shaping aero-engine development outcomes.
- e) To propose strategic recommendations for achieving indigenous aero-engine capability for future programmes such as AMCA.

5. Research Methodology

This study adopts a comparative, qualitative-analytical methodology to evaluate India's Aero Engine development trajectory in relation to global benchmarks and to derive policy-relevant insights. [14], [19], [20] The Kaveri aero-engine program is used as the primary case study, examined through its historical evolution, technical challenges, and programmatic outcomes. This is complemented by selective secondary cases from leading aero-engine-producing nations to provide comparative context. [6], [16], [29]

The research methodology was performed in five phases (Fig. 3). Step one consisted of a research design that comprises the identification of a type of study to be employed, data sources to be used for the primary case study of the Kaveri Aero Engine Development Programme, and a comparative analysis of benchmarked countries, and defining a problem and research objectives. Data Collection and Data Organization were done in step two to collect data from primary and secondary sources and to organize the collected data for classification into the Kaveri Programme primary case and comparative benchmarked countries as secondary cases. After data organization, the classified data was validated through triangulation across multiple sources and expert consultation to ensure credibility. This was followed by a Data Matrix development of India and benchmarked countries across all comparative dimensions. Step three consisted of an Analytical Framework that includes Technology and Performance Mapping using cause-effect analysis, comparative analysis through Cross-Country Benchmarking, and Policy and Institutional Analysis using an ecosystem perspective. Step four entailed Synthesis and Interpretation. This phase interprets findings through a dynamic innovation lens. The findings and outputs of the study are discussed in step five. The findings are discussed and presented in the Road to AMCA, Discussion, and Conclusion sections.



Figure 3: Research Methodology [19]

This comparative methodology enables a holistic evaluation of aero-engine development as an integrated techno-industrial process, thereby bridging the gap between engineering performance analysis and strategic policy design.

Table 2. Key Words Used in Electronic Databases

Key Words Used in Electronic Databases
Kaveri Aero Engine Development Programme
Light Combat Aircraft Tejas
Advanced Medium Combat Aircraft (AMCA)
Key Technological Gaps in Kaveri Aero Engine Development Programme
Comparative Cases of Countries Aspiring for Fighter Aircraft Development
Indian Defence Policy
Indian Industrial Ecosystem for Fighter Aircraft and Engine Development

5.1 Data Sources

The search was performed in search engines such as Google, Google Scholar, and Research Gate, which led to databases such as Sage, MDPI, Science Direct, and ASME, to mention a few. Also, Defence News and Global Defence portals have been extensively explored for this study. The keywords used in the search are mentioned above (Table. 2). Many articles were reviewed until relevant articles were identified for the systematic literature review. Once it was found that there was a lower number of peer-reviewed publications on this topic and no more data was available, the search was ceased.



Figure 4. A row of LCA Tejas Mk.1A fitted with GE404 engines at HAL Nashik. [22]

6. Kaveri Engine Programme

With the retirement of the MiG-21 fighter aircraft looming in the mid-1980s and the LCA on the drawing board, the Ministry of Defence (MoD) sanctioned the Gas Turbine Research Establishment (GTRE) to begin the development of an indigenous fighter-class turbofan so that the airframe wouldn't be hostage to imports. Full-scale development of the GTRE GTX-35VS engine (Fig. 1), designated 'Kaveri', was approved in 1989, with an ambitious ~80 KN (wet) requirement. The first tangible milestone of the programme was achieved when the GTRE's Kabini core ran in 1995, giving India a working hot-section around which to build the full engine.[17] Full-engine prototypes entered ground testing (1996–1998), establishing the mechanical layout, control philosophy, and test sequences, even as design margins began to show strain (e.g., mass growth and vibration) (Table. 6). Component-level learnings surfaced early. GTRE's finite-element work on the fan shaft and bearing mounts documented stress hot-spots, stiffness trade-offs (IN718 vs Ti), and fracture-toughness limits that made "simple weight shaving" unsafe, becoming an engineering reality that foreshadowed later the engine's overweight and vibration concerns (Table. 6).[3]. However, the project faced severe headwinds in the wake of the 1998 Pokhran Nuclear tests as Western Sanctions disrupted access to much-needed advanced superalloys, single-crystal blades, flight control systems, and test capabilities, forcing GTRE to adopt a slower and more conservative route to attain hot-section



maturity.[23] Meanwhile, India's starting point lacked deep CFD toolchains, large wind-tunnel datasets, and mature turbine and compressor blade metallurgy [33], all of which are paramount for the close optimization of weight, specific-fuel consumption (SFC), and durability of modern fighter cores simultaneously.[5]

As the programme dragged on, as stated previously a thrust gap soon developed, and in 2009-11 the Comptroller and Auditor General of India (CAG) flagged several issues including compressor deficiencies (Table. 1 and 6), delays in manufacturing and lack of critical technologies such as single-crystal blades and superalloys and most importantly a major weight overrun (1424 kg against the required ≤ 1100 kg). [11], [17] This led to the Kaveri being officially delinked from the LCA Tejas programme, and the aero engine quickly pivoted to learning and derivatives, providing Indian defence with usable offshoots. In November 2010, a K-9 prototype flew on a Russian testbed, showing airworthy behaviour in a controlled envelope, even if not to the specifications of the Tejas. In 2022–2023, high-altitude tests at the Central Institute of Aviation Motor (CIAM), Russia, demonstrated 48.5 kN dry at a simulated altitude of $\sim 13,000$ m, validating the dry-engine path for UCAV roles, aligning with the DRDO Ghatak's weight and mission profile.[1] This was a time when private manufacturing stepped up as Godrej produced Kaveri derivative engine modules, marking meaningful industrial diffusion beyond GTRE/HAL (Hindustan Aeronautics Limited) and seeding capacity for future programmes.[1] In parallel, GTRE–BHEL (Bharat Heavy Electricals Limited) collaboration signalled a marine/industrial gas-turbine lane for Kaveri-class technology, as the aforementioned Kaveri Maritime Gas Turbine (KMGH) emerged as a ~ 12 MW marine/industrial derivative, proving that Kaveri's core physics could power turbomachinery outside fighter aviation and broadening demand signals for India's turbomachinery base.[5].

Table 3. Kaveri Design Requirements [17]

Name	GTRE GTX-35VS Kaveri
Developer	Gas Turbine Research Establishment (GTRE), Bengaluru
Type	Low-bypass, twin-spool turbofan with afterburner
Dry Thrust	49 to 51 kN
Wet Thrust (Afterburner)	Designed for 81 kN
Bypass Ratio	$\sim 0.16:1$
Fan Pressure Ratio	Design aimed for 4:1
Overall Pressure Ratio	27:1
Mass Flow Rate	78 kg/s
Thrust-to-Weight Ratio	6.9:1
Target Weight	1,100 kg
Length	~ 3.49 m
Diameter	~ 0.91 m
Compressor Stages	6-stage low-pressure + 3-stage high-pressure compressor (transonic design)
Compressor Type	Full annular combustor with advanced fuel injection
Turbine Stages	1 high-pressure + 1 low-pressure turbine
Turbine Blade Material	Directionally solidified (DS) blades
Cooling Technology	Internal cooling passages for high-temperature performance Variable
Stator Vanes	Stator Vanes First three compressor stages for optimized airflow
Control System	Twin-lane Full Authority Digital Engine Control (FADEC) with manual backup
Materials	Titanium alloys (Ti-6Al-4V, Ti6242, Ti6246), nickel and cobalt superalloys
Environmental Adaptation	Optimized for India's extreme conditions (hot deserts to Himalayan altitudes)



Figure 5. Kaveri mounted on a Russian IL-76 Flying Engine Test Bed. [30]

Table 4. Status of various tests of Kaveri as of 2009 [11]

Status of various tests as of 2009					
Milestone Achieved	Originally planned	Completion date	Revised PDC	Status as on 08/09	Delay
Core Engine demonstration	December 1990	March 1995	--	Achieved	4 years +
Full Engine demonstration	June 1992	September 1995	--	Achieved	3 Years +
High Altitude tests	June 1994	--	June 2006	Not Achieved	15 Years
Preliminary Flight Rating Test	December 1995	--	December 2007	Not Achieved	14 Years
Type test	June 1996	--	June 2008	Not Achieved	13 Years
FTB	September 1998	--	May 2007	Not Achieved	11 Years
Production Clearance	December 1996	--	December 2009	Not Achieved	13 Years

7. Why are propulsion programmes "turbulent" in nature?

The history of fighter propulsion is not a neat R&D waterfall; it is a sequence of build, test, fail, redesign, and build again, often under compressed timelines and changing requirements. In his study of U.S. military jet propulsion from WWII through the early Cold War, Philip Scranton characterizes this as dynamic innovation: programmes advance through what he described as "concurrency" (fielding while still developing), serial redesign, and materials-science catch-up, with reliability emerging only after extended, failure-rich iteration.[32] Attempts to "freeze the design" are repeatedly overturned by the discovery of new failure modes or by fresh performance demands.

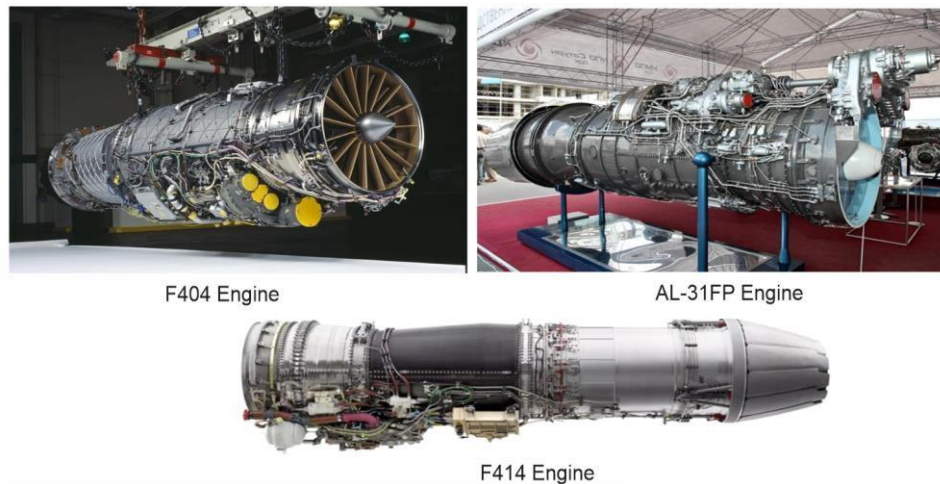


Figure 6. Comparable engines to the Kaveri. [17]

This lens normalizes what we observe in the Kaveri record. Weight overruns, afterburner combustion oscillations, low-pressure compressor blade vibration, and delays in altitude/Flying Test Bed testing milestones are not outliers; they are instead the expected artefacts of pushing an indigenous fighter-class core up a steep learning curve without a mature ecosystem of single-crystal metallurgy, thermal-barrier coatings, deep CFD/wind-tunnel data, and serial rig capacity (Table. 1 and 6).

Scranton shows how the U.S. services in the late 1940s–50s faced a persistent paradox: production needs a frozen design, but competitiveness demands redesign, and wartime realities forced them to pursue both simultaneously.[32] The result was prolonged concurrency, high accident rates, and factory “quick-fix” cultures until materials, test infrastructure, and procedures finally stabilised the turbofan era. Interestingly, Kaveri exhibits the same paradox. Audit trails and programme histories describe the inability to freeze the early configuration precisely because each test unlocked a new redesign demand. Delinking from Tejas in 2008 was not a repudiation of the engine effort; it was a sequencing choice, allowing the airframe to progress on F404/F414 while the engine continued the redesign cycles needed to reach fighter-grade confidence (Fig. 6).

In his research, Scranton identifies four traps of fighter-engine development [32]:

Trap 1 - Concurrency:

- **Scranton exemplar:** U.S. engines were shipped to airframe lines before qualification was complete, with “fix-it” teams co-located to chase failures, an expensive but situationally rational choice that raised accident risk and extended rework.
- **Kaveri link:** India avoided full operational concurrency by delinking Kaveri from Tejas, but developmental concurrency still existed: core and full-engine rigs exposed oscillations and vibration that triggered redesigns while other subsystems (controls, accessories) continued maturing, stretching schedules and complicating design freeze.[3], [17]

Trap 2 - Materials lag:

- **Scranton exemplar:** Early U.S. turbojets repeatedly hit alloy limits; each increase in turbine inlet temperature reshuffled failure modes and forced a fresh materials/process round.
- **Kaveri link:** India’s starting point lacked domestic single-crystal blade capability and robust TBC process lines (Table. 1 and 6); post-1998 technology denial magnified that gap. The result was conservative hot-section choices that constrained reheat thrust and durability until materials capacity could catch up.[33]

Trap 3 - Upgrade pressure:

- **Scranton exemplar:** Continuous demands for higher thrust, altitude performance, and durability repeatedly overturned design freezes, elongating the redesign spiral.
- **Kaveri link:** The Tejas envelope required $\geq 81\text{--}85\text{+ KN}$ wet thrust but Kaveri prototypes plateaued at $\sim 70.5\text{KN}$ with reheat (Table. 3 and 5). Test-discovered issues and the push to close the remaining thrust gap fed back into the design, delaying stabilization of a fighter-qualified configuration.

Table 5. Comparison of the Kaveri with other existing aero engines. [17]

Parameter	Kaveri	GE F404	GE F414	AL-31FP
Technical Parameters				
Engine Type	Low-bypass twin-spool turbofan with afterburner			
Bypass Ratio	0.16:1	0.34:1	0.25:1	0.59:1
Overall Pressure Ratio	27:1 (target)	26:1	30:1	20.8:1
Fan Pressure Ratio	4:1 (target)	4:1	4.2:1	4:1
Turbine Inlet Temperature	~1,427°C	~1,500°C	~1,700°C	~1,400°C
Weight	1,180 kg	1,035 kg	1,110 kg	1,570 kg
Length	~3.9 m	~3.9 m	~3.9 m	~4.9 m
Diameter	~1 m	~0.89 m	~ 0.89 m	~1.2m
Dry Thrust	49.2 KN	53.9 KN	62 KN	74.5 KN
Wet Thrust (Afterburner)	73-75 KN	84 KN	98 KN	122.6 KN
Thrust-Weight Ratio	~6.2:1	~8.1:1	~8.9:1	~7.8:1
Specific Fuel Consumption	~0.85 kg/KN.H (dry) ~1.8 kg/KN.H (wet)	~0.83 kg/KN.H (dry) ~1.77 kg/KN.H (wet)	~0.81 kg/KN.H (dry) ~1.78 kg/KN.H (wet)	~0.88 kg/KN.H (dry) ~1.95 kg/KN.H (wet)
Materials	Directionally solidified blades; Kaveri 2.0 targets single-crystal blades	Nickel-based superalloys, blisks	Single- crystal blades	Nickel- based superalloys, titanium
Financial aspects and Current Induction				
Current Use	DRDO Ghatak UCAV, Kaveri Marine Gas Turbine (KMGT)	HAL Tejas Mk1/Mk1A, F/A-18 Hornet, T-7A Red Hawk	F/A-18E/F Super Hornet, HAL Tejas Mk2 (Planned)	Su-27, Su-30MKI, J-11
Development Cost (Est.)	~₹3,000 crore (~\$360 million)	~\$1 billion (1970s-80s)	~\$1.5 billion (1980s)	~\$500 million
Year of Completion	2010 (initial testing)	1983	1998	1985

Trap 4 - Certification drag and production discipline:

- Scranton exemplar: U.S. programmes learned, expensively, that uncontrolled change and fragmented documentation wreck schedule credibility and reliability growth.
- Kaveri link: India had to build this discipline while building the engine: Approach Papers, conduct Critical Design Reviews, perform Qualification Testing, test-bed calibration, and develop test suites that are suited to the Indian environment, all became critical path items for any production-standard outcome.[22]

Seen through Scranton's frame, the Kaveri record reads less like a binary of "worked / didn't work" and more like a sequence of capability unlocks constrained by materials, test infrastructure, and certification maturity.[32] Even the United States required decades to stabilize reliable turbofans; expecting a first-programme fighter core to meet a demanding wet-thrust target without the same depth in materials/test infrastructure is historically unrealistic.



Figure 7. Fifth-Generation Fighter programmes outside traditional aerospace giants like the US and Russia

8. Contemporary Comparators

A cross-case comparison indicates a recurring structural pattern in fighter development: airframe development timelines tend to outpace indigenous engine maturation, necessitating interim solutions (Fig. 7). This pattern can be systematically analyzed across countries using common criteria.[1], [6], [16], [25]

India (LCA Tejas / Kaveri Programme)

- **Initial Constraint:** Indigenous Kaveri engine failed to achieve required thrust, weight, and reliability for fighter integration (Table 1, 6, and 7).
- **Interim Solution:** Adoption of imported engines (GE F404 for Mk.1/Mk.1A; GE F414 for Mk.2) to maintain flight testing, training, and operational timelines (Fig. 6).
- **Indigenous Engine Strategy:** Continued development of Kaveri derivatives (e.g., dry engine for UAVs) and ongoing collaboration with Safran for future AMCA propulsion.
- **Ecosystem Approach:** Partial development of testing capability (e.g., high-altitude facilities) and emerging private-sector participation, but with gaps in materials, manufacturing, and certification infrastructure.
- **Outcome/Implication:** Demonstrates a dual-track strategy where imported engines ensure programme continuity while indigenous capability evolves over a longer reliability cycle.

Turkey (TF-KAAN Programme)

- **Initial Constraint:** Delays in achieving a sovereign engine due to intellectual property and partnership frictions in the Rolls-Royce–Kale joint venture (Table. 7).
- **Interim Solution:** Selection of the GE F110 for early prototypes to enable near-term flight testing.
- **Indigenous Engine Strategy:** Revival of domestic engine efforts through Turkish Air Engine Company (TAEC) with renewed negotiations involving Rolls-Royce.
- **Ecosystem Approach:** Focus on joint development models and technology partnerships, with increasing emphasis on domestic manufacturing capability.
- **Outcome/Implication:** Highlights dependence on external engines for schedule assurance, with indigenous capability contingent on resolving collaboration and IP-sharing constraints.

South Korea (KF-21 Programme)

- **Initial Constraint:** Absence of a mature indigenous high-thrust turbofan at programme initiation (Table. 7).
- **Interim Solution:** Deployment of the F414-GE-400 (license-produced domestically) to ensure schedule adherence and export credibility.
- **Indigenous Engine Strategy:** Government-funded long-term development programme targeting a next-generation engine for Block 3 integration (2030s timeframe).
- **Ecosystem Approach:** Strong integration of domestic industry (e.g., Hanwha Aerospace), supported by structured funding and phased capability development.
- **Outcome/Implication:** Illustrates a phased transition model where licensed production builds industrial capacity before full indigenous engine development.

China (J-10 / J-20 Programmes)

- **Initial Constraint:** Long-term dependence on imported Russian engines and limited initial domestic reliability in high-performance turbofans (Table. 7).
- **Interim Solution:** Continued use of Russian AL-31 engines during early development and fleet induction phases.
- **Indigenous Engine Strategy:** Parallel development of WS-10 (for broad fleet use) and WS-15 (for high-end applications such as J-20).
- **Ecosystem Approach:** Highly centralized, state-driven model under the Aviation Industry Corporation of China with large-scale investment, multiple parallel programmes, and integration across aircraft platforms.
- **Outcome/Implication:** Demonstrates that sustained, large-scale ecosystem investment enables gradual reliability improvement, though over extended timelines and with significant resource commitment.

8.1 Cross Case Synthesis

Applying consistent analytical criteria across all cases reveals several common patterns [6], [9], [25]:

- **Universal Presence of Interim Engine Use**

All programmes employ imported or licensed engines during early phases to mitigate schedule risk and ensure operational continuity.

- **Extended Indigenous Engine Timelines**

Indigenous engine development consistently lags behind airframe development due to the complexity of achieving high thrust, durability, and reliability simultaneously.

- **Central Role of Ecosystem Maturity**

Countries with stronger industrial ecosystems (e.g., China) demonstrate faster iterative progress, while those with fragmented ecosystems face prolonged development cycles.

- **Importance of Structured Transition Strategies**

Successful programmes adopt phased or dual-track approaches, combining interim imports with long-term indigenous development.

- **Process Knowledge as a Critical Variable**

Access to testing, certification, and reliability-growth processes, rather than design knowledge alone, emerges as a key determinant of eventual success.

Comparative evidence indicates that the use of interim imported engines is a structurally rational response to the temporal mismatch between airframe and engine development. Programme outcomes are primarily determined by



the depth of ecosystem development, continuity of investment, and the ability to internalize process knowledge. Differences across countries are therefore less about the presence of interim solutions and more about the speed and effectiveness with which indigenous capability is developed alongside them.

9. The Road to AMCA

The propulsion path to AMCA requires a spiral advance toward a 90 –100 KN class engine, grounded in realistic physics and reliability timelines. This means deep investment in single-crystal blade (SCB) and thermal-barrier coating (TBC) capability, improved combustor acoustics to avoid the oscillation issues seen in Kaveri, and aeroelastic fixes for low-pressure compressor stages that historically produced vibration.[5], [33] Weight reduction must follow fracture toughness and informed design rather than brute thinning, another lesson from early Kaveri component redesign. [3], [4] India also needs upgraded altitude and mission-endurance rigs to validate turbine inlet temperatures (TIT), exhaust-gas-temperature (EGT) margins, surge-margin retention, specific-fuel-consumption (SFC) tracking, and thrust-to-weight (T/W) improvements at every spiral gate (Table. 1 and 6).

What India lacks is not intent, but programme architecture. AMCA propulsion should be funded as a projectized, multi-year portfolio, a structure more akin to Defence Advanced Research Projects Agency (DARPA) than Defence Research Development Organization (DRDO), supported by independent cost realism and earned-value milestones so redesign cycles do not stall. Certification must follow a standardised playbook: a formal Approach Paper, Critical Design Reviews (CDRs), subsystem and core Qualification Testing, and strict concerned regulating authority documentation to ensure vendor repeatability.[22] Parallel efforts must develop sovereign flying test beds as well as upgrade test-bed calibration, institute Indian-environmental test suites (high heat, dust, humidity), and raise domestic vendor standards so that each module can be certified without bespoke intervention.[17] These requirements emerge directly from India's earlier JV challenges on the Shakti and Kaveri lines.

Where foreign collaboration is necessary, India should negotiate tiered technology-transfer menus that emphasize process rather than IP ownership: access to manufacturing steps, resident experts, joint trials, and instrumented test data even when core recipes, FADEC source code, special coatings, and SCB chemistries remain restricted.[1] Progress must be measured against design-learning KPIs at each JV milestone, and the AMCA engine must be architected with export-ready modularity, so politically sensitive modules can be swapped without redesigning the entire core. The next steps require updated, instrumented data from Kaveri-derivative tests to build credible reliability-growth curves. India also needs a comparative analysis of "best value against quota-based workshare" to design AMCA's industrial model in a manner compatible with India's export policies.

10. Discussion

The analysis indicates that the Kaveri aero-engine programme should be evaluated not solely against its initial performance targets, but in terms of its contribution to the development of national technological capability. The evidence shows that while the programme did not meet the thrust requirements for direct integration with the LCA Tejas, it generated several critical technical and institutional outcomes [8], [12]. These include the realization of a functional core engine, the development of derivative configurations such as the KMGTD and Dry Kaveri, the establishment of high-altitude testing capability, and the initial formation of a domestic supplier base (Fig.1 and 2). Collectively, these outputs represent a measurable expansion of India's aero-engine development capacity and provide a technological baseline for future programmes such as the AMCA (Fig. 7).

The findings further demonstrate that the technical limitations encountered in the Kaveri programme, specifically in thrust-to-weight ratio, turbine entry temperature, materials capability, and component-level technologies, are structurally interdependent. Deficiencies in single-crystal turbine blade technology, thermal barrier coatings, and cooling systems constrained achievable turbine entry temperatures, which in turn limited specific thrust and thermal efficiency (Table.1 and 6). Similarly, the absence of compressor blisk technology and advanced powder metallurgy turbine discs contributed to higher engine weight and reduced structural integrity, thereby lowering the overall thrust-to-weight ratio. [3], [17] These interrelated constraints explain the gap between demonstrated and required performance levels and highlight the need for synchronized advancement across multiple technological domains.

Comparative analysis with other national programmes indicates that such developmental challenges are consistent with the characteristics of advanced propulsion system development.[6], [25] Evidence from countries including Turkey, South Korea, and China shows similar patterns of iterative development, extended timelines, and reliance on foreign technologies during early stages.[15], [16], [29] This supports the interpretation that the Kaveri programme's setbacks are not anomalous, but indicative of the complexity of achieving high-performance aero-engine capability. The data also suggests that programmes achieving eventual success have followed prolonged, failure-intensive development cycles supported by sustained investment and institutional continuity.

The analysis identifies the industrial ecosystem as a primary determinant of aero-engine development outcomes.[4], [13] Programmes in countries with mature capabilities are characterized by integrated supply chains, advanced materials infrastructure, specialized manufacturing capacity, and established testing and certification systems (Table. 7). In contrast, the Kaveri programme was constrained by gaps in high-temperature materials, limited domestic access to critical rare earth elements such as Zirconium, Rhenium, and Ruthenium (found in countries such as South Africa), absence of large-scale forging infrastructure, and insufficient coating and manufacturing technologies (Table. 6). These limitations were compounded by inadequate testing infrastructure, including delays in the availability of altitude test facilities and flying test beds, which slowed validation cycles and reliability growth.

Financial analysis highlights a significant disparity between the scale of investment in the Kaveri programme and that observed in comparable international programmes.[13] Estimated expenditure of approximately USD 250 million is substantially lower than the multi-billion-dollar (2.5 to 4.5 billion USD) investments typically required for fifth and sixth-generation fighter engines.[13], [24] This funding gap directly affected the pace of technology maturation, infrastructure development, and iterative testing. The findings therefore indicate that funding scale and continuity are critical variables influencing programme outcomes (Fig. 3).[24].

Table 6. Kaveri's challenges and their consequences [24]

Kaveri Programme Challenges and Performance Consequences	
Challenge	Technical/Performance Consequence
Low Thrust to Weight Ratio	Lower specific thrust, poorer acceleration, reduced payload, and agility
Excess engine weight	Reduced thrust-to-weight ratio, lower aircraft range, and maneuverability
Insufficient Turbine Entry Temperature (TET)	Lower thermal efficiency, lower core power, reduced dry/wet thrust
Lack of Single-Crystal turbine blades	Lower creep resistance, lower temperature capability, shorter hot-section life
Inadequate thermal barrier coatings	Lower thermal protection, faster degradation, reduced service life
Immature cooling technologies	More bleed air required, lower core efficiency, reduced net thrust
Absence of powder metallurgy discs	Reduced fatigue strength and thermal tolerance in rotating parts
Lack of advanced forging infrastructure	Lower manufacturing quality and structural integrity of critical parts
No compressor blisk technology	Higher compressor weight, greater aerodynamic loss, lower efficiency
Gap in high-specific-strength materials	Higher component mass, lower creep/fatigue resistance, lower durability
Limited access to critical alloying elements	Lower hot-section temperature capability and lower blade life
Inadequate test infrastructure	Slow validation of altitude, reflight, endurance, and operability performance
Afterburner/wet thrust shortfall	Lower maximum thrust and weaker combat/takeoff performance
Interrupted funding	Slowed subsystem maturation, weaker continuity in testing, and redesign
Weak industrial ecosystem	Slower iteration, quality inconsistency, limited scale-up potential
Evolving certification capability	Longer qualification cycles and conservative operating limits

The comparative assessment also underscores the importance of process knowledge in achieving mature propulsion capability.[1] Countries with advanced aero-engine programmes demonstrate strong competencies not only in design and manufacturing, but also in testing methodologies, certification protocols, and reliability growth processes. In the Kaveri case, limitations in these areas contributed to extended development timelines and a delayed transition from prototype to operational readiness. This suggests that the acquisition of tacit process knowledge is as critical as access to design data or manufacturing technology. [1]

The evaluation of development strategies indicates that decoupling airframe and engine timelines can reduce programme risk. [17] Evidence from international programmes shows that interim reliance on foreign engines has been used to maintain aircraft development schedules while indigenous propulsion systems undergo



extended maturation. The findings support the effectiveness of this dual-track approach as a mechanism for managing technological uncertainty without compromising overall programme timelines.

Global capability assessment confirms that only a limited number of countries, the United States, Russia, the United Kingdom, and France, currently possess fully integrated capabilities for designing, manufacturing, testing, and certifying advanced fighter aero engines (Table. 7). China is approaching this level of capability, although with less publicly available validation data. [25]

This concentration of capability highlights the high barriers to entry and reinforces the importance of long-term, ecosystem-based development strategies.

The analysis also quantifies the technological requirements for next-generation engine development. Achieving thrust-to-weight ratios in the range of 8:1 to 10:1 requires increases in turbine entry temperature to approximately 2200–2300 K, along with the deployment of single-crystal turbine blades, advanced thermal barrier coatings, ceramic matrix composites, powder metallurgy discs, and high-efficiency compressor systems such as blisks. [33] These requirements are directly linked to improvements in thrust, efficiency, and durability, and represent critical technology gaps that must be addressed.

Recent developments, including the successful testing of the Manik small turbofan engine and the certification of indigenous aerospace superalloys, indicate incremental progress in addressing some of these gaps.[8], [12]

These outcomes demonstrate improvements in materials capability and subsystem-level development, although they do not yet constitute full-system fighter-engine capability. Equally critical is the retention and cultivation of high-skilled human capital, necessitating policy interventions to provide competitive career pathways and mitigate the persistent challenge of talent outflow.[24]

Table 7. List of Countries and Their Fighter Aero Engine Capabilities.

Countries with the Capability of Manufacturing Advanced Fighter Aero Engines			
Country	Representative Companies; Engines	5th Gen Fighter Capability	6th Gen / Next-Gen Fighter Capability
United States of America	GE Aerospace, Pratt & Whitney; F119, F135, XA100, XA101	Proven and operational	Most advanced globally; demonstrator stage and beyond
United Kingdom	Rolls-Royce; EJ200, GCAP/Tempest propulsion, Orpheus	Proven, though at a smaller industrial scale than the USA	Strong developmental capability for next-generation combat air propulsion
France	Safran Aircraft Engines; M88, future FCAS propulsion work	Proven and operational	Credible next-generation capability, especially with European collaboration
Russia	UEC Saturn and broader UEC ecosystem; AL-41 class, Izdeliye 30	Proven in advanced fighter engines	Likely capable, but public evidence is less transparent than USA / UK / France
China	AECC and associated programs; WS-10, WS-15, future adaptive concepts	Emerging to increasingly credible	Developing rapidly; not yet as transparent or as proven as the USA
India	GTRE, HAL, MIDHANI and related ecosystem; Kaveri derivatives, future AMCA engine efforts	Not yet proven for frontline 5 th -generation fighter-class engines	Developmental aspiration rather than demonstrated capability

South Korea	Hanwha Aerospace and national KF-21-related industrial ecosystem	Limited sovereign capability; major progress in manufacturing and integration	Early-stage developmental potential
Turkey	TEI and associated indigenous fighter propulsion effort	Developing, not yet fully sovereign at the top tier	Emerging developmental capability

Overall, the findings indicate that aero-engine development outcomes are determined by the interaction of technological capability, industrial ecosystem maturity, testing infrastructure, funding scale, and institutional processes. The Kaveri programme illustrates that partial success in these domains can generate significant capability gains, even in the absence of immediate operational deployment. Future progress will depend on coordinated advancement across these dimensions, with particular emphasis on materials technology, testing infrastructure, and sustained investment.

11. Conclusion

Kaveri should be understood as unfinished capacity rather than a failure. While it did not meet the thrust demands of Tejas, it delivered the foundations India needs for a fighter-class engine: a running core, validated derivatives such as dry Kaveri and KMGT, high-altitude test competence, and the emergence of private-sector manufacturing capability. These are tangible national assets rather than sunk costs. Measured against historical experience, propulsion is inherently turbulent; the U.S. jet age matured through redesign loops, concurrency, and materials catch-up, not linear progress. Modern programmes show the same pattern: many nations field airframes with interim imported engines while their domestic turbfans accumulate reliability, a pattern visible from Tejas to TF-KAAN and KF-21.

This context normalizes Kaveri's trajectory. What matters now is programme design. India can convert Kaveri's accumulated learning into AMCA power by treating propulsion as a long-horizon portfolio: sustained funding, a deeper supplier ecosystem, rigorous certification, upgraded rigs and materials lines, and collaboration structured around process learning rather than IP fantasies. Done right, the K-series path to a 90–100 KN Indian core becomes a realistic timeline-bound spiral rather than a leap of faith. In this sense, Kaveri's legacy lies not in what it could not power, but in what it now enables, the first credible foundation for India's AMCA engine.

12. Limitations of the Study

This study is subject to both data-related and methodological constraints. From a data perspective, the analysis relies primarily on secondary and open-source information, including technical reports, policy documents, and publicly available literature. The limited availability of disaggregated, high-fidelity data on engine performance parameters, materials specifications, testing outcomes, and certification processes, particularly for advanced and classified aero-engine programmes, restricts the precision of cross-country comparisons. In addition, inconsistencies in reporting standards and the absence of standardized benchmarking metrics across countries introduce uncertainties in comparative evaluation.

Furthermore, the data presented in Tables 3 and 5 comprise a combination of technical parameters and quantitative estimates derived from secondary sources. Table 3 reflects the design requirements for the Kaveri engine as specified by GTRE and documented in published references. Table 5, in contrast, includes both design targets and achieved performance parameters across the engines considered. For the Kaveri engine, the values reported represent a mix of intended design specifications and partially realized performance metrics; consequently, discrepancies between Tables 3 and 5 arise due to the distinction between targeted and achieved values of Kaveri, with the latter concerning Kaveri not fully meeting the original design requirements.

For the remaining engines listed in Table 5, the reported parameters are treated as representative of achieved design performance, given that these engines are operational and have undergone extensive validation. Table 4 presents the developmental status of the Kaveri programme based on data extracted from a Comptroller and Auditor General (CAG) report, while the other tables primarily synthesize qualitative insights interpreted from published literature and credible open-source material.

It is important to note that the Kaveri topic under study is characterized by limited availability of peer-reviewed technical literature and restricted access to high-fidelity data. As a result, both the quantitative and qualitative information presented in the tables and, by extension, elsewhere in the paper, are subject to inherent



uncertainties and potential inconsistencies. These limitations should be considered when interpreting the comparative and analytical findings of the study.

From a methodological standpoint, the study adopts a qualitative, comparative framework, which, while suitable for identifying structural patterns and systemic relationships, does not incorporate quantitative modelling or simulation-based validation of engine performance. As a result, the analysis is constrained in its ability to establish precise causal magnitudes between specific technological gaps and performance outcomes. Furthermore, the comparative approach is limited by asymmetry in data availability across countries, which may lead to partial representation of certain national programmes. Future research could address these limitations by integrating primary data sources, expert elicitation, and thermodynamic or system-level modelling to strengthen empirical robustness and analytical depth.

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15. Conflict of Interest

The author declares no competing conflict of interest.

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17. Author Biographies

Vidyasagar Kotha is an aerospace propulsion researcher and a retired defence professional with over 27 years of experience in military aviation, performance optimization of aero engines, aero engine maintenance, diagnostics, and prognostics. During his service with the Indian Air Force, he specialised in preventive, corrective, and predictive maintenance of gas turbine aero engines, including the Rolls-Royce Adour engines, with hands-on expertise in engine stripping and assembly, module change workshops, aero engine testing in engine test beds, and ground test runs across line and overhaul environments. He trained on aircraft such as the SEPECAT Jaguar and BAE Systems Hawk, was awarded the Sir Roy Fedden Scholarship by Cranfield University, UK in 2018, has published multiple international research papers, and is a Member of the Royal Aeronautical Society (MRAeS), UK. He holds a Diploma in Mechanical Engineering from Government Polytechnic College, Anantapur, along with BS and MS degrees from Birla Institute of Technology and Science, Pilani, and an MSc in Aerospace Propulsion from Cranfield University, UK. He is currently pursuing a Ph.D. in Aircraft Propulsion at the University of the Witwatersrand, South Africa, focusing on life prediction and extension of legacy gas turbine aero engines through reengineering with an emphasis on sustainability, emissions reduction, and reliability. He is also the Founder and CEO of Kotha Aerospace, where he mentors students and professionals while advancing research-informed practices in aerospace propulsion.



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P Midhun is an Aeronautical Engineer specializing in aerodynamics, Computational Fluid Dynamics (CFD), aeroelastic stability, and store separation trajectory analysis. She graduated from Anna University and is also an independent aerospace researcher with prior research experience at the National Aerospace Laboratories (NAL) and the Aeronautical Development Establishment (ADE) under DRDO, India. Contributing to major defence programs including SARAS Mk II, High Altitude Platform Station (HAPS), and the Long Range Land Attack Cruise Missile (LRLACM). Areas of expertise include aerodynamic design and optimization, turbulence modeling, CFD–FEA coupling and configuration analysis. To date, two research papers have been published. Research interests focus on defence modernization, integrating advanced aerospace engineering with innovative explorations of ancient technology.



Manya Sachdeva is an undergraduate Aerospace Engineering student at the University of Petroleum and Energy Studies (UPES), Dehradun, India. Her research interests include propulsion systems, aerodynamics, and computational fluid dynamics (CFD). She has gained practical experience through internships with Prime Toolings and the Indian Air Force's 3 Base Repair Depot, working on CFD, FEA, and aircraft maintenance systems. She is currently involved in research on Pulsed Detonation Engines (PDE), focusing on performance optimization using GasTurb and CFD simulations. She also serves as Managing Director of the AeroHobby Club at UPES and is a student member of the Royal Aeronautical Society (RAeS). Her work has been recognized with the Best Poster Award at ISC 1.0, NSC 4.0.

