DETAILED PROJECT REPORT (DPR)

Hybrid Digital Twin Framework for Aero Gas Turbine Engine Health Usage Monitoring System

Executive Summary

This Detailed Project Report outlines the development of a hybrid Digital Twin (DT) framework for aero gas turbine engine health monitoring over 36 months. The project integrates physics-based thermodynamic models with AI-driven analytics across 17 DT blocks, achieving ≤5% model error and ≤10% virtual sensor accuracy. **Total Project Cost: ₹15.30 Cr**, including manpower (₹4.50 Cr), hardware (₹2.04 Cr), software (₹0.98 Cr), infrastructure (₹0.43 Cr), academic partnerships (₹0.57 Cr), testing/travel (₹1.50 Cr), overhead (₹1.41 Cr), and other expenses (₹3.46 Cr).

---

1. TITLE OF PROJECT

Development of Hybrid Digital Twin Framework for Aero Gas Turbine Engine Health Usage Monitoring System

Project Duration: 36 months
Project Type: Research & Development
Implementing Agency: Industrial Partner (Technology Development Partner)
Funding Agency: DRDO / Government Technology Development Scheme

---

2. PROPOSED SOLUTION

2.1 Brief Explanation of Solution

The project aims to develop a comprehensive hybrid Digital Twin (DT) framework that creates a high-fidelity virtual representation of a deployed aero gas turbine engine. The Digital Twin shall integrate:

- **Physics-Based Thermodynamic Models:** Foundation-level models of major engine components (inlet, compressor, combustor, turbine, nozzle) and subsystems based on design and engineering parameters, simulating aero-thermodynamic behaviors across the Brayton cycle.

- **Data-Driven AI Models:** Machine learning algorithms (regression techniques, neural networks) that augment physics-based models using ~400 test runs (70% training, 30% validation split) from ground tests, simulated altitude tests, and flight tests to enhance fidelity and adaptability.

- **Virtual Sensors:** Synthesized sensor algorithms providing both measurable and derived non-dimensional parameters, validated against actual sensor data to enable real-time monitoring without physical sensor redundancy.

- **Anomaly Detection & Diagnostics:** Fault seeding systems and error-banding algorithms to isolate anomalies within engine-to-engine tolerance bands, supporting prognostics for engine health management.

The DT serves as a simulation platform for studying normal and failure-mode behaviors of engines and subsystems under various flight conditions, enabling diagnostics and prognostics algorithms for lifecycle health monitoring.

2.2 System Configuration

The hybrid DT framework comprises 17 critical building blocks (DT blocks) organized as follows:

Core DT Model Blocks (Physics-Based):

1. Inlet/Intake Module
2. Compressor Module (multi-stage thermodynamic representation)
3. Combustor Module
4. High-Pressure Turbine Module
5. Low-Pressure Turbine Module
6. Nozzle/Exhaust Module
7. Control System Module (fuel flow, variable geometry)
8. Bleed/Cooling System Module
9. Accessory/Drive Module

Integration & Sensor Blocks (Hybrid):

10. Virtual Sensor Fusion Engine
11. Data Pre-processing & Feature Extraction Pipeline
12. Machine Learning Model Repository (regression/neural networks)
13. Anomaly Detection & Isolation Engine
14. Fault Diagnostics Module
15. Prognostics/Health Monitoring Module
16. Graphical User Interface (GUI) with Drag-Drop Features
17. Real-Time Integration Platform (RTOS, data storage/retrieval)

System Resources:

- **Computational Platform:** Real-time capable servers with RTOS, multi-core processors for parallel computation.
- **Data Management:** Large data handling infrastructure for heterogeneous datasets.

- **Tools Integration:**

2.3 Approach to Solution

2.3.1 Design Phase (Months 0-6, PDR):

- Conduct literature survey on AI-augmented thermodynamic models and contemporary DT systems.
- Finalize System Requirement Document (SRD) via mutual agreement with DRDO.
- Define architecture of the 17 DT blocks using commercial off-the-shelf (COTS), open-source, or in-house tools.
- Identify critical technologies: AI-augmented thermodynamics and virtual sensors.
- Preliminary design of model structure, data flow, and integration strategy.

2.3.2 Analysis Phase (Months 6-12, Detailed Design):

- **Thermodynamic Analysis:** Develop physics-based models for each of the 9 core component modules using component maps, cycle analysis, and conservation principles (mass, energy, momentum).
- **Data Analysis:** Collect and pre-process test runs with feature selection from engine tests.
- **Feasibility Study:** Determine physics-based vs. data-driven modeling strategy per component.
- **Sensor Strategy:** Employ observability-based concepts to identify optimal sensor set, types, and locations; design virtual sensor algorithms for non-measurable states.
- **Design Specifications:** Produce Detailed Design Document (DDD) and System Design Document (SDD) covering 17 DT blocks, data pipelines, and integration framework.

2.3.3 Realization Phase (Months 12-18, Prototype Development):

- **Model Development:** Implement 17 DT blocks with hybrid physics/ML fusion; train regression models and nonlinear models on 70% training data.
- **Integration:** Cluster fused data into performance regimes; integrate models into unified framework via RTOS platform.
- **Offline/Online Testing:** Execute prototype in offline mode and online mode; verify subsystem-level and integrated-level performance against synthesized test data.
- **Data Fusion:** Develop algorithms to combine physics-based outputs with ML predictions for improved fidelity.
- **Approval:** Obtain Critical Design Review (CDR) approval and Approval of Critical Design Document (CDD).

2.3.4 Validation & Testing Phase (Months 18-30, Production & Supply):

- **Model Validation:** On-site training with DRDO using actual engine test data (no external data export) for final model calibration; execute 70/30 split validation with error metrics (MAE, R^2, max error).
- **Hardware Integration:** Procure and integrate real-time supported hardware, RTOS drivers, and GUI; test hardware/software platform for real-time execution.
- **Anomaly Detection Validation:** Perform PLA/flight condition input comparisons; test anomaly isolation logic within prescribed error bands and engine-to-engine tolerance bands.
- **GUI & Visualization:** Develop drag-drop interface, alarm queue display, pictorial component representations, and data storage/retrieval systems.
- **ATP Preparation:** Finalize Acceptance Test Plan (ATP) document based on 17 DT blocks' functionality; execute ATP under committee supervision.

2.3.5 Qualification & Acceptance Phase (Months 30-36, Documentation & ToT):

- **Committee Testing:** Formally constituted DRDO committee conducts comprehensive ATP testing; evaluates Figure of Merit (FoM), indigenous content, and performance against targets.
- **Performance Metrics:** Validate DT models (≤5% error) and virtual sensors (≤10% error) via comparison of simulation vs. experimental results.
- **ATP Approval:** Record measurements, demonstrate functionality in lab/operational environment, analyze deviations, and recommend way forward.
- **Documentation:** Complete project documentation (SRD, SDD, DDD, CDD, ATP, user manual, project success report).
- **Transfer of Technology (ToT):** Execute ToT per TDF Scheme SOP; train DRDO personnel on framework operation, model updates, and maintenance.
- **IPR Handover:** Share intellectual property rights as per RFP terms and Project Definition Document.

2.3.6 Acceptance Test Plan (ATP) Overview:

ATP shall validate:

1. **Functionality:** 17 DT blocks operate per specifications; virtual sensors provide accurate derived parameters.
2. **Performance:** DT models achieve ≤5% error (MAE, R^2, max error); virtual sensors achieve ≤10% error across flight envelope.
3. **Real-Time Execution:** Framework executes at real-time rates on designated computational platform.
4. **Anomaly Isolation:** Anomaly detection correctly isolates failures within prescribed tolerance bands.
5. **Data Integrity:** Data pre-processing and storage/retrieval systems ensure data quality.
6. **GUI Functionality:** Drag-drop features, alarm visualizations, and component pictorials function per design.

7. **Indigenous Content:** Quantified and documented per industry standards.

---

3. SUPPORT EXPECTED FROM DRDO OR OTHER GOVERNMENT INSTITUTIONS

The following support is required from DRDO on a cost-reimbursable basis (not funded by project budget):

3.1 Data Access & Infrastructure:

- **On-site Facility Access:** Laboratory space at DRDO facility for model development, training, validation, and ATP testing; secure data handling environment compliant with defense protocols.
- **Engine Test Data:** Provision of ~400 test runs from 2-3 aero gas turbine engines across various flight conditions (ground, simulated altitude, flight tests); data to remain within DRDO premises.
- **Sensor Data Access:** Real-time and historical sensor measurements from deployed engines for validation of virtual sensors.

3.2 Technical Collaboration:

- **Mutual Requirement Finalization:** Joint sessions with DRDO technical team for SRD finalization, FoM definition, and ATP criteria.
- **Review & Approval:** DRDO technical committee to conduct PDR, CDR, and final acceptance review; provide technical feedback and approval signatures.
- **Data Format Specifications:** DRDO to provide standardized formats, naming conventions, and metadata descriptions for engine test data.

3.3 Hardware & Infrastructure (Optional Cost):

- **Real-Time Platform Specification:** DRDO to identify or provide mutual-agreed computational platform specifications for on-site deployment.
- **RTOS & Libraries:** Supply or approval of real-time operating systems, communication protocols, and software libraries as per system requirements.

3.4 Training & Capability Building:

- **Personnel Training:** DRDO to nominate 3-4 personnel for intensive ToT on DT framework operation, model updates, fault diagnostics, and prognostics.
- **Handover Sessions:** Post-delivery handover sessions for knowledge transfer, documentation review, and troubleshooting protocols.

3.5 Regulatory & Compliance Support:

- **Certification Pathways:** Technical guidance on compliance with defense/aerospace standards for model validation, software quality, and system

integration.
- **Indigenous Content Verification:** Assistance in documenting and verifying indigenous content per defense procurement guidelines.

---

4. TOTAL PROJECT COST OVERVIEW

Complete financial overview with 20% milestone payments:

Category	Cost (Cr INR)	% of Total	Key Components
Manpower	4.50	29%	20 team members, 14 FTE avg., 305 Person-Months
Hardware & Computational Equipment	2.04	13%	Servers (₹70L), RT PCs (₹24L), Storage (₹25L), Workstations (₹30L)
Software & Licenses	0.98	6%	NPSS (₹25L), ANSYS (₹20L), MATLAB (₹10L), Cloud (₹15L)
Infrastructure & Facilities	0.43	3%	Lab setup (₹20L), Security (₹8L), Consumables (₹10L)
Academic Partnerships	0.57	4%	IITs (₹30L), IIT Madras NCCRD (₹12L), NAL/ADA (₹15L)
Testing/Travel/Contingency	1.50	10%	Travel (₹15L), Testing (₹1.00 Cr), Contingency (₹40.9L)
Overhead (10%)	1.41	9%	Project management overhead
Other Expenses	3.46	23%	Patents (₹30L), 3rd-party testing (₹60L), Legal (₹20L)
TOTAL	**~15.30**	**100%**	**Phase-aligned with 5 milestones**

Testing/ Travel/ Contingency: Expenses include equipment contingency, software license contingency, travel and site visits, technical training & certification, miscellaneous & unforeseen.

Other Expenses: Includes testing & validation, travel & logistics, third-party testing, patents & IP filing, publications & conferences, legal & compliance, insurance & bonding.

Payment Schedule: 20% per milestone (MS-1 to MS-5) = ₹3.06 Cr each.

---

5. DETAILS OF ACADEMIC PARTNERS & SCOPE OF WORK

5.1 Recommended Academic Partners

S.No.	Institution	Role & Scope of Work	Deliverables
1	**IIT (Kanpur/Delhi/Bombay)**	Physics-based thermodynamic modeling expertise; neural network architecture design for hybrid models	Design guidelines for 9 core DT blocks (inlet, compressor, combustor, turbines, nozzle); ML architecture recommendations
2	**Cranfield University (UK)**	Gas turbine cycle analysis expertise; digital twin methodology consultancy	Technical review of DT framework architecture; validation approach recommendations
3	**National Aerospace Institute (ADA/NAL)**	CFD integration expertise; aerodynamic validation support	CFD-based component model validation; performance map generation
4	**DRDO-HAL Collaboration Units**	Engine test data analysis; fault diagnostics expertise	Anomaly isolation algorithms; fault mode characterization from test data

5.2 Scope of Work for Academic Partners

- **Literature Review & Technology Survey:** Conduct comprehensive survey on AI-augmented thermodynamic models, virtual sensors, and hybrid DT methodologies in aero engines.
- **Model Architecture Design:** Develop and review physics-based and data-driven model structures for 17 DT blocks; optimize feature selection and ML model selection.
- **Algorithm Development:** Design anomaly detection, feature extraction, and prognostics algorithms; validate via simulation and historical data.
- **Technical Reviews:** Participate in PDR, CDR, and final review meetings; provide technical recommendations for model improvements.
- **Training & Knowledge Transfer:** Conduct workshops on hybrid modeling approaches; assist in ToT execution.
- **Validation Support:** Validate models against theoretical benchmarks and published performance data; provide independent assessment. s

---

6. RISK ANALYSIS & MITIGATION PLAN

6.1 Technical Risks

S.No.	Risk	Probability	Impact	Mitigation Strategy
1	Model Convergence Failure	Medium	High	Establish rigorous data quality assurance; leverage DRDO test data (400+ runs); use ensemble learning methods (multiple algorithms); allocate 2-3 months for iterative refinement during prototype phase
2	Data Availability Delays	Medium	High	Establish data-sharing protocol at project kick-off; use synthetic/historical data initially; secure interim data access agreements; maintain contingency dataset from literature
3	Virtual Sensor Validation Issues	Medium	High	Design virtual sensors with observability analysis; validate incrementally with subsystem data; include sensor fusion algorithms for redundancy; allocate extended validation phase
4	Real-Time Performance	Low	Critical	Perform early computational benchmarking; optimize critical path algorithms; use GPU acceleration for ML inference; select platform with sufficient margin (2-3x performance headroom)
5	Hybrid Model Fidelity	Medium	High	Use iterative validation; test individual block accuracy; employ sensitivity analysis; incorporate cross-validation with multiple ML techniques (regression, neural networks, ensemble methods)

6.2 Schedule Risks

S.No.	Risk	Probability	Impact	Mitigation Strategy

S.No.	Risk	Probability	Impact	Mitigation Strategy
1	Delayed PDR Approval	Low	Medium	Initiate pre-PDR discussions with DRDO at proposal stage; establish clear requirement elicitation process; weekly alignment meetings with user; prepare multiple SRD versions for rapid iteration
2	Extended Data Pre-processing	Medium	Medium	Allocate 4-6 weeks buffer in detailed design phase; engage data scientists early; automate data validation pipelines; establish parallel data processing workflows
3	Hardware Procurement Delays	Medium	Medium	Place orders immediately after CDR; maintain alternative vendor list; use interim workstations for initial development; negotiate delivery schedules with penalties
4	On-site Testing Duration	Medium	Medium	Prepare ATP document early (at PDR); conduct pre-ATP testing with test data; maintain test team on-site continuously; establish clear pass/fail criteria in advance

6.3 Resource & Budget Risks

S.No.	Risk	Probability	Impact	Mitigation Strategy
1	Key Personnel Attrition	Low	High	Establish competitive compensation; cross-train team members; document critical knowledge; retain contingency budget for recruitment/backfill
2	Cost Overrun	Medium	Medium	Obtain fixed-price quotes; phase procurement; negotiate volume discounts; maintain 10% budget contingency; approve only essential acquisitions early

S.No.	Risk	Probability	Impact	Mitigation Strategy
3	Scope Creep	Medium	Medium	Establish formal change control process; define scope baseline at PDR; require DRDO approval for scope changes; apply time/cost impact analysis

6.4 Technology & Integration Risks

S.No.	Risk	Probability	Impact	Mitigation Strategy
1	Tool Interoperability	Medium	Medium	Evaluate tool versions early; establish test environment; use middleware/APIs for tool integration; employ containerization (Docker) for portability
2	Data Security Breach	Low	Critical	Implement air-gapped development on DRDO site; enforce encryption for all data transfers; establish audit logs; conduct security training for all personnel; restrict USB/external device access
3	Algorithm Performance Degradation	Medium	Medium	Employ physics-based constraints in data-driven models (Physics-Informed Neural Networks); test with out-of-distribution data; design prognostics algorithms to flag degradation; use ensemble methods for robustness

6.5 Organizational & Governance Risks

S.No.	Risk	Probability	Impact	Mitigation Strategy
1	Review Committee Delays	Low	Medium	Establish review schedules 2 months in advance; provide complete review packages on time; designate single DRDO liaison; schedule monthly progress reviews with committee

S.No.	Risk	Probability	Impact	Mitigation Strategy
2	Changing User Requirements	Medium	High	Baseline requirements at PDR in formal SRD; establish formal change control; require mutual sign-off on changes; apply schedule/cost impact analysis
3	IPR Disputes	Low	Medium	Finalize IPR terms in RFP; document contributions clearly; establish IP steering committee; engage legal counsel early

6.6 Risk Monitoring & Escalation

- **Risk Register:** Maintain live risk register updated monthly; track risk status (open/mitigated/closed).
- **Review Cadence:** Monthly review with project team; quarterly review with DRDO steering committee.
- **Escalation Threshold:** Risks impacting schedule >4 weeks or budget >₹50L escalated immediately to program director.
- **Contingency Allocation:** 10% schedule buffer (3.6 months) and 10% cost buffer (retained for emergencies).

---

7. PROPOSED INDIGENOUS CONTENT

Indigenous Content Target: **75-80%**

Indigenous content includes:

- Custom algorithm development (AI-augmented thermodynamics, virtual sensors, hybrid fusion, anomaly detection, prognostics)
- Python/open-source framework utilization
- RTOS integration and real-time optimization
- GUI and visualization development
- Documentation and knowledge transfer

Not counted as indigenous:

- COTS tools
- Hardware platforms
- Foundational ML libraries

---

8. INDUSTRY PROFILE IN DETAIL (TBD)

8.1 Company Overview

8.2 Technical Capabilities & Track Record

8.3 Financial Credentials

8.4 Compliance & Regulatory Status

---

9. PROJECT EXECUTION PLAN & GOVERNANCE

9.1 Project Management Structure

```
                    DRDO Steering Committee
                            |
                            |--- Program Director (DRDO)
                            |
                    Industrial Partner
                    Project Director
                            |
     +---------+--------+-----------+----------+---------+
     |         |        |           |          |         |
   Therm.Eng. ML Eng. Soft. Arch  Data Sci. QA Lead   Sys.
 Eng.
     |         |        |           |          |         |
   Team      Team     Team        Team       Team      Team
```

9.2 Governance & Review Gates

- **Monthly Technical Reviews:** Project status, technical blockers, risk updates.
- **Quarterly DRDO Reviews:** Schedule, budget, milestone compliance, quality metrics.
- **Formal Gate Reviews:** PDR (6M), CDR (12M), System Integration Review (18M), ATP (30M), Project Completion (36M).

9.3 Quality Assurance Plan

- **V&V Activities:** Verification against design specs; validation against acceptance criteria.
- **Testing Strategy:** Unit, integration, system, and UAT testing as per ATP.
- **Metrics:** Test coverage >95%; defect density <0.5 per KLOC; traceability 100%.

---

10. PROJECT SUCCESS CRITERIA & METRICS

10.1 Technical Success Criteria

Criterion	Target	Acceptance
DT Model Accuracy	≤5% error (MAE, R^2, max error)	YES/NO per component
Virtual Sensor Accuracy	≤10% error vs. measured data	YES/NO per sensor
Real-Time Execution	≥100% real-time factor (engine clock)	YES/NO
Anomaly Detection	Correct isolation >95% of test cases	YES/NO
Data Integrity	Zero critical data losses; >99.9% availability	YES/NO
GUI Functionality	All 20+ features operational per specifications	YES/NO

10.2 Schedule Success Criteria

Milestone	Target Date	Tolerance
MS1 (PDR)	Month 6	±2 weeks
MS2 (Detailed Design)	Month 12	±2 weeks
MS3 (Prototype)	Month 18	±4 weeks
MS4 (Production ATP)	Month 30	±4 weeks
MS5 (Completion)	Month 36	±2 weeks

10.3 Budget Success Criteria

Category	Budget (INR)	Variance Tolerance
Manpower	[₹4.5 Cr]	±5%
Hardware	₹2.04 Cr	±5%
Software	₹98 L	±5%
Infrastructure	₹43 L	±10%
Academic Partnerships	₹57 L	±5%
Other Expenses	₹346 L	±5%
Contingency	₹150 L	Reserved for emergencies

10.4 Figure of Merit (FoM) & Key Performance Indicators

FoM Metric	Baseline	Target	Measurement
DT Fidelity Score	-	>95%	Aggregate accuracy across 17 DT blocks
Virtual Sensor Reliability	-	>98%	Availability & accuracy metrics
System Uptime	-	>99.5%	RTOS platform availability
Data Processing Latency	-	<500ms	End-to-end prediction time
Indigenous Content	-	75-80%	Quantified by DRDO
User Satisfaction	-	>4.5/5	Post-delivery survey

11. EXPECTED OUTCOMES & DELIVERABLES

11.1 Technical Deliverables

1. **Hybrid Digital Twin Framework** (Physical + Virtual)
    - 17 fully integrated DT blocks (physics + data-driven)
    - Source code repository with version control
    - Real-time execution on designated RTOS platform
2. **Model Components**
    - Physics-based thermodynamic models (9 core components)
    - Data-driven ML models (regression, neural networks, ensembles)
    - Virtual sensor algorithms (8-12 sensors)
    - Anomaly detection & isolation logic
    - Prognostics/health monitoring module
3. **Software Artifacts**
    - Graphical User Interface (GUI) with drag-drop features
    - Data management system (pre-processing, storage, retrieval)
    - Real-time integration platform (RTOS layer, middleware)
    - Fault diagnostics & alarm system
4. **Hardware Deployment**
    - Real-time computational platform (servers, I/O modules)
    - Network infrastructure (redundant links, security)
    - Data storage system (500TB RAID)
    - Sensor interface & data acquisition modules

11.2 Documentation Deliverables

1. **Design Documents**
    - System Requirement Document (SRD)
    - System Design Document (SDD)
    - Detailed Design Document (DDD)
    - Critical Design Document (CDD)
    - Software Requirements Specification (SRS)
    - Software Design Document (SDD for GUI)
2. **Test Documents**
    - Acceptance Test Plan (ATP)
    - Test Case Specifications (500+ test cases)
    - Test Results Report
    - Validation & Verification Report (V&V)
3. **User Documentation**
    - User Manual (operation, maintenance, troubleshooting)
    - System Administrator Guide (hardware/software setup)
    - API Documentation (for future integrations)
    - Quick Start Guide
4. **Project Documentation**
    - Project Success Report
    - Lessons Learned & Best Practices
    - Risk Register & Mitigation Summary
    - Financial Closeout Report

11.3 Knowledge Transfer Deliverables

Training Materials

- Training course
- Training slides, videos
- Reference manuals

11.4 Intellectual Property Deliverables

1. **Access to Developed Work including:**
    - Version-controlled repository
    - Build/deployment scripts
    - Test harnesses and utilities
2. **Data & Models**

- Trained ML models (weights, architectures, training data specifications)
- Physics-based component models
- Calibration data & tuning parameters

3. **IP Rights Documentation**

    - List of all custom algorithms, designs, and methodologies
    - Patent applications (if applicable)
    - Licensing terms for third-party tools used

---

12. PROJECT TIMELINE & MILESTONE SCHEDULE

Refer to Section 2 of the PDD for detailed milestone schedule:

Phase	Duration	Key Milestones	Cumulative Payment
Preliminary Design Review (PDR)	0-6 months	Approved SRD, PDD, tech survey	20%
Detailed Design	6-12 months	Approved SDD, DDD, design reviews	40%
Prototype Realization	12-18 months	Approved CDD, prototype validation	60%
Production & Supply	18-30 months	ATP execution, acceptance testing	80%
Documentation & ToT	30-36 months	Project completion, IPR sharing	100%

---

13. FINANCIAL SUMMARY

13.1 Project Cost Breakdown

Category	Estimated Cost (INR)	% of Total
Manpower (36 months, ~16 FTE avg.)	₹4.50 Cr	45%
Tangible Assets & Equipment	₹3.86 Cr	25%
Software & Tool Licenses	₹98 L	7%
Testing, Travel & Contingency	₹1.50 Cr	10%
Academic Partnership & Consultancy	₹57 L	4%
Overhead & Admin (10%)	₹1.41 Cr	9%

Category	Estimated Cost (INR)	% of Total
TOTAL PROJECT COST	**~₹15.00 Cr**	**100%**

13.2 Milestone-Based Payment Schedule

Milestone	Months from Start	Deliverables	Payment (% of Total)	Cumulative (INR)
MS-1 (PDR)	6	SRD, Approved PDD, tech survey	20%	₹3.00 Cr
MS-2 (Detailed Design)	12	SDD, DDD, design documents	20%	₹3.00 Cr (cumulative ₹6.00 Cr)
MS-3 (Prototype)	18	CDD, prototype code, validation reports	20%	₹3.00 Cr (cumulative ₹9.00 Cr)
MS-4 (Production)	30	Hardware, software, ATP report	20%	₹3.00 Cr (cumulative ₹12.00 Cr)
MS-5 (Completion)	36	Full documentation, ToT, source code	20%	₹3.00 Cr (cumulative ₹15.00 Cr)

---

14. CONCLUSION

This Detailed Project Report outlines the comprehensive approach for developing a hybrid Digital Twin framework for an Aero Gas Turbine Engine Health Usage Monitoring System. The project leverages state-of-the-art physics-based thermodynamic modeling, advanced machine learning techniques, and real-time integration to create a high-fidelity virtual replica of aero-engines, enabling diagnostics, prognostics, and lifecycle health management.

Key Strengths of the Proposal:

1. **Hybrid Approach:** Combines physics-based rigor with data-driven adaptability for robust, fidelity-enhanced modeling.
2. **Comprehensive Scope:** 17 DT blocks covering all major engine systems and subsystems.
3. **Rigorous Validation:** 70/30 train/validate split on 400+ test runs; <5% error targets; formal ATP acceptance.

4. **Indigenous Capability:** 75-80% indigenous content, building sustainable DRDO capability.
5. **Structured Governance:** Clear milestones, gated reviews, risk management, and QA protocols.
6. **Scalability:** Framework designed for adaptation to other aero-engines for future DRDO projects.

Expected Impact:

- **Operational:** Real-time engine health monitoring, predictive maintenance, extended time-between-overhauls.
- **Strategic:** Indigenous digital twin technology; reduced dependence on external diagnostics tools; technology leadership in aero-engine health management.
- **Capability Building:** DRDO in-house expertise in hybrid AI-physics modeling; sustainable ToT for future engine variants.

The project is technically feasible, strategically aligned with DRDO objectives, and positioned for successful delivery within the 36-month timeline and ₹15 Cr budget.

This Detailed Project Report is prepared in accordance with DRDO Technology Development Scheme (TDS) guidelines and is ready for technical and financial evaluation by the DRDO Steering Committee.

APPENDICES

Appendix A: Glossary of Terms

- **DT (Digital Twin):** Virtual representation of physical systems enabling real-time monitoring and simulation.
- **Brayton Cycle:** Thermodynamic cycle of gas turbine engines (compression, combustion, expansion, exhaust).
- **NPSS:** NASA's Numerical Propulsion System Simulation software for engine modeling.
- **RTOS:** Real-Time Operating System ensuring deterministic, low-latency execution.
- **FoM (Figure of Merit):** Quantitative measure of system performance against objectives.
- **ATP (Acceptance Test Plan):** Formal testing protocol to validate acceptance criteria.
- **ToT (Transfer of Technology):** Knowledge and capability handover to user organization.
- **MAE (Mean Absolute Error):** Average prediction error metric.
- **PLA (Pilot Lever Angle):** Throttle command input in aircraft engines.

End of Detailed Project Report

Prepared by: [Company Name]
Date: [Date]
Authorized by: [Project Director Name & Signature]
Reviewed by: [DRDO/User Committee Representative Signature]