

# DETAILED PROJECT REPORT (DPR)

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## 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  $\leq 5\%$  model error and  $\leq 10\%$  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).

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### 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

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### 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 ( $\leq 5\%$  error) and virtual sensors ( $\leq 10\%$  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  $\leq 5\%$  error (MAE,  $R^2$ , max error); virtual sensors achieve  $\leq 10\%$  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.
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### 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
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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



### 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 <sup>2</sup> , 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.**

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*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.*

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## 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.
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## **End of Detailed Project Report**

**Prepared by:** [Company Name]

**Date:** [Date]

**Authorized by:** [Project Director Name & Signature]

**Reviewed by:** [DRDO/User Committee Representative Signature]