TECHNICAL REVIEW

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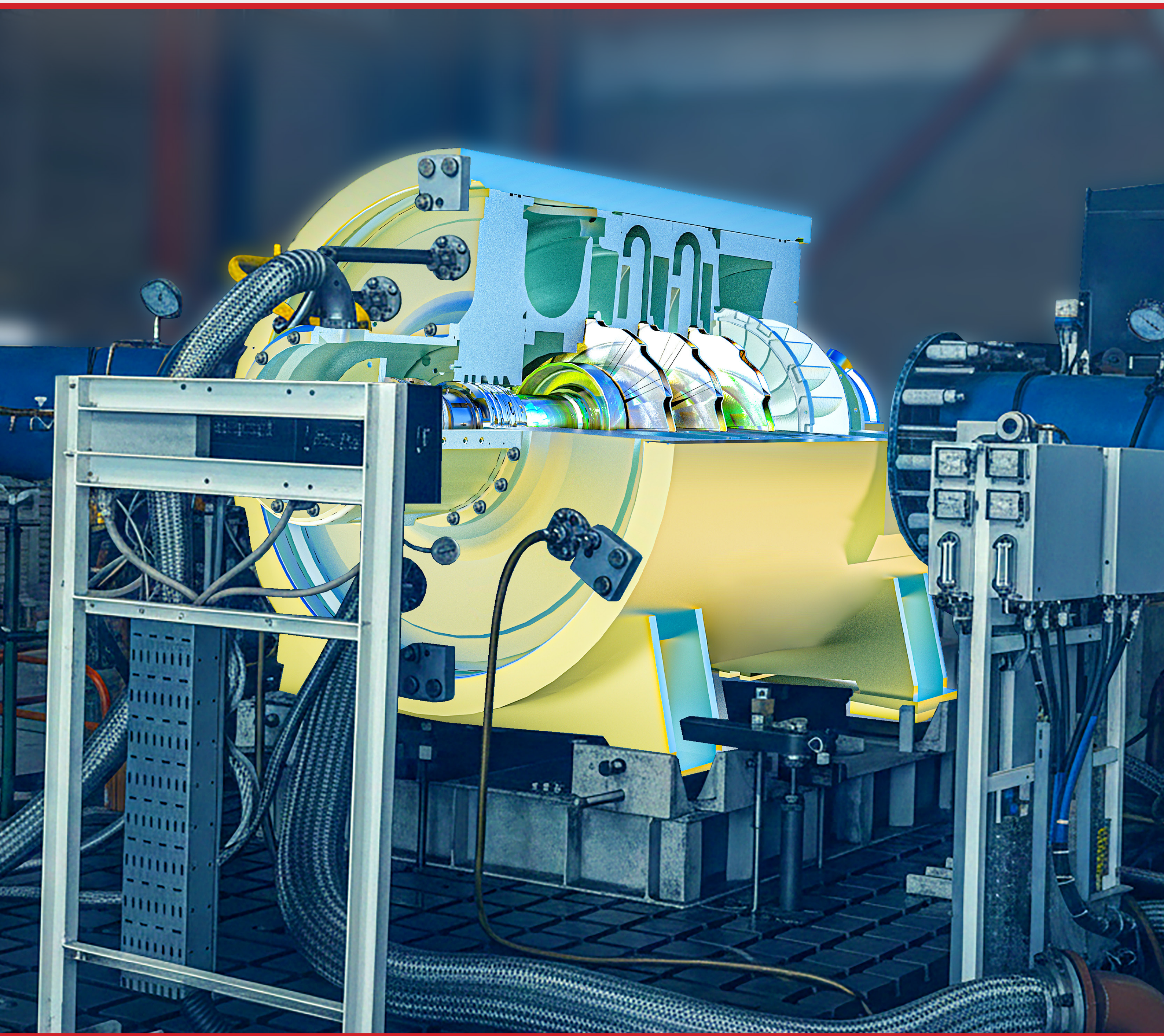

Technical Review

Willpower to Empower Generations

MAPNA GROUP
MAPNA Turbine Engineering
and Manufacturing Company

TECHNICAL REVIEW

Editorial & Production

Cover Page:
TUGA compressor test bench

Editorial

Dear Colleagues, Partners and Professionals,

In today's dynamic industrial landscape, staying ahead means not just meeting standards, but redefining them. At the heart of MAPNA Turbine's mission lies a strong commitment to innovation and deep customer partnership, driving us to continuously enhance our capabilities and solutions. It is in this context, and with great pleasure, that we present to you, our valued readers, a brief account of a few recent technological achievements in this edition of TUGA Technical Review.

To further solidify our position as a leading compressor manufacturer, we have successfully modularized our centrifugal compressor test bench. This strategic upgrade empowers us to rigorously test and validate fully customized, made-to-order compressors. The first article delves into the bench's modularization process, highlighting the improvements made to support diverse compressor configurations.

The second article introduces an integrated Reliability-Centered Maintenance (RCM) and Risk-Based Inspection (RBI) approach to improve turbo compressor maintenance. By combining reliability analysis and risk evaluation, this method reduces downtime, enhances availability, and lowers maintenance costs, as demonstrated in a gas transmission case study.

The third article highlights TUGA's development of a high-temperature vacuum brazing process using three filler metals (nickel, palladium, and gold) to produce reliable compressor impellers. The study validates the proposed brazing process, ensuring high joint strength and setting a foundation for future applications with advanced alloys.

Focusing on the development of a test rig for liquid fuel burner design, the fourth article presents a modular, experimental platform that enables precise control over injector geometry. It aims to improve combustion performance and operational flexibility in gas turbines by providing high-fidelity data for burner optimization.

The last article presents a predictive maintenance tool for monitoring injector health in diesel engines. Hardware development of this monitoring was previously addressed in Technical Review No.24. By using machine learning to analyze exhaust port temperatures, the system provides real-time fault detection, health assessment, and maintenance optimization, shifting maintenance strategies toward proactive, data-driven approaches.

Please join us in exploring a detailed account of these subjects in this issue of the Technical Review.

Respectfully,

Roohollah Jabery,

Vice President for Engineering and R&D

R Jabery

MAPNA Turbine Company (TUGA)

March 2026

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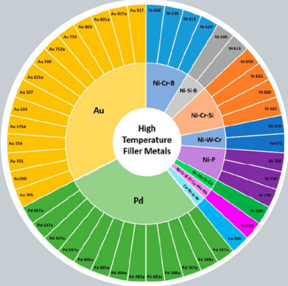
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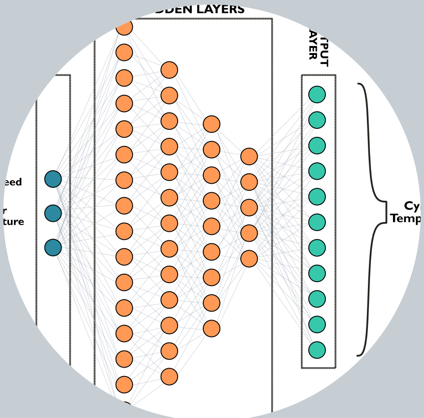
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1

Development of TUGA Compressor Test Bench for Tailor-Made Designs

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MAPNA Turbine Engineering & Manufacturing Co. (TUGA)

Introduction

Centrifugal compressors play a vital role in industries such as oil and gas, chemicals, steel manufacturing, and aerospace. They are primarily used for compressing gases and air in applications like gas transmission and storage systems, as well as air conditioning. These compressors rely on centrifugal force for gas compression, offering advantages such as high speed, large capacity, and superior efficiency, making them a popular choice in many industrial applications.

To ensure the correct and optimal operation of centrifugal compressors, it is crucial to conduct Mechanical Running and Performance tests. However, given the tailor-made design and manufacturing of centrifugal compressors, adaptability of test stations to various configurations is of utmost importance for compressor manufacturers. While TUGA's existing test bench could conduct these tests, its rigid design limited its ability to evaluate compressors tailored for specific projects. To overcome this challenge, TUGA launched a development project aimed at modularizing its test bench, enhancing flexibility and enabling compatibility with a wider range of compressor designs.

This article explores the mechanical running and performance tests conducted at TUGA's test bench and delves into the bench's modularization process, highlighting the improvements made to support diverse compressor configurations.

Figure 1 - TUGA compressor test bench

This new test bench design had to ensure that variations in parameters such as power, pressure, and flow rate of the compressor, as well as the number of temperature and vibration signals and their corresponding alarm and trip limits, would not pose an obstacle to testing new compressors on the test bench. Furthermore, since the sizes of connections in compressors are not standardized, the design had to allow the installation and connection of different connectors to the existing pipeline with minimal modifications. As a result, various systems of the test bench, including the control system, lubrication system, seal support, chassis, and pipeline systems were redesigned.

Mechanical Running and Performance Tests

Mechanical running and performance tests are crucial for ensuring the correct and optimal operation of centrifugal compressors. These tests (conducted according to API-617 and ASME PTC 10, respectively), evaluate the compressor's capability under various operating conditions, assess its performance across different flow and speed ranges, and analyze the results to simulate site conditions. These tests not only help identify potential issues, but are also critical for improving and upgrading the design and reducing maintenance and repair costs.

► Mechanical Running Test (MRT)

The Mechanical Running Test (MRT) of centrifugal compressors, conducted according to API-617, evaluates the mechanical function of the equipment and ensures proper installation and operation under working conditions. This test verifies the functionality of essential components while identifying potential issues such as excessive vibrations, temperature anomalies, or unusual noises.

■ MRT Steps and Requirements:

Equipment Preparation: The compressor must be fully assembled, with all supporting systems—lubrication, cooling, and electrical—correctly set up.

Initial Startup: The compressor is started gradually and under no-load conditions, with a gradual increase in rotational speed to prevent component damage.

■ Measurement of Key Parameters:

- Temperature: The temperatures of critical components such as bearings, lubrication systems, and air should be monitored throughout the test.
- Vibration: The compressor's vibrations must remain within the acceptable range, as excessive vibration may indicate installation or design flaws.
- Noise: Any unusual noise must be reported, as it could signal bearing or rotation issues.

Run at MCS and Trip Speed: The compressor must be tested at the maximum speeds it will encounter, including Maximum Continuous Speed (MCS) and Trip Speed, to verify real-world operational stability. The compressor's speed is initially increased in steps until it reaches Trip Speed, then decreased and raised again to MCS at a specific gradient. The compressor operates at these speeds for four hours while being monitored. The process is shown in Figure 2.

Test Duration: As outlined in API-617, the test should be generally conducted within a specific time frame, as defined by the standard, to ensure the compressor's performance remains stable over time.

Results Review: All collected data is analyzed to compare actual performance with API-617 requirements, documenting any deviations. The main goal of this test is to ensure that the centrifugal compressor operates effectively and safely under actual operational conditions and has no mechanical issues.

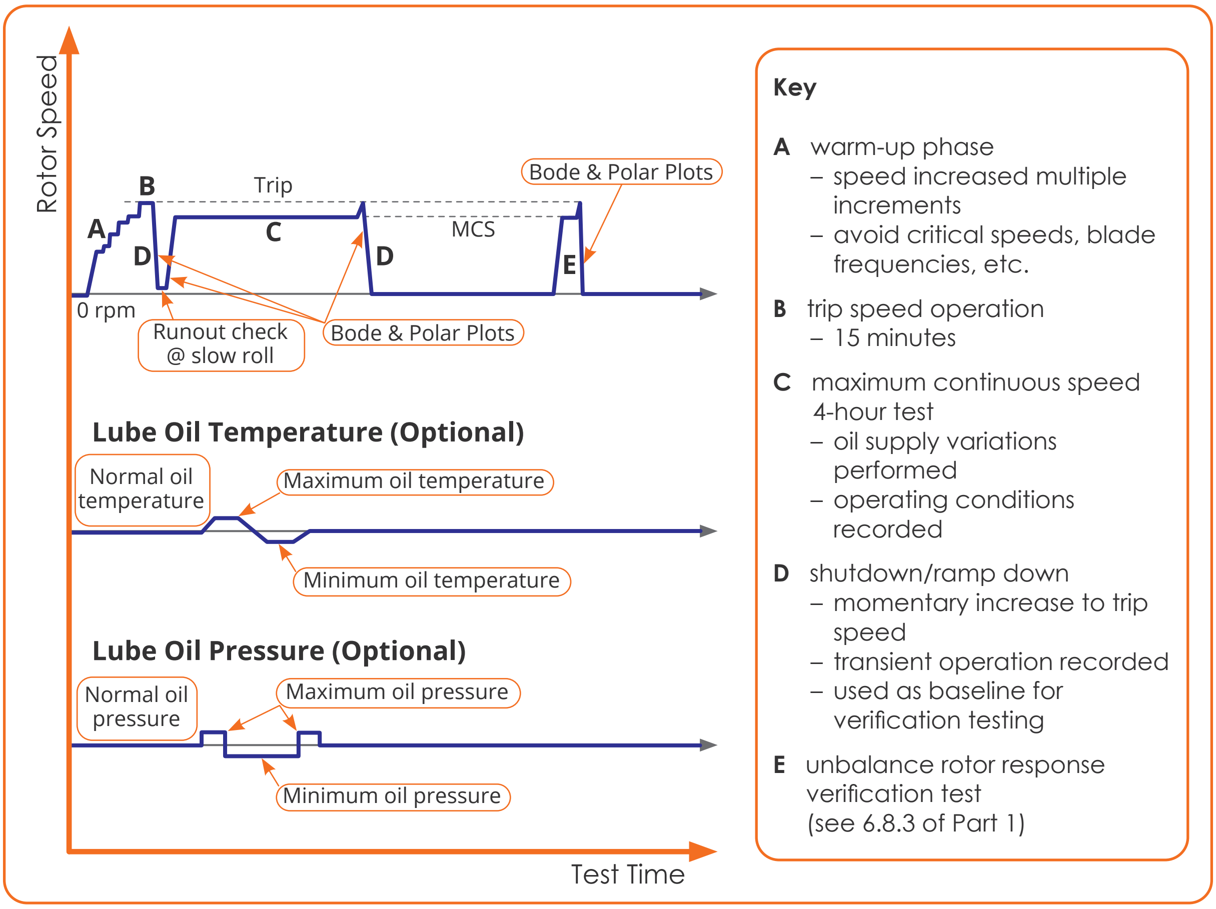

Figure 2 - Mechanical running test procedure (API-617)

► Performance Test Based on ASME PTC10

This standard establishes test procedures to evaluate the thermodynamic performance of axial or centrifugal compressors and exhausters, including measurements of gas flow, pressure rise, shaft power, and efficiency. The goal of applying ASME PTC 10 to centrifugal compressors is to provide a standardized method for testing and evaluating the performance of these compressors, ensuring that they meet design specifications and operate efficiently under site conditions. ASME PTC 10 defines two types of performance tests:

- Type 1: Closed-loop testing, where various gases can be used.
- Type 2: Open-loop testing, using air as the test gas.

The TUGA test bench is designed for Type 2, which uses air as the testing medium.

■ Goals of Performance Testing under ASME PTC10:

- Performance Evaluation:

The test is conducted under ASME PTC 10 to evaluate the performance characteristics of centrifugal compressors. This includes determining efficiency, flow rates, pressure ratios, and power consumption.

- Evaluation of Surge and Stability Limits:

Testing may also involve evaluating the compressor's performance near its surge limits or operating margins, ensuring it remains stable under a variety of conditions.

- Verification of Design Parameters:

The test helps confirm whether the actual performance matches the design parameters of the compressor, such as the expected flow rate and pressure rise at different speeds.

■ Summary of Performance Test Procedure:

- Setup: Measuring instruments must be calibrated to ensure accurate data collection. Additionally, support systems such as lubrication and sealing must function correctly to prevent compressor damage.
- Defining test conditions: Since the TUGA test bench uses air, testing speeds must align with ASME PTC 10 specifications.
- Data collection: Required data including inlet/outlet temperature and pressure, mass flow, and gas properties are recorded across various operating points on the calculated test speed from surge to choke. Tests may be conducted at multiple speeds based on client requests.
- Correction to site conditions: Since shop conditions (the place where performance test is done) differ from actual site conditions, collected data must be adjusted accordingly.
- Comparison to design specification: Final results after correction need to be compared with the guarantee point and also meet the standard criteria.

By applying ASME PTC 10, centrifugal compressors undergo rigorous, standardized testing to maximize performance, reliability, and compliance with industry standards.

Modulariziation of the Compressor Test Bench

Centrifugal compressors are custom-designed to meet specific operational requirements, including capacity, pressure ratios, temperature conditions, gas composition, installation constraints, and environmental factors. Given these variations, the number and type of sensors required for each compressor differ significantly and accordingly, the number and type of signals sent from the compressor to the control system will also vary. This is particularly true for temperature and vibration sensors. On the other hand, in some applications, the compressor needs to be directly connected to the driver (turbine or electric motor), while in others, the rotational speed of the compressor needs to be adjusted using a gearbox. This addition of a gearbox can also lead to an increase in the number of signals.

The new test bench design had to ensure that variations in parameters such as power, pressure, and flow rate of the compressor, as well as the number of temperature and vibration signals and their corresponding alarm and trip limits would not pose an obstacle to testing new compressors on the test bench. Furthermore, since the sizes of connections in compressors are not standardized, the design had to allow the installation and connection of different connectors to the existing pipeline with minimal modifications. As a result, various systems of the test bench, including the control system, lubrication system, seal support, chassis, and pipeline systems were to be redesigned.

Taking this into account, a comprehensive study was initially conducted on the different types of centrifugal compressors under various working conditions. This research resulted in a reference Piping and Instrumentation Diagram (P&ID), which accounts for the maximum possible signals required in testing a compressor.

A key component of the test bench upgrade was modularizing the control system to accommodate diverse computer configurations. Based on this, the hardware design of the control system was carried out, and the necessary equipment to support the new signals was integrated. As the previous test bench already allocated part of its hardware to connect signals from common systems such as the electrical motor, hydro-coupling, and lubrication system, the design process was carried out in a way that maximized the utilization of the existing control system capacity.

The hardware changes in the control system were the first step toward achieving the goal of modularizing the system and it was eventually necessary to enhance the system's flexibility in the software domain as well. In the previous test bench design, a specific software was developed for each compressor type, and the corresponding software was called up to test the corresponding compressor. Given the increasing variety of future compressor types, this approach was deemed inefficient. Instead, a single Human-Machine Interface (HMI) and control logic were developed based on the reference P&ID. This update enables the import of a configuration file containing all signals for a given compressor, along with the corresponding alarm and trip values. This approach enables operators to test different compressor types using a unified software.

The differences in compressor types, inevitably lead to changes in the auxiliary equipment required during the compressor test, in addition to the compressor itself. These systems include piping lines, lubrication systems, dry gas seal support systems, cooling water systems, drivers, and hydro-couplings. In the previous test bench, all piping equipment was based on non-ASME standards, whereas newer TUGA compressors adhere to ASME standards. Adapters were designed and fabricated to convert non ASME-compliant connections to ASME-compliant ones. These adapters have been successfully integrated into the lube oil system and the DGS Panel pipelines, ensuring compatibility with both standards. Additionally, an oil flow rate measurement system was introduced, meeting API-617 requirements for the Mechanical Running Test of compressors.

Concluding Remarks

This study focused on the advancement of the TUGA compressor test bench to accommodate a diverse range of tailor-made centrifugal compressors. Thanks to improvements in hardware, control systems, and software, new compressor models can now be tested using a standardized approach and a unified control system. The upgraded piping and connection systems further enable rapid test setup, reducing time and cost.

2

Optimizing Turbo Compressor Periodic Maintenance through RCM-RBI Approach

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Introduction

The global energy sector, particularly the gas transmission industry, depends heavily on turbo compressors. These critical assets play a vital role in maintaining operational efficiency, yet ensuring their reliability and availability presents significant challenges. Effective maintenance planning is crucial to prevent costly failures and downtime.

Traditional maintenance approaches for turbo compressors are typically either preventive or reactive. Preventive maintenance follows fixed time intervals regardless of the equipment's actual condition, often causing unnecessary downtime and increased costs. Reactive maintenance, on the other hand, only addresses issues after failures occur, leading to unplanned outages, expensive repairs, and prolonged disruptions. These methods reduce equipment availability and create operational inefficiencies, highlighting the need for a more optimized strategy.

This paper proposes an integrated approach combining Reliability-Centered Maintenance (RCM) and Risk-Based Inspection (RBI) to optimize maintenance intervals, improve planning, lower costs, and enhance equipment reliability. RCM evaluates the operational context, identifies functional failures, analyzes failure modes, and assesses their consequences. RBI then develops a risk matrix to prioritize inspection and maintenance tasks. By embedding risk management into the RCM framework, this method enhances decision-making and asset management. A case study at a gas transmission station demonstrates the approach's success in boosting reliability and availability, reducing costs, and increasing production capacity.

Methodology

An integrated approach combining Reliability-Centered Maintenance (RCM) and Risk-Based Inspection (RBI) was developed to optimize periodic inspections and maintenance planning for industrial gas turbines. RCM, which was first established for the aviation industry, evolved into a structured methodology widely adopted across multiple sectors. Many industries and organizations follow the minimum criteria for RCM processes as defined in the technical standard SAE JA1011 [1], which outlines the criteria for Reliability-Centered Maintenance (RCM). Further guidance on its application is provided in SAE JA1012 [2].

According to the Society of Automotive Engineers, seven fundamental questions guide the implementation of RCM, regardless of industry:

- What are the equipment's primary function and performance standards?
- What are the possible ways in which it can fail to perform the main function?
- What are the causes of each failure?
- What happens when each failure occurs?
- What are the impacts of each failure on the system?
- How can you prevent or minimize the impact of each failure?
- What actions should you take if failure cannot be prevented?

Building upon the results of the RCM analysis, the RBI methodology is then applied as a complementary risk assessment tool. RBI quantitatively and qualitatively evaluates the identified failure modes by combining the probability of failure with the severity of its consequences, thereby assigning a risk level to each item. This risk-based evaluation enables the prioritization of inspection and maintenance activities, with particular emphasis on identifying low-risk components and failure modes where maintenance intervals can be safely optimized. By integrating RBI into the RCM process, the proposed approach not only ensures reliability and safety but also enables targeted optimization of maintenance tasks, leading to reduced costs, improved availability, and more efficient allocation of maintenance resources. Figure 1 illustrates the overall workflow of the integrated RCM–RBI methodology. In the combined RCM-RBI method, risks are measured using the RBI approach instead of making decisions after completing the steps for failure modes, effects, and consequences. This allows for better and more reliable decision-making when it comes to maintenance.

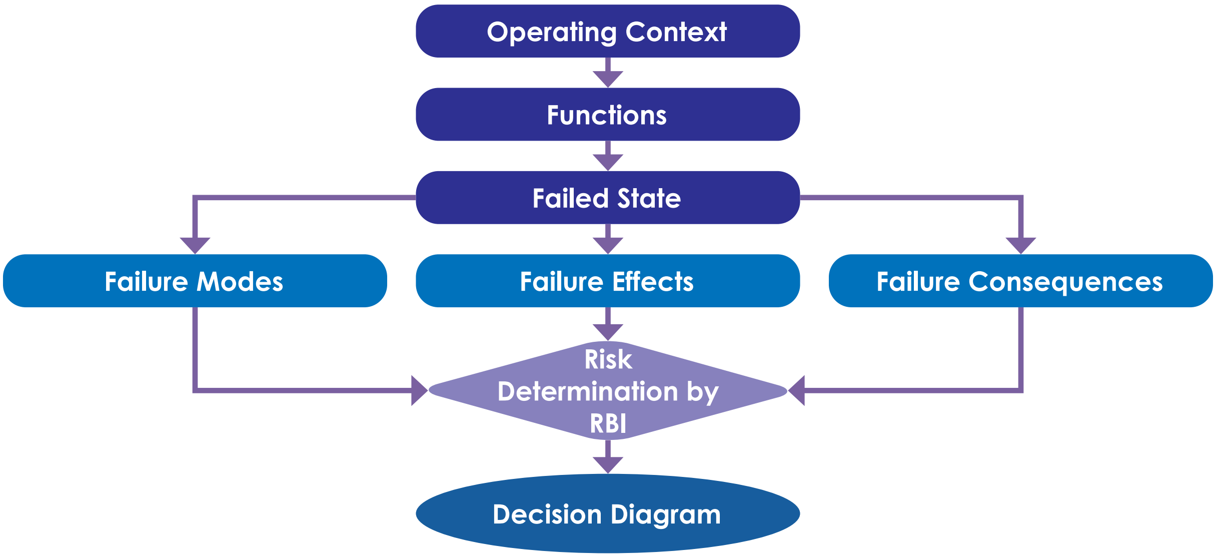


Figure 1 - RCM-RBI flowchart

► Defining the Scope and Objectives

The RCM-RBI approach focuses on optimizing inspection intervals and improving maintenance effectiveness through a proactive and risk-based strategy. The main objective is to minimize planned downtime while maintaining operational reliability and safety.

► Identifying Critical Maintenance Items

A thorough RCM analysis is conducted to identify critical components and their failure modes. Historical data, technical specifications, and operational experience are reviewed to prioritize assets based on their impact on safety, environment, and production.

► Establishing Performance Standards

Performance and reliability standards are defined for each critical component to ensure maintenance activities are technically justified and aligned with operational targets.

► Implementing Preventive Maintenance Strategies

Preventive maintenance strategies are developed, defining inspection frequencies and methods directly linked to the identified failure mechanisms. This ensures targeted, efficient, and cost-effective maintenance planning.

► Integrating RBI Assessment

The Risk-Based Inspection (RBI) methodology is a structured approach for optimizing inspection planning by focusing resources on equipment with the highest risk levels [3]. In this approach, risk is defined as the product of the probability of failure and the consequence of failure, as shown in Equation (1):

$$\mathbf{R = PoF \times CoF} \tag{1}$$

Where:

R = total risk (expected loss or impact value),

PoF = probability of failure.

CoF = consequence of failure.

■ Probability of Failure (PoF)

The PoF represents the likelihood that a specific asset or component will fail within a given timeframe. It is influenced by factors such as:

- Material Properties: Susceptibility to wear, corrosion, or fatigue.
- Operating Conditions: Pressure, temperature, and exposure to aggressive chemicals.
- Historical Data: Past failures, maintenance records, and inspection reports.

Quantifying PoF often involves statistical models and tools that account for these factors, allowing for a data-driven estimation of the likelihood of failure.

■ Consequence of Failure (CoF)

The consequence of failure can be represented as the sum of multiple impact categories according to Equation (2):

$$\mathbf{CoF = C_S + C_e + C_p + C_f} \tag{2}$$

Where:

C_s = safety consequence (e.g., injury or fatality cost)

C_e = environmental consequence (e.g., emissions, spills)

C_p = production loss (e.g., downtime, lost throughput)

C_f = financial loss (e.g., equipment damage cost, impact on production volume cost)

This calculation provides a quantitative or qualitative measure of the overall risk associated with an asset. Assets with high PoF and high CoF are given the highest priority for inspection and maintenance, as they pose the greatest threat to safety, environment, and operational continuity. Conversely, assets with low PoF and CoF may require minimal inspection resources.

A risk matrix is a very effective way to visualize the distribution of risk throughout the plant or process unit without using numerical values. This is typically shown with the probability on one axis and the consequence on the other. According to Table 1, in the qualitative risk matrix example below, a five category probability and consequence is used to visually display the asset's risk. It’s also helpful to assign numerical values to the categories to provide guidance to the assessment team [3].

Table 1 - Qualitative risk matrix

		Consequence of Failure (COF)				
		A	B	C	D	E
Probability of Failure (POF)	1	Low	Low	Low	Medium	Medium
	2	Low	Low	Medium	Medium	Medium High
	3	Low	Medium	Medium	Medium High	Medium High
	4	Medium	Medium	Medium High	Medium High	High
	5	Medium	Medium High	Medium High	High	High

Once the probability of failure (PoF) and consequence of failure (CoF) for each equipment item have been determined, a comprehensive risk matrix can be developed to quantify the overall risk. In this process, the PoF is primarily derived from historical failure data, maintenance records, and reliability statistics of each component. The CoF, on the other hand, is assessed by evaluating the potential impacts across four main categories: safety, environmental, production, and financial consequences.

By integrating these two dimensions (PoF and CoF) the overall risk level for each asset can be calculated and positioned within the risk matrix. This enables the prioritization of equipment based on its associated risk levels. Assets with higher combined risk values are ranked at the top of the inspection and maintenance schedule, demanding more frequent monitoring and preventive actions. Conversely, components with lower risk levels may follow extended inspection intervals or reduced maintenance intensity. Consequently, this integrated approach allows the development of an optimized, risk-informed maintenance and inspection plan that ensures resource allocation is both efficient and technically justified.

▶ Prioritizing and Mitigating Risks

Inspection activities are scheduled according to risk ranking, with high-risk components prioritized. Mitigation measures, including engineering improvements and procedural modifications, are defined and evaluated for technical and economic feasibility.

Once the risk levels are identified and ranked, appropriate strategies are implemented to control or reduce them. These strategies may involve reducing the probability of failure (PoF) through enhanced maintenance practices, material upgrades, or improved operating conditions, as well as minimizing the consequence of failure (CoF) by adding protective systems, revising operating procedures, or improving emergency response plans. In some cases, risk can be eliminated entirely by redesigning the component or substituting the equipment with a more reliable alternative. This systematic approach ensures that inspection and maintenance efforts are not only prioritized but also effectively targeted to achieve tangible risk reduction and improved overall reliability of the plant.

► Monitoring, Feedback, and Continuous Improvement

In the final step of the RCM-RBI approach, condition monitoring technologies and data analytics are integrated to provide real-time feedback, enabling dynamic adjustments of inspection and maintenance plans. All analyses and actions are documented, and a structured continuous improvement process is established to ensure that the strategy remains adaptive and performance-driven.

The combined approach of Reliability-Centered Maintenance (RCM) and Risk-Based Inspection (RBI) has proven to be a comprehensive, data-driven strategy for optimizing inspection and maintenance processes, thereby enhancing system reliability over the long term. This methodology, by identifying and prioritizing critical components and failure modes, not only reduces planned downtime but also allocates resources more effectively to high-risk components.

Additionally, by defining precise performance standards and utilizing advanced monitoring tools, it enables improved safety and integrated system health management. This approach allows engineers and operational teams to make better decisions regarding maintenance scheduling and inspections, based on real-time data and risk analysis. As a result, the methodology not only reduces maintenance costs but also improves overall operational efficiency and helps achieve organizational performance goals.

Engineering Studies for Optimizing Periodic Maintenance

In the conventional approach, periodic inspections for each MGT-30 unit are performed over a 25,000-hour operating life, comprising eight inspection stages that are divided into two scopes: 3,000 hours and 6,000 hours. The 3,000-hour scope encompasses 32 evaluation items, while the 6,000-hour scope includes 42 items.

Operational and maintenance data from 24 turbo compressor units were gathered and analyzed over a three-year period in the initial phase of this study, in accordance with the requirements of ISO 14224 [4], a standard that emphasizes the standardized processes for collecting and exchanging reliability and maintenance data for industrial equipment. One of the primary contributors to reduced unit availability, as revealed by the analysis of the collected data, is these periodic inspections. Notably, the availability factor (AF) for the units was calculated using Equation (3) [5].

$$\mathbf{AF = 1 - (FOH+POH) / PH = AH / PH} \tag{3}$$

Where:

FOH = forced outage hours

POH = planned outage hours

PH = period hours

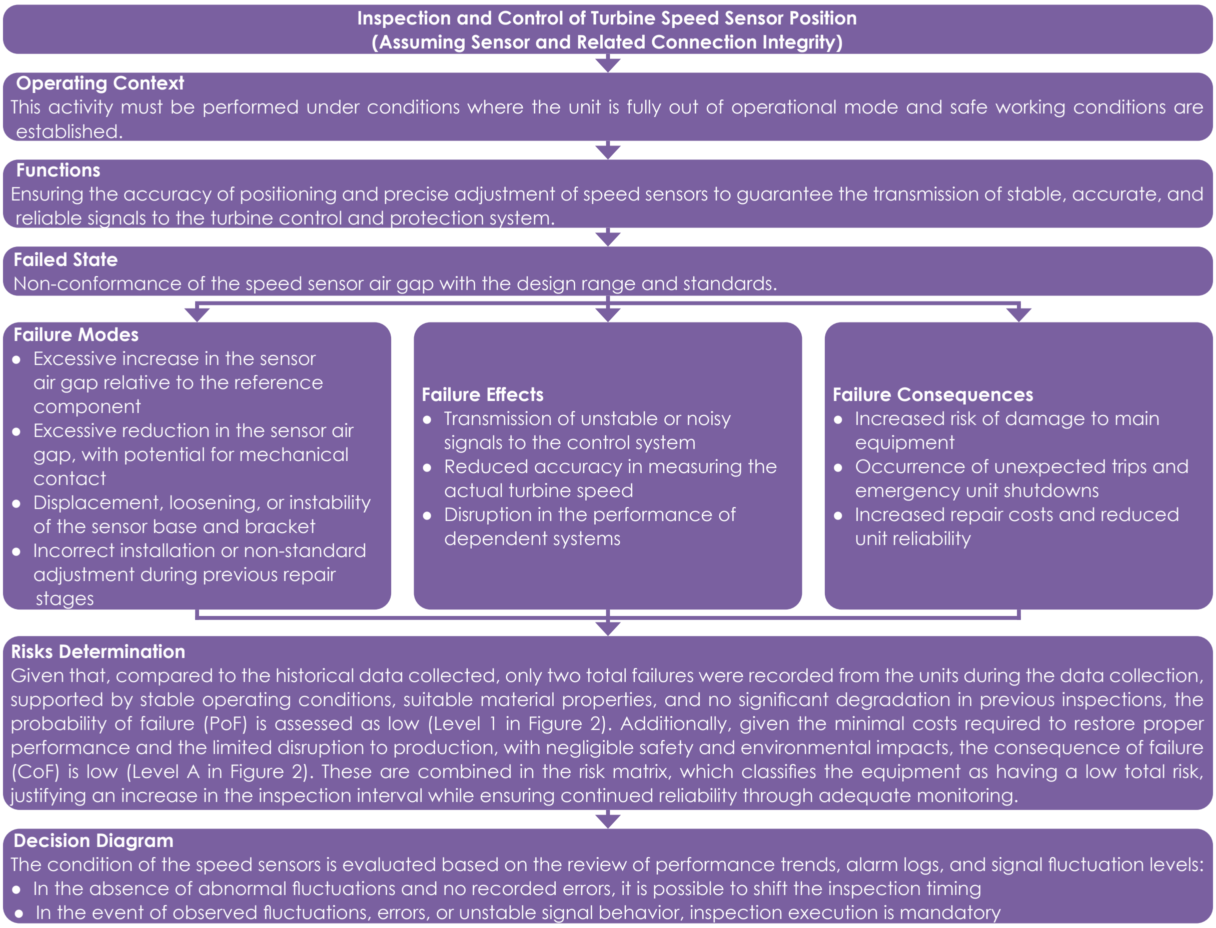
AH = available hours

Insights derived from this analysis were leveraged in the subsequent phase, through which a project for optimizing periodic inspections was implemented based on an integrated Reliability-Centered Maintenance (RCM) and Risk-Based Inspection (RBI) approach. This initiative resulted in enhanced operational efficiency and reduced maintenance costs.

From a manpower management perspective, each inspection stage within the 6,000-hour interval typically requires an average of 190 expert man-hours and 537 technician man-hours. This substantial demand highlights the constraints in the availability of skilled personnel and underscores the critical importance of their efficient allocation. When inspections are conducted simultaneously across multiple operational units, the likelihood of unplanned or prolonged outages increases. Such circumstances not only reduce production rates but also compromise inspection quality and elevate operational costs. Ultimately, these factors directly contribute to lower overall efficiency and diminished revenue.

As detailed in the preceding section, planned outages were minimized, production was increased, and execution costs (including expert man-hours, spare parts, and consumables) were reduced, all as part of the deployment of the RCM-RBI methodology. Within the framework of this project, 16 items were selected from the initial 42 for modification and optimization measures, informed by technical analyses and risk assessments concerning equipment criticality. The outcomes of the risk evaluation and classification process grounded these selections by which inspection activities that exert the most substantial influence on overall risk levels and the safe, stable operation of the units were identified. Among these, 10 have pertained to auxiliary systems, 4 to the turbine domain, and 2 to the centrifugal compressor for gas transfer.

Figure 2 illustrates detailed analysis of one representative inspection item (the turbine speed sensor position check) to demonstrate the applied methodology. This example shows how the evaluation framework, data-driven screening, and risk-based considerations were implemented in practice. The same systematic approach was applied to all candidates, through which the final set of 16 inspection items was identified and confirmed for ongoing monitoring and interval optimization.



Inspection and Control of Turbine Speed Sensor Position
(Assuming Sensor and Related Connection Integrity)

Operating Context
This activity must be performed under conditions where the unit is fully out of operational mode and safe working conditions are established.

Functions
Ensuring the accuracy of positioning and precise adjustment of speed sensors to guarantee the transmission of stable, accurate, and reliable signals to the turbine control and protection system.

Failed State
Non-conformance of the speed sensor air gap with the design range and standards.

Failure Modes
- Excessive increase in the sensor air gap relative to the reference component
- Excessive reduction in the sensor air gap, with potential for mechanical contact
- Displacement, loosening, or instability of the sensor base and bracket
- Incorrect installation or non-standard adjustment during previous repair stages

Failure Effects
- Transmission of unstable or noisy signals to the control system
- Reduced accuracy in measuring the actual turbine speed
- Disruption in the performance of dependent systems

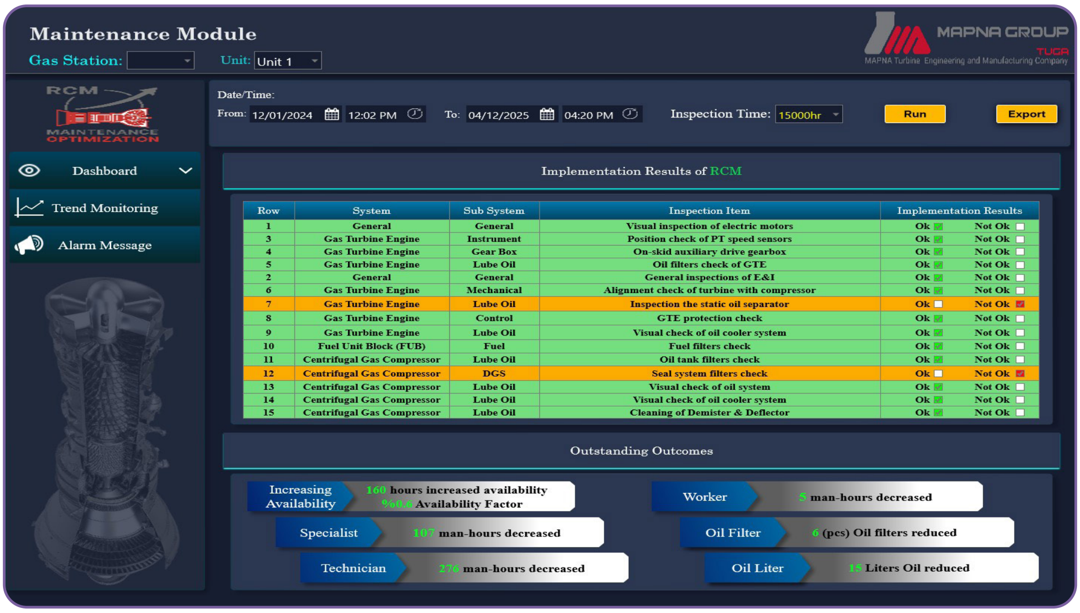
Failure Consequences
- Increased risk of damage to main equipment
- Occurrence of unexpected trips and emergency unit shutdowns
- Increased repair costs and reduced unit reliability

Risks Determination
Given that, compared to the historical data collected, only two total failures were recorded from the units during the data collection, supported by stable operating conditions, suitable material properties, and no significant degradation in previous inspections, the probability of failure (PoF) is assessed as low (Level 1 in Figure 2). Additionally, given the minimal costs required to restore proper performance and the limited disruption to production, with negligible safety and environmental impacts, the consequence of failure (CoF) is low (Level A in Figure 2). These are combined in the risk matrix, which classifies the equipment as having a low total risk, justifying an increase in the inspection interval while ensuring continued reliability through adequate monitoring.

Decision Diagram
The condition of the speed sensors is evaluated based on the review of performance trends, alarm logs, and signal fluctuation levels:
- In the absence of abnormal fluctuations and no recorded errors, it is possible to shift the inspection timing
- In the event of observed fluctuations, errors, or unstable signal behavior, inspection execution is mandatory

Figure 2 - Sample workflow for inspection item evaluation

To assess the risks associated with the 16 selected inspection items, various factors must be examined, including trends in data from pertinent sensors between consecutive inspections and daily operational reports. Specifically, variations in 20 sensors linked to these inspection items must be scrutinized and analyzed over the inter-inspection interval. Approximately 311 million data points per unit must be processed for each three-month inspection cycle, as these sensors are logged every 500 milliseconds in the control system. In addition to the aforementioned 20 sensors, the status of 21 switches must also be monitored for changes.



Gas Station:
Unit: Unit 1

Date/Time:
From: 12/01/2024 12:02 PM To: 04/12/2025 04:20 PM Inspection Time: 15000hr

Implementation Results of RCM

Row	System	Sub System	Inspection Item	Implementation Results	
1	General	General	Visual inspection of electric motors	Ok ☑	Not Ok ☐
3	Gas Turbine Engine	Instrument	Position check of PT speed sensors	Ok ☑	Not Ok ☐
4	Gas Turbine Engine	Gear Box	On-skid auxiliary drive gearbox	Ok ☑	Not Ok ☐
5	Gas Turbine Engine	Lube Oil	Oil filters check of GTE	Ok ☑	Not Ok ☐
2	General	General	General inspections of E&I	Ok ☑	Not Ok ☐
6	Gas Turbine Engine	Mechanical	Alignment check of turbine with compressor	Ok ☑	Not Ok ☐
7	Gas Turbine Engine	Lube Oil	Inspection the static oil separator	Ok ☐	Not Ok ☑
8	Gas Turbine Engine	Control	GTE protection check	Ok ☑	Not Ok ☐
9	Gas Turbine Engine	Lube Oil	Visual check of oil cooler system	Ok ☑	Not Ok ☐
10	Fuel Unit Block (FUB)	Fuel	Fuel filters check	Ok ☑	Not Ok ☐
11	Centrifugal Gas Compressor	Lube Oil	Oil tank filters check	Ok ☑	Not Ok ☐
12	Centrifugal Gas Compressor	DGS	Seal system filters check	Ok ☐	Not Ok ☑
13	Centrifugal Gas Compressor	Lube Oil	Visual check of oil system	Ok ☑	Not Ok ☐
14	Centrifugal Gas Compressor	Lube Oil	Visual check of oil cooler system	Ok ☑	Not Ok ☐
15	Centrifugal Gas Compressor	Lube Oil	Cleaning of Demister & Deflector	Ok ☑	Not Ok ☐

Outstanding Outcomes

Increasing Availability	160 hours increased availability %0.6 Availability Factor
Specialist	107 man-hours decreased
Technician	276 man-hours decreased
Worker	5 man-hours decreased
Oil Filter	6 (pcs) Oil filters reduced
Oil Liter	15 Liters Oil reduced

Figure 3 - TUGA turbo compressor maintenance module

Owing to the substantial data volume per unit, precise data mining models have been used to perform this analysis, implemented through a maintenance module that has been developed by MAPNA Turbine Engineering and Manufacturing Company (TUGA). A sample interface of this module is illustrated by Figure 3, by which advanced algorithms have been employed to facilitate performance trend analysis, detection of anomalous deviations, and data-driven scheduling of inspections. Furthermore, operators have been empowered by this module not only to achieve these capabilities but also to identify gradual drifts or fluctuations, by which more precise investigations have been enabled to avert unplanned outages.

Case Study

As previously discussed, the effectiveness of the proposed improvement was evaluated through its implementation on two turbo compressor units. Following a two-year pilot application, the total downtime required for conducting periodic inspections within the 3000-hour and 6000-hour scopes was reduced by 1128 hours through the adoption of the RCM-RBI methodology. This reduction corresponded to an increase of approximately 4.3% in the availability factor of these units.

Given a gas transmission capacity of 30 Million Metric Standard Cubic Meters per Day (MMSCMD) for each unit, the improvement has been estimated to provide an additional transmission capacity of approximately 1400 MMSCM.

In addition, the total man-hours required for conducting periodic inspections in both units decreased by 77.2% for specialists (980 man-hours), 77.6% for technicians (2664 man-hours), and 50% for skilled workers (44 man-hours).

Furthermore, the implementation of the RCM–RBI-based inspection strategy resulted in an approximately 50% (200 liters) reduction in oil consumption during filter replacements and a reduction of about 33% (42 pieces) in the number of required oil filters. These achievements have not only significantly lowered operational costs but also improved the environmental impacts of the operations.

Figure 4 presents a visual summary of these outstanding outcomes achieved through the implementation of the proposed methodology.

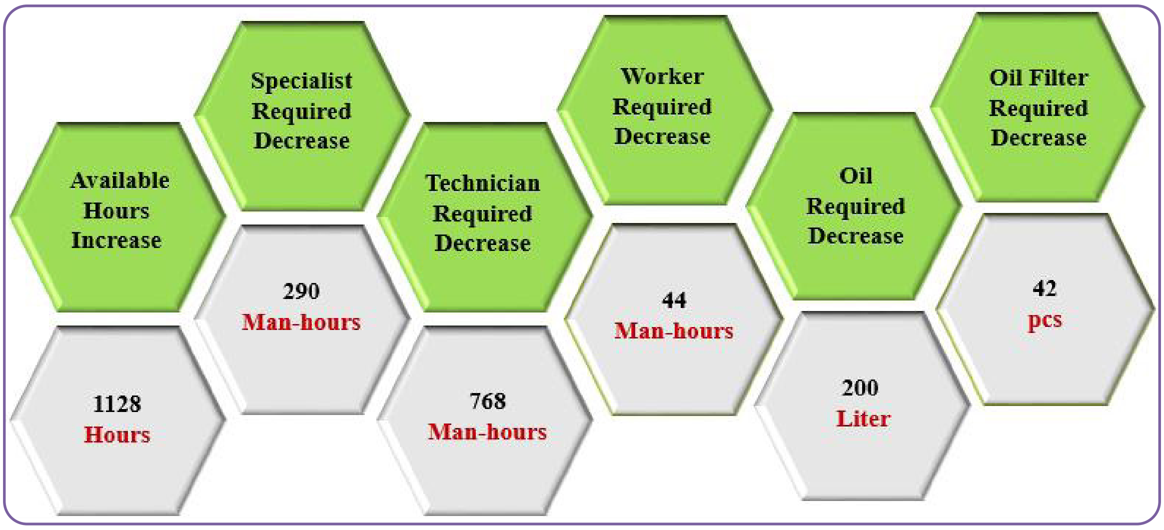


Figure 4 - Outstanding results following two years of RCM–RBI implementation

Concluding Remarks

The integrated Reliability-Centered Maintenance (RCM) and Risk-Based Inspection (RBI) methodology has proven to be effective in optimizing maintenance planning for turbo compressor units. By combining reliability analysis with risk evaluation, inspection intervals are optimized, and maintenance resources are allocated more efficiently. Implementation on two units over a two-year period resulted in a 1128-hour reduction in total downtime and a 4.3% increase in availability, equivalent to an additional 1400 million metric standard cubic meters of gas transmission capacity. Man-hour requirements and consumable usage were also significantly reduced, contributing to lower maintenance costs and improved environmental performance. These outcomes confirm that the RCM-RBI approach provides a technically justified and data-driven framework for enhancing availability, minimizing planned outages, and sustaining long-term operational efficiency in gas transmission systems.

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3

Process Development for Brazing of Compressor Impellers with High-Temperature Fillers

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Introduction

One of the key industrial applications of modern brazing technologies is the fabrication of centrifugal compressors. In such equipment, the impeller is usually the most critical component, and many centrifugal impellers are traditionally produced using two-piece fabrication methods. Among the available joining techniques, brazing offers considerable advantages over fusion welding, particularly the absence of distortion and the ability to join narrow or difficult-to-access internal passages. These characteristics make brazing an effective method for producing impellers with tight geometries and thin flow channels. The most common brazing technique is furnace brazing, which—depending on the base metal—may be carried out in vacuum, inert gas atmospheres, or air [1].

TUGA, as an original equipment manufacturer of centrifugal compressors, gas turbines, and steam turbines, works extensively with advanced and hard-to-join materials. These include nickel-based superalloys such as Inconel 718, titanium alloys, and precipitation-hardened stainless steels such as 17-4PH. These materials are widely used in highly loaded components including compressor impellers, turbine blades, combustion chambers, and other critical engine parts [2].

Joining such alloys presents significant challenges due to their complex metallurgical behavior. In addition, modern brazing technologies must meet strict performance requirements while remaining cost-effective and environmentally sustainable. To address these needs, TUGA has developed a high-temperature vacuum brazing process using various filler metals and successfully applied it to fabricate compressor impellers. Due to the superior joint cleanliness and metallurgical quality achievable in vacuum, TUGA employs vacuum furnace brazing as its primary joining method. The company has validated the brazing of impellers and other precision components using three high-temperature filler metals—nickel-based, palladium-based, and gold-based alloys—and currently possesses full manufacturing capability with all of them.

Brazing Filler Metals Suitable for Joining Impeller Components

High-temperature brazing is a joining process carried out in a vacuum furnace or controlled atmosphere at temperatures above 800–900 °C to create strong joints with good corrosion and oxidation resistance. Because the process takes place at elevated temperatures, special attention must be given to the furnace conditions or the protective atmosphere used. The selection of the filler metal is very important in this process. The filler plays a key role in the joint's strength, corrosion resistance, and temperature tolerance; therefore, special care must be taken in choosing the right filler [3].

Brazing filler metals are elements that are placed between two or more base metals in form of a thin layer for the purpose of filling the gap and therefore joining them. The filler metal must be compatible with the base metal, joint clearance, and the brazing procedure. When designing a brazed joint for a specific service application, it is important to consider the properties and compatibility of the base material and filler in the brazing operation, as well as the final brazed joint in the environment in which they will operate [4]. Filler metals are available in a variety of forms, namely foil, paste, sheet, powder, wire, and rod.

According to ISO 17672:2016, seven families of brazing filler materials are defined for joining common metals. These families are grouped into four categories based on their working temperature range:

- Low-temperature brazing filler metals (Class Al), used in the range of 580–630 °C
- Silver-based alloys, used below 200 °C
- Copper–phosphorus and copper-based alloys (Class CuP and Class Cu), used in the range of 590–650 °C
- High-temperature brazing filler metals (Class Ni, Class Pd, and Class Au), intended for use at temperatures above 800 °C (see Table 1).

Table 1 - The standard classifications for filler metals and the applications for each [4]

Class designation	Applications and features
Classes Ni: Nickel (and cobalt) based filler metals	• Filler metals often brittle • Typically requires a vacuum • Excellent corrosion resistance and high Services temperatures
Class Pd: Palladium based filler metals	• Rotary equipment, aerospace, power generation, chemical industries • Possess good strength at elevated temperatures, excellent corrosion resistance
Class Au: Gold based filler metals	• Rotary equipment, aerospace, power generation, chemical industries • Excellent corrosion resistance and strength at high temperatures

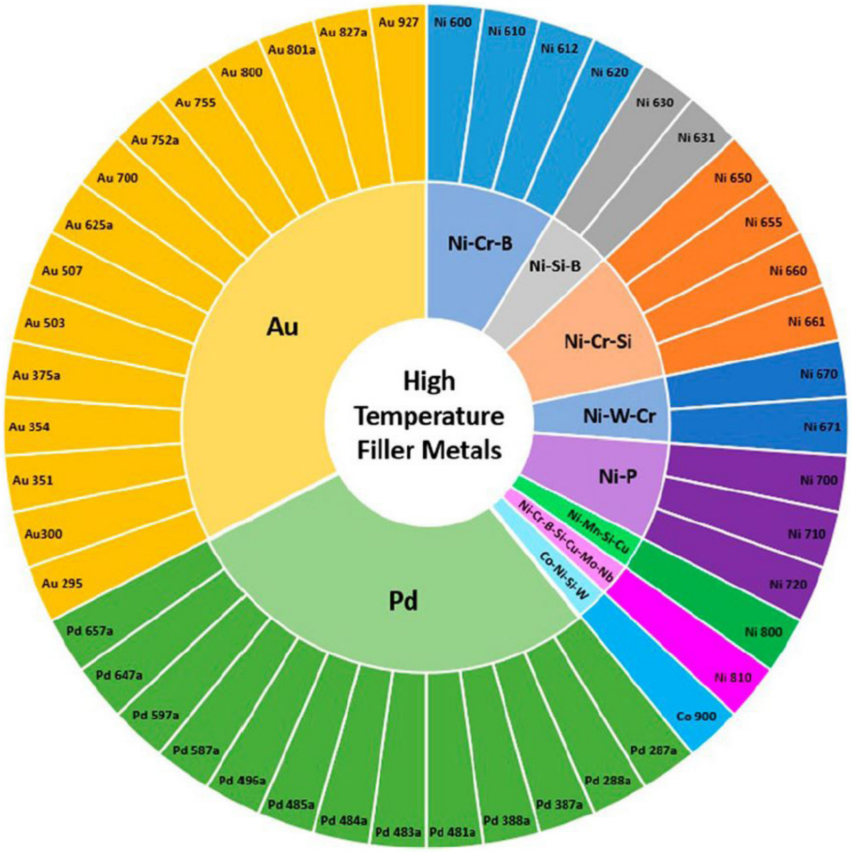

Figure 1 - Sunburst chart displaying the nickel, palladium, and gold-based filler metals (Class Ni, Class Au, and Class Pd.) defined in ISO:1762:2016 and the alloy systems they belong to. [5]

Given that the production of centrifugal compressors is a key focus at TUGA, and many brazed parts feature complex geometries and require high assembly accuracy, a knowledge gap in brazing was identified at TUGA. Therefore, the development of brazing technology was added to TUGA's technical agenda, and the Vacuum Brazing method was implemented for producing impellers with a diameter of around 600 mm and a vane height of 5 to 8 mm. The impellers studied in this work are made of 17-4PH, a martensitic precipitation-hardened stainless steel. This class of stainless steels is hardened by quenching from the austenitizing temperature (approximately 1040 °C), followed by aging in the range of 480–620 °C. Because the carbon content of these alloys is typically below 0.07%, the martensite formed after quenching is not very hard, and most of the strengthening is achieved through the aging (precipitation) process.

Studies have shown that the most suitable brazing fillers for joining these materials in high-temperature applications are nickel-based, gold-based, and palladium-based alloys. These fillers were shown to provide the high joint strength required for bonding the two impeller disks (hub and shroud). They also exhibit excellent resistance in corrosive environments, making them a suitable choice for harsh impeller conditions. A brief introduction to these three types of high-temperature filler metals is provided below.

► Nickel-Based Filler Metals

Nickel-based filler metals are widely used for brazing high-temperature and corrosion-resistant ferrous and non-ferrous alloys. They offer high strength from cryogenic temperatures up to elevated service temperatures. Because pure nickel has a very high melting point, nickel alloys are especially used for joining stainless steels and heat-resistant alloys. These fillers must be free of low-melting elements, such as Zn or S, which can embrittle nickel, and care must be taken to avoid stress-cracking during heating and cooling. Different nickel-based brazing alloys are listed in Table 2.

Table 2 - Nickel-based brazing filler metals [6]

AWS designation	Composition (% weight)													
	Cr	B	Si	Fe	C	P	S	Al	Ti	Mn	Cu	Zr	Ni	Other
BNi-1	13.0-15.0	2.75-3.50	4.0-5.0	4.0-5.0	0.6-0.9	0.02	0.02	0.05	0.05	—	—	0.05	Bal	0.05
BNi-la	13.0-15.0	2.75-3.50	4.0-5.0	4.0-5.0	0.06	0.02	0.02	0.05	0.05	—	—	0.05	Bal	0.05
BNi-2	6.0-8.0	2.75-3.50	4.0-5.0	2.5-3.5	0.06	0.02	0.02	0.05	0.05	—	—	0.05	Bal	0.05
BNi-3	—	2.75-3.50	4.0-5.0	0.5	0.06	0.02	0.02	0.05	0.05	—	—	0.05	Bal	0.05
BNi-4	—	1.5-2.2	3.0-4.0	1.5	0.06	0.02	0.02	0.05	0.05	—		0.05	Bal	0.05
BNi-5	18.5-19.5	0.03	9.75-10.50	—	0.10	0.02	0.02	0.05	0.05	—	—	0.05	Bal	0.05
BNi-6	—	—	—	—	0.10	0.0-12.0	0.02	0.05	0.05	—	—	0.05	Bal	0.05
BNi-7	13.0-15.0	0.01	0.10	0.2	0.08	9.7-10.5	0.02	0.05	0.05	0.04	—	0.05	Bal	0.05
BNi-8	—	—	6.0-8.0	—	0.10	0.02	0.02	0.05	0.05	21.5-24.5	4.5-5.0	0.05	Bal	0.05
BNi-9	13.5-16.5	3.25-4.0	—	1.5	0.06	0.02	0.02	0.05	0.05		—	0.05	Bal	0.05
BNi-10	12	2.5	3.5	3.5	0.5	—	—	—	—		—	—	Bal	16W
BNi-11	10	2.5	3.5	3.5	0.4	—	—	—	—		—	—	Bal	12W

Gold-Based Filler Metals

Gold-based fillers exhibit excellent ductility, corrosion resistance, and compatibility with many base metals. They operate mainly below 538 °C and cause minimal erosion of stainless steels, super-alloys, and refractory metals.

For joints requiring high strength and oxidation resistance at around 870 °C, gold fillers are highly attractive despite their higher cost. Their reliability and excellent performance in stress-critical assemblies often justify this cost. Gold-based filler compositions are presented in Table 3.

Table 3 - Gold-based brazing filler metals [6]

AWS classification	UNS number	Composition (% weight)				
		Au	Cu	Pd	Ni	Other elements
BAu-1	P00375	37.0-38.0	Remainder	—	—	0.15
BAu-2	P00800	79.5-80.5	Remainder	—	—	0.15
BAu-3	P00350	34.5-35.5	Remainder	—	2.5-3.5	0.15
BAu-4	P00820	81.5-82.5	—	—	Remainder	0.15
BAu-5	P00300	29.5-30.5	—	33.5-34.5	35.5-36.5	0.15
BAu-6	P00700	69.5-70.5	—	7.5-8.5	21.5-22.5	0.15

Palladium-Based Filler Metals

Palladium is a light, oxidation-resistant metal whose addition significantly improves the performance of silver–copper brazing alloys. As a result, a range of Pd-containing fillers have been developed often in combination with Ni, Mn, or Au (Table 4). These fillers retain many of the advantages of gold-based alloys but at lower cost, offering:

- Good mechanical integrity with reduced brittle intermetallic formation.
- Superior high-temperature strength compared to gold alloys without platinum-group additions
- Excellent oxidation resistance, especially in Pd–Ni alloys.
- Good corrosion resistance (though lower than Au-based).
- Low vapor pressure and consistently narrow melting ranges (typically 25–50 °C).

Table 4 - Palladium-based brazing filler metals [6]

Composition (% weight)					Melting range (°C)
Pd	Ag	Cu	Ni	Other	
65	-	-	-	35 Co	1230-1235
60	-	-	40	-	1273
54	-	-	36	10 Cr	1232-1260
25	54	21	-	-	900-950
21	-	-	48	31 Mo	1120
15	65	20	-	-	850-900
5	68.5	26.5	-	-	805-810

Experimental Work and Impeller Production

To further develop the vacuum brazing process for manufacturing impellers using high-temperature fillers, three different foils, BNi-2 (nickel-based), BVAu-4 (gold-based), and PGK-1000 (palladium-based) with a thickness of 100 µm were selected for experimental testing. Their chemical compositions are listed in Table 5.

Table 5 - Chemical composition of the brazing fillers [3]

Brazing Filler	%Ni	%Cr	%Pd	%Au	%Fe	%Si	%B
BNi-2	Rem.	6 - 8	-	-	2.5 - 3.5	4-5	2.7 - 3.5
BVAu-4	Rem.	-	-	81.5 - 82.5	-	0.2 max.	-
PGK-1000	Rem.	18 - 20	45.8 - 50	-	-	-	-

For each filler, a thermal cycle was designed based on its melting temperature. To evaluate these cycles and the tensile properties of the brazed joint, two samples were used: one for the shear test, and one to assess the base metal properties after undergoing the cycle in the furnace. Tensile and impact test specimens were extracted from the base metal sample to ensure that, after completing the brazing cycle, the impeller body retains the standard mechanical properties of 17-4PH stainless steel as specified by the design requirements.

For all three fillers, the base metal properties met the specified requirements, and the tensile strength of the brazed samples exceeded the minimum allowable strength for 17-4PH stainless steel (i.e., 1000 MPa of tensile stress). In case of the gold-based filler, the braze strength was so high that failure occurred in the base metal itself. Figure 3 shows the tensile sample made from gold-based filler after test. Ductile fracture in the base metal can clearly be seen.

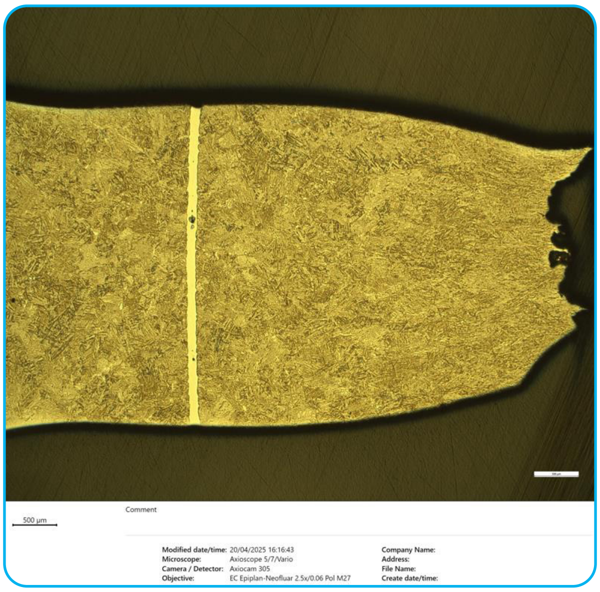

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Figure 2 - Brazed sample with gold-based filler after fracture

Regarding the shear test samples, it is worth noting that in all cases the shear strength exceeded 600 MPa, which is higher than the design shear strength required for this impeller.

Before producing a full impeller, only a portion of the impeller with a single vane was machined, and one vane was brazed using the established cycle (Figure 3). After ensuring proper brazing of the single vane sample, a complete impeller was assembled with filler metal and subjected to the brazing cycle. Following brazing, the impeller was inspected and successfully tested under over-speed conditions.

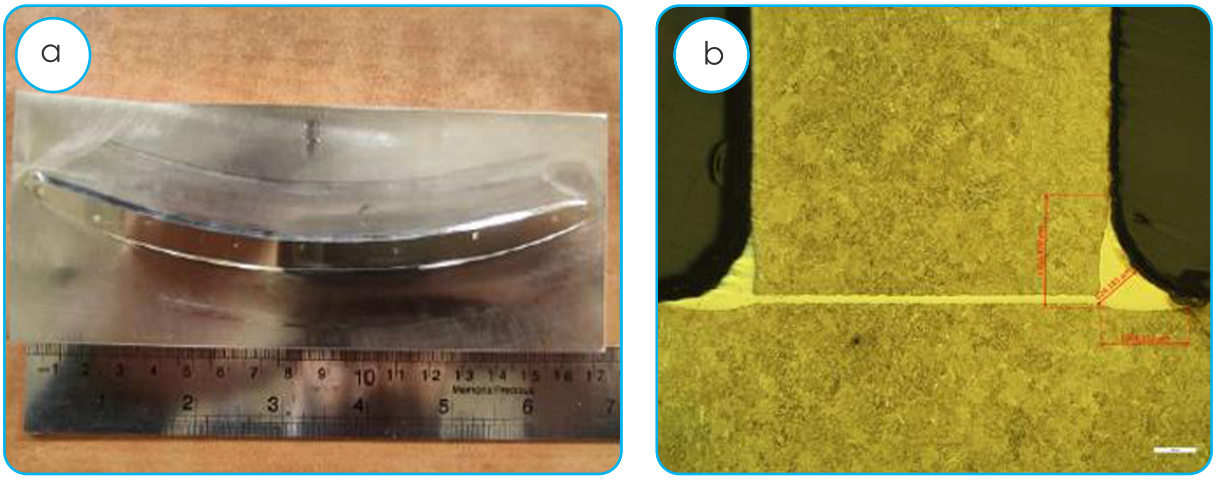

Figure 3 - Filler applied on the single vane sample, (b) Cross-section of the single vane sample

Concluding Remarks

This study focused on the development of vacuum brazing technology using three high-temperature fillers for the production of high-speed compressor impellers. The three filler metals—nickel-based, gold-based, and palladium-based—were evaluated through experimental tests, including tensile, shear, and base metal property assessments. The results demonstrated that all three fillers offer excellent joint strength, with the gold-based filler achieving such high strength that failure occurred in the base metal itself.

After validating the brazing cycles on single vane samples, a complete impeller was successfully brazed, inspected, and subjected to over-speed testing. This work effectively addressed TUGA's knowledge gap in high-temperature brazing and provided the company with operational expertise in using all three filler metals for reliable impeller manufacturing. Building on this success, TUGA is now capable of conducting vacuum brazing and plans to apply this knowledge to other alloys, such as titanium and superalloys for future applications.

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4

Development of an Experimental Facility for JICF Mechanism of Liquid Fuel in Premixed Gas Turbine Burners

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Introduction

Modern gas turbines are increasingly required to operate with high levels of flexibility in order to accommodate wide operating ranges, deep turn-down capability, and diversified fuel portfolios. With this regard, fuel flexibility has become a key enabler for reliable power generation, particularly under conditions in which the availability of primary fuels is uncertain or seasonally constrained. In this context, the capability of gas turbines to operate on liquid fuels remains an essential component of flexible operation strategies. In countries such as Iran, where structural imbalances in natural gas supply to the power plants have become a recurring challenge, the importance of fuel flexibility and specifically capability to burn various liquid fuels is further amplified. Therefore, the development of advanced liquid fuel combustion systems that can meet increasingly stringent emission requirements while maintaining stable and efficient performance is crucial for gas turbine OEMs like MAPNA. Regarding the use of liquid fuels in gas turbines, premixed low-emission combustion technology poses significant challenges due to limitations associated with governing parameters such as atomization quality, evaporation time, and fuel–air mixing under lean conditions. However, JICF[1] injection mechanism has been widely employed in advanced gas turbine engines as an effective aerodynamic phenomenon for promoting rapid primary breakup, enhanced dispersion, and improved premixing prior to combustion. Despite the widespread industrial adoption of these concepts, the design and optimization of premixed liquid fuel burners cannot rely solely on numerical and analytical methods. The study of complex interaction between liquid jets and turbulent air crossflow requires experimental investigation to capture the actual phenomena and provide verification data. This article focuses on the design and development of a high-fidelity experimental facility that provides systematic investigation of liquid JICF behavior under specific laboratory conditions representing actual operation of gas turbine combustion chamber.

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[1] Jet In Cross Flow

Design Philosophy and Similarity Framework

During the design phase, experimental investigation of liquid fuel injection in a prototype premixed burner under actual engine operating conditions is often impractical due to the high complexity and cost imposed by high-pressure infrastructure, safety and operational considerations in the presence of fuel oil combustion and the necessity of clean optical access to the liquid fuel premixer duct. Instead, non-combustible testing at near-atmospheric pressure provides a practical and cost-effective alternative during early design phases, allowing detailed investigation of liquid jet behavior crossed by high-temperature air flow while isolating aerodynamic effects arising from combustion-related phenomena. The objective is not only to replicate engine conditions directly, but also to reproduce the dominant flow physics governing the liquid jet penetration and trajectory through appropriate similarity considerations.

Accordingly, the JICF test rig developed by TUGA is geometrically identical to the burner passage of the target engine, without any geometrical scaling down and similarity between engine operating conditions and laboratory test conditions. Therefore, it is established through preservation of the dominant non-dimensional parameters governing liquid JICF behavior as mentioned previously. The primary objective of the JICF test rig design is the accurate determination of liquid jet trajectory due to its importance in the safe and normal operation of premixed fuel oil burner. Therefore, particular emphasis is placed on matching the momentum flux ratio between the liquid jet and the crossflow air ,which governs fuel oil jet penetration and deflection. Due to practical constraints, not all engine-relevant parameters can be matched simultaneously. These limitations are managed by prioritizing the parameters with remarkable influence on jet trajectory and initial dispersion in such a way that similarity of the breakup regime is maintained during the test. A summary of the relevant non-dimensional parameters considered in the similarity framework is provided in Table 1.

Table 1 - Key non-dimensional parameters used for engine-to-test-rig similarity

Parameter	Symbol	Definition	Physical Significance in JICF	Similarity Treatment in Present Study
Momentum Flux Ratio	J	$\rho_l U_l^2 / \rho_g U_g^2$	Governs liquid jet penetration, trajectory, and crossflow deflection	Primary parameter; directly matched
Gas Weber Number	We_g	$\rho_g U_g^2 d / \sigma_l$	Governs aerodynamic breakup of the liquid jet in crossflow	Regime similarity; representative breakup regime
Ohnesorge Number	Oh	$\mu_l / \sqrt{\rho_l d \sigma_l}$	Represents viscous influence on jet breakup	sufficiently low to neglect viscous dominance
Liquid Jet Reynolds Number	Re_l	$\rho_l U_l d / \mu_l$	Characterizes inertial vs. viscous forces in the liquid jet	Regime similarity; maintained in turbulent range
Crossflow Reynolds Number	Re_g	$\rho_g U_g D / \mu_g$	Influences crossflow turbulence and shear interaction	Regime similarity; maintained in turbulent range

Index l: related to Liquid injection
Index g: related to Gas crossflow
ρ: Density,
U: Velocity,
d: liquid injection hole diameter,
D: Main burner diameter,
μ: Viscosity,
σ: surface tension

Experimental Facility

The overall view of the designed single burner JICF test rig for MAPNA F-class gas turbine is shown in Figure 1. The flow passage represents one-eighth of the MGT-75 main burner and includes one main burner lance, premixer can, and upstream annulus section. The upstream flow passage is designed to replicate the reverse-flow configuration and homogenization characteristics of the gas turbine combustor resulting in an air flow pattern, that is identical to that of the target engine, crossing the liquid jet.

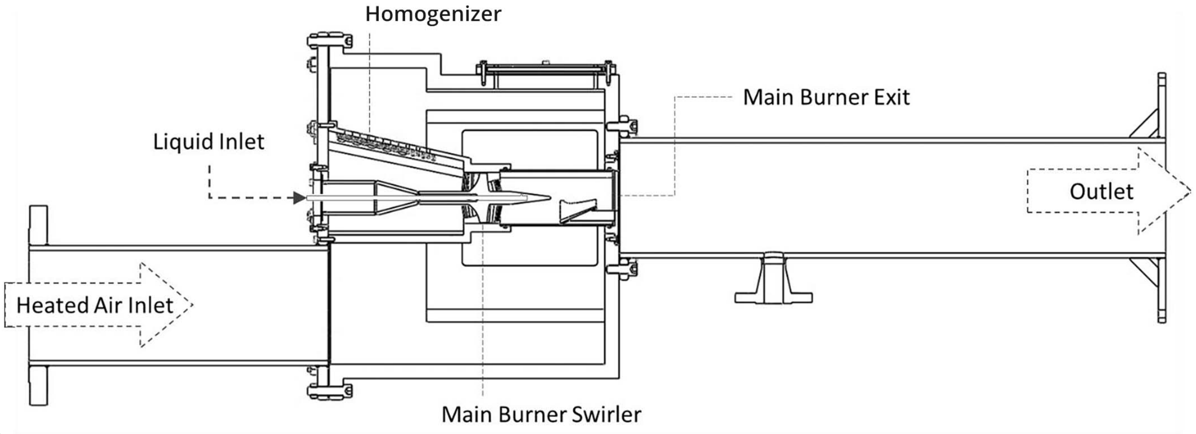

Figure 1 - Overall view of designed JICF test rig

This test rig operates under near-atmospheric pressure, while the inlet air is heated to approximately 420°C, corresponding to the MGT-75 compressor discharge temperature at base load. This configuration preserves the aerodynamic characteristics of the burner passages while providing optical access as shown in Figure 2.

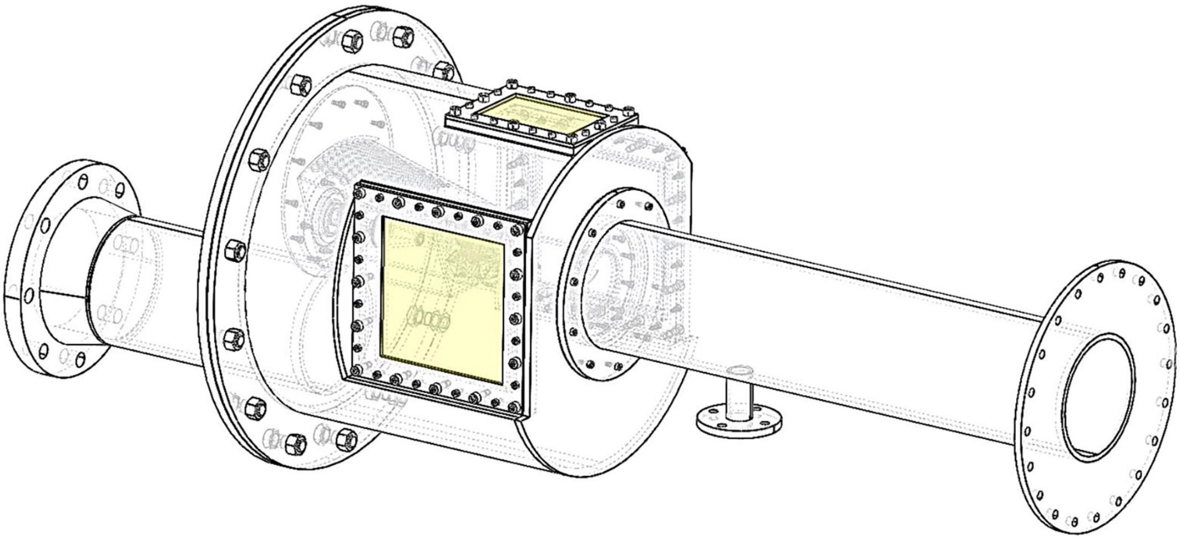

Figure 2 - Optical access of the test rig

The JICF test rig is installed within the TUGA combustion laboratory, which provides the necessary infrastructure for controlled experimental operation. The laboratory enables precise control of air mass flow rate, temperature, and pressure, as well as comprehensive data acquisition and monitoring capabilities. The air supply system consists of a screw compressor capable of delivering up to 2.5 kg/s at 2.5 bar, coupled with an electrical heater that raises the air temperature to 500 °C. Flow control is achieved using electrically actuated butterfly valves, while mass flow meters, thermocouples, and pressure transmitters provide real-time measurements and feedbacks. All systems are monitored and controlled via a PLC-based control system with an HMI interface.

Liquid Injection System

For safety considerations and operational simplicity, water is employed as a clean easy-to-use substitute liquid instead of diesel fuel in laboratory tests. Previous experimental investigations have demonstrated that replacing diesel with water results in less than a 5% deviation in liquid jet trajectory under comparable non-combustible conditions. As a result, strict matching of the Ohnesorge number is not required for the present tests, since viscous effects play a secondary role compared to aerodynamic forces that govern liquid jet penetration. To ensure uniform and controllable liquid injection, a pressurized liquid supply system is implemented in the water supply circuit. Water is stored in a sealed metallic reservoir that is pressurized using high-pressure service air. The liquid is then routed through a Coriolis mass flow meter and a tunable needle valve before entering the injector. A schematic of the liquid supply and injection line is shown in Figure 3. This approach provides stable and repeatable liquid flow conditions by suppressing flow-rate fluctuations associated with pump-driven systems. In addition, the system allows straightforward substitution of alternative liquids if required.

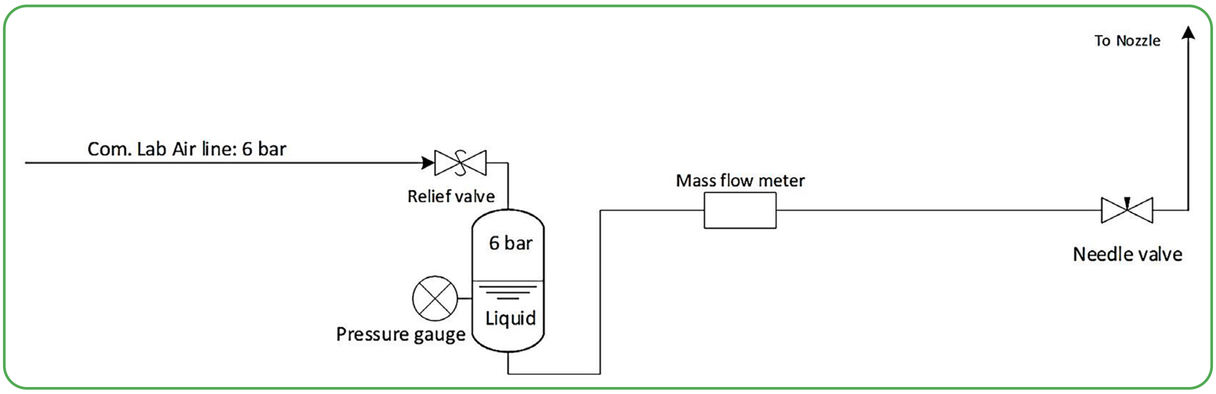

Figure 3 - A schematic of the liquid supply and injection line

Test Rig Manufacturing and Modular Lance Prototyping

Manufacturing of the test rig and fuel lance prototypes was a major milestone of the present project. The design of premixed fuel oil lance is an experiment-based process, which requires manufacturing and testing a series of prototypes in addition to numerical and analytical survey. Therefore, to reduce prototyping cost and testing time simultaneously, a modular fuel lance structure is adopted, featuring a threaded and interchangeable tip section that enables rapid replacement without modification of swirler or surrounding flow passages as depicted in Figure 4. Also, additive manufacturing techniques are employed for the fabrication of the swirler and lance tips, enabling rapid iteration and precise control over injector geometry. A family of interchangeable lance tips is produced to systematically investigate the effects of injection hole location, diameter, inclination angle, and multi-hole arrangements on liquid jet trajectory and dispersion.

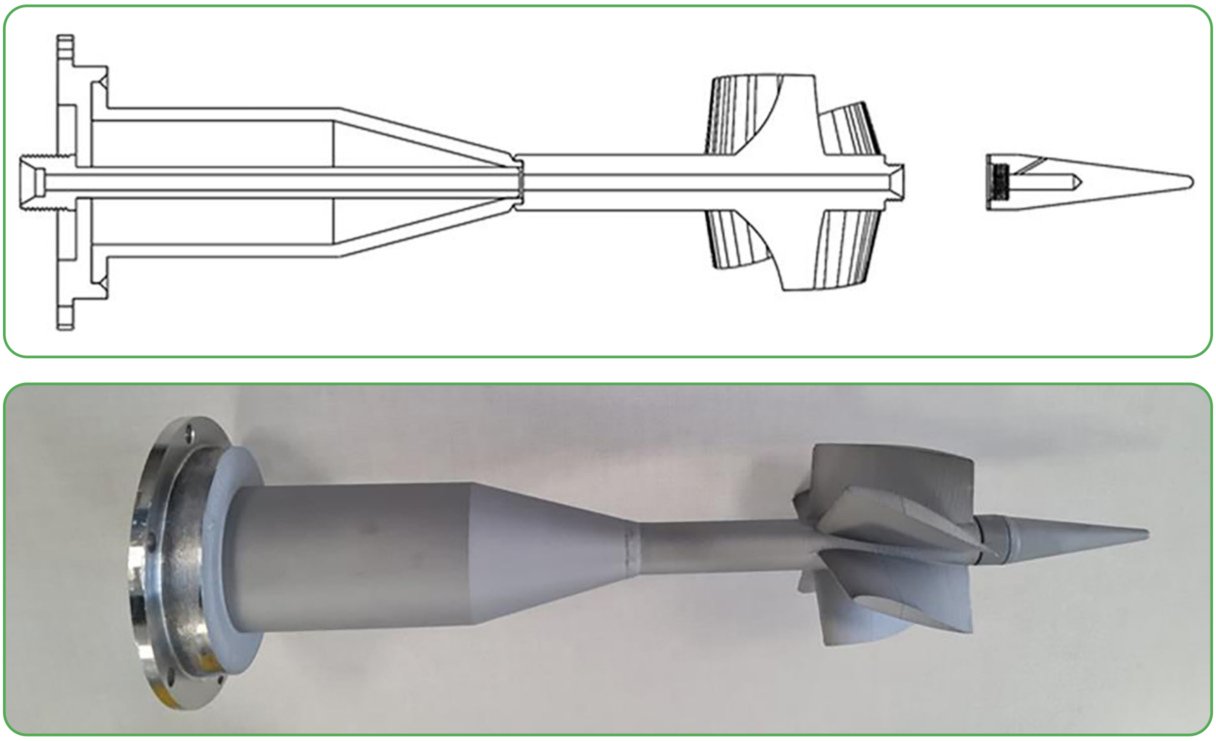

Figure 4 - Modular lance prototyping

This modular and iterative approach provides an efficient pathway for injector optimization while generating high-quality experimental data for numerical model verification. An overall view of the manufactured test rig is also shown in Figure 5.

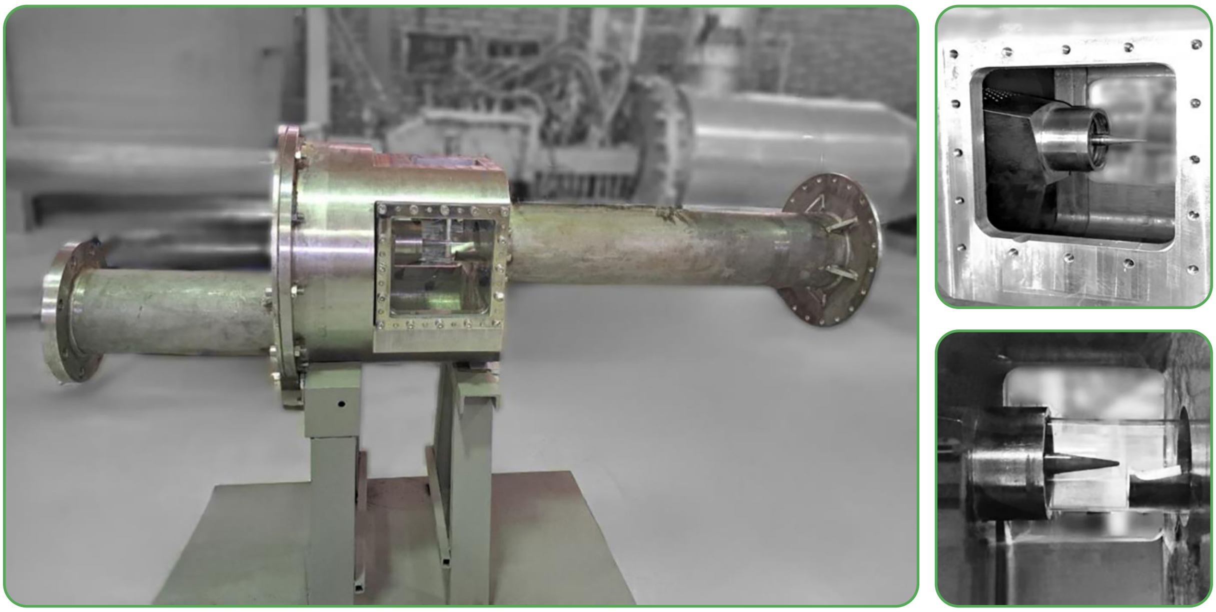

Figure 5 - JICF test rig

Optical Diagnostics and Data Processing

Shadowgraphy is employed to visualize the liquid JICF behavior. The imaging system comprises a high-speed camera (PCO pco.1200hs), an optical lens assembly, and a continuous light source. The camera is equipped with a CMOS sensor providing a resolution of 1280 × 1024 pixels and a maximum frame rate of 1357 fps. Image acquisition and camera control are performed using the manufacturer-provided Camware software.

Figure 6 - Imaging system comprising a high-speed camera and an optical lens

The liquid spray exhibits inherently unsteady behavior. To extract representative jet trajectories, time-resolved image sequences are acquired for each injector configuration, typically consisting of 2000 frames, as shown in Figure 7.

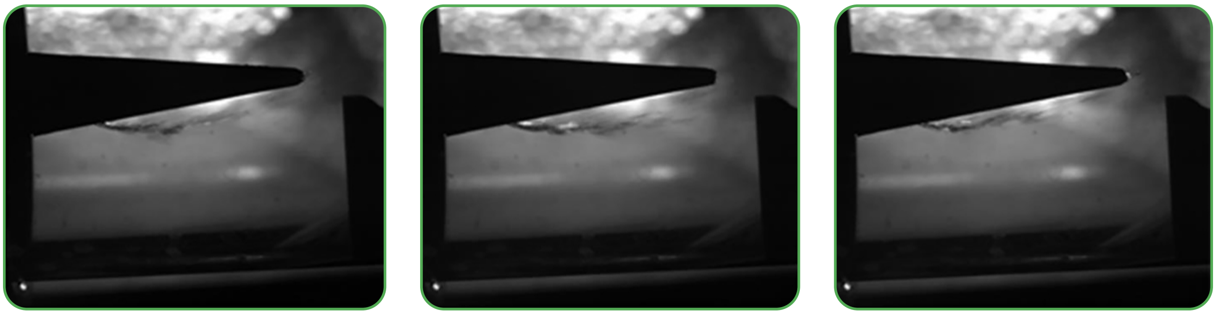

Figure 7 - Raw images of an injector configuration at a specified momentum flux ratio

Image processing includes background subtraction, noise reduction, normalization, and contrast enhancement. These procedures enable consistent and objective comparison among different injector configurations. Two complementary trajectory definitions are employed: a time-averaged trajectory representing the most probable jet path, and a conservative envelope trajectory that accounts for rare jet–wall interaction events, as shown in Figure 8.

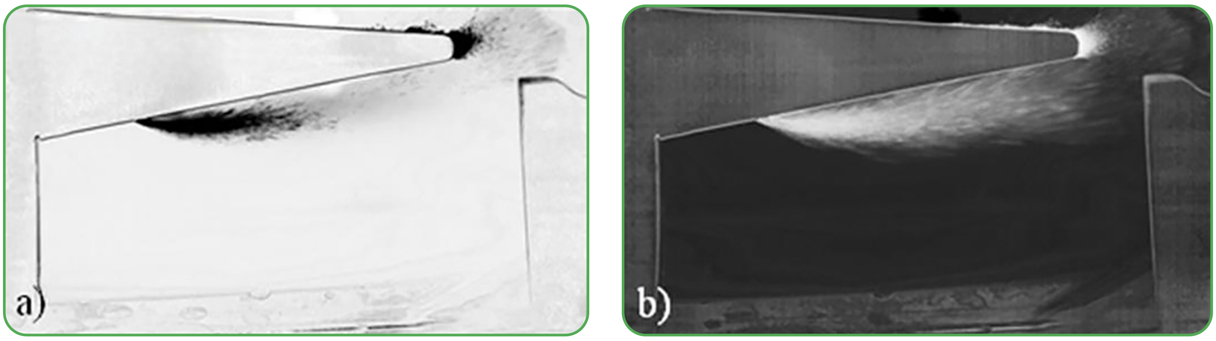

Figure 8 - Jet trajectories for an initial injector configuration based on (a) Ensemble-averaged images and (b) Presence-based evaluation independent of occurrence probability

Each injector configuration is installed sequentially, and the test conditions are selected to map laboratory operating points to represent engine conditions based on similarity considerations. Repeatability is ensured through controlled boundary conditions and standardized data acquisition procedures. Figure 9 shows an overall view of the prepared test setup.

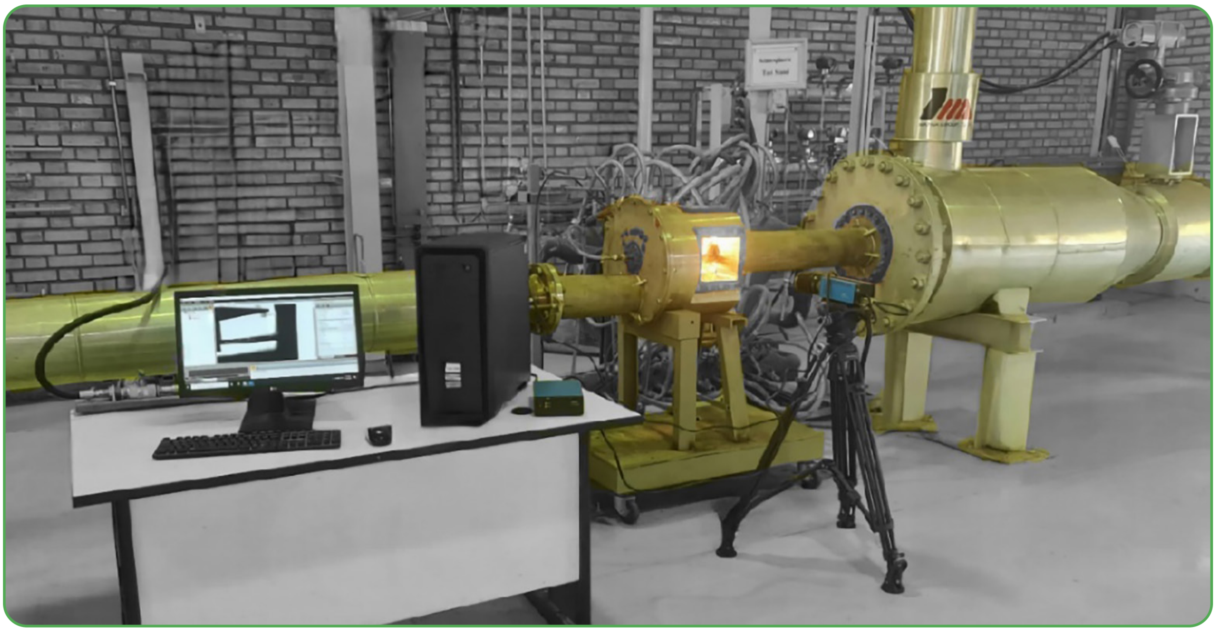

Figure 9 - Test setup

Concluding Remarks

The developed test rig serves as a dedicated experimental platform for the design and development of premixed liquid fuel burner. The modular and iterative design of the fuel lance, combined with advanced additive manufacturing techniques, allows rapid prototyping and precise control of injector geometry, facilitating detailed parametric studies of injection-hole configurations and liquid jet dispersion. This test rig enables wise design decisions during early development stages, reduces reliance on costly full-scale testing, and provides high-fidelity verification data for numerical simulations. Therefore, the facility bridges the gap between conceptual injector design and final combustor implementation. This established methodology offers a robust framework for future investigations of liquid fuel injection, supporting both improved combustion performance and enhanced operational flexibility in industrial gas turbines.

5

Fault Prediction of Diesel Engine Injector Using Deep Learning

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Introduction

Health of injectors is a critical factor in ensuring the reliable and efficient operation of heavy duty diesel engines. Since direct measurement of injector operational parameters is often impractical, injector health can be assessed indirectly using the analysis of accessible engine data. Furthermore, conventional maintenance strategies often result in suboptimal fuel efficiency and approximately 30-40% unnecessary component replacements. Therefore, maintenance planning must evolve from static timetables toward proactive and predictive techniques. By combining condition-based monitoring (e.g., vibration, fluid analysis, and thermography) with data-driven RUL[1] models, operators can minimize unplanned outages. These approaches are particularly valuable considering current procurement constraints, such as limited spare part availability and long shipping times. While industrial strategies range from run-to-failure and preventive maintenance to RCM[2] and TPM[3], targeted interventions for predictive maintenance are essential for critical subsystems.

Early detection of subcomponent failures in large-scale industrial machinery provides substantial economic benefits. For instance, failures in fuel-system components like injectors can cascade and compromise pumps, pistons, and turbochargers, resulting in high repair costs and prolonged downtime. Hence, a data-driven non-intrusive approach provides early fault detection which supports optimized maintenance planning and reduced costs, contributing to extended engine lifetime. This study represents a component of an ongoing, comprehensive project within the Department of Heavy Duty Diesel Engines. The broader initiative employs state-of-the-art machine learning and AI techniques to assess the condition of various engine subsystems and predict potential failures. This article offers a novel, deep learning-based methodology, leveraging the monitoring of exhaust port temperature under full-load conditions.

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[1] Remaining Useful Life
[2] Reliability-Centered Maintenance
[3] Total Productive Maintenance

Injector Health Assessment

Given the sensitivity of common-rail diesel injectors to fuel quality and pressure transients, injector-related failure modes are a common, repeatable source of engine damage and require prioritized monitoring.

To establish a baseline for a healthy system, a DNN[1] was developed using key engine operational parameters. Comparing the actual measured exhaust port temperature with the DNN-predicted "reference injector" temperature, enables quantitative evaluation of degradation for individual injectors. To address this, a digital twin was developed based on data from the engine's baseline period of the optimal operation. This model utilizes a neural network to predict the expected exhaust port temperature of each cylinder under full-load conditions.

By comparing the actual exhaust temperature against the model's prediction, a specific deviation is calculated. The normalized magnitude of this deviation serves as a proxy for the health score of the injector associated with that specific cylinder.

Deep Neural Network System

The conventional methods for evaluating injector performance are to test it individually on a test bench; the injected mass is measured at defined points and compared with reference values. Although the conventional testing method requires removal of the injector from the engine, it could not detect their actual operating state in engines operating in the fleet. This removal of the injector results in increased labor, downtime, testing costs and the risk of damage or leakage in high-pressure fuel system components due to the sensitivity of the precision parts. Indeed, even well-designed test-bench conditions cannot fully represent real engine operating conditions. Furthermore, certain sporadic faults may not be revealed during the test. Correspondingly, there are built-in ECU diagnostic functions related to injector monitoring which may have limited capability in reliably identifying injector faults. Other techniques including thermography, acoustic and vibration measurements show limited effectiveness for injector fault detection.

Injection quantity affects the exhaust gas temperature. Therefore, exhaust port temperature measurement can be used as another diagnostic tool to indirectly assess the working condition of the injectors or other engine-related malfunctions such as charge-air system faults, valve malfunctions, piston ring wear, or cylinder liner degradation. As the injection system malfunction is a dominant factor, it is a recommended practice to check them when a warning signal arises.

Preceding efforts included development of an online monitoring system that collects standard operating parameters measured by the ECU along with data from additional sensors, including exhaust port temperature for each cylinder, and streams them to an online server where the data are stored and used for subsequent monitoring and analytical processes. The segment regarding hardware development was reported in a previous issue of TR [1].

As previously mentioned, a DNN model is an adaptive system to approximate complex functions. Rather than being directly governed by predefined rules, these models learn from data. They adjust the weights and biases of their neurons during a so-called training process to identify patterns and map inputs to outputs. In associated literature, input and output parameters are often called features and targets, respectively.

Based on previous knowledge, Engine speed, demanded fuel quantity per stroke (Q_{fuel_demand}), Intake Air temperature (T_{intake}), Charge Air Pressure (P_{Charge_air}) and Charge Air temperature (T_{Charge_air}) are the most common correlated parameters determining the exhaust temperature.

---

[1] Deep Neural Network

To reduce the number of features, a derived parameter φ (equivalence ratio) is defined based on Q_{fuel_demand}, T_{Charge_air}, P_{Charge_air}. By defining this feature, the number of model features is reduced to 3 which include Engine speed, T_{intake} and φ (equivalence ratio); and the target outputs are individual exhaust port temperatures. The model structure concept is shown in Figure 1.

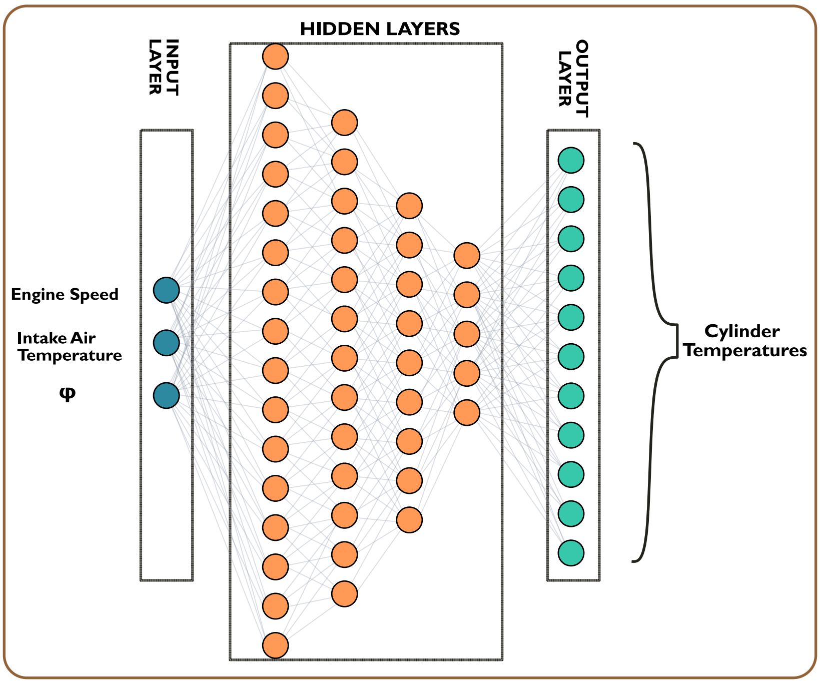


Figure 1 - Concept for neural network systems

► Neural Network Architecture

Topology:

- Input layer: Variable dimensionality (dependent on sensor suite)
- Hidden layers: [256→128→64→32] neurons with progressive dimensionality reduction
- Output layer: 16 neurons (cylinder-specific predictions)
- Activation: ReLU with batch normalization
- Regularization: 10% dropout to prevent overfitting

Technical Strengths:

- Adaptive learning rate: ReduceLROnPlateau scheduler enables dynamic convergence optimization
- Batch normalization: Stabilizes training across varying operational conditions
- Multi-output regression: Simultaneous prediction of all cylinder states that maintains inter-cylinder correlations

This work is based on the assumption that the engine injectors operate properly when they are new. Their corresponding exhaust port temperatures during this period are considered as representative of 100% healthy operating behavior, and the neural network is created using data collected during the period when all the injectors are new. Then, this neural network is used in later stages as a reference to determine the expected temperature of each cylinder port corresponding to a certain injector. For this purpose, an injector health score parameter is defined, which represents the percentage of temperature deviation between the actual exhaust port temperature and the reference temperature inferred by the neural network.

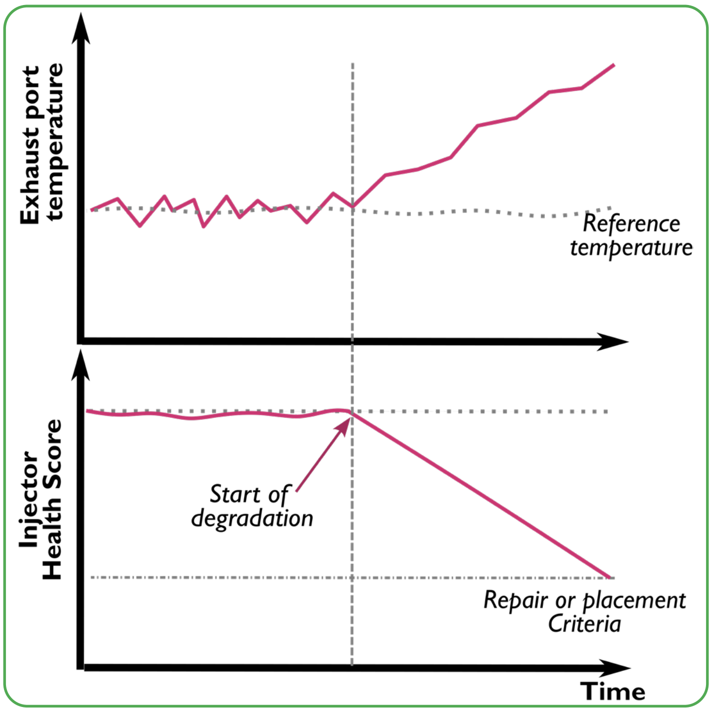


Figure 2 - Health score definition

Software Development

The software is developed using python programming language and PyTorch and scikit-learn libraries for machine learning. It consists of two sections. First section gathers the operating data of engine from sensors, then cleans the data and filters them to the steady state, full load condition.

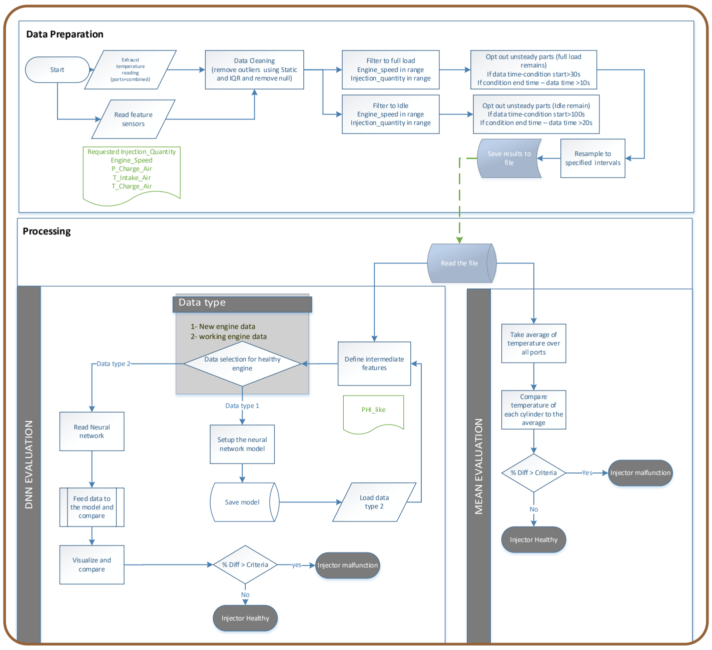
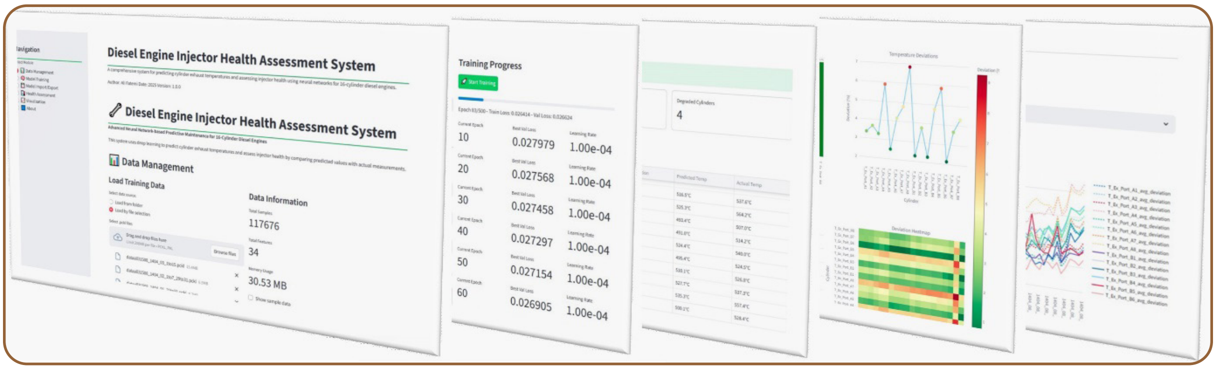


Figure 3 - Flowchart of the model

The second part including a web-based dashboard is shown in Figure 4.



Diesel Engine Injector Health Assessment System

A comprehensive system for predicting cylinder exhaust temperatures and assessing injector health using neural networks for 16-cylinder diesel engines.

Author: Ali Fateni Date: 2025 Version: 1.0.0

Diesel Engine Injector Health Assessment System

Advanced Neural Network-based Predictive Maintenance for 16-Cylinder Diesel Engines

This system uses deep learning to predict cylinder exhaust temperatures and assess injector health by comparing predicted values with actual measurements.

Data Management

Load Training Data

Select data source:

○ Load from folder

● Load by file selection

Data Information

Total Samples: 117676

Total Features: 34

Memory Usage: 30.53 MB

☐ Show sample data

Training Progress

Epoch 83/500 - Train Loss: 0.026414 - Val Loss: 0.026624

Current Epoch	Best Val Loss	Learning Rate
10	0.027979	1.00e-04
20	0.027568	1.00e-04
30	0.027458	1.00e-04
40	0.027297	1.00e-04
50	0.027154	1.00e-04
60	0.026905	1.00e-04

Degraded Cylinders: 4

Figure 4 - An overview of the web-based software workflow

This structure facilitates data management as well as model development, assessment, visualization and historical condition overview.

The data acquired from three railway diesel engines for one year of continuous operation was approximately 150 gigabytes. The first three months of data for each engine were used for baseline creation, with 80% used for training and 20% for validation. Figure 5 shows the linearity of the model prediction for different cylinders.

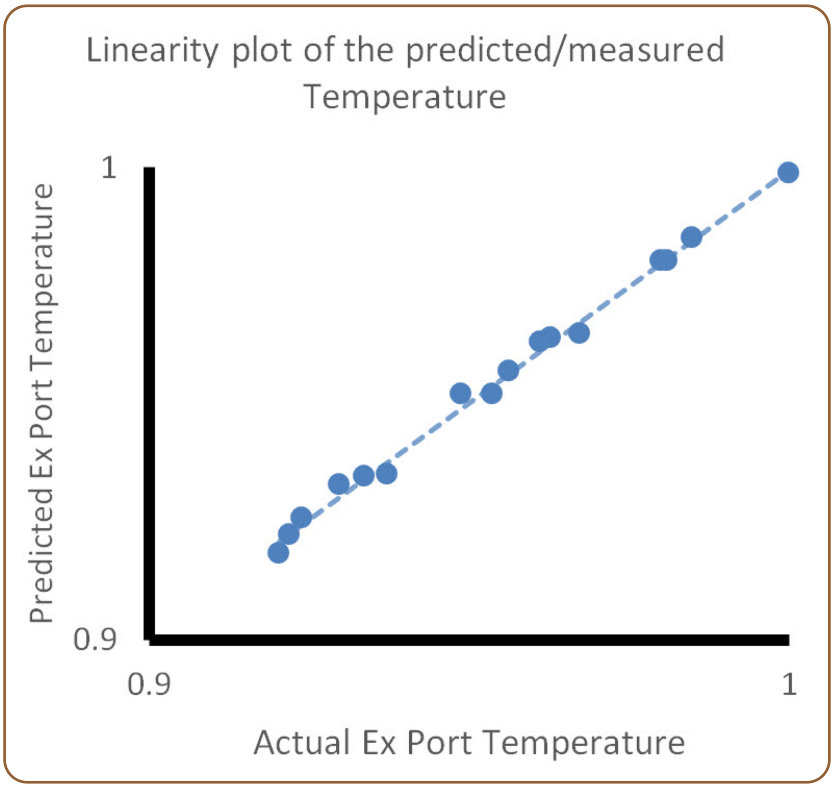


Figure 5 - Linearity Plot for Predicted exhaust port temperature in relation to actual measured port temperature

```
MAIN
 ├─ Data Management
 ├─ Model Training
 |            ├─ Structure Configuration (hidden sizes, dropout, lr , …)
 |            └─ Training Process
 ├─ Model management
 |            ├─ Export Recently trained model
 |            └─ Import Pre saved model
 ├─ Health Assessment
 |            ├─ Load and Assess data
 |            └─ Visualize individual day data
 └─ Visualization
              ├─ Training History
              ├─ Model Performance
              └─ Health Trends
```

Figure 6 - GUI structure

The daily visualization dashboard is presented in Figure 7.

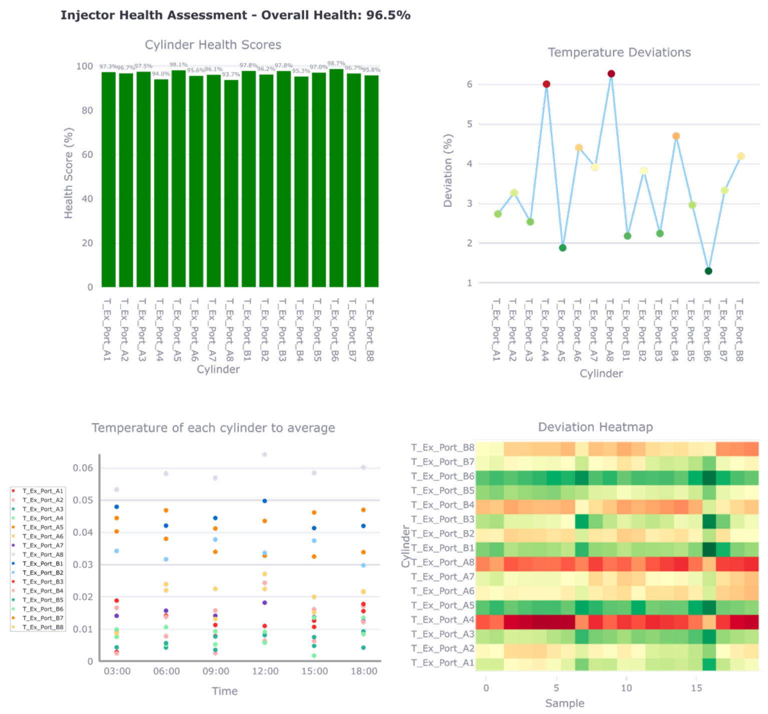


Figure 7 - Injector daily health assessment dashboard

Concluding Remarks

The presented injector health assessment tool represents a significant shift from reactive toward predictive maintenance in large-scale diesel engine operations. By synthesizing multi-sensor data streams through advanced deep learning architectures, the system achieves three critical objectives:

- Real-time fault detection
- Quantitative health assessment
- Predictive maintenance optimization

In conclusion, this tool represents more than a diagnostic software; it exemplifies a strategic enabler for operational excellence in heavy industry, where reliability, efficiency, and environmental responsibility are increasingly interdependent requirements. Organizations that adopt such advanced analytics platforms will gain decisive competitive advantages in an era where data-driven decision making differentiates industry leaders from followers.

References

[1] A. Emami, M. Izanloo, H. Deldar, "*Online Condition Monitoring for Locomotive Diesel Engines: Improving Reliability and Maintenance Efficiency.*" Technical Review MAPNA TURBINE ENGINEERING & MANUFACTURING CO. (TUGA), No.24, 2025, September, pp. 22-27.

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