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INDUSTRIAL APPLICATION OF GAS TURBINES COMMITTEE

Trent 60 Design and Validation for Mechanical Drive Service

by

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Scott Nolen, Product Marketing Manager, studied Mechanical Engineering at the University of Vermont and holds a MBA from the University of Rochester. Scott joined Rolls-Royce Energy in 2001 and assumed the role of leading the marketing effort for the Trent. Previously he was employed by the Dresser-Rand Company for 11 years based in New York and the Middle East. In 2004, Scott led the team that captured the Dolphin Project, the first contract using the Trent for mechanical drive service. He is currently responsible for the Rolls-Royce Power Generation marketing group based in Mount Vernon, Ohio.

Kevin Goom received his formal education at Loughborough University in the UK, where he obtained BSc and Masters degrees in Aeronautical Engineering. He then joined Rolls-Royce in Derby, where he worked initially in the Combustion Department, and later moved to the Advanced Projects group. In 1978 Kevin emigrated to Canada where he worked for Pratt & Whitney Canada in the Combustion Department, Product Support, Operations Program Management, Helicopter Marketing and Industrial & Marine Marketing. He is now employed by Rolls-Royce Canada as an Applications Engineer and is a member of the Ordre des ingenieurs du Quebec.

Abstract: Trent 60 Design and Validation for Mechanical Drive Service

The Trent 60 is a 3 spool high pressure ratio gas turbine based on the RR Aero Trent 800 that powers the Boeing 777. There are 3 compressor rotors: LPC - 2 stages, IPC - 8 stages and HPC - 6 stages and three turbine rotors driving the compressors: LPT - 5 stages, IPT - 1 stage and HPT - 1 stage. The 3 spools are not mechanically coupled so each shaft may turn at its optimum speed. The driven load is coupled to the LP rotor.

The Aeroderivative lineage of the Trent 60 when used for Mechanical Drive Service allows a number of advantages when compared to a single shaft gas turbine, i.e. short start time, 105-70% variable speed envelope, low weight and low power starting.

In 2002 and 2003 the Trent 60 engine and control system were validated for mechanical drive service on a test bed by using novel and sophisticated generator control. This allowed the use of a synchronous generator to mimic the load / speed characteristics of a gas compressor while simulating all of the potential operation issues that may occur during compressor operation.

The Trent 60 can be supplied with a Wet Low Emissions (WLE) combustor or a Dry Low Emissions (DLE) combustor. For DLE service, eight cannular staged combustors are fitted to the engine. Each combustor uses series staged fuel injection. Emissions are minimized by close control of the flame temperature in each stage.

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Nomenclature

DLE	Dry Low Emissions - Emission control by using a staged temperature controlled combustion system.
HPC	High Pressure Compressor – The compressor section of the high speed shaft of the Trent Gas Turbine. This shaft is used to start the Trent engine and is driven by a hydraulic expansion motor in start-up mode.
HPT	High Pressure Turbine – The turbine section of the high speed shaft of the Trent Gas Turbine.
IPC	Intermediate Pressure Compressor – The compressor section of the intermediate speed shaft of the Trent Gas Turbine.
IPT	Intermediate Pressure Turbine – The turbine section of the intermediate speed shaft of the Trent Gas Turbine.
LNG	Liquified Natural Gas
LPBOV	Low Pressure Blow Off Valves
LPC	Low Pressure Compressor – The compressor section of the low speed shaft of the Trent Gas Turbine. This shaft is coupled to the driven load.
LPT	Low Pressure Turbine – The turbine section of the low speed shaft of the Trent Gas Turbine.
LPVIGV	Low Pressure Variable Inlet Guide Vanes
MD	Mechanical Drive
MW	Megawatts = 1000 kW = 1,000,000 Watts
NL	Speed of the low pressure compressor shaft
PG	Power Generation
TMD	Trent Mechanical Drive
WLE	Wet Low Emissions - Emission control by using water injection into the combustor.
vppmd	Parts per million in dry exhaust gas

1) Introduction

The Trent Mechanical Drive (TMD) engine is a 3 shaft gas turbine derived from the Rolls-Royce Aero Trent 800. It is the most powerful aeroderivative engine on the market and first entered Power Generation (PG) service in 1998. In simple cycle the engine can deliver 58 MW at 42% thermal efficiency in PG applications.

A programme to develop and validate the engine for Mechanical Drive service was undertaken in 2002. This included testing the engine in a power station where the generator controls were reprogrammed to give variable load / speed characteristics and simulate the behaviour of a centrifugal compressor or pump. A shaft brake was also used to validate the loaded start capability of the engine.

2)Trent 60 Engine Overview

The Trent 60 is based on the Aero Trent 800. For the industrialization of the aero engine the high bypass front-end fan is replaced by a 2 stage axial compressor while the Intermediate Pressure (IP) and High Pressure (HP) rotors are aero common parts. Industrial specific Dry Low Emissions (DLE) combustors and Low Pressure (LP) Turbine are used. The generator is directly coupled (i.e. no gearbox) through the "hot" end. Figure 1 shows cutaways of the Aero Trent 800 and Industrial Trent 60.

Multi-shaft engines have a number of benefits over single shaft engines that contribute to good mechanical drive performance:

- Variable speed operation
- Rapid start
- Low starter power
- Light weight and compactness
- High efficiency

The multiple shafts are not mechanically coupled thus each rotor turns at its optimum speed. The ability to run the engine core relatively independently from the load allows low starter power, high breakaway torque and wide speed / load flexibility. Aero commonality is maintained as much as possible thus profiting from aero design methods and materials.

The engine has 8 serial staged DLE combustors. Fuel staging maintains tight control of flame temperatures to minimize production of CO and NOx. Emissions are guaranteed < 25 vppmd NOx and CO at 15% O_2 at baseload. The combustor also uses novel fuel mixing technology to avoid the low NOx = high noise mechanism that has plagued other industrial gas turbines.

For the Trent 60 the aero high bypass fan has been replaced by a smaller 2-stage low pressure compressor (LPC). This is driven by an increased diameter power turbine to recover the maximum amount of power. The net effect is a large increase in rearward axial thrust loading on the bearings. Thus, an active thrust piston system is used to control the axial load on the bearings and maintain bearing life.

Two versions of PG Trent are available; a 50 Hz and a 60 Hz version. They differ only in Low Pressure Compressor (LPC); the 50 Hz compressor blades have a reduced stagger angle (i.e. are more open) to pass the same airflow at 3000 rpm as the 60 Hz LPC at 3600 rpm. The TMD engine uses the 60 Hz LPC with the design speed set at 100% NL = 3400 rpm.

3) Trent History

The first Trent 60 DLE engine was installed in 1998, with mixed results. This design was improved in 2001 for existing customers. The final design used for new customers and for TMD was available in 2003. To date, the Trent PG fleet has accumulated over 120 000 hours. PG engines are installed in Whitby, Ontario; Grande Prairie, Alberta; Copenhagen, Denmark and 6 sites in England.

The Trent Wet Low Emissions (WLE) PG engine was standardized in 2001 and the lead WLE site has over 10 000 h operation.

The Dolphin TMD engines are currently being delivered and will enter service in 2006.

4) The Opportunity to use the Trent for Mechanical Drive Service

4.1) The Dolphin Project

In the summer of 2002, the Dolphin Project began to take its final shape. This project is the development of the large non-associated North Gas Field located in the Persian Gulf north of Qatar. The gas is processed at Ras Lafan, in northern Qatar and then transported through a 480 km undersea pipeline to the UAE. In order to boost the gas from the outlet pressure of the gas plant in Ras Lafan to the inlet pressure of the export pipeline, 167 MW of compression power is required. The project is jointly owned by Mubadala Development Company, Total of France and Occidental Petroleum of the USA

Rolls- Royce recognized the opportunity to meet this duty with the Trent 60 by using five trains; each containing one Trent 60 gas turbine driving one two section compressor. The Trent's high power at site conditions, variable speed capability, low power starting and high efficiency made it ideal for this project.

4.2) Other TMD Opportunities:

Natural Gas Liquifaction Plants (LNG) – LNG plants require a large amount of power to drive the refrigeration trains in order to liquefy the gas for transportation.

Offshore oil and gas production – Fixed and floating production facilities require high power, light weight and compact machines.

Gas Transportation – Gas pipelines require variable speed high efficiency operation.

5) Trent Mechanical Drive Validation Testing Overview

In order to prove the Trent 60 engine capable of meeting the demands of mechanical drive service, Rolls-Royce outlined a testing and validation program. In order to properly evaluate the successful validation of the Trent Engine for mechanical drive service the R-R Derwent Process was employed. This process is a gated quality procedure where project plans and results are presented, evaluated and approved by technical experts from across the Rolls-Royce Company. Certain criteria must be cleared before passing from one phase of the project to the next and the project may be stopped or delayed if key criteria are not met at each gate. Figure 8 shows the test programme and the respective Derwent gates. Test performed in each phase of this program would attempt to mimic the operational characteristics of a compressor train operating in variable speed mode.

Ideally the MD validation testing would be carried out using an actual compressor to accept the load from the gas turbine. This option was quickly rejected due to the cost and the required lead time. However, Rolls-Royce was able to mimic all of the characteristics of a compressor drive by using a unique generator arrangement.

5.1) R-R Test Cell 7

Test Cell 7 is a combined power station and test cell owned by Rolls-Royce Canada and the City of Montreal (figure 11). It was built after the 1998 ice storm to provide power to the City of Montreal water treatment plant in the event of another extended power interruption. The facility is located in Verdun, adjacent to downtown Montreal. Prior to the need for variable speed operation to prove the Trent 60 engine for mechanical drive service, the test cell operated at 50 or 60 Hz for Trent PG engine development and production acceptance testing.

The cell uses a 100 MW generator to accept the load from a gas turbine and may operate on the grid or in "island" mode. In island mode, the generated power is dissipated through loadbanks which are suitable for testing at 50 Hz, 60 Hz or variable generator speed operation.

The generator manufacturer limited excitation of the generator to above 800 rpm. They also provided information on manually exciting the generator to load the engine at speeds other than 3000 or 3600 rpm. Facility control software was written to allow slewing the load anywhere within the zone shown in figure 3.

5.2) Requirements for proving the Trent 60 for MD service

The following elements were required to prove the engine acceptable for mechanical drive service:

- Low Speed Operation and Breakaway Torque
- Acceptable operation in the TMD Running Zone
- Idle Operation
- Partial Load Shed
- LPT Dynamics
- General Engine Performance
- Endurance Running

5.2.1) Low Speed Operation and Breakaway Torque

Mechanical Drive (MD) installations typically require a higher level of breakaway torque than PG (e.g. starting a compressor in a charged pipeline). Analysis showed the multi-shaft design of the Trent, where the IP and HP core can run with a stationary LPT, should develop around 20 kNm of starting torque. Starting torque was limited by the core capacity with no LP compressor boost and concerns regarding the stationary LPT bearing. HP rotor speed was limited to 7200 rpm, which is the PG sub synchronous idle speed for the engine. LPC and LPT flutter were also risks.

Very low speed loading and breakaway torque testing was performed by fitting a 1400 mm diameter disk brake on the LP rotor train in place of the torquemeter. The design provided 29 kNm of torque (figures 4, 5). The brake frame was also fitted with loadcells in order to measure braking torque.

Testing was performed successfully. Strip examination of the LPT bearings found no distress. Review of the LPC pressure ratio showed that there was no LPC flutter concern. LPT flutter was cleared as part of the Turbine Dynamics validation. Validated breakaway torques and loaded start curves are shown in figure 6.

5.2.2) TMD Running Zone

The core engine swallows compressed air from the LPC. In PG, the compressor turns at a constant speed and air flow is controlled by scheduling the Low Pressure Variable Inlet Guide Vanes (LPVIGV) and Low Pressure Bleed off Valves (LPBOV). For TMD, the LPC speed and flow varies in addition to the core power. Calculation showed the operating regime in figure 3 should be possible. Engine power above the zone in figure 3 is limited by compressor flutter and the lower limit in figure 3 represents the customer minimum requirement. Flutter can occur when the core is running at a high power and demanding a large mass flow of air but the LP compressor is running slowly and can not deliver the required flow. Running below the zone represents low core power and air flow. The LPC is running fast and delivering a large airflow so excess air is bled off by opening the LPBOV's. Engine running anywhere within the envelope was theoretically possible. New LPVIGV and LPBOV maps were required to manage the LPC airflow to the core.

The engine could be run along a preset curve or in "Slew Mode". Slew mode consisted of changing engine power (at constant LPT speed) or LPT speed (at constant power) to maneuver the engine within the figure 3 zone. Generator excitation control was programmed to allow Slew Mode or movement along the curve.

LPC pressure ratio was monitored to ensure avoidance of LPC surge or flutter. The LPVIGV and LPBOV movements were compared to the prediction to ensure that appropriate amounts of air was fed to the core.

Testing validated the complete operating zone from figure 3.

5.2.3) Idle Operation

There are two low power or idle points in TMD. TMD idle requires the LPT to operate at approximately 800 rpm to warm up the turbine air system. Additionally the low speed point at the turbine was set at 70% of the LPT speed or 2380 rom. This represents the lowest speed that the driven compressor could operate. There is typically a band of rotor natural frequencies between these two points where steady state operation is not allowed.

TMD idle point was equivalent to PG subsynch idle. However, in PG subsynch idle, only the high pressure rotor speed is controlled. For TMD, the control system was redesigned to close loop on LPT speed. The core engine speed would result from the LPT speed and ambient conditions. There was a risk of running the core below the engine's self sustaining speed or below the combustor's lean limit at some ambient temperatures. Only the primary combustor stage is operating at this power.

70% LPT speed was roughly equal to PG synchronous idle. Both stages of the combustor are flowing at this power level. This required a software update to manage the introduction of the secondary fuel without introducing an excessive engine perturbation.

Testing to TMD idle and 70% NL took about 1/3'rd of the validation testing time. LPT overshoot and stabilization issues were seen and resolved to arrive at stable TMD idle operation. Many iterations were done to control the combustors and core to reach 70% LPT speed in a stable manner.

5.2.4) Partial Load Shed

All gas compressor systems employ an anti-surge system tied to a recycle or blowoff valve to protect the compressor from surging. However, in the worse case scenario, surge in the compressor may be unavoidable. Surge would produce a short load drop and reapplication as shown in figure 7. Rapid load fluctuations may lead to engine speed oscillations and shaft overspeeds.

The load profile, figure 7, was programmed into the generator control, again by manipulating the generator excitation voltage and current. It was tested on the engine with acceptable results, thus validating the control system response to fast transients.

In general, this test would be repeated on site as the rotor train inertia would differ from the testcell generator thus affecting the overall system dynamic response. A client would supply the relevant information to RR and a prediction of the dynamic response would be made before on site validation.

5.2.5) LPT Dynamics

The LPT rotates at constant speed in PG operation. In TMD, it would operate at a range of speeds thus blade dynamics were a potential issue. All the blades and vanes were analysed using in-house software and methods. This included flutter analysis in addition to normal modes calculation. Most of the resonant frequencies were cleared during analysis.

As expected, some modes were identified that could not be dismissed by analysis. During testing, the engine was operated at speeds meant to excite the flutter and normal modes. Post-test strip and examination found no turbine distress and cleared the modes as non damaging or non existent.

5.2.6) General Engine Performance

Engine performance and emissions were monitored throughout testing. These data were extrapolated for different ambient temperatures to develop figures 9 and 10. The wide flexibility, efficiency and power of the engine are apparent and agrees with the performance predictions.

6) Results

The development programme achieved its objectives of identifying and clearing the issues required to convert a multispool PG gas turbine into a MD machine. In particular, the following were validated:

- Speed / Load envelope
- Partial Load shed
- Loaded Start
- 341 h operation in development testing (operability, transients, endurance)
- high power and efficiency throughout a range of ambients

As a result of these successful tests, the Trent 60 engine has been cleared for sale as a mechanical drive gas turbine and will enter service in 2006 when it begins operation on the Dolphin pipeline.

7) Acknowledgements

The authors wishes to acknowledge the contributions of the following and their teams:
E. Lemonde, TMD development team leader; S. Mhanna, Controls and Software development; V. Perez, Performance analysis; S. Boisvert, Test cell 7 Electrical modifications; N. Hardy and Y. Brasseur, Test cell 7 Mechanical modifications.

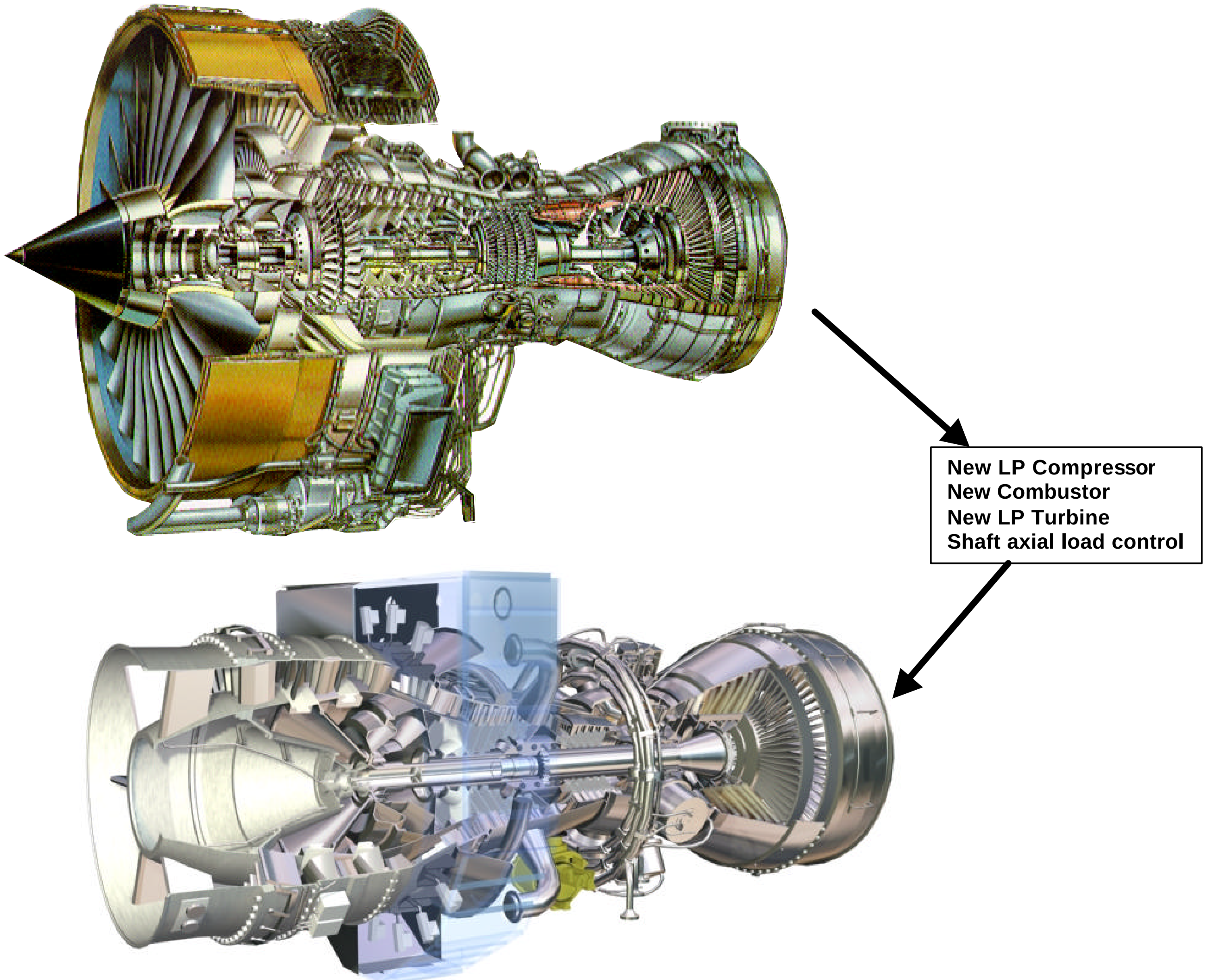

Figure 1) Aero Trent (above) converted to TMD (below).

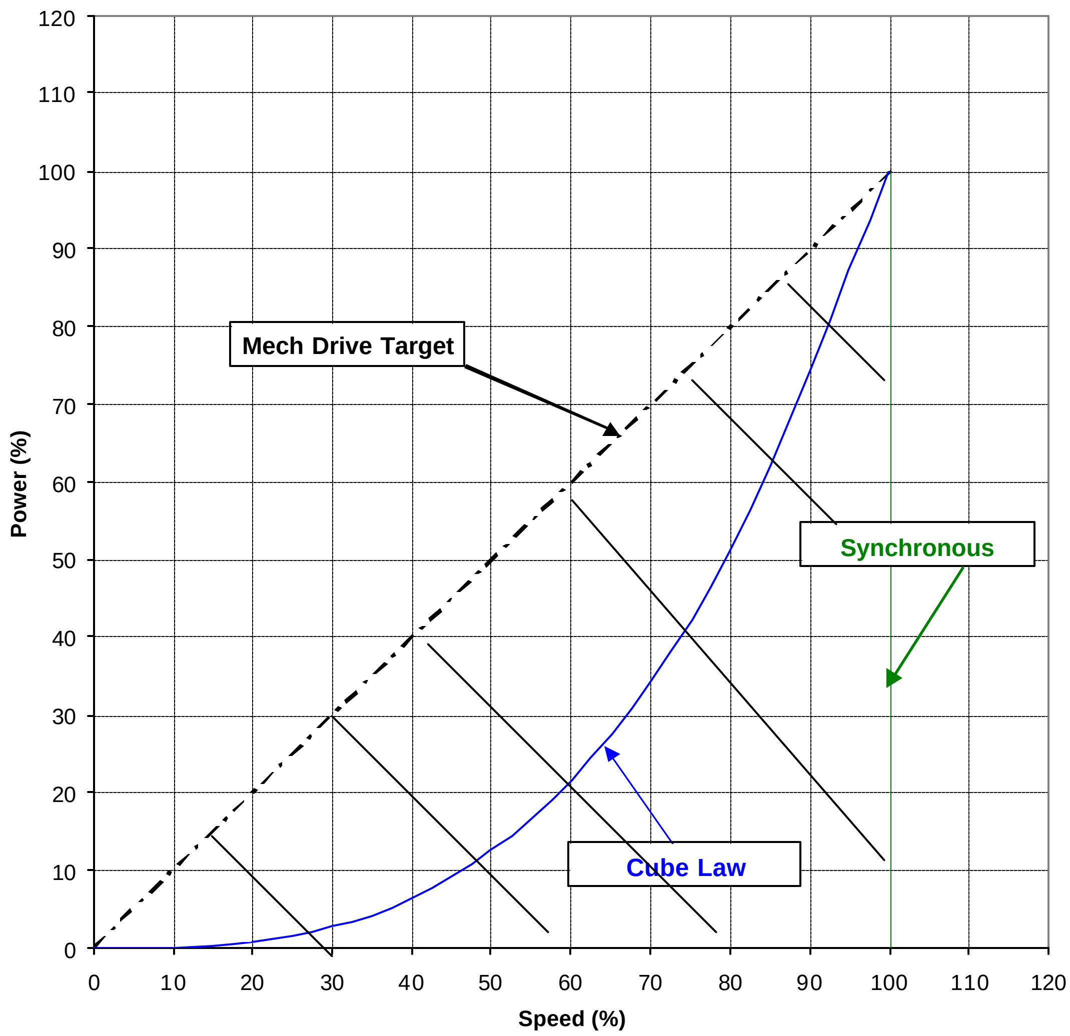

Figure 2) TMD Operating Objective. Typical compressors have a cubic power / speed relationship.

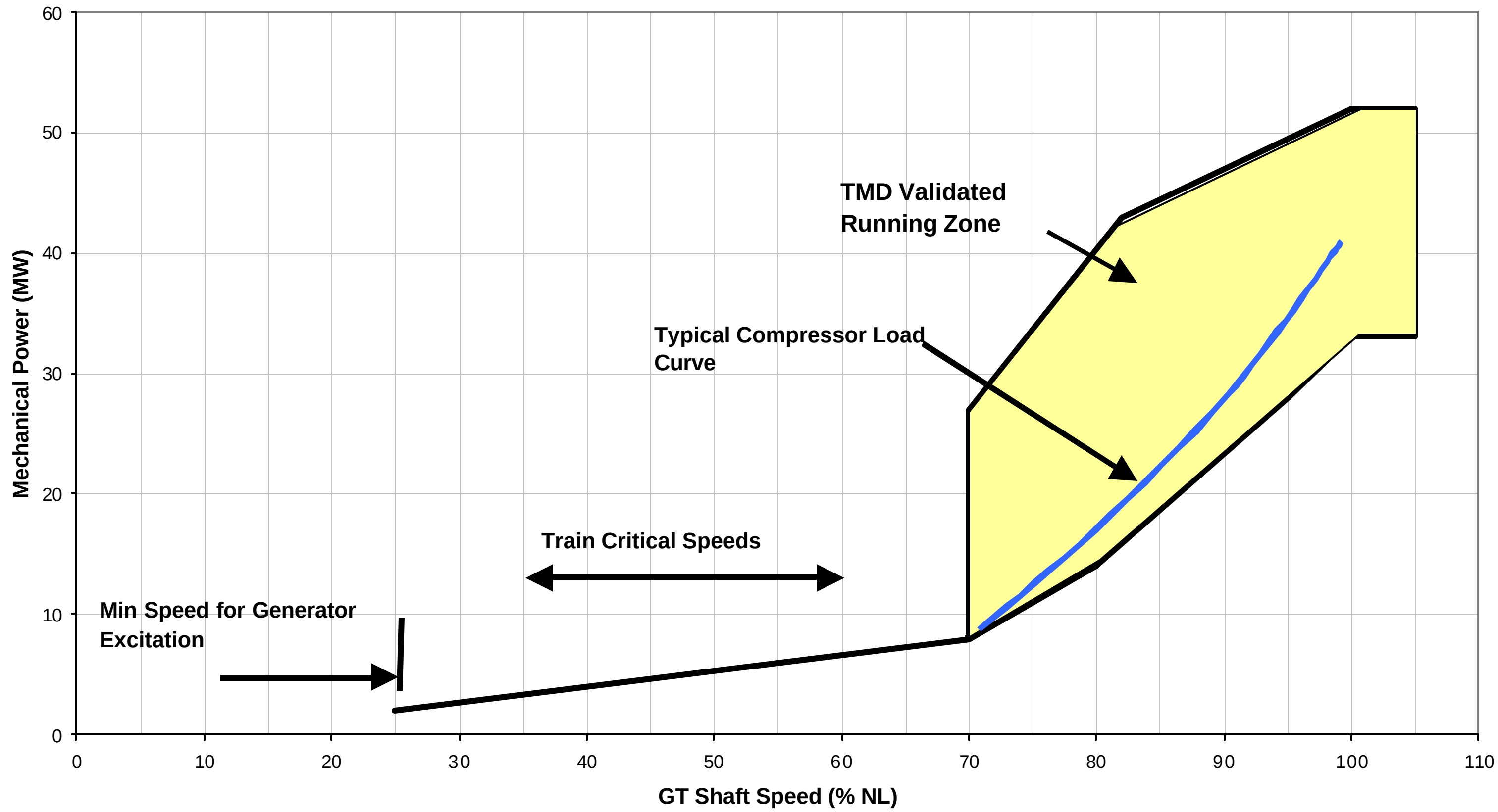

Figure 3) Validated TMD Operating Regime. The Running Zone covers a large part of the target in figure (2).

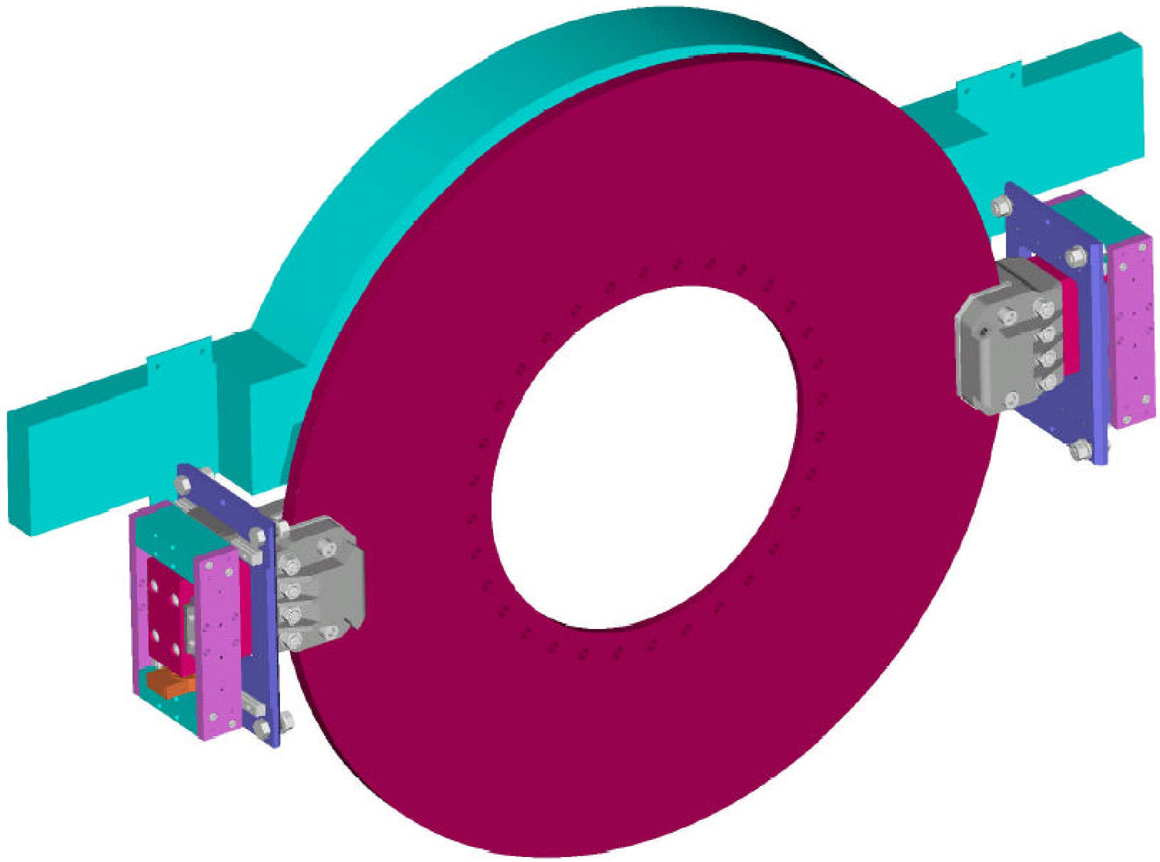

Figure 4) Shaft Brake Design.

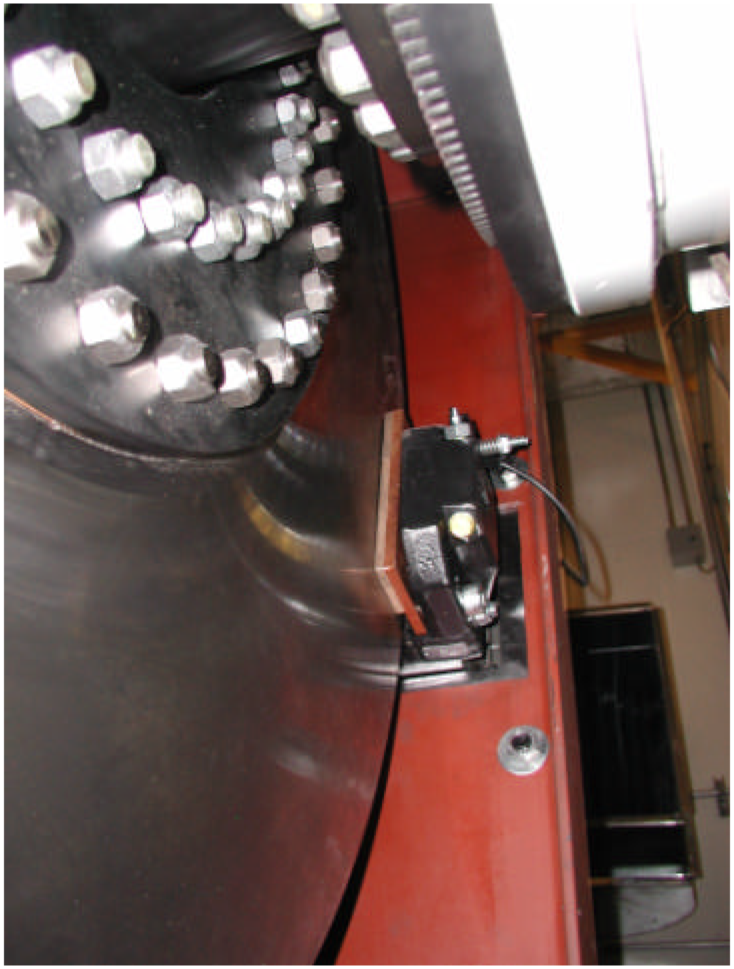

Figure 5) Photo of Installed Shaft Brake.

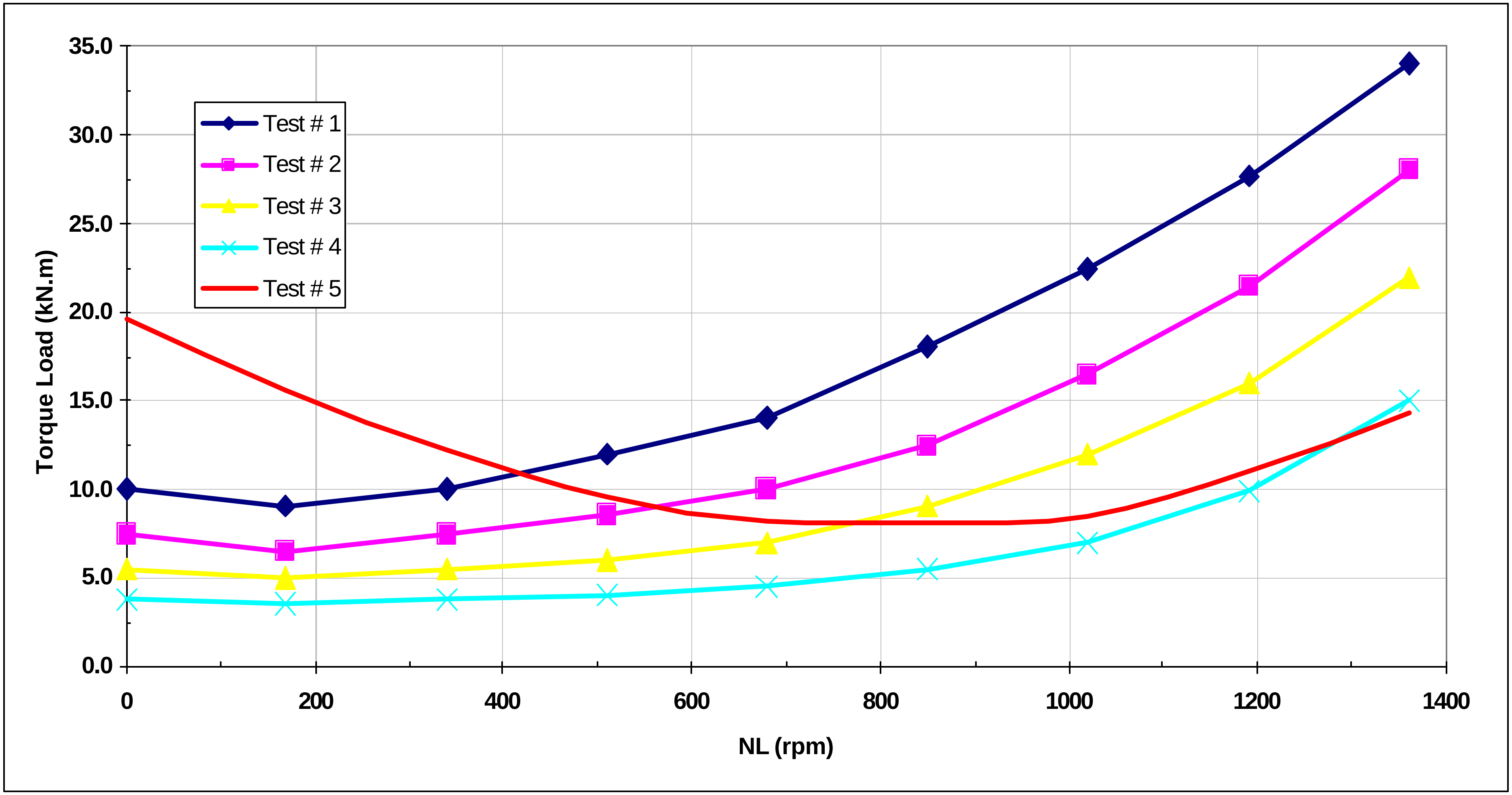

Figure 6) Validated Breakaway Torque and Loaded Start Curves.

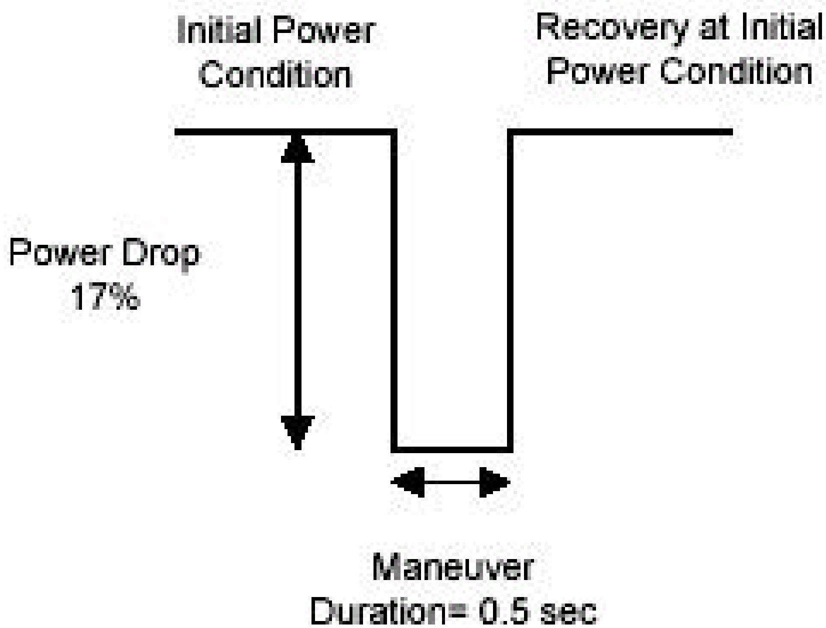

Figure 7) Validated Partial Loadshed.

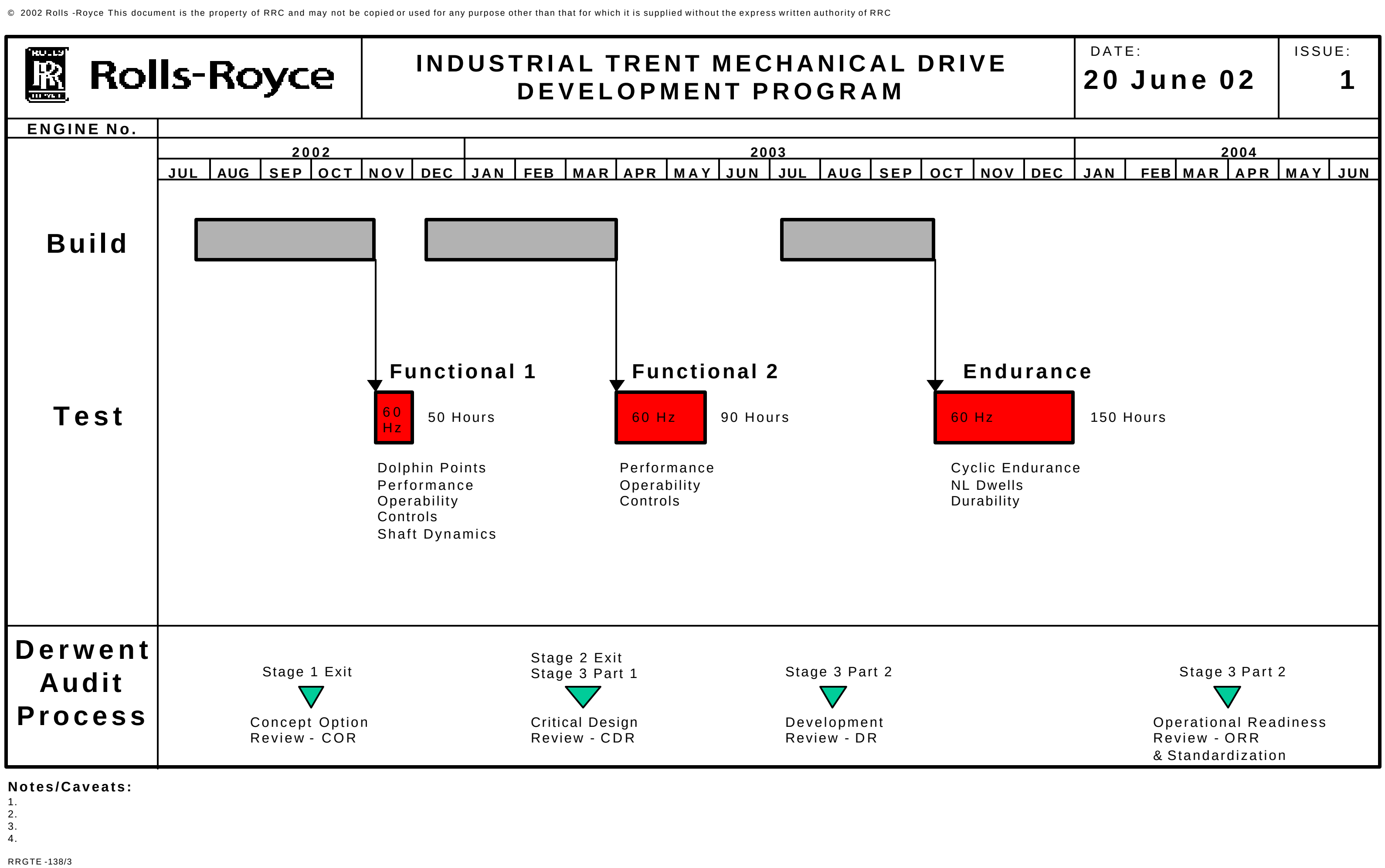

Figure 8) TMD Project Plan.

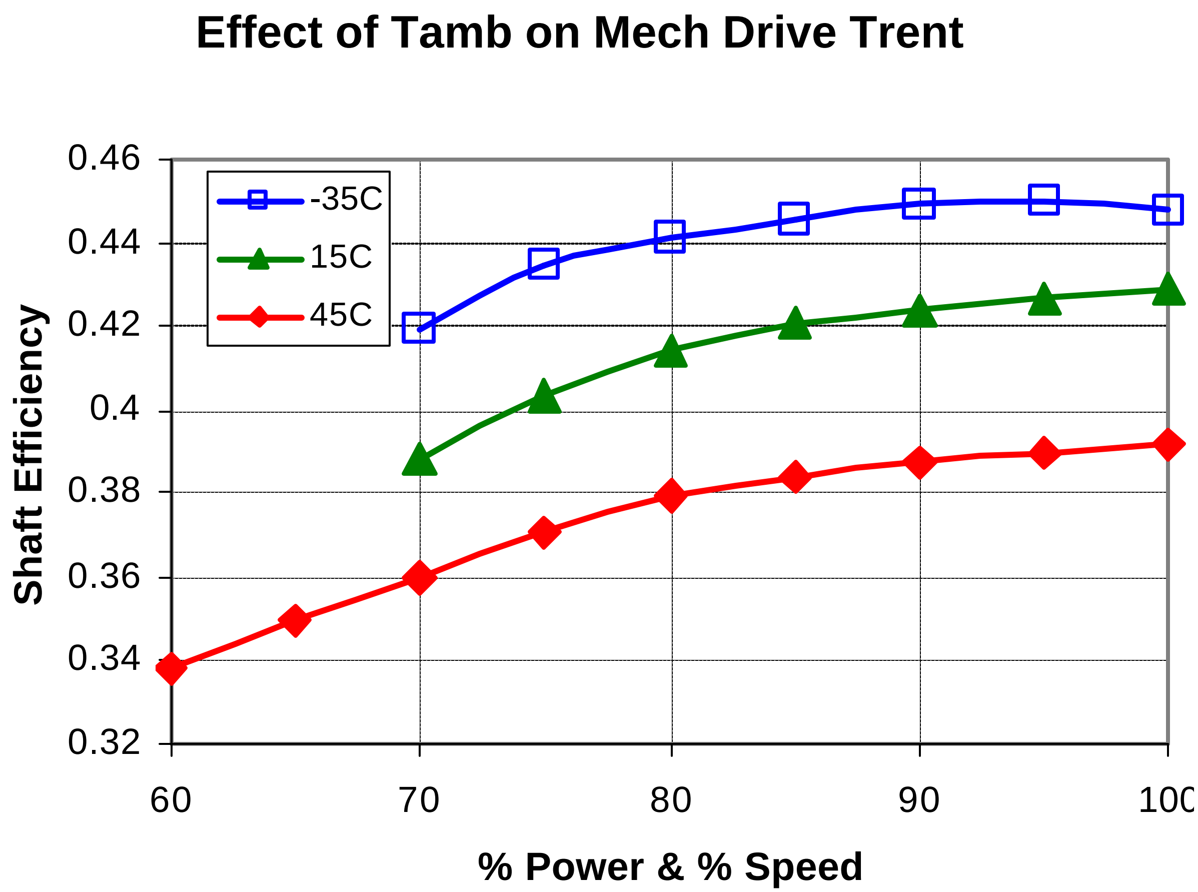

Figure 9) TMD Efficiency Variation with Ambient Temperature, Power and Speed.

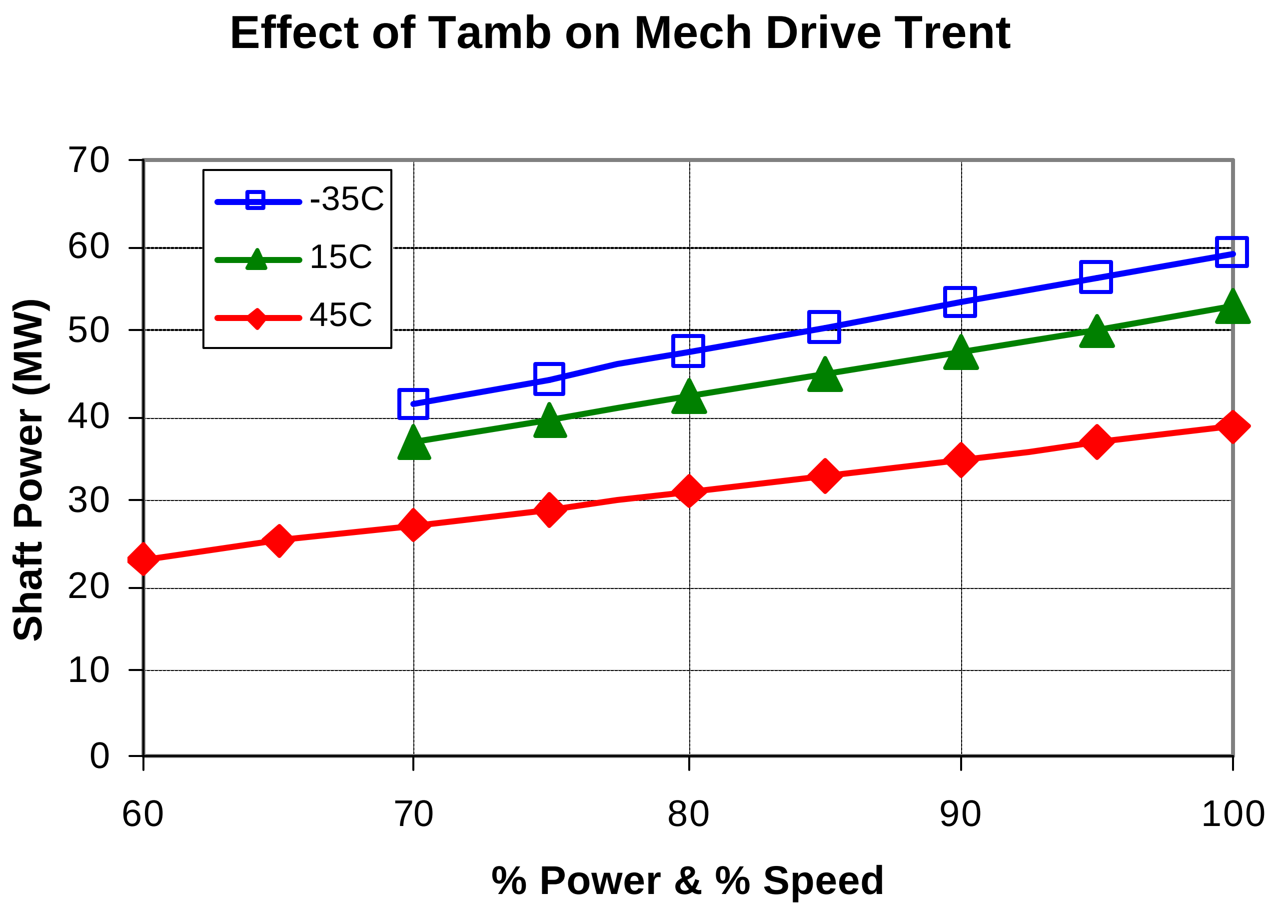

Figure 10) TMD Power Variation with Ambient Temperature, Power and Speed.

Figure 11) RR Testcell 7 in Verdun, Quebec.