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THE DEVELOPMENT & APPLICATION OF THE ROLLS-ROYCE MT30 MARINE GAS TURBINE

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ABSTRACT

The MT30 is the latest and most powerful gas turbine to enter the marine market. Recently entering US Navy service in USS Freedom, the first-of-class Littoral Combat Ship (LCS), MT30 has now been selected to be the prime power plant for two further classes of front-line warships; The Queen Elizabeth Class Aircraft Carriers for the Royal Navy, and the US Navy DDG-1000 Destroyers.

This paper tracks the development of the MT30 from its well-established Rolls-Royce Aero Trent parent, discussing the changes necessary to adapt and harden the gas turbine for the marine application. The MT30 development program is described, including the rigorous testing undertaken to qualify the engine to American Bureau of Shipping (ABS) rules.

Existing and future applications for the MT30 are described. Systems for achieving efficient hybrid propulsion utilising electric motors for cruise and the MT30 for boost are presented. The latest all-electric marine propulsion architectures as used on DDG-1000 and the Queen Elizabeth Class Carriers is discussed -in particular, the issue of maintaining the quality of power supply through transient load demands.

The paper concludes with an insight into the latest MT30 package, which sees the system reaching class-beating power densities whilst ensuring maintainability through innovative design features.

INTRODUCTION

The MT30 is a 40MW class gas turbine which is based upon the very successful Rolls-Royce Trent 3-shaft architecture. MT30 is the third member of the family which comprises the Aero Trent and Industrial Trent, all of which share a common architecture and, in most areas, part-number-identical High Pressure (HP) and Intermediate Pressure (IP) spools. The engine is therefore an excellent example of the Rolls-Royce philosophy of developing technology and products which can be used across air, land and sea applications.

Aero-derivative gas turbines such as MT30 have proved very successful in the marine market as they provide much more compact power units than gas turbines designed for land based use. This power density is often critical to the design of high performance ships, particularly in the Naval sector.

The process of adapting an aero gas turbine to marine use is well proven through engines such as the RR Olympus, Tyne and Spey all of which continue to serve Navies around the world. New features in the case of MT30 include the significant increase in power level relative to previous engines, qualification to American Bureau of Shipping (ABS) rules and the need to design the engine to operate in mechanical and electrical drive applications.

THE MT30 GAS TURBINE

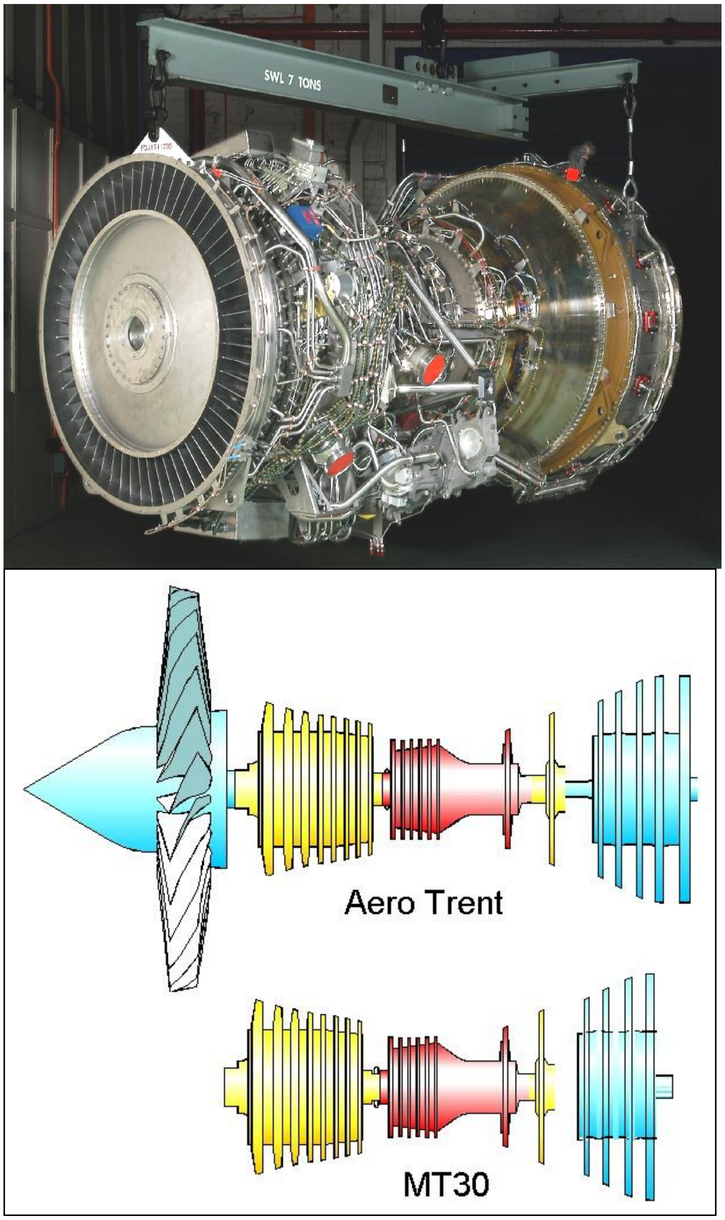


FIGURE 1- MT30 CORE GT AND AERO-MARINE COMPARISON

Design Approach

The MT30 is based upon the well-established Trent family of aero engines, which consequently brings the significant technology and reliability benefits of a modern aero derivative gas turbine to the marine industry. The MT30 GT, shown in Figure 1, shares significant commonality with the Aero Trent, having an excellent pedigree with over 15 million hours. Deviations from this well proven design are limited only to those required to modify the engine for marine use. In summary, the steps involved in modifying the Trent style of engine are as follows;

1. Removal of the fan module and drive shaft
2. Modification of the low pressure turbine to extract maximum power from the gas stream and to operate at the rotational speed required for the ship operation.
3. Modification of the bearing arrangement to provide shaft power drive
4. Addition of corrosion protection for the marine environment
5. Modification of the combustion system to operate on fuels available to marine operators
6. Packaging the gas engine with its control system and support systems for installation in the ship.
7. Certification of the engine to Marine Classification society rules.

Power Output

The MT30 Gas Turbine is flat-rated to provide 36MWb of output power from an ambient inlet temperature of –40ºC to +38ºC, with inlet and exhaust losses of up to 100mm (4in) and 150mm (6in) WG respectively. If required, an alternative tent rating performance is available providing up to 40MW at 15 ºC. (Figure 2).

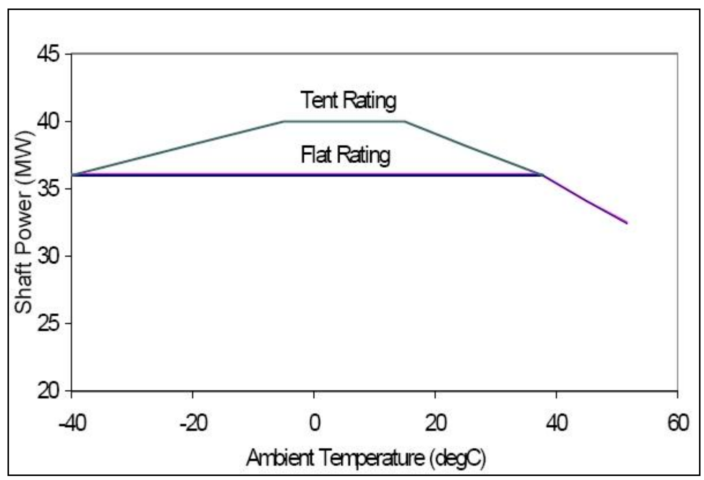


FIGURE 2- MT30 RATING

The MT30 delivers high power even at high-ambient air temperatures. A development route has been identified for increasing the power output from the MT30, as the engine has growth potential due to its relatively low thermal loading at its current rating.

Testing and Certification

The MT30 program has its roots in concept studies that commenced in 1999. This led to a program of work to carry out the necessary design changes to the aero Trent engine to produce the first MT30 development engine in 2002. The high power level and requirement to demonstrate both mechanical and electrical drive configurations required that a purpose-designed test facility was needed to carry out the development and endurance test program. This facility absorbs load through an electrical generator which features a control system that allows the simulation of both electrical and mechanical drive systems. The facility dissipates energy produced by the generator to the atmosphere via a series of resistive load banks.

FIGURE 3- MT30 TEST BED, BRISTOL UK (SHOWING LOAD BANKS AND HEATED AIR INTAKE)

The first development engine, D1, started testing in August 2002. The purpose of this initial programme was to commission the new test bed and to complete proof of concept and initial functional testing of the engine. This testing was successful, demonstrating the robustness of the design concept. The engine was removed from test in March 2003, having achieved 258 hours of running, including 126 hours of endurance testing. In addition it ran to powers of 41.7MW and achieved 866 start-full power-stop cycles.

The second development engine, engine D2, went to test in June 2003 for functional testing. This engine was built closely to production standard and was fitted with a high level of instrumentation. This was the main development test vehicle and had a test program aimed at clearing the majority of the functional operating requirements of the MT30. This engine completed 110 hours of functional testing, covering investigation of the engine's behaviour in both mechanical and electrical drive modes. It included control system investigative and optimization testing concluding in August 2003.

Based on testing completed with D1 and D2, Rolls-Royce then commenced a program of testing in October 2003 aimed at clearing the MT30 for an ABS Type Approval to Naval Vessel Rules (NVR). In order to achieve type approval the engine had to complete an endurance test including 198 8 hour cycles to give a total of 1500 hours of running.

In order for the engine to become type approved for both mechanical and electrical drive operation, half the cycles were performed at a constant power turbine speed of 3600 rpm and the remainder with power turbine speed following a cubic load line passing through 36 MW at 3300 rpm.

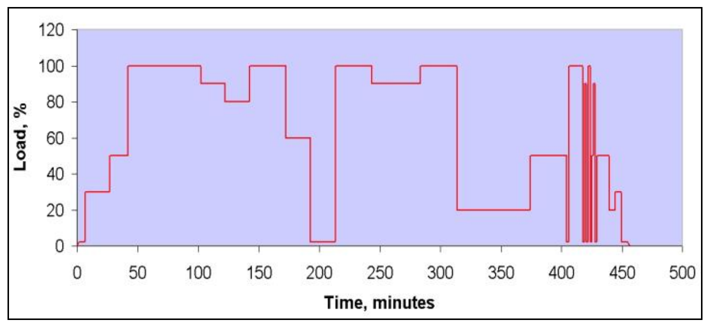


FIGURE 4- ABS ENDURANCE TEST PROFILE

The profile shown in Figure 4 had to be run at conditions representative of those experienced by the gas turbine during operation at an inlet air temperature of 38 deg C (100 deg F). For the MT30 ABS testing this was achieved by modifying the test bed to provide heated intake air for the gas turbine. The exhaust of one resistive load bank was ducted to combine with ambient air through a valve, controlled to a mixed temperature of 38 deg C. This air was then ducted to the engine intake. And so, the MT30 became the first large gas turbine to be certified to ABS Naval Vessel Rules by running the gas turbine to actual Navy Standard Day inlet temperature conditions. This method offers significant advantages over the more usual technique of elevating turbine temperatures through the use of engine bleeds or throttle push, as it exposes all areas of the gas turbine to elevated ambient temperatures. It also maintains standard engine compressor and turbine stage matching.

The ABS qualification test was completed in July 2004 with only one significant issue arising during the test. This related to distress seen on the power turbine rear double-stacked thrust bearing. Some surface damage to

the bearing was observed from debris trapped by magnetic chip detectors in the oil system. The testing was paused for an investigative strip of the power turbine bearing. This showed evidence of skidding of the rear of the two bearings. Analysis showed that load-reversals between the two bearings was occurring during shutdowns.
The test was completed after removing one of the two bearing rows and rebuilding with a single row. Analysis showed that a single bearing row had perfectly adequate life to complete the remainder of the 1500-hour test. This solution was agreed with ABS and the testing was successfully completed. An improved bearing was then introduced for production and an additional 150 hours of focussed endurance testing completed to further validate the design.

APPLICATIONS FOR THE MT30

Commercial Applications

Super-Yachts and Fast Ferries - The MT30 is suitable for super-yacht and large fast ferry applications (Figure 5). A simple CODAG (Combined Diesel and Gas Turbine) arrangement with two MT30's allows the operator to satisfy his range requirements whilst offering impressive top speeds.

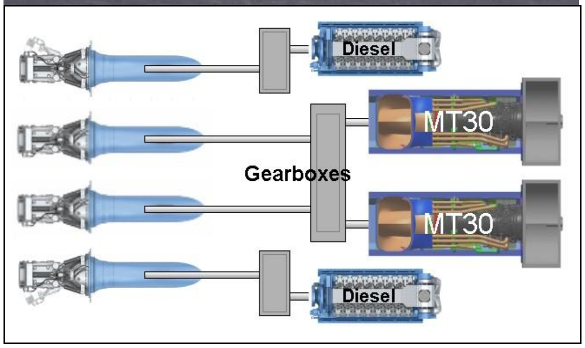


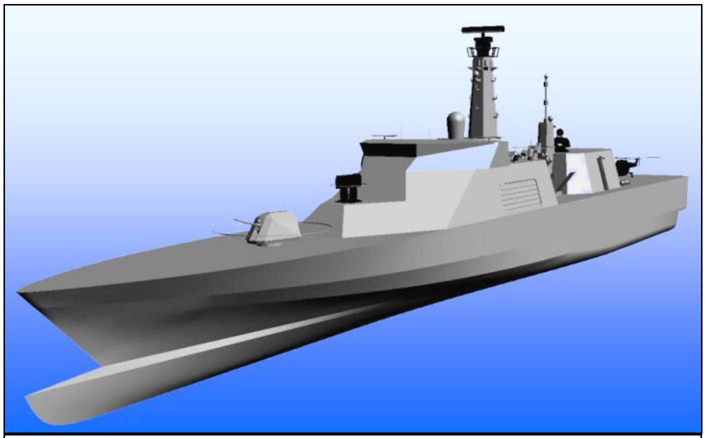
FIGURE 5- COMMERCIAL FAST VESSEL PROPULSION

Naval Applications

Single-GT Combatant - The modern Frigate needs somewhere between 30 and 40MW to achieve a top speed of around 30 knots and around 6 to 10MW to achieve a good cruise-speed of 18 to 20 knots. A combination of single gas turbine and smaller diesel or diesel-electric motors offers an attractive solution, either by way of a CODOG (Combined Diesel or Gas Turbine) or CODLOG (Combined Diesel Electric or Gas Turbine).

The use of only one, large gas turbine has the following advantages:

- Reduced number of prime movers
- Lower initial Cost
- More Compact installation, both in respect of machinery and ducting



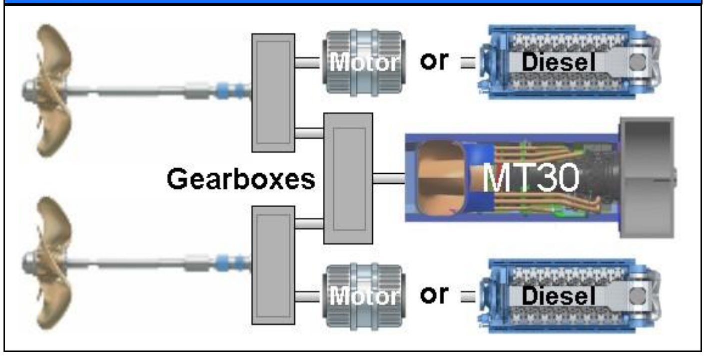


FIGURE 6- SINGLE-GT WARSHIP

High-Speed Combatant - The US Navy has developed the Littoral Combat Ship (LCS), a class of high-speed vessels intended for operations close to shore. The Lockheed Martin mono-hull version already in service, USS Freedom, has two MT30s and 2 diesels in a CODAG arrangement, providing a maximum speed well in excess of 40kts. There is significant interest from other Navies for vessels of this capability.

Integrated Electric Propulsion- The MT30 has already been chosen to power two of the world's most potent future warships, the US Navy DDG-1000 and the Royal Navy Queen Elizabeth Class (QEC) aircraft carrier. In both these applications the MT30 is used to drive an alternator that provides electrical power in to the ships electrical grid. Two MT30s are used in both of these applications together with smaller gas turbines or diesels. The QEC power and propulsion system can be seen in Figure 7.

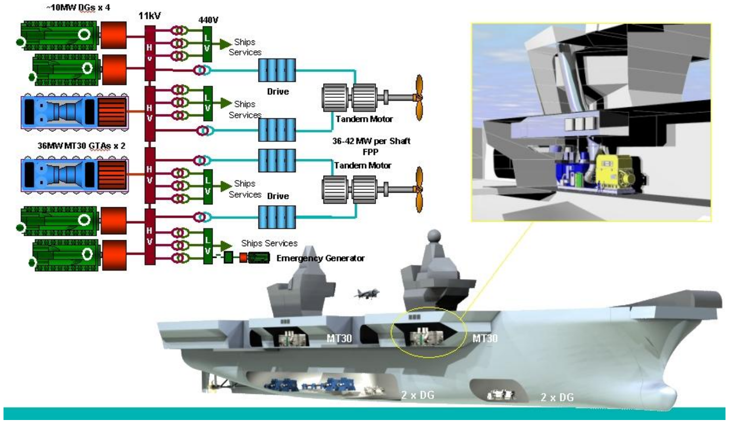


FIGURE 7- QEC POWER & PROPULSION SYSTEM

A key requirement for a prime mover in a warship using Integrated Electric Propulsion is the need to meet stringent Quality of Power Supply (QPS) requirements. This means that the engine must cope with significant changes in power demand while maintaining the output speed of the alternator (and therefore Power turbine) within close limits. The requirements are defined in terms of maximum frequency differences from nominal and time outside of close frequency limits and are enshrined in standards such as STANAG 1008.

The MT30 control system has been optimised for its response to step changes in load. The system utilises classical control theory, with multiple closed-loop lead-lag compensators to derive the correct fuel mass flow demand for each possible control loop. Each compensator is carefully tuned to provide responsive, accurate control, whilst maintaining phase and gain stability margins. The controller then selects the optimum, safest fuelling loop for the current condition, bounding this with rate-limits and open-loop schedules to protect against flame-out and surge. This selected loop is defined the 'Loop-In-Control'.

Figure 8 shows test results from an MT30 engine tested in an electric drive configuration. The plots show the variation in Power Turbine speed as a result of load step reductions of up to 6MW. The data shows that the response of the MT30 maintains the power turbine speed and hence generator output frequency well within the envelope defined in STANAG 1008.

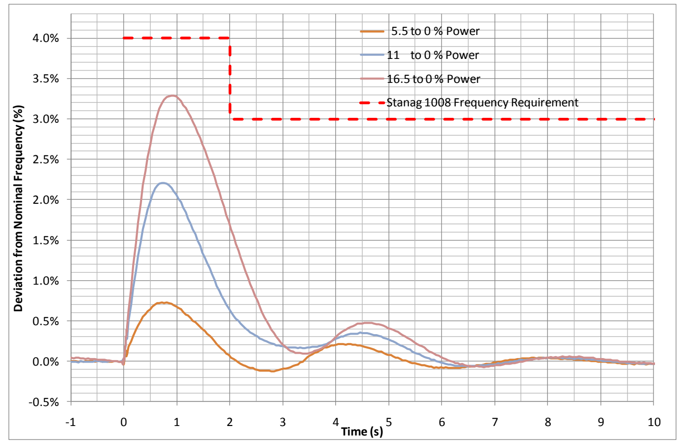


FIGURE 8 - MT30 ALTERNATOR OUTPUT FREQUENCY CHANGES IN RESPONSE TO LOAD CHANGES

Another aspect of Integrated electric ship propulsion is the opportunity for total loss of electrical load in the event of a circuit breaker opening while the engine is at full power. Again, this situation has been tested on MT30 with excellent results. To achieve this performance, the controller constantly monitors the speed and acceleration of the power turbine shaft for indications of large reductions in load resulting in a load-shed event. If a load-shed event is detected the controller dissipates any stored energy by opening bleed valves whilst reducing the fuel flow to an open loop schedule in order to minimise the power turbine speed overshoot that would occur, all whilst maintaining stable conditions in the core. The high iteration rates of the sub-components allow this process to take place within 30ms. As the power–turbine decelerates the system returns to closed-loop control, stabilising at the current demanded speed set point, allowing load to be maintained and/or reapplied to the generator, thus maintaining generator frequency throughout the load-shed event

THE COMPACT PACKAGE

A gas turbine used in a marine application is usually required to be installed in a package. This consists of a base-plate, acoustic enclosure and ancillary systems such as lube-oil and fuel forwarding. In order to maximise the power density advantages of gas turbines, it is essential that the gas turbine package is made as compact as possible. RR has recently undertaken the design of a new compact package which enables MT30 to be an increased power density option for frigate type combat ships – either in a single GT or twin GT configuration.

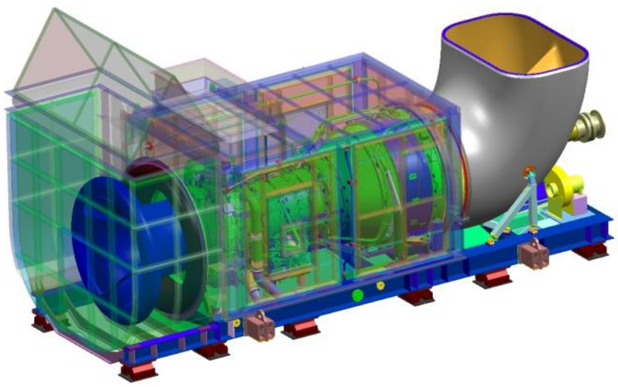


FIGURE 9 - COMPACT PACKAGE ISOMETRIC DRAWING

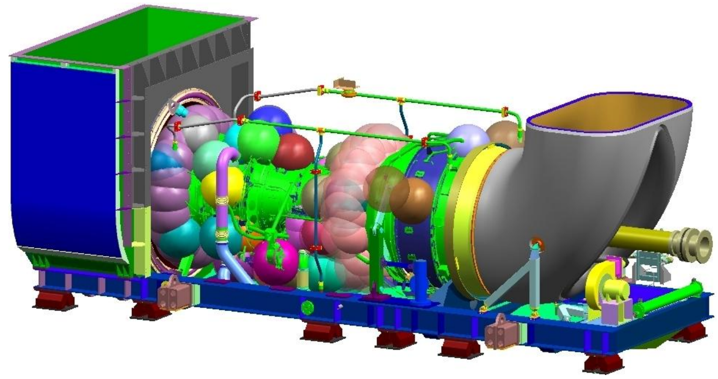


FIGURE 10- MAINTENANCE ACCESS ENVELOPES

The footprint of the new Compact Package is 8.6 m x 2.7 m with a target weight of 32 tonnes. This represents a 37% reduction in footprint and more than 10% reduction in weight whilst maintaining the same delivered power at the same efficiency. Following Rolls-Royce's GT package philosophy, the Compact Package will have as many base-plate-mounted systems as possible to minimise the ship integration cost and commissioning time. Height is also a consideration for installations where ship machinery spaces have restricted headroom and has been kept as low as possible.

Environmental Design Conditions

Navies operate worldwide in extremes of ambient temperatures, such as from the very hot Gulf of Oman to Arctic areas. This places rigorous demands on the gas turbine package systems, particularly with respect to cooling. The MT30 Compact Package is being designed to operate with full capability under the following key environmental ranges:

- External Air Temperature, –35C to + 50C.
- Seawater temperature, -2C to + 40C.

Package Systems

The biggest challenge the design team face is ensuring the GT and its ancillary systems are maintainable. A 'keep-out zones' drawing has been produced and transposed into the 3-D model, the information being used to carry out clash detection (see Figure 10). As the space around the GT has been kept to a minimum, the conventional opening door philosophy has been revised and instead large removable panels will be fitted to both sides of the package to open up a large clear area (see Figure 11). Lightweight temporary platforms will be deck mounted, straddle the base-plate/enclosure and fix into pre-defined slots thus forming safe, easy access to the gas turbine and the ancillary systems.

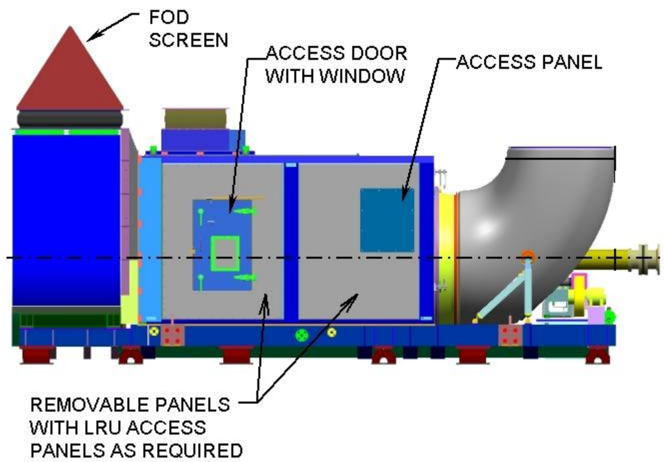


FIGURE 11- COMPACT PACKAGE MAINTENANCE ACCESS

Base-plate and Enclosure Design

The base-plate structure is critical to the overall package design as it has a direct affect on drive train alignment, accommodating gas turbine failure modes, i.e. blade off, and the loading to the ships deck through the resilient mounts. By using the latest analysis tools, and detailed data for COTS resilient mounts, the complete base-plate structure can be analysed for ships movement characteristics and naval requirements. The base-plate design is analysed against ships 'G' loadings and deemed to be acceptable before the enclosure structure is added. This enables the acoustic enclosure structure to be as lightweight as possible. With the acoustic panels and sliding doors being non-load bearing, the framework itself is designed to support the enclosure and the features to enable gas turbine removal.

The enclosure and base-plate are also designed to meet the overall acoustic performance requirements of 85 dB(A) in free field environment. Modelling of the fire detector field of view is an important aspect of this package design.

Enclosure Ventilation System

Radiated heat from the GT drives the requirement for an enclosure ventilation system. Ventilation air performs two functions - dispersal of any fuel or oil leak vapours, and cooling of sub-systems, especially electrical equipment, mounted on and around the engine. A negative-pressure ventilation system is employed, with an eductor system around the exhaust annulus creating a negative pressure in the package. A modest fan mounted in the ventilation intake system will provide forced cooling during engine shutdown.

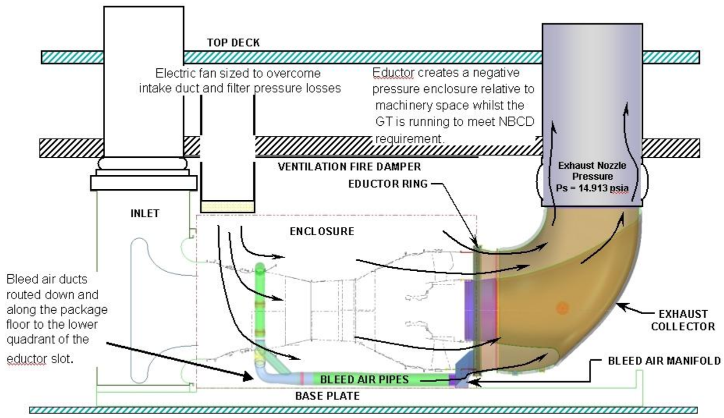


FIGURE 12- ENCLOSURE VENTILATION SYSTEM

Exhaust Collector Design

The challenge for the new exhaust collector design is to keep the high performance of the existing design whilst reducing the overall package length. This has been achieved through several iterative CFD analyses (Figure 13). The performance of the MT30 Compact Package exhaust collector is comparable with the original design, with parameters of Total pressure loss and Turbine-exit static pressure distortion satisfied.

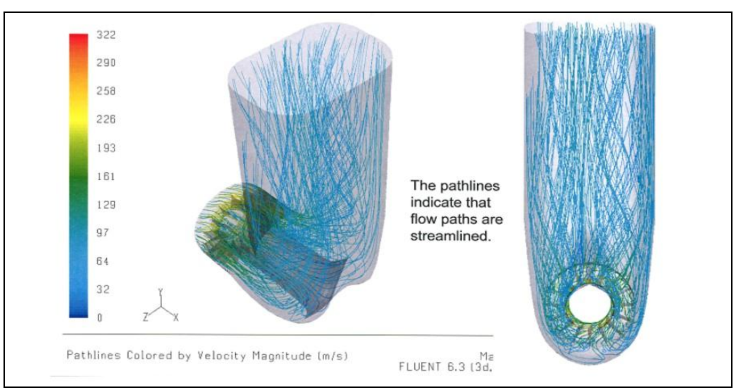


FIGURE 13- EXHAUST COLLECTOR FLOW SIMULATION

CERTIFICATION

The MT30 gas turbine already has classification with three major bodies, Lloyds, ABS and DNV. The package designs for each application have been assessed individually by the Classification society defined by the relevant customer.

FIGURE 14- CERTIFICATE SNAPSHOTS. LLOYDS, ABS AND DNV

SUMMARY

The MT30 is unique amongst gas turbines in the marine sector in being capable of delivering 36 MW of power and maintaining that power up to high ambient temperatures. It has been designed from the outset to satisfy both mechanical drive applications and electrical drive propulsion systems, and to be certified to Marine class society rules for both commercial and naval applications. These unique requirements have led to a number of new challenges which have been addressed through advances in test bed design, development and certification testing, control strategies, and installation design.

REFERENCES

Ref 1; STANAG 1008, (Edition 9, 24 August 2004) Characteristics of Shipboard Electrical Power Systems in Warships of the North Atlantic Treaty Navies.