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# THE DRIVING FACTOR IN THE SEA 1000 CHOICE THE SUBMARINE PROPULSION CHAIN

A submarine's propulsion chain is a fundamental consideration in the context of a submarine design. It consists of all components used to power and propel the submarine. In a conventional submarine's case the major subsystems include the fuel store, diesel-generators, Air Independent Propulsion ('AIP'), batteries and main propulsion motor.

Why the significance? The propulsion chain accounts for up to 35% of a submarine's weight and more than 50% of its space allocation. Its design is inherently linked to the submarine's hull size and shape, range and endurance and top speed. Its design determines how fuel energy is stored and then converted to electrical energy and again to propulsive energy. Importantly, it also determines the efficiency of those conversions. Because equipment in the propulsion chain is large and powerful its constitution also has an impact on a submarine's thermal, magnetic and acoustic signature. Finally there are also very serious propulsion chain reliability, maintainability, redundancy, ubiquity and safety considerations to be included in the design mix.

This month's APDR looks at the likely propulsion chains of TKMS' SEA 1000 concept design and makes a limited comparison to the likely DCNS and Japanese solutions.

## AN INTEGRATED AND UNIQUE SYSTEM

Before delving into the components of the propulsion chain it is worth emphasising that they are sub-systems within a carefully designed system. They shouldn't be considered in isolation and they can't be 'mix and match'.

By way of example, the diesel-generator can only be selected after the charging characteristics and profiles of the proposed battery solution are decided. The battery must only be selected after due consideration of the operating characteristics of the proposed main motor.

It also makes little sense to integrate an unreliable diesel sub-system into the chain of an otherwise reliable system, nor would a designer select an inefficient main motor at the end of an otherwise efficient set of other propulsion chain sub-systems.

The components must be designed or chosen to match each other, and with regard to unique submarine requirements.

## A SYSTEM WITHIN A SYSTEMS-OF-SYSTEMS

It is also necessary to appreciate that the entire propulsion chain is part of the system-of-systems that is a submarine.

A greater top speed will result in a need to increase propulsion equipment size and therefore, for a given size of submarine, a need to decrease payload space. Likewise, inserting an AIP plug into a submarine will affect form and skin friction drag that could either decrease or increase the propulsion energy requirements for any given speed.

The propulsion chain design must be considered in the context of the total submarine design.

## FUEL STORAGE

If one discounts leaving harbour with a full battery and returning with it fully discharged, the total (propulsion and hotel) energy requirements of a submarine, including any operational commander's reserve, has to be met by embarked fuels/reactants.

In the case of the TKMS' SEA 1000 solution this will mean the carriage of diesel fuel for the diesel-generators along with methanol and liquid oxygen ('LOX') for the Methanol-Reformer/Fuel Cell ('FC') AIP system. Diesel will be stored in standard seawater compensated fuel tanks. Whilst methanol can also be stored in tanks, it needs to be separated from compensating seawater and so a flexible rubber bladder arrangement will be used. LOX will be stored in an internal cryogenic tank.

For DCNS, the fuelling system will be simplified by the need to carry only two fuels; diesel for the diesel-generators and the diesel-reformer/FC AIP system and LOX for the diesel-reformer/FC AIP system.

The Japanese will not offer an AIP solution. This simplifies the enhanced Soryu's fuel storage requirements to just diesel.

Before progressing, and with fuel in the reader's mind, it is worth introducing the critical importance of propulsion chain efficiency. As energy conversion takes place, from reactant to electric and electric to propulsive, any efficiency advantage over another CEP contender's solution is important. Better efficiency results in greater submarine endurance or a reduction in fuel storage requirements for any given endurance.

## DIESEL-GENERATORS

The primary purpose of a diesel-generator is to convert stored diesel fuel energy into electrical energy that can be stored in the submarine's main battery. Noting the energy-density of diesel is significantly higher than any AIP reactant, all CEP contenders will have diesel-generators as part of their offering.

TKMS will likely include four MTU 12V4000U83 diesels each coupled to a Pillar NTB 60.40-12 generator in their concept design.

The 12V4000U83 is the submarine variant of MTU's Series 4000 diesel. It outputs 1300 kW at 1800 RPM and can do so with up to eight metres of swell above the exhaust outlet. This provides for a robust snorting capability and stable power output under severe sea conditions and will help ensure no unwanted 'stop snorts' occur. This is achieved with a special

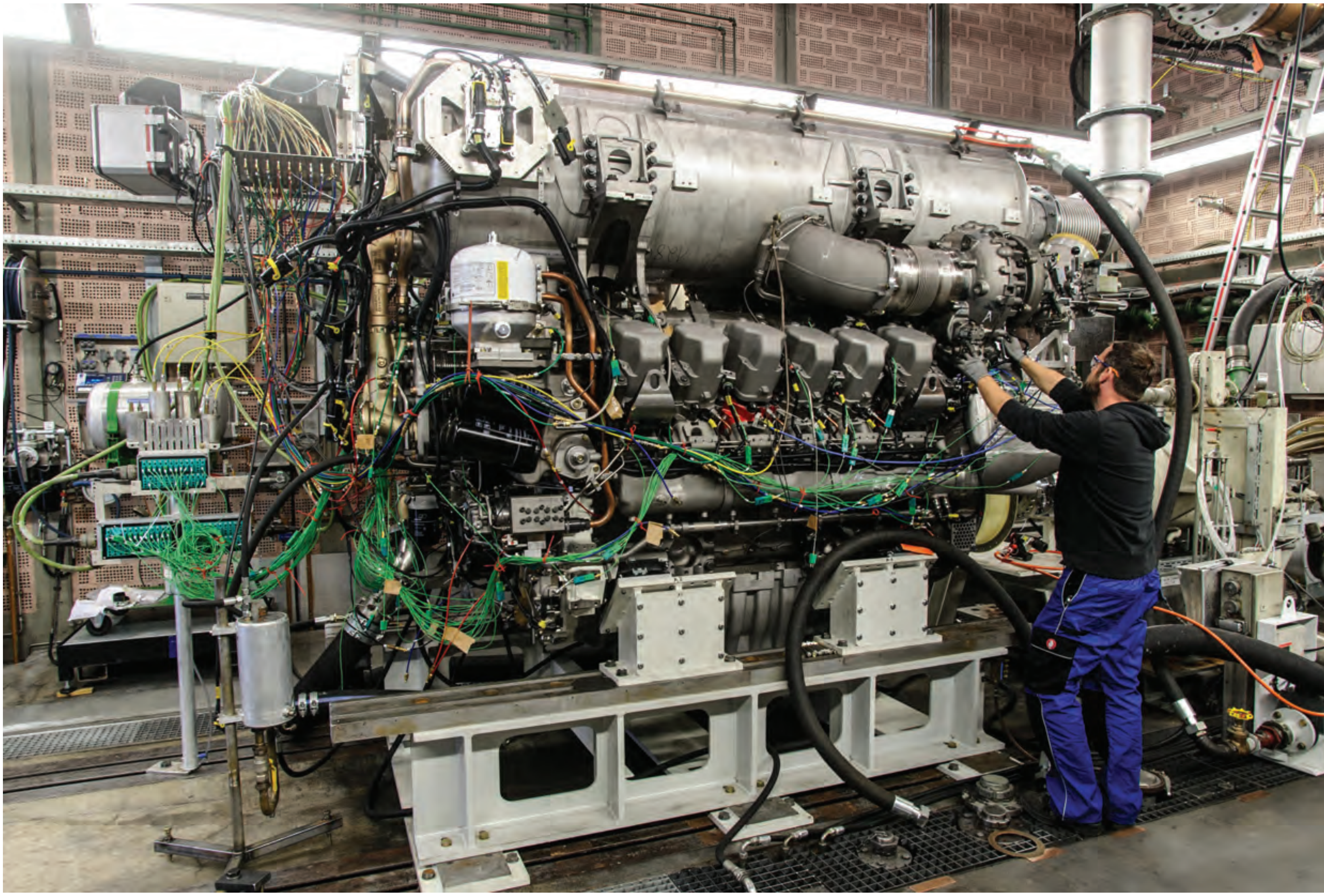

*Figure 1 – MTU 12V4000U83 Submarine Diesel under Test*

'waste gate' regulator that serves to maintain constant combustion pressure, which also aids in the reduction of component stresses and acoustic signatures.

The 12V4000U83 has been optimised for use with lithium Ion ('Li-Ion') batteries.

The engine has a 'boost mode' that offers an additional 200 kW output for circumstances that require it. 'Boost mode' can only be used for 10% of operating time without effecting time-between-overhauls. Of course, there is little to stop a Commanding Officer exceeding 10% during times of conflict and accepting that small penalty. The diesel also has an 'economy' mode which reduces fuel consumption by 5 g/kWh for a slight acoustic penalty.

Special noise quietening has been designed into the diesel with air intake silencers, special mounting arrangements, specially shaped piston crowns, specially programed fuel injection timings, engine structure stiffening and a combined exhaust gas silencer/cooler. The 12V4000U83 submarine diesel is quieter than the already quiet and popular MTU 16V 396 submarine engine, but outputs more power.

The diesel can be operated by one person from the Integrated Platform Management System or from a local panel. It has both an alternator and secondary air start mode. When operated locally it can even be started from a 'black boat state' using an emergency battery.

MTU have supplied more than 760 submarine diesels to 20 different navies since 1955. The Series 4000 is not a new engine; over 30,000 units have been sold, with 4000 of those for direct marine applications. More than 1000 are in operation in Australia (supported locally by Penske Power Systems), including a very early variant in use by the RAN. Its submarine tailoring began in 2009 and the first unit will be provided to TKMS in 2016 for integration into an undisclosed customer's submarine.

The generator coupled to the 12V4000U83 diesel will be the self-contained and highly efficient Pillar NTB 60.40-12 generator. This is an enhancement of Pillar's existing submarine generators, designed to deal with the boost mode output power of the new diesel. It will also be delivered to TKMS in 2016.

With the new MTU diesel and the new Pillar generator both on test beds, this solution is a low project risk element of the German SEA 1000 proposition.

DCNS may not offer up a French diesel solution for its SEA 1000 concept. The last indigenously developed submarine specific diesel was the 'M.A.N' (formerly 'Pielstick') 12 cylinder PA4V200SM. This was developed several decades ago. 'M.A.N' is just in the process of releasing a new Series 175 diesel that will compete with the MTU Series 4000, but only in the commercial/marine sector. It is not tailored for submarine operations and it is unlikely M.A.N would undertake the costly and lengthy exercise of doing so for the Shortfin Barracuda. Whilst MTU declined to comment on whether they might supply the MTU 12V4000U83 diesel to DCNS for SEA 1000, it is noted that the MTU Series 396 has been sold to submarine designers outside Germany including the British, Chinese, Spanish, Swedish and indeed the French.

The Japanese will almost certainly use the Kawasaki Heavy Industries 12V25/25SB combined supercharged/turbo diesel in their SEA 1000 concept design.

## AIR INDEPENDENT PROPULSION

The primary purpose of an AIP system is to convert stored reactant energy into electrical energy for the submarine's main battery and to do so independently of the surface atmosphere. It provides little benefit during transits but is invaluable when operating slowly within an operational area.

TKMS will almost certainly offer Australia a reformer/FC solution. Being a large submarine, it will demand two reformers and four 120 kW FCs.

The first element of TKMS' AIP solution is a Methanol reformer that extracts hydrogen from methanol and feeds it directly into the FC. Methanol is selected because of its worldwide availability, high hydrogen content, low reforming temperature (250°C), reformation ease and high reforming efficiency (80 to 90%). LOX is also used in the reforming process. Sub-system waste is pressurised CO2 which can be discharged to sea down to full diving depth. The reformer is packaged in an enclosure with its own special ventilation system for cooling.

Each reformer is capable of producing enough hydrogen to supply two fully loaded 120 kW cells. It removes the need to store hydrogen on board, which is problematic from a supply availability and refuelling complexity perspective, and is also difficult on 2000+ tonne submarines because of the weight of the hydrogen's metal hydride storage bottles.

The reformer has a two to three hour start-up time. Operationally, the idea is to start it up in the patrol area in block periods where AIP can be exploited, potentially for weeks on end, dependant on the amount of reactant stored on board.

The reformer has been in development since 1995 and a test site has been in operation for a decade, with FCs connected to it since 2010. A reformer suitably packaged for installation on board submarines is currently undergoing set-to-work in Kiel. Whilst the reformer has not been fielded on a submarine yet it is at the test bed state and therefore it attracts a low SEA 1000 project risk label.

Moving to the FC, TKMS will offer the second generation Siemens 120 kW Polymer Electrolytic Membrane (PEM) FC. The PEM FC works by feeding standard industry-grade LOX and high purity hydrogen into the cell which generate electricity in response. It does this silently and at a low temperature (80°C). It is different to a battery in that it stores no charge; it simply generates electrical energy so long as the reactants are fed into the cell. The cell is extremely (fuel burn) efficient at between 50 and 70%. Its 'waste' outputs are potable water, which is fed into holding tanks, and (1%) oxygen, which is fed into the submarine's atmosphere to assist in maintaining breathable air during prolonged AIP dived periods.

The FC has been under development by Siemens since the early eighties. It was first trialled on a German Type 205 test submarine in 1988 and then contracted for supply into the German and Italian Type 212 program. The first production FC went to sea in 2002 and it is now a very mature system at sea on 24 submarines, meaning it is a minimal project risk component of the German SEA 1000 solution.

The reformer/FC system meets all of the fundamental requirements of an AIP system; high efficiency, silent, low magnetic signature, light and compact, generates no pollution or heat, reliable, relatively easy to maintain and requiring no additional operating personnel.

Public domain information shows DCNS have abandoned their MESMA AIP solution on the Pakistani Agosta 90s and will use a diesel reformer/FC solution on the Shortfin Barracuda.

It is interesting that the German Defence Department funded TKMS starting in 2007 to conduct a methanol vs diesel reformer comparison, because the diesel reformer approach would negate the need for storage of an additional fuel, methanol, on board the submarine. TKMS built a small 10 kW diesel reformer to support the study. The study conclusions were instructive. The diesel reformer was less efficient because diesel has a hydrogen to carbon ratio of only two to one, whereas methanol has a hydrogen to carbon ratio of four to one. The diesel reformer also needs to run at around 850 degrees which implies heat inefficiency as compared methanol. The higher temperature also means a longer start-up time than the methanol reformer. Finally, unless the diesel carried by the submarine is sulphur free, and standard diesel is not, the required sulphur purifier at the reformer output would likely take up considerable space (as big as the reformer itself). The idea was abandoned.

As to the French FC, it appears as though two options are on the table; a PEM or Solid Oxide FC ('SOFC') type. If a SOFC is chosen, noting they offer good energy conversion efficiency, long life and operating cost advantages, other drawbacks need to be addressed. Most of these drawbacks relate to the high 600 to 1000°C operating temperature which brings hot exhaust issues and brittleness related shock-resistance problems.

Novelty, complexity and uncertainty put this solution's inclusion in the French package as high risk. Even if the technical challenges of the diesel reformer and FC are solved, the enemy of the DCNS development will be schedule. DCNS are believed to have started their reformer/FC work back around 2006/7 and announced it as a future solution in 2008 as part of their SMX 24 concept design. It is instructive that the Germans have developed and perfected their reformer/FC solution over four decades. It is also worthy of note that the Spanish have had issues with their S-80 submarine ethanol reformer/FC solution and have announced that the first S-80 will now be fitted-for-but-not-with AIP.

The Japanese will not offer up an AIP solution, rather fill any potential AIP space with additional Li-Ion batteries. It is believed this decision stems from their experience with the inefficiency of the Swedish origin Stirling AIP solution. All things considered with respect to reported Stirling engine maintenance overheads and the lack of differential between the Stirling energy density and the Li-Ion energy density, the decision is likely valid.

However, the energy-density differential between the DCNS and TKMS FC and the Japanese Li-Ion's is large, giving the Japanese solution a poorer indiscretion ratio than the Europeans' FC approach. It is known that the Japanese originally approached TKMS about adopting their FC AIP solution, but the adoption of the German technology was problematic for two reasons; firstly, the reformer necessary for the larger Soryu submarine was not mature at the time and TKMS/Siemens were not inclined to transfer knowledge of what they considered to be the 'crown jewels' of their submarine program. Whilst Li-Ion may have advantages in transit situations, which is why the French and Germans have Li-Ion as part of their solutions, the FC provides the advantage where it really counts; in the operational area. Whilst an all Li-Ion Japanese solution may have advantages with respect to transiting, it means little if the boat is then sunk upon arrival in its assigned patrol area.

## BATTERY

All three CEP contenders are likely to offer Li-Ion batteries as an energy cache.

Li-Ion batteries have significant advantages over standard submarine lead acid batteries. They have a higher energy-density and much lighter weight; for slow speed operations they offer approximately 1.3 times capacity, but for higher speeds they offer up to three times. It also makes them ideal for pairing with high-powered diesel-generators during rapid transits. Also more efficient high-speed runs can be conducted deep with regular snorting periods. Li-Ion batteries are also able to take very large charging currents over the entire charge range of the battery compared to lead acids, which can only be charged at full rates up to about 85% after which time the charging rate must be reduced to avoid a dangerous gassing situation.

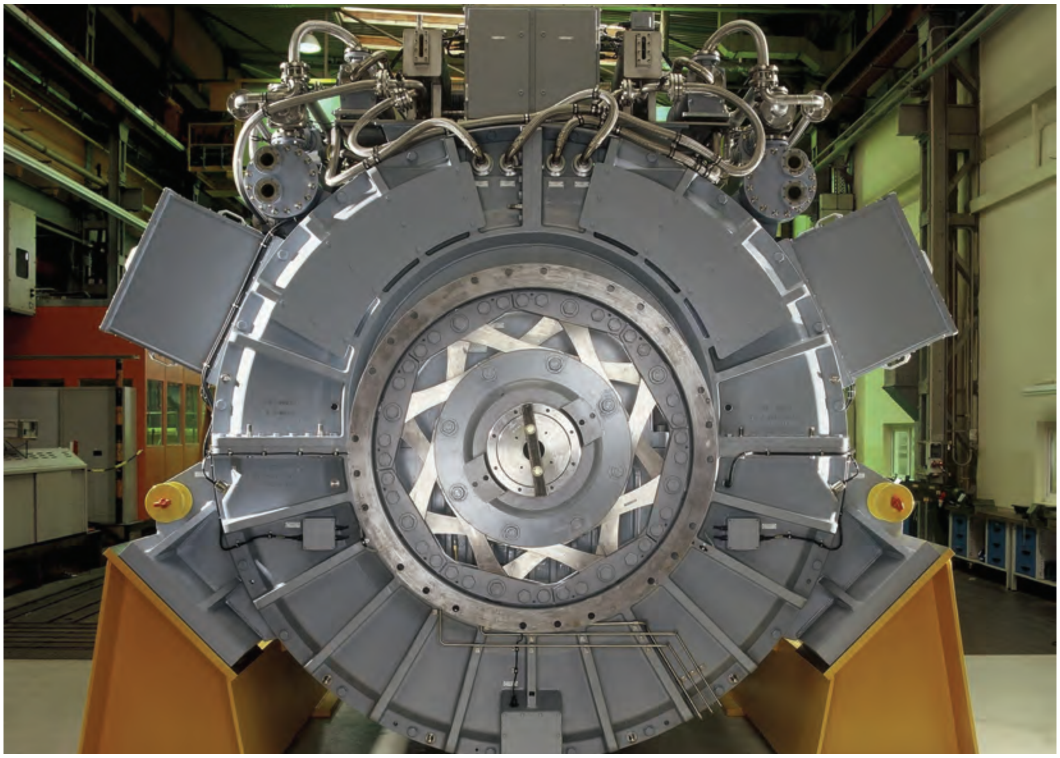

*Figure 2 – Siemens Permasyn™ Motor*

Unlike lead acid cells, which can develop a 'memory', Li-Ion cells don't. Li-Ions are maintenance free in normal operation, do not consume distilled water, require no cooling water systems and do not release gas therefore eliminating the need for battery ventilation systems, hydrogen monitoring, hydrogen elimination systems and battery compartment flushing systems. This saves space and reduces hotel loads. Ten-year life cycles can be expected from these batteries.

The French, Germans and Japanese have all been working on submarine Li-Ions for some time now. The European's have both got to the point of having integrated test sites, although it appears the Japanese will beat the Europeans in having Li Ion's at sea. It remains to be seen, however, what the capability aim point of each contender's solution is.

Inclusion of Li-Ions on Australia's future submarine is an almost given and will attach low project risk.

## MAIN MOTOR

DCNS, TKMS and the Japanese will all use permanent magnet (PM) motors in their SEA 1000 offerings. PM motors differ from standard DC motors by replacing rotor coils, which require electrical excitation (and therefore energy), with rare-earth permanent magnets. They deliver high torque at low RPM that allows for the use of large diameter propellers turning at low RPM. This facilitates high propulsive efficiency and a reduction in the potential for propeller cavitation noise.

TKMS will offer a 6+ MW Siemens Permasyn™ motor for its concept design.

The Permasyn is the result of the totality of Siemen's experience in a wide range of motor applications. It has an ingenious bell shaped rotor that permits the stator switching electronics to be housed inside the bell, thereby allowing the motor to occupy a much smaller space than its French and Japanese equivalents.

The 6+ MW Permasyn motor will have up to 18 inverter modules with half of them powered from different sources. These inverters control the stator current phase, magnitude and curve shape which permits efficient and seamless operation over the motor's full speed range, including astern. If any of the invertor modules fail the motor will keep running; it will even run (albeit poorly) on one module. The motor design has large thermal reserves that only requires ventilation/cooling at high speed, making the motor quieter and more efficient in the crucial low speed range likely within an operational area.

The housings of the motor are available in nonmagnetic material.

A comparison of a Permasyn and French Magtronic motor using available public domain figures is instructive as to the Permasyn's efficiency. A published UDT paper reveals the efficiency of the 3.3 MW Scorpene motor to be 2% less than the similar generation 4 MW Type 214 Permasyn at high speed and 7% less at all-important low speeds. This is significant in the context of an entire patrol.

The Permasyn has been under development since the early eighties with ten 2 MW variants and ten 4 MW variants at sea.

Design work has already started on the SEA 1000 Permasyn. From a risk perspective, the project involves complexity and uncertainty, but is being conducted by a very experienced team. With respect to that experience the company has built a 6 MW submarine DC motor (i.e. non PM) for the Argentinian TR1700 program and recently supplied 11 MW PM motors to Australia for the RAN's LHDs. The company has also produced 100 MW motors for commercial application. Additionally, the Permasyn team in Berlin has already up-scaled their motor twice, once from a one MW surface ship motor to a two MW Type 212 motor and a second time from a two MW motor to a four MW Type 214 motor. When considering these factors, the project risk must be assessed as low edging towards medium.

The French have designed and developed a 7 MW PM motor for the Brazilian nuclear submarine program; it was delivered this year to form part of the program's propulsion land based test site. Little is known about it, but it is unlikely to possess some of the beneficial and patented features of the Permasyn described above. Noting it exists but has not yet been to sea, it would justify a project risk characterisation of low.

The intentions of the Japanese with respect to SEA 1000 are unknown. They have a 5.9 MW Fuji Electric PM Motor on the Soryu class, and whilst it comes under the power rating of the DCNS and TKMS solutions, its inclusion in their SEA 1000 solution would ensure minimal project risk.

## AN IMPRESSIVE SYSTEM

Unfortunately, whilst DCNS and the Japanese were approached with a view to having this article detail all three contenders' wares, both declined to participate in an objective comparison. As such this article predominantly showcases the likely TKMS SEA 1000 concept design submarine propulsiwon chain.

The TKMS submarine propulsion chain comprises tightly coupled and well matched components totally integrated into an Integrated Platform Management System for primary control, with local control for backup. The system has been developed and enhanced across four decades and is likely reliable, compact, efficient and have low signatures. Some changes will be required to meet the needs of a larger TKMS SEA 1000 submarine, but the risks associated with the changes have been shown to be relatively low in nature and well worth accepting. ■

**DISCLOSURE:** Rex Patrick has visited DCNS, MHI/KHI, Navantia and SAAB Kockums submarine yards in the past 18 months. This month he travelled to MTU, Siemens and TKMS in Germany as a guest of the German-Australian Chamber of Industry and Commerce.