Introduction to

Submarine Design

ABSTRACT

The submarine is a unique platform that is capable of dealing with conventional as well as asymmetric threats from the littorals. As a stealthy platform that possesses a robust capability for conventional open water anti-surface and anti-submarine warfare, a submarine is also increasingly called upon to undertake intelligence gathering, counter-terrorism and special force operations. The need for stealth, range and flexibility while controlling the size and cost of the submarine has resulted in innovative submarine designs. Four solutions are presented in this article.

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INTRODUCTION

Since the end of the Cold War, navies have shifted their focus from preparing for open-water conflicts to dealing with conventional as well as asymmetric threats from the littorals. At the same time, navies have to fulfil new requirements such as supporting intelligence gathering, counter-terrorism and special force operations. Submarines offer a unique capability proposition as a stealthy platform, and they also possess a robust capability to meet both the conventional demands of open water warfare and new demands of navies. However, acquiring and maintaining a submarine fleet is costly. Therefore, the key challenge for submarine designers is to strike a balance between the need for stealth, range and adaptability, and the need to control the size and cost of the submarine.

In response to these challenges, this article presents four critical solutions, namely:

- Modularity
- Design for Special Operations Forces
- Battery Technology
- Air Independent Propulsion (AIP)

MODULARITY

Cutbacks in fleet sizes and budgets have led to the demand for more capabilities to be incorporated in submarines so that they can perform multiple roles. As a result, submarine builders have incorporated modular design in their latest generation of submarines. Modular design allows the addition of capabilities and easier upgrades at the component and system levels without the need for a substantial growth in the submarine's size. The modularity concept is embraced at all levels of submarine production and operation, namely:

- Modularity at Design (Deconittignies, 2001)
- Modularity at Construction (Deconittignies, 2001)
- Deployment of Modular Payloads

Modularity at Design

Modularity can be applied to the design at the component, system and boat levels. It allows tailoring to suit individual requirements without the need to change the entire design of the submarine.

The concept of modularity relies on a clear segregation of functions in the submarine as illustrated in Figure 1. For example, a submarine can be divided into modules with sections dedicated to certain functions e.g. diesel engine room and living quarters. These modules are designed as stand-alone systems with their own support functions.

Some of these modules can be customised subsequently to meet the requirements of different customers. For instance, the diesel engine module can be customised to provide additional power in a long version with four sets of diesel engines, or to provide less power in a short version with two sets of diesel engines. Similarly, there can be two versions for the sail section: a longer one for additional masts to meet multiple operations, or a shorter one for a dedicated role. Figure 2 shows a generic submarine type in two variants with different engine modules.

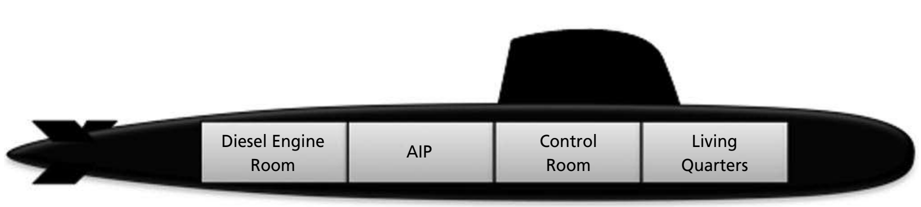

Figure 1. Segregation of functions in a submarine

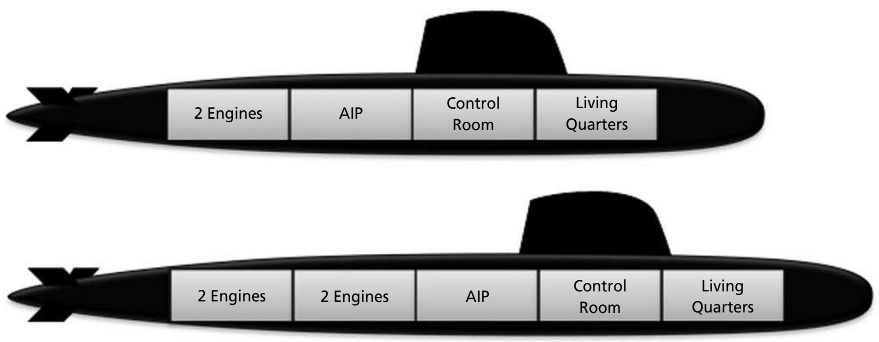

Figure 2. Modular customisation for customer's needs

Modularity at Construction

'Modularity at Construction' refers to the sharing of submarine manufacturing processes at different shipyards. Each hull section can be fabricated and assembled in shipyards located in different countries. The final assembly is then carried out at one of these shipyards. Modularity at Construction avoids production bottlenecks and speeds up the manufacturing process considerably. Such a concept, however, requires an integrated information system, extensive quality control and tightly controlled production tolerance. This concept has been used by the French submarine builder, DCNS, in the manufacture of the Scorpene family of submarines for Chile and Malaysia (Deconittignies, 2001). Both DCNS and Spain-based Navantia share the construction and outfitting of the hull sections. The final assembly is then carried out at either DCNS or Navantia.

Modular Payloads

The introduction of modular payloads is one of the most significant and newest changes in submarine design. Instead of carrying only a fixed payload of torpedoes, submarines with modular payloads can be re-configured for a range of payload options. These include intelligence, surveillance, reconnaissance and target acquisition systems; special operations forces (SOF) support systems; strike weapons; mines and mine countermeasures; undersea communications and sensor network systems; and unmanned vehicles. Modularity of payload removes the need to incorporate a single submarine with the complete set of payload options required for all its capabilities. Instead, the submarine can be designed to allow the customisation of payloads depending on specific mission needs.

Figure 3 illustrates a modular sail section using the Universal Modular Mast (UMM) concept, which consists of cartridges installed in the sail of a submarine. These cartridges are used to house different mission-specific masts as required. Besides masts, auxiliary systems can also be fitted into the cartridge

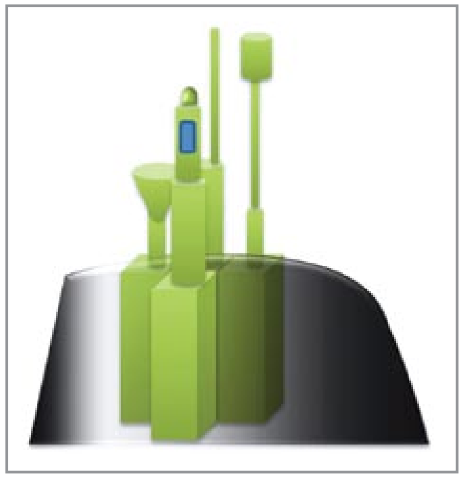

Figure 3. The UMM concept

of the UMM. For example, a machine gun can be stowed in a UMM cartridge, which can then be raised to deploy the gun. The UMM concept has been adopted by new generation submarines such as the UK Royal Navy's latest Astute-class submarines.

DESIGN FOR SPECIAL OPERATIONS FORCES

The SOF form an important element of modern warfare. Armed forces require the SOF to perform a wide variety of missions such as Search and Rescue, Reconnaissance and Sabotage, and Forward Observation. For these operations, the SOF may be sent to their mission areas using submarines, aircraft, helicopters, parachutes or surface craft. As submarines are the only platform that can guarantee covert delivery, they are a vital element of the SOF.

Covert Delivery

Up to the 20th century, covert delivery of the SOF could only be achieved by a large submarine with a dedicated external lock that is carried as an attachment on the submarine hull. Figure 4 illustrates an example of such an arrangement. This lock acts as an interface between the submarine and the sea to transfer the SOF in and out of the submarine while keeping the interior of the submarine dry. Following the flooding and pressurisation of the lock, the SOF team is able to swim out to its mission area. The SOF team also returns to the submarine via the lock after its mission. These transfer locks are as heavy as 30 tonnes and very few navies can afford submarines that are large enough to carry them.

Designers of smaller submarines which are incapable of carrying such heavy locks have explored innovative means to achieve covert delivery. For example, the German builders of the U212A class diesel-electric submarines overcame the lack of space in the submarines by modifying part of the sail fin to become an internal lock (Wallner, 2006).

Besides supporting the covert delivery and extraction process, the submarine has to allocate supporting resources to the SOF team, such as accommodation, food, stowage space for equipment, as well as mission planning and control areas. At the same time, the submarine has to maintain sufficient space for its own equipping needs to maintain its core fighting capability. It is difficult to optimise the small conventional submarines to support SOF operations while maintaining their core war fighting capability without a substantial increase in the submarines' size.

Modular Add-on for the SOF Operations

To overcome size constraints, submarine designers have used modular design to create capacity to accommodate the requirements of the SOF without compromising the submarine's performance and core mission capability. For example, the torpedo room can be designed such that the designated torpedo racks can be removed to allow the fitting of additional bunks for the SOF (see Figure 5). This allows the submarine to be customised without having to lengthen its hull to house the additional SOF crew.

Figure 4. Covert delivery of the SOF using external lock

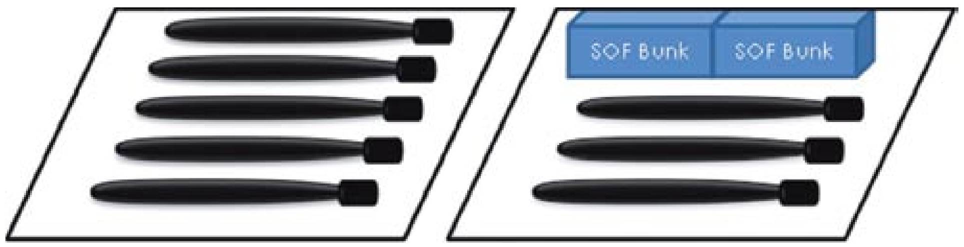

Figure 5. A re-configurable torpedo room

The US Virginia-class submarine is an excellent example of an SOF-friendly submarine. It has a dedicated modular lock section that can deliver a nine-man SOF team for a single operation. The submarine also features on-board modular spaces that can be re-configured to accommodate additional bunks, stowage space as well as mission planning and control equipment. The submarine can also carry swimmer delivery vehicles and a decompression chamber externally (Graves and Whitman, 1999).

BATTERIES FOR SUBMARINE APPLICATIONS

Batteries are standard features in all submarines to provide standby and propulsion power (Szymborski, 2008). Prior to the advent of AIP and nuclear technology, a submarine's submerged endurance depended entirely on its battery life. Thus, the time required to charge its batteries remains as one of the submarine's key performance indicators – this determines how long a submarine has to snorkel and risk detection by adversaries. While lead-acid batteries have been the standard used in submarines, their dominance is increasingly challenged by a new generation of batteries that offer better power and energy density.

Lead-Acid Battery

The lead-acid battery has been the battery of choice for submarine applications. Despite having a low energy-to-weight ratio and a correspondingly low energy-to-volume ratio, lead-acid batteries are able to supply high surge currents and maintain a large power-to-weight ratio. This explains why they are chosen for submarine applications. The lead-acid battery stores electrical energy in the form of chemical energy and releases this stored energy into an electrical circuit as the battery discharges. The operation of a lead-acid cell is described in the reversible chemical reaction shown in Figure 6.

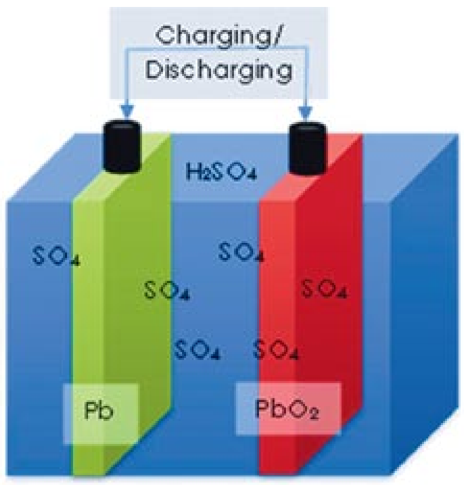

Figure 6. Operation of a lead-acid battery

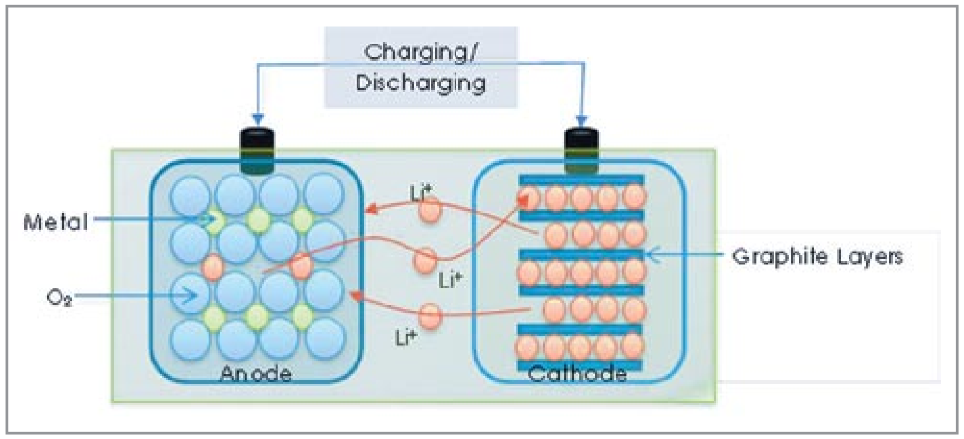

Figure 7. The charging and discharging sequence of a Li-ion battery

Lithium-Ion Battery

Lithium-ion (Li-ion) batteries are currently one of the most popular types of battery for portable electronics. They have a superior energy-to-weight ratio and a slow loss of charge when not in use. Lithium is one of the lightest metals and has great electrochemical potential. In addition to the wide-ranging applications of Li-ion batteries in the consumer electronics domain, there is also a growing demand for it in the defence, automotive, and aerospace industries. This is due to the high energy density and technological maturity of Li-ion batteries. Figure 7 shows a simplified diagram of the charging and discharging sequence of a Li-ion battery.

One of the key advantages of Li-ion batteries is their ability to be moulded into different shapes and sizes to fill any space available in the devices they power efficiently. It has a low self-discharge rate of approximately five to ten percent, which is significantly lower than other battery types in the market. No memory and scheduled cycling is needed to prolong the battery's life. Due to these desirable traits, Li-ion battery systems were tested for application in underwater vehicles and have demonstrated high potential in replacing lead-acid battery systems in diesel-electric submarines.

Major submarine designers such as DCNS and Howaldtswerke-Deutsche Werft (HDW) have initiated research and development programmes to explore the replacement of lead-acid batteries with Li-ion batteries.

Molten Salt Battery

The molten salt battery is a class of electric cells that uses molten salts as its electrolyte. It offers a higher energy density through a proper selection of reactant pairs (i.e. anode or cathode) and better power density by means of a high conductivity molten salt electrolyte. It is used in applications where high energy density and power density are required.

The main drawback of the molten salt battery is the need to charge the battery constantly so that the electrolyte will remain in liquid state and be ready for use when required. If the battery pack is shut down and left to solidify, a re-heating process must be done to restore the battery pack and this usually takes three to four days. The most notable example of molten salt batteries used for underwater application is the molten sodium aluminium chloride based ZEBRA battery that was first developed in 1985. However, its application in submarines has been limited, with usage seen only in small submersibles rather than submarines.

AIR INDEPENDENT PROPULSION

The period of time that a conventional submarine can remain submerged continuously is limited by its battery capacity. Despite emerging battery technologies, it is difficult to achieve a quantum leap in the submerged endurance due to volumetric and cost constraints. Submarines with AIP capabilities can extend their submerged endurance from days to weeks.

Conventional submarines run on diesel engines which require oxygen for combustion. AIP enables the submarine to operate without the need to surface or use its snort mast to access atmospheric oxygen. The oxygen required for combustion is stored on board as liquid oxygen. AIP technologies include Stirling engines, fuel cell (FC) systems, steam turbine systems, and closed cycle diesel systems. Thus, nuclear propulsion can also be considered as AIP. However, due to the size of nuclear submarines and their seemingly limitless submerged endurance, nuclear propulsion is seldom mentioned under the same category as non-nuclear AIP submarines.

In line with the modularity design concept, all AIP systems are built as modular plug-in sections (Bergande and Larsson, 2003). This characteristic makes them suitable for deployment in new and existing submarines. The following sections describe the dominant AIP systems.

Stirling Engine

The Stirling engine solution developed by Kockums is regarded as a well-established AIP technology. All Swedish submarines employ the Stirling AIP system. The Japan Maritime Self Defence Force also deploys Stirling engines in its Soryu-class submarines.

The Stirling engine produces heat by burning low sulphur diesel fuel and oxygen (stored in cryogenic tanks) in a pressurised combustion chamber. The heat is then transferred to the engine's working gas (usually helium) operating in a completely closed system. The working gas forces the pistons in the engine to move, thus producing mechanical energy to drive the alternator as illustrated in Figure 8. The combustion pressure is higher than the surrounding seawater pressure, which allows exhaust products dissolved in seawater to be discharged overboard without the use of a compressor. This results in low

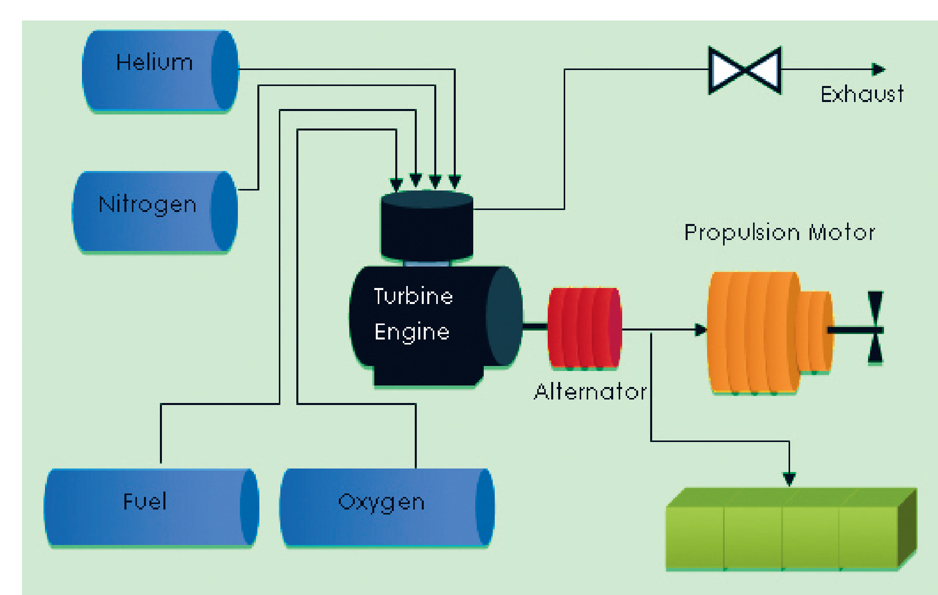

Figure 8. The Stirling AIP system

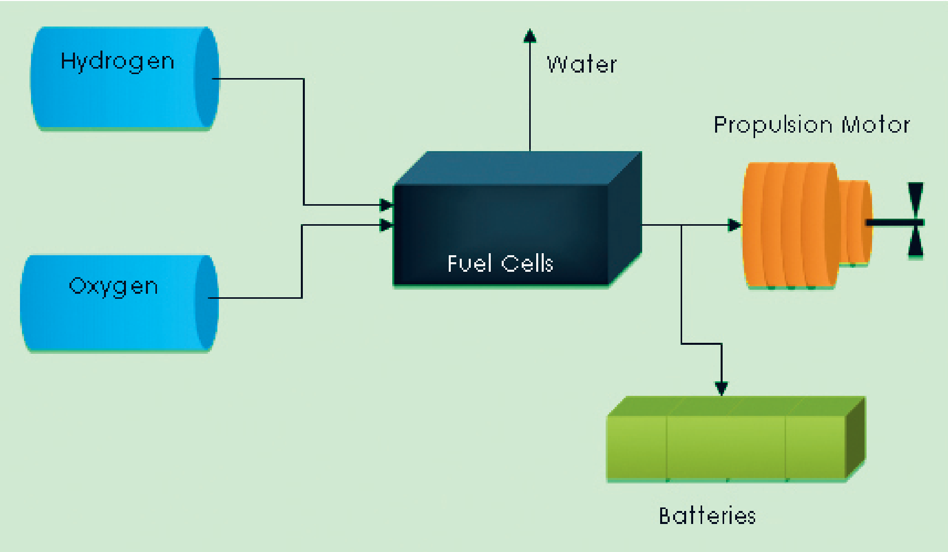

Figure 9. The FC AIP system

infrared signature and noise emission levels. The submarine's submerged endurance is determined by its storage capacity for the liquid oxygen.

Fuel Cell System

The FC system is developed by HDW in Germany. The system uses Polymer Electrolyte Membrane (PEM) fuel cells. PEM fuel cells are electrochemical energy converters in which hydrogen ions and oxygen ions are combined to produce electrical charge as illustrated in Figure 9. Similar to the Stirling engine, the FC system generates electricity at a slow and steady rate, suitable for low-speed submarine operations. For high-surge operations, the submarine relies on its regular battery system, which in turn is recharged by the FC system.

The FC system is operational on board the German U212A class submarines and the Type 214 class submarines. It has also been selected for the S80 class submarines built for the Spanish Navy. The FC system is advantageous because the only by-product is pure water and it does not generate any exhaust gas. Furthermore, the FC system is much quieter than other AIP systems, has the lowest oxygen consumption rate and potentially offers the highest underwater endurance.

However, the hydrogen required in FC systems is stored in the form of liquid hydrogen in metal hydride which requires costly maintenance and support facilities. The S80 class submarines will feature reformer technology that generates the required hydrogen from ethanol through a reformer.

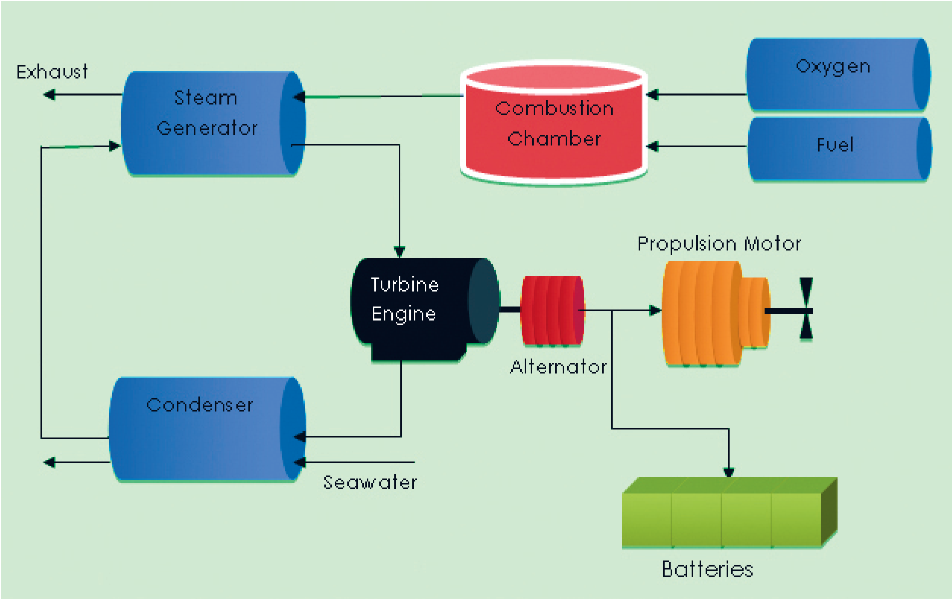

Figure 10. The MESMA system

An established reformer technology will resolve the issue regarding the supply and storage of hydrogen, which allows the FC AIP solution to be implemented more easily in conventional submarine designs.

MESMA

The French Module d'Energie Sous-Marine Autonome (MESMA) closed cycle steam-turbine system burns ethanol and liquid oxygen in a combustion chamber, generating steam to drive a turbo-electric generator. Figure 10 illustrates the MESMA's working principle. MESMA is currently fitted in the Pakistani Agosta 90B class submarines.

In the search to extend the submerged endurance and operating capability of conventional submarines, AIP technologies proved to be a cost-effective solution.

CONCLUSION

The key challenge to submarine design is to balance the requirements for stealth, range and adaptability with the need to control cost and size of the submarine. This article presents critical solutions in response to these modern challenges.

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BIOGRAPHY

Ong Li Koon is a Senior Engineer (Naval Systems) managing the submarine upgrade programme. He was previously the Deputy Head of the Resident Project Office overseas. He was a member of the Specialised Marine Craft Project Team which received the Defence Technology Prize Team (Engineering) Award in 2006. Li Koon obtained a Bachelor of Engineering (Naval Architecture and Ocean Engineering) degree with First Class Honours as well as a Master of Science (Naval Architecture) degree from University College London in 2000 and 2001 respectively.

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