ONCE YOU START ASKING

PREVIEW

HMS Enterprise

Systems

INSIGHTS, STORIES AND EXPERIENCES

from ten years of reporting on science and engineering

MARKUS VOELTER

The MCR. Through a door, around a corner, one staircase down. Through more doors, then to the right. Or something—I don't quite remember. The couple of days that I was in Enterprise were not enough to really understand the structure of the decks below the one I was berthed on, and the bridge. Too many doors and staircases. Anyway. I arrive in the machinery control room, where I chat with marine engineers Ian Sutton and Lee Williams. They are ultimately responsible for propulsion and "hotel services", which is what they term the infrastructure that relates to living on the ship.

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Engines. The Enterprise's propulsion is diesel-electric: the engines in the Azipods that propel the ship are electrical, and the electrical power to run them is created by diesel generators. This has several advantages, which I discuss below.

The ship has a total of three generators, two main ones and a harbor generator. Depending on how much power is needed, only a subset of these engines may be running, which reduces fuel consumption. Enterprise can comfortably sail at around 12 knots with one main generator running at full power. Adding the second main generator gets the ship to 14 knots. The final, lower-power engine only adds a knot or so. There is no battery to buffer the energy created by the generators, so they have to produce the required power in real time: if the ship wants to go faster, more generators are brought online. This is done automatically by IPMS, the ship's management system, whenever the "spinning reserve"—the difference between the required power and the power available from the running generators—reaches a predefined minimum of 180 kW.

Relying on multiple engines also provides redundancy in the case of engine failure. More generally, it helps with availability: depending on the required maneuvers, maintenance can be performed on one of the generators while the other powers the ship. If only a single larger engine was installed Enterprise would have to go into dock for maintenance much more often. IPMS keeps track of the maintenance intervals, and the engineers often choose to run the generator with more time available its next service. Maintenance itself is also simpler compared to turbines, and, according to Phil, "If properly maintained, the generators run forever."

Diesel-electric propulsion also leads to a simpler mechanical infrastructure in the ship. There is no need for a shaft from the engine to the Azipod and no need for complex gearboxes, both simplifying maintenance. It also allows more flexible positioning of the diesels, as they don't have to be in a straight line ahead of the Azipods. Thus, one of the main generators are installed in the forward main engineering space together with the harbor generator, and one in the aft. This allows better management of the ship's trim, as well as resilience: in the case of flooding or a fire it is better if not all engines are in the same compartment.

A final benefit of diesel-electric propulsion is that the engines can be designed to run at their optimally efficient speed: they do not have to ramp up or down to adjust the speed of the propellers. In fact, similar to a power station, the generators run at a constant speed, because that speed directly translates into the frequency of the generated AC voltage, which must be kept stable. As the requested power changes, a governor adjusts the power output of engines—and the fuel burn—while keeping the RPM constant.

Like any engineering decision, this approach to ship propulsion also has drawbacks. I presume two engines with power P are more expensive to buy than one engine of power 2 x P. Regular maintenance, such as checking and refilling of oil, coolant and lubricants, also has to be done twice, and there are more moving parts, so I suspect there are potentially more parts to fail.

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Switchboard. While shafts and gearboxes are not required, Enterprise of course has to have an infrastructure for distributing the electrical power. Most of the ship's systems are supplied with two buses of 440 and 220 volts respectively. However, a bus of 690 volts is used to supply the up to 1,700 kW for each propeller, to reduce resistance losses. As power is the product of voltage and current ($P = U * I$), for the same transmitted power you can increase either and correspondingly reduce the other. However, resistance loss is proportional to current ($W_R = I^2 * R$), so it is generally better do use higher voltage and lower current. This is also demonstrated by power grids, which run at up to 380 kV in Europe.

As another example of resiliency, Enterprise has two main switchboards, one forward and one aft. The main buses are also installed on both sides of the ship. Each Azipod has two supplies, one from each switchboard. There is also an emergency switchboard with an emergency generator. If this detects any failure in the main systems it starts automatically to provide power to critical components such as steering motors, radars, water pumps, a compressor for starting air for the main engines, and some limited lighting. During the 45 seconds it might take for the emergency generator to come on line the ship goes dark, but important systems are buffered with their own, locally-installed uninterruptible power supplies and therefore stay "alive".

The fact that the emergency generator powers the steering motors is a requirement of the IMO, which specifies that a ship has to retain rudder power even if its propulsion system fails. As Enterprise has no actual rudders and the Azipods can only act as such when the propellers are turning, providing power to the steering motors alone does not provide any steering. Nevertheless, it's a requirement.

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Azipods. One more level down and (of course) all the way aft is the Azipod compartment. I was there while the crew was exercising the steering of the ship directly from here. The same throttle-like Azipod controllers that are available on the bridge can also be found here, right next to each pod. One of the many contingency procedures is to control the ship from various internal locations and on deck, where there are no actual engine controllers—just a telephone to talk to the guy down here, who then controls the pods.

Each 1,700 kW Azipod engine is installed in a teardrop-shaped gondola under the ship's (flattened) aft hull and drives its own propeller. They engines cannot be accessed from the Azipod compartment. Because the Azipods also serve as the rudder and must be rotatable through 360 degrees, they are mounted onto what looks like a tank turret ring that is driven by two electrical motors through a gearbox. There is also a converter to control the motors' speed and direction, as well as a brake to lock each pod into position. The day before, around 2 am if I remember correctly, there was a pipe through the ship that woke me up. It announced something about a "steering gear breakdown". I wasn't quite sure what to make of it and went back to sleep quickly. I asked Ian what this was about. "We lost steering control on one of the Azipods. One of the brakes got stuck. It was very hot, so we couldn't touch it for three hours." He continued, "Luckily it got stuck in the midships position. So we could still use the propeller, but we could only use the other Azipod to control steering." Effectively, the Enterprise had a less effective rudder. Once the brakes had cooled down the next morning they were stripped down. "We found a broken disk. It has happened before. We had all the parts on board, so we could repair the problem quickly." Interestingly, just this scenario was practiced a day earlier as part of a steering gear breakdown exercise.

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Ballast. A ship is designed to handle optimally at a particular weight and resulting draft. The total weight of the ship depends on the equipment loaded on deck, the size of the crew and the amount of consumables such as as fuel and drinking water. To compensate for varying loadings the Enterprise has ballast tanks that can be filled with seawater. More importantly, the distribution of the weight along the ship's long and lateral axes—its center of gravity—also impacts the ship's handling characteristics. This is why ballast water can be pumped between tanks at various locations in the hull. The pumping is controlled manually by the engineers and relies on calculations performed on a laptop that determine the optimal load and distribution. I assume that weight and balance is not such a huge concern for a relatively slow ship like the Enterprise. It's probably more important for faster and more maneuverable frigates. However, they usually pump fuel around instead of ballast water.

Managing the ballast is not as trivial as it might seem. An international treaty, the Ballast Water Management Convention, prohibits "transporting" water from one ocean to another, mainly to avoid introducing new organisms into foreign waters. "So taking on and dumping ballast requires quite some planning", Lee Williams explains.

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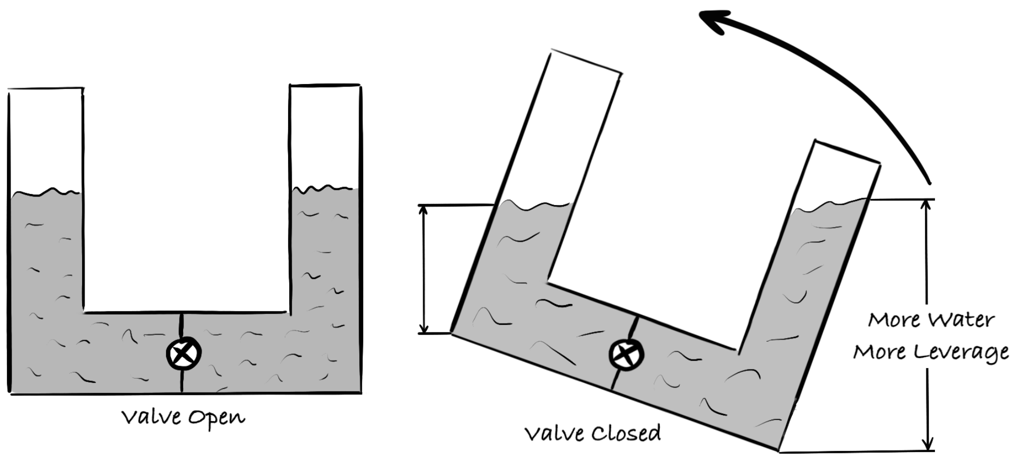
Stabilization. Another system that relies on water is the stabilisation system. Its purpose is to dampen any roll induced by wave action. Some ships use actively controlled fins for this purpose, but the Enterprise relies instead on a U-shaped tank installed in the hull that is partially filled with water. If the ship rolls, for example to the right, the water in the tank moves to the right, rising in the starboard part of the "U". Once the rolling motion has reached a maximum amplitude (on the starboard, in our example), valves in the bottom of the "U" close, trapping the water in its starboard side. This water, because it is higher in the tank and further away from the axis of rotation, has a higher inertia, and therefore slows the next roll to the port.



The bridge crew swear by the system. "It makes it a much more pleasant place to live," Kyle said. On the other hand, it is not so noticeable in the lower parts of the ship, for example in the engineering spaces. "The best place on the ship is low down and laterally in the middle. We've got a McDonalds there", Ian jokes.

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Fuel. Fuel is also interesting. Enterprise basically consumes "diesel oil that you could put into your car", not the heavy oil that is commonly used by large cargo ships. While Enterprise can in principle be resupplied at sea from a supply ship, she usually takes on fuel in port. As Phil says: "Setting up an underway replenishment requires a lot of planning. Considering that we have great endurance anyway, it is just so much easier to take on fuel in ports."

However, different ports supply fuel with different levels of quality. Of particular importance is the "cloud point", the temperature below which fuel starts to "wax into sludgy stuff", because this makes it harder to be burned by the engines. This has two consequences. First, different quality fuel is stored in different tanks. Each fuel is tested for its cloud point and other quality attributes, and there's quite a bit of book-keeping around this. Second, fuel with a relatively higher cloud point has to be used before the Enterprise travels into colder climes.

Before fuel its injected into an engine it is cleaned in fuel separators, where water and particulates are filtered out. From the main storage tanks, fuel goes into satellite tanks, then into the separator, then into the service tanks from which the engines are fed. Unburned or spilled fuel is returned to the satellite tanks, and gets cleaned in the separators once more before it is used by the engines.

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(Waste)Water. Further down into the bowels of the Enterprise. Steep staircases are now replaced by vertical ladders that descend from higher levels through hatches in the floor. This is where we find a lot of the infrastructure that runs "Hotel Enterprise".

There are freshwater tanks, two holding 44 cubic meters at the stern and two with 51 cubic meters in the bow. "Far more than we can ever use. Hollywood showers for everyone every day", Ian quips, adding that average use is ten cubic meters per day. Enterprise can also make its own fresh water from salt water: reverse osmosis removes salt and other particles from water by pressing it through semipermeable membranes.

Of course there is also waste water treatment. This is performed by "huge machines that look like they were designed by a crazed man". Ian. These incorporate membranes, shakers and the like, and allegedly produce drinking water—which then goes overboard. The remaining sludge is collected and disposed of when alongside. Prompted by my asking that this must be the favorite system to work on, Ian replies that "It's not a beautiful place to be. It has exploded once or twice due to overpressure. It made a huge mess." I stopped asking.

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HVAC. Heating, ventilation and air conditioning—abbreviated to HVAC—is crucial, because a ship is basically a huge metal can. Many rooms have no windows, so fresh air has to be brought in by other means. Some of these windowless rooms contain equipment that produces heat that has to be moved out of the ship. In addition, humidity has to be maintained at a level that is both healthy for the crew and suitable for the electronics. Fresh air is created both by "scrubbing" used air and by replenishing with air from outside the ship.

Enterprise is divided into three HVAC zones. Each has a separate air-conditioning system, so that if one fails only a third of the ship suffers. In addition, for redundancy each zone's HVAC system has two compressors—the central components of an HVAC system. Rooms with computers have extra coolers, and equipment that produces especially high heat loads can also be cooled through a chilled-water loop.

There are a few additional and less obvious aspects to the HVAC system. First, in the event of a fire on board the HVAC must be shut down immediately to prevent it from spreading smoke throughout the ship. They don't just shut down the particular zone, because "The smoke is going to go outside anyway and the next zone will suck it back in", Ian explains. The diesel generators, however, require continued cooling to avoid overheating, posing an interesting tradeoff in the case of an emergency. In the worst case the ship must slow down or stop. In addition, special fans over-pressurise the central staircases, which act as the route for rescue operations. The inhabited parts of the ship are also designed so that they can be over-pressurised; this is to avoid the entry of potentially hazardous gases or contaminants, a precaution for chemical and biological warfare. Enterprise also has a "pre-wet" system that sprays the superstructure of the ship with water to prevent chemical, radiological and biological contaminants from sticking to it.

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Fire. Fire is one of the biggest dangers for a ship. I mentioned the problem of smoke in the context of HVAC above, and I will talk more about fire exercises later. But there are more consequences for the ship's systems. For example, there are hundreds of fire and smoke detectors, and CO_2 and foam systems are available in the engine, Azipod and bow thruster spaces.

Dealing with water inside the ship is also crucial. First, water is needed to fight fires. Second, water must be pumped between the various ballast tanks, we discussed those earlier. But water must also be pumped out of the ship in the case of a leak. These three tasks are performed with a single system, the details of which I found particularly interesting. It uses "eductors", also known as jet pumps. These rely on the Venturi effect: if a gas or a liquid flow is choked (that is, its the section is reduced), its flow speeds up. This, in turn, increases its dynamic pressure, but also reduces the static pressure at the same time. In other words, choking creates negative pressure. An eductor is a device that consists of two water flows: one is choked to create negative pressure, which then creates a second flow through suction. It is basically a pump without moving parts, which makes it very robust.

The catch is, of course, that you have to create that first flow, usually with "real" pumps. In the case of Enterprise the "first flow" is the high pressure saltwater main ring. The 6 bar of pressure that drives the flow in this ring is created by six electrical pumps. The main ring can be segregated into zones for resilience, and there are two pumps per zone. Eductors are spread throughout the ship, all driven by the flow in the main ring. By opening valves, the eductors can be activated and used for sucking water out of spaces, for moving water between ballast tanks, and to provide water for fighting fires.

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IPMS. Up the ladders and back into the machinery control room. I chatted with Ian and Lee while sitting in front of their IMPS (integrated platform management system) consoles. The IMPS system manages all the technical systems of the ship. Users can switch between screens that show the status of the ship's systems. It collects, prioritises and reports alarms and status messages, and also automates some of the processes in the ship, such as starting up generators if the spinning reserve goes below the specified threshold.

Because of the automation provided by this system, fewer people are required in the engineering department: ordinarily only two crew are on duty during the day. In addition to working with IMPS, Ian and Lee also perform occasional walks through the various spaces to inspect the systems visually, although there are also cameras.

How can modern gliders fly 100s of kilometers, and why do they take water ballast to do it • How can the SR-71 fly at Mach 3 at 80,000 feet • How does it feel to fly in an F-16 fighter jet • How do computers control an A-320 and why is it so hard to fly a helicopter • How do you control 17-ton telescope mounted on a 747, and why would you do that in the first place • How is life on a miltary survey ship, and how do multibeam sonars map the sea floor • How do you inter-ferometrically combine many telescopes into one • How do you engineer a system to measure gravitational waves • What is it like to stand right under the world's largest optical telescope, as the dome opens, and the milky way reflecting in its giant mirrors • How do you control the LHC's beam • Why are models so important in science and engineering?

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