WARSHIP PROPULSION -- THE ALTERNATIVES

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The United States largely depends for its security on its ability to project forces overseas , so that we generally fight nearer our enemies' homes than ours. Historically, the key to projection has been naval forces. Because ships are buoyant, they can remain at sea without expending energy. Moreover, it takes remarkably little energy to move over the sea, albeit at moderate speeds. Even so, a large navy burns a great deal of oil each year, and it seems likely that naval propulsion will have to change as oil is depleted.

Now there is a real question as to the future of fossil fuels like oil. In force projection, ships are one of several current options, and there are often suggestions that the sheer speed of air delivery makes long-range aircraft more attractive than ships. However, aircraft speed is bought by accepting extreme inefficiency in the use of fuel; it takes many times as much fuel per ton of cargo to move anything by air rather than by sea. If fuel does become scarce, the first effect of scarcity will almost certainly be to restrict the use of aircraft. Probably the first victims will be long-range aircraft. Serious fuel shortages may well also preclude the use of tactical aircraft from long ranges, meaning that aircraft carriers will become much more important in situations requiring tactical air support. Whether any of this will happen in the near or medium term depends on just what fuel shortage means.

Right now the world runs on oil. That has had, as we all know, important political consequences. Right now the center of world oil production is the Middle East, which is also the most unstable part of the world. In the past, the United States was the dominant world oil producer; in 1941 the Japanese, for example, had to accept that a U.S. oil embargo would shut down their fleet within eighteen months. They opted to seize the oil they wanted, touching off the Pacific War. Lack of access to oil supplies seriously slowed the German war machine at about the same time. The Germans tried to substitute synthetic oil based on coal, and the Allies tried (apparently unsuccessfully) to destroy this resource. Many observers were stunned by the fact that the apparently modern German war machine employed hundreds of thousands of horses, and that in turn was probably due to a lack of oil. More recently, confronted by an embargo and further threats from the Middle East, the United States embarked on a program to produce synthetic oil from our own very large coal deposits, and there have also been attempts to produce oil from tar sands in Canada. These efforts failed not because they were unfeasible but because the price per barrel of the oil they would have produced would have exceeded that on the world market. One might speculate that the Middle Eastern producers were canny enough to protect their monopoly position by backing off before synthetic fuels displaced them.

These points can be projected ahead. One explanation of the rising price of oil is that demand is soaring as countries like China and India modernize. As prices rise, we can use oil more efficiently, but ultimately there is some limit to world supplies. It is not entirely clear that prices will simply rise to warn us that we are approaching a limit, or whether at some point it will become clear that fresh oil reserves simply do not exist. Nor is it clear when either will occur, but those arguing for limits generally imagine a crisis some decades from now. What happens then?

The first point to keep in mind is that the civilian economy dwarfs the military. Since about 1950 the U.S. military has done rather well by historic standards, so that it has been able to develop most of the technology it needs. However, beginning with computers, the military is beginning to find itself compelled to buy civilian off the shelf technology. Fuel is already an off the shelf product, so obviously so that we do not even point that out. That has an important implication for the future.

Whatever happens to fuel in general will be felt most strongly by the civilian economy, which is probably far more sensitive to fuel costs. That economy will develop some kind of alterantive fuel. If you think of fuel as a way of storing chemical energy, then it seems clear that some kind of new fuel will appear -- hydrogen and ethanol are currently-advertised examples. The source of energy in the oil and coal we burn is ancient sunlight, concentrated underground in the remains of ancient plants and animals. We still have other sources of energy: nuclear, solar, wind, tide, among others. Generally we convert this kind of energy into electricity. Some applications, like cars, can be redesigned to operate directly from sources of electric power. However, in many cases we are likely to want some portable means of storing energy, and that would seem to mean some kind of fuel created by feeding electric power into a chemical process (one source of the feedstock may be plastics).

So it would seem that the navy will face two situations. First comes a period of rising fuel cost in which fuel economy matters more and more. After that comes a transition to some new sort of fuel, to which current kinds of powerplants may or may not be adaptable. Consider first the alternative powerplants. A glance among the world's navies shows steam, diesel, and gas turbine plants. Steam is the oldest and in many ways the most difficult to operate. From the point of view of alternative fuels, it does have one interesting advantage. Because the fuel is burned outside the system (to produce steam), it may be relatively painless to shift from one kind of fuel to another (as when navies shifted from coal to oil). Note the word 'relatively' here. Although they burn their fuel internally, gas turbines may be the next easiest to shift; all that really matters is the heat content of the fuel. Diesels, which are the most efficient plants at present, may also present the greatest transition problem. In effect they are tuned to particular fuel characteristics: the fuel in a diesel ignites when the air in the cylinder reaches a particular pressure and temperature. If the fuel is more sensitive, it pre-ignites and the engine knocks and fails to work properly. In this sense a gasoline engine is more flexible, and this difference probably explains why car (gasoline) engines have been adapted successfully for alternative fuels like ethanol and hydrogen: ignition is controlled, by spark plug or some equivalent. At one time navies did use gasoline engines, but they were abandoned because the fuel was so dangerous. Gasoline exploded, and its fumes could be quite dangerous. At least that was the experience in early submarines using gasoline power. It may be that something like a gasoline engine, but using different fuels, will come back.

In the past, fuel economy was not the primary issue in the choice of powerplants. Navies have generally been far more intent on reducing running costs by reducing the number of personnel needed to operate and maintain powerplants. That is why steam, which was relatively economical but very manpower-intensive, gave way in almost all navies to diesels and to gas turbines. The few navies which still build steam-powered ships are the ones less sensitive to the need to cut crews. Diesels require much less maintenance (and less attention while running), but are heavy and relatively noisy. Many current warships have diesel powerplants. Gas turbines are compact and relatively quiet, but they are very uneconomical when running much below maximum speed. As fuel has become more expensive, there have been several attempts to make gas turbines more economical, for example by extracting energy from the engines' exhausts. Thus the U.S. Navy of the 1980s considered a semi-steam plant called RACER, but ultimately abandoned it. The Royal Navy is currently installing a regenerative gas turbine, the Rolls-Royce/Northrop Grumman WR-21, in its new Type 45 destroyers. The key question in such plants is whether the added complexity involved is paid for by better fuel economy. It is also possible to stretch the endurance of a gas turbine powerplant by adding a lower-powered supplement (a cruise engine), which may be either a gas turbine or a diesel. This alternative was quite popular at the beginning of the gas turbine era, but has been less popular lately, as basic gas turbine economy has improved.

Note that fuel economy can have tactical importance even in an era of cheap fuel. Few if any ships carry enough fuel for their entire missions; they have to refuel in forward areas. The more frequent the refuelling, the more often the ship has to retire to a safe area for replenishment -- and the more effort should go into protecting the chain of tankers which ultimately provides the fuel. Refuelling itself is always a time of increased vulnerability, e.g. to submarine attack. Refuelling also has a larger significance, in that it makes widespread dispersal difficult (there will never be enough tankers to service widely-dispersed ships). It can be argued that such considerations may be particularly significant if the fleet is to operate in a very dispersed fashion, as has been suggested for the current type of war. If ships cannot fuel regularly at sea, they must put into ports -- as USS *Cole* put into Aden before being attacked. Note, however, that in her case the fuelling stop was likely more important as a way of demonstrating U.S. resolve and interest, so it probably would have occurred even had the ship had unlimited endurance.

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What can we say about the future? We can imagine a period of ramped-up oil prices which lead the civilian economy to seek alternatives to current fossil fuels. Because fuel is a relatively small part of the navy's budget, it seems likely that ship propulsion would be insulated from such developments, and thus would be able to wait to take advantage, if possible, of civilian developments. Shipboard (and land-based) aircraft might well be in a very different position. They require vast amounts of fuel,which must be supplied more or less continuously.

The most likely candidate to replace fossil fuel power, if indeed fossil fuels are beginning to run out, is surely nuclear power. Even if it does not become dominant, we can lump it with renewable sources such as wind and solar power as a means of generating electricity. The question is how we can substitute some source of electrical power, using massive fixed generators, for fossil-fuel power which has such enormous advantages of compactness and portability. We can barely build efficient electric cars, but there seems to be little or no possibility of, say, an electric airliner or even a long-range electric bus. We are beginning to sense a solution in the form of synthetic fuels, such as hydrogen, which can be generated by electricity but which can then substitute for gasoline and other oils. This leaves out fully-renewable oil substitutes such as ethanol; presumably there is not enough growing area for full substitution.

Large ships can of course use nuclear power directly. A nuclear plant has a considerable fixed cost, and, at least in a large surface ship, it requires a substantial highly-trained crew. Note that the fixed cost includes sheer size, due to the need to shield the reactor. One of the unpleasant surprises of early U.S. nuclear submarine development was that the low-powered plant in USS *Tullibee* turned out to be considerably more massive than expected, so that the submarine also turned out to be considerably larger than first imagined.

These factors have been barriers to the spread of nuclear powerplants. That was not always understood to be the case. In the mid-1960s the U.S. Navy expected all future major surface combatants large enough to accomodate nuclear powerplants to have them; a law was passed requiring that all such ships over 8000 tons be nuclear-powered, unless special waivers were given. This view extended beyond the U.S. Navy; the British thought of the new gas turbines they introduced at about this time as an interim step before their fleet went all-nuclear. It turned out, however, that nuclear surface combatants were unexpectedly expensive, both in money and in manpower. The U.S. Navy built a series of nuclear cruisers, but they were retired without successors. Proposals for other nuclear combatants, except for large carriers, went nowhere. The only other navy to build such ships was that of the Soviet Union. Its big *Kirov* class cruisers have unusual combination nuclear and conventional steam plants, almost certainly to achieve nuclear endurance without investing in a nuclear plant for full power (the Russian explanation reverses these two requirements, but that seems illogical). Note that the U.S. Navy and the British also considered mixed nuclear-fossil plants, both with steam and with gas turbines, but in the end decided not to adopt them.

There have been suggestions that alternative types of nuclear plants may be substantially lighter. At one time, probably in the 1970s, it was suggested, for example, that using helium (which cannot be made radioactive) as a working fluid would make for a reactor so light that it would be the ideal powerplant for an air-cushion vehicle. Apparently that proved impractical. There were also attempts to navalize the lightweight reactors proposed for the abortive nuclear aircraft program of the 1950s and early 1960s. The failure of these ideas should not be attributed to conservatism in the U.S. Navy. The Soviets were intensely interested in nuclear power, and they were willing to try all sorts of radical alternatives, some of them probably inherently unsafe (the safety record of the Soviet nuclear submarines was not a happy one). With many incentives, they found themselves following much the same path as the U.S. Navy. The main exception was a serious attempt to develop liquid-metal reactors, which turned out to be unaffordable (they were used in the Alfa [Project 705] class).

Nuclear fusion may be about forty or fifty years from commercial maturity, but it seems to entail massive plants which would not be suitable for shipboard use.

Perhaps nuclear power can be used indirectly, to generate synthetic fuel (say hydrogen) which a ship with a conventional powerplant can burn directly. This application would seem to fit into the existing civilian economy, which dwarfs whatever the military can do, and thus which ultimately dominates military choices. If indeed fossil fuel is running out, some substitute will have to be found, and most likely it will be some kind of synthetic. Which kind is currently an open question, with hydrogen the most frequently offered. One problem is that it has vastly more volume per unit energy than conventional fuel, which is why hydrogen-powered aircraft so often show enormous fuel tanks. It may be that a solution to this problem already exists in metals into which hydrogen can be packed for storage.

If the future synthetic fuel really does need a great deal more volume than current fuels, then either future warships will be larger (to accomodate that fuel), or more attention will have to be paid to whatever transports fuel to forward areas. There have been suggestions for ships which can make fuel in those areas; the question will be how vulnerable such valuable units will be. If fuel really cannot be compact, the problem will be far more acute for aircraft than for ships, and a fuel crisis might conceivably eventually kill off tactical aviation (not to mention civil aviation, which would die sooner).

Besides existing types of plant (diesels, gas turbines, nuclear) probably the main future contender is the fuel cell. Whether it becomes a practical proposition depends on how it develops, both for greater efficiency and for greater power production per cell. Fuel cells offer several attractions. One is that they are cold, hence do not generate a heat signature which has to be countered. Another is that they are inherently quiet, apart from their pumps. A third is that they can probably use a very wide variety of fuels.

If the future of propulsion is clouded, how can ships be designed? A ship may well have to last thirty or forty years or more; otherwise it is almost impossible to maintain the sort of numerous fleet the United States needs. Thirty to fifty years is probably the time scale for dramatic changes in the availability of fossil fuels. To what extent can a ship be designed with what amounts to an open architecture for propulsion?

It turns out, remarkably, that the path now being taken by the U.S. Navy -- for other reasons -- offers just such an open architecture. In the past, naval powerplants were connected either directly or by gearing to propellers. Replacing the powerplant was essentially impossible, because of that direct or nearly direct connection. The sole exception was diesel submarines, in which the diesel engine drove a generator which in turn fed current into a battery. The submarine's propeller was driven by a motor fed by the same battery. This arrangement was adopted so that the submarine could run on battery power while submerged. As it happened, it also made it possible to run the diesel at its most efficient speed whenever it ran, because propeller speed was independent of engine speed. The U.S. Navy was unique in adopting this arrangement before World War II. After the war, the choice turned out to be extremely good, because it was possible to add motor power (for higher underwater speed) without changing the diesels. The indirect propulsion technique was less efficient than an earlier one in which diesels were connected directly to the propellers (clutched out for underwater running), and it was inherently heavier; in the U.S. case any extra weight was reduced by adopting very fast-running lightweight diesels.

The U.S. Navy is now adopting electric drive in major surface warships. Note that this is *not* a substitute for fossil power, as is the case in an electric car (it is literally unimaginable that a ship could be battery-powered for any useful distance). It is, rather, an alternative means of conveying power from a prime mover, usually a gas turbine, to the ship's propellers or propulsors. Electric drive was used by the U.S. Navy in capital ships in the 1920s, then dropped because it imposed a significant weight penalty. At that time, total ship size was limited by international treaty, and any weight penalty of this sort was unacceptable. Thus other important virtues associated with electric drive had to be eschewed. During World War II several classes of smaller ships used electric drive. They included destroyer escorts (which would now be called frigates), which used electric drive because national gear-cutting capacity was limited; and minesweepers, for which it was valuable to be able to shunt much of a ship's power into a magnetic sweep cable. However, there was no interest in electric drive for major surface warships until the late 1980s, when the predecessors of the current DD(X) were being conceived.

The main motive for adopting electric drive in DD(X) is the hope that the whole power of the ship can be shunted periodically into future electric weapons, such as rail guns. However, electric drive has other advantages, some of them relevant to the subject treated here. One is great potential economy of operation. The ship's powerplant can be broken down into smaller units, and at lower (cruising) speed only a fraction of her powerplant needs to be running -- and that at maximum efficiency. At least in theory, an electric ship can operate like a hybrid car, shifting to full electric power at very low speed, and storing power in a battery. It is not clear just how practical such operation would be, however. It is clear that by adopting electric power and by splitting up the powerplant, the ship can gain enormously in survivability, since it becomes much more difficult to disable her with one or two hits. Incidentally, the U.S. Navy adopted electric drive in battleships in the early 1920s for exactly this reason. It became possible to put the prime movers deeper in the ship, further from any threats.

However, from the point of view of future powerplants the most interesting effect of adopting electric drive is that it cuts the direct connection between prime mover and propeller. As long as there is enough space in the ship, it is much easier to substitute an alternative prime mover producing electric power. In some important sense, an electric-drive ship is an open-architecture ship from the point of view of propulsion. No other type of powerplant can be so described.

Given open architecture, the focus shifts to alternative means of generating electric power. That opens the possibility that *if* fuel cells really do fulfill their supposed potential, they can be adopted in place of the current gas turbines or diesels. This is a question, not an answer, at least right now.

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