Efficiency

Aidan Morrison

11/12/2017

Contents

1 Contents

2 Introduction

The purpose of this paper is to investigate the suitability of the pump-jet selection for Australia's future fleet of submarines. In particular, the question of the relative efficiency, and quietness of pump-jets in comparison to open propellers is of particular importance. Much has been made of the significance of the pump-jet in the DCNS (now Naval Group) bid for the submarine, to the extent that it has been claimed that the pump-jet rendered propellers obsolete.

Necessarily, this topic depends upon a considerable amount of physics, particularly around hydrodynamics, fluid mechanics, and turbomachinery, all of which might be difficult or daunting topics to usefully inform a public policy debate. However, in the case of a $50 billion dollar military acquisition, neglecting to engage with the technical matters that are so crucial to such a decision would be deeply foolish. To that end, this paper has a very specific ambition. It doesn't seek to advance the technical field with any new research or insight. Instead, it aims to make as much of the relvant physics as possible to this particular question comprehensible in laymans terms, and connect the essential concepts as directly as possible with the most important conclusions of public import.

As such, it will tend to make frequent use of diagrams, illustrations, as well as simple prose, and relatively infrequently use mathematical equations, (unless of crucial importance), though some effort is made to point to references where the fuller and more formal derivations of these relationships can be found.

It should be noted that the technical fields involved here are vast and rapidly evolving. The author makes no claim to be a world authority on the entirety of the topics which are touched. It is quite possible that there are other effects and phenomena which could be relevant which aren't mentioned here, and it's also true that additional advances in the state of the art are being made continually, and might not be known about in public literature.

However, the nature of scientific discovery and technical progress is that many of best discoveries are actually built-upon and confirmed, rather than swept aside, by later developments. As such, plenty of foundational principals, in particular the conservation laws of energy and momentum and essential principals of mechanics and thermodynamics are just as true, right, and relevant as they were hundreds of years ago. Consequently, whilst we cannot always know the precise degree of advance in a particular field of engineering, we can still confidently know some of the fundamental bounds and constraints that will be inherent in that field.

In this paper, since we cannot know the precise details of the particular state of the art in largely classified military programs, I will attempt to be particularly clear about those things for which we can have great confidence (often broad principals or relationships which determine trade-offs) and those things which we can't (the precise degrees or points and sensitivities). To that end, in this paper I've underaken modelling based upon the broad principals which we can have confidence, and conducted sensitivity testing based on a range of plausible values which seem realistic for those things about which we can have less confidence. I have also, in discussion with experts and through reading the available literature, attempted where possible to identify the most plausible of the uncertain values, in order to advance discussion.

With the support of the principal sponsor of this paper, the relevant models may be found in a user-friendly format as a web-app to allow their further interrogation and testing for other plausible scenarios. In addition, for increased transparency, the relevant code and equations underlying are available on github.

3 Executive Summary

3.0.0.1 The difference between nuclear and conventional for speed

This paper was commissioned in order to investigate whether pumpjets could plausibly be as efficient, or more efficient than a suitably designed open propeller for a conventional submarine. A crucial input to the investigation is a rough understanding of what the speeds of operation are likely to be for a submarine. Whereas nuclear submarines are reportedly capable of reaching speeds in excess of 30kt, and might transit long distances at such high speeds, conventional sumbarines are not thought of as being able to reach speeds far above 20kt in a sprint, and can only sustain speeds of 8-10kt for long-distance transits. Moreover, on patrol, a large portion of thier work is done at very low speeds, typically thought to be in the range of 2-4kt.

3.0.0.2 The importance of low speed operation for diesel-electric submarines

The efficiency of the propulsion system at such low speeds is of great significance for a conventional submarine, since it must rely on batteries or other air-independent propulsion sources for power when entirely submerged. Consequently, excessive energy consumption results in greatly reduced dived endurances. Since a submarine's position is vastly more likely to be discovered when it is on the surface operating its diesel engines, this ability to remain submerged for a long time is crucially important for combat operations, and in transiting through sensitive or contested areas. For nuclear submarines, which posess a practically infinite supply of energy from the nuclear reactor, efficiency at low speeds is of no concern. In fact, dispersing additional energy, (provided it can be done quietly) is probably advantageous for a nuclear submarine, since it will allow the nuclear reactor to avoid running at very low power levels, where the stability of the reactor is reduced.

3.0.0.3 What is cavitation

Pumpjets have been widely adopted by navies operating nuclear submarines. The principal advantage of a pumpjet relevant to submarines is their ability to avoid problems associated with cavitation, which is known to occur for propellers attempting to operate at high speeds. Cavitation, which is the rapid expansion and collapse of a bubble or void in the water, is particularly problematic for submarines, since it results in the creation of a great deal of noise which could be detected by an enemy.

3.0.0.4 How does a pump-jet work

A fundamental requirement of a pump-jet in order to avoid this cavitation is that the the working parts of the jet (the rotating blades inside it, known as the impeller) operate at a higher pressure than propeller blades operating in open water would. This means that the blades can turn at a lower speed relative to the water they are connected with, allowing a less violent action, which induces less cavitation. In this way, the jet does it's work less by directly acelerating the water, but by raising its pressure. This raised pressure is converted back to movement, which produces thrust, as it exits the jet and returns to the same pressure as the surrounding environment.

3.0.0.5 The necessity of drag, and decelleration, induced by the duct

The role of the shroud (or tunnel, mantel, duct) around the jet is to allow the pressure to be raised around the impeller, in a way that is not possible for an open propeller. By a fundamental requirements of physics, this actually requires that the water's incoming speed be **reduced** before it reaches the impeller. (The kinetic energy embodied in movement is converted into potential energy, or pressure.) Whilst the duct narrowing at the nozzle also necessarily accelerates the water, (as the additinal pressure imparted by the impeller is converted back to kinetic energy) it's an essential feature of all pump-jets that the water flow is decelerated at the point of reaching the impeller. Consequently, an elementary form of the pump-jet is also termed the 'decelerating duct' applied to a propeller. Put simply, the water has to slow down to go fast again.

3.0.0.6 What happens to a jet at low speed, in simple terms

The problems for pump-jets arise when the water is already going slow, and you don't want it to go that much faster. This is the case when a jet designed for high-speed attempt to operate at a dramatically reduced speed. (Not to be confused with a vessel with very little water speed working very hard, as might be the case for a tug or barge.) In this case, the slowing down and speeding up results in an unnecssary additional step which reduces greatly the efficiency of propulsive system. Or, put another way, overcomign the resistance of moving water through the shroud becomes much greater relative to the total thrus produced by the jet.

3.0.0.7 Why this isn't easily noticeable in normal circumstances

It is for this reason that waterjets of any kind are known to have an efficiency curve that falls off towards zero as the net thrust they produce also diminishes to zero (which for a given vessel will correspond to water speed). This doesn't mean that they don't still work at low speeds and produce some thrust. All it means is that far more power per unit of thrust will be required than might be at other speeds, as a higher fraction of energy is expended producing the turblence (random, round-and-round movement) inside and around the jet shroud than goes towards direct front-to-back acceleration of the water column, which produces thrust.

3.0.0.8 What the submarine requirement tells us about the duct

Whist estimating the exact shape and level of the efficiency curve for a particular pump-jet and propeller is impossible without detailed knowledge of their design, the over all trends of their shapes in the extremes can be known from well-established principals. Moreover, the particular demands of a pump-jet suited to a nuclear submarine, (eliminating all cavitation in as wide a range of operating circumstances as possible) considerably narrows the plausible range concerned. In order to minimise cavitation, the degree of pressure elvation at the impeller would be relatively high, or the total surfaces of the impeller blades much aslo become larger. Both of these design requirements necessitate changes to the duct or blade designs which would be in tension with overall efficiency, and most pronounced at the lowest of operating speeds.

3.0.0.9 Quantitative Conclusions

In the production of this paper I have developed a computational model which maps the impact of different efficiency curves directly to the dived range and endurance of a submarine. The most plausible scenarios I find include the reduction of dived endrance and range between 20% and 50%, or effectively halving time and distance that submarine may remain submerged for during combat operations at speeds around 3-5kt.

3.0.0.10 The acoustic advantage of jets at higher speed

My review of the literature confirms that a pumpjet may produce a significant acoustic advantage in circumstances where an open propeller would experience any degree of cavitation. Indeed, it has been remarked by naval researchers that pump-jets could be designed which would not cavitate past the point when the body they propel experienced caviation. As such, it seems perfectly plausible that pump-jets confer one advantage on a submarine, in that they can accelerate to a higher speed without cavitation occurring. This is known as a higher 'tactical silent speed'.

3.0.0.11 Turbulence and flow separation at low speed

However, at much lower speeds such as patrol speeds (2-4kt) it is most likely that a propeller will be able to operate well below the point of any cavitation inception, and would consequently also be extremely quiet. Moreover, a jet will necessarily incur substantially larger degrees and types of turbulence in order to produce net thrust in this regime. These likely include discontinuities and instability in the flow entering the duct and passing through the impeller and stator (flow separation) as the water is acelerated sufficient to be slowed, and then re-accelerated. In certain circumstances where resonances might arise these could be highly adverse to acoustic performance. However, assuming that by careful design such resonances can be eliminated (which we assume has been achieved) these effects would not result in any cavitation, and would only increase the noise attributable to turbulence in solid water, which is far less than for any cavitation.

3.0.0.12 The acoustic question at low speed

But in either case, given the necessarily raised levels of turblence generated by a jet than a propeller at very low speeds, the claim that the jet is quieter in this regime must rely entirely upon shielding effects from the shroud. These could be substantial in a directions perpendicular to the direction of travel, but would be much smaller when viewed from the aft or forward directions. It should also be noted that many underwater acoustic environments, sound tennds to reflect and bend in different directions as it propagates. As such, the claim that pump-jets are universally quieter than propellers should be treated with caution. In a variety of circumstances, including most operations at patrol speed, it may not always be true.

3.0.0.13 The inevitable trade-off

However, as a direct and necessary result of this higher tactical silent speed, some disadvantages will be incurred, owing to the additional drag induced by the shroud which prevents cavitation at the impeller. These are a lower dived endurance, a lower dived range, a lower overall endurance, a lower overall range, and a worse indescretion ratio.

3.0.0.14 The contradiction between stated requirement and chosen technology

Given the substantial emphasis which was placed on overall range and endurance of the submarine, it is difficult to understand how one particular unique requirement would be elevated so high above the other strategic and tactical advantages afforded by propellers.

4 Speed and Drag - Why very slow is very very $(very)^2$ economical

Perhaps the most important relationship to understand is the relationship between speed and drag as it pertains to submarines. This is immportant because it sets out the fundamental framework as it applies to any submarine, regardless of propulsion type. (It's also a pretty important for planes, cars, missiles, torpedoes, and basically everything else.)

Drag is the resistance that a fluid (air or water, in our case) gives to a body that is passing through it. Quite simply, it's a force that acts in the opposite direction. There are multiple sources of drag for different types of scenarios. For scenarios where an object is in contact with two different types of fluid (like a ship, on the ocean) or when the fluid doesn't really have contact with all of the object (supersonic flight, and supercavitating torpedoes) some more complex physics applies. For a fuller discussion of types of drag, see (Carlton 2007) But in the case of a submarine, which does it's business completely immersed in the ocean, the relevant physics is dominated the skin friction on the hull, which follows a very simple rule and relationship. The amount of drag (F_D) an objet experiences increases directly in proportion to the surface area A. For any given object of a certain (unchanging shape) there will be a constant coefficent (C_D) which reflects how aerodynamic or hydrodymanic the shape is. The drag is also directly proportional to the density of the fluid being moved through, ρ. (Air creates roughly one-thousandth the drag as water does on any given object at a given speed, since it's roughly one thousand times less dense.)

But the most sensitive factor in this relationship is the speed at which the object moves through the liquid. The drag increases not with the speed (v), but with the **square** of the speed. This means if the speed doubles, the drag increases by four. If the speed triples, the drag increases by a factor of nine.

$$F_D = \frac{1}{2}\rho v^2 C_D A$$

, Figure 1: Xenon poisoning effect following shutdown from Garland (2005)

(Technical aside: This law applies wherever the the flow over the surface is turbulent. It is true that for very small objects, or very viscous fluids, or very slow movements a different apples called Stokes Equation, in the case wher Reynolds numbers are less than 1. Given that sea-water is not particularly viscous, and sumbarines not particularly small, Reynolds numbers are liekly to be much much greater than 1 (one or two thousand), even when moving at only one or two knots. Since it is unlikely that a significant proportion of the flow over the hull will be laminar, we'll use the drag equation in all modeling going forward when considering drag on the hull).

It's crucial to understand, however, that drag is only a force, and doesn't directly inform us about how much energy is consumed, until we multiply it by the **distance** over which it is applied, not the time for which it is applied. To think about it simply, gravity exerts a force on you downwards all the time. But you don't expend any energy overcoming it when sitting still. If you climb stairs, the amount of gravitational potential you attain depends on how high up you climb, not how long you spend on the ladder or stair-case.

This has a significant consequence for propulsion, since the amount of power (energy expended in a given time) required for thrust scales with the drag, multiplied by the distance covered in a given time. As such, power required (and fuel/battery consumption) scales with velocity **cubed** rather than velocity squared. This means that if you double your speed of travel, fuel consumption for a given period of time will increase by a factor of eight. Due to the increased speed of travel, the fuel required to cover a given distance will only quadruple. Hence the range that can be covered with a given amount of energy (assuming propulsion dominates energy requirements) tends to scale with the inverse of velocity squared, whereas the endurance (amount of time that can be spent travelling) scales with the inverse of velocity cubed.

This has a profound impact on the operation and engineering of maritime vessels. Reducing velocity has such a substantial reduction on hull drag that going slower is almost always a reasonable means of conserving fuel overall. To the extent that time is non-critical, slower is always much much better. It's for this reason that during the financial crisis, many cargo shipping companies adopted the practice of slow steaming (Liang 2014) in order to conserve fuel, despite this causing a range of possible new engineering issues which need to be accounted for in order to operate the engines at lower than normal power for sustained periods (Sanguri 2012, 8–10). The fuel saving from operating even 30% slower means that around half the total energy is required for a given journey. Other incremental costs and inefficiences from operating 'off-design' are frequently outweight by such a dramatic reduction in overall power demand.

This effect is of profound importance to understanding the operations of conventional submarines, which have extremely constrained energy stores when operating under the surface. Diesel fuel when burned has an energy density of approximately 45MJ/kg. In contrast, a lead-acid battery might have energy densities in the range of 0.08-0.14MJ/kg. With something like 400 times as much energy per kg embarked in diesel, operating on batteries imposes an extreme demand for economy on propulsive power. Happily for submarines, the square law for drag, and cubed law for power, allow an almost commensurate reduction in power demands to take place by slowing down to very slow speeds when submerged. Hypothetically, a conventional submarine might have a total range of 10,000nm from using it's diesel payload at 8kt. If an equal weight of lead-acid batteries as fuel were carried, the submarine could only travel about 25nm when submerged at the same speed in a single charge. But by travelling at 4kt, that quickly increases to 100nm, and 400nm at 2kt (neglecting hotel load here for simplicity).

It's worthwhile pointing out that extreme demand for economy imposed by the poor energy density of batteries distinguishes submarines quite remarkably from other types of boat or ship design. In every other application, the propulsion system is designed around a particular speed and loading condition which it is optimally efficient for, and a band of plausible variation around this. For example, a cargo ship designed for operation at 22kt will have it's propeller and engine (propulsion system) very carefully designed around these speeds and the plausible levels of loading at those speeds. A top-speed which might be somewhat higher than 22kt would be calculated, but would be relatively unlikely to be used for any purpose other than an emergency. Lower speeds might be considered 15-18kt for the purposes of slow-steaming. However, the relative efficiency at 3kt is of little concern, since the drag at that speed will be under 2% of what it would be at 22kt, and the power required around 0.25%. Even if the efficiency was substantially worse, or better (by a factor of two or three even) the impact on the overall economics of the operation would be negligible when compared to marginal improvements at the design speed.

The same consideration applies to other types of vessels, which might use water-jets. Fast pilot-boats, for instance, might spend quite a considerable time manouvering in and out of harbour or alongside at very low waterspeeds. However, their overall fuel consumption is still likely to be dominated by the fast section of their trip to a ship. If the in-harbour water-speed was 8kt, but 32kt was the optimum speed for the open-water section of their journey, the fuel requirement for a given distance could still be over ten times greater at 32kt. (Aside, the physics described above would say 16 times, but some reduction due to the reduction of surface area from planing might offset this.) Consequently the owner/operator would be at least ten times as concerned about efficiency at 32kt as at 8kt, (unless the harbour transit was much much longer than the open water section), and have negligible concern about effiencies at 2kt or 3kt, which would rarely amount to more than a couple of percent of total propulsion energy demand.

In stark contrast, a submarine operator might have less than 1% of the energy store available for the submerged movements at 2-3kt, and consequently be substantially **more** concerned about efficiency in this regime, particularly since this would be the regime in which all of their combat operations would be conducted.

This imposes a constraint on the way in which literature on jets, propellers, and propulsion systems in general is read, since almost all of it is deeply concerned with how a particular system would operate at one particular design speed, and choosing the optimum system for that design speed and load. Considerable attention is given to how a propeller would work in off-design conditions relating to changes in load, such as in cases when a ship is more lightly laden, or a tug-boat is pushing a different sized ship. There is, however, a relative scarcity of attention given to the performance of a propulsion system operating at a dramatically different speed, with the same load. It also corresponds to scenarios where engineers and manufacturers seem from discussion to be far less confident in making quantitative claims about the performance of their own systems. (They are perfecly happy to make qualitative claims, “it would be alright”, “nothing very bad would happen” etc.)

Given that submarines almost by definition (since their hull shape doesn’t change, and they must carry ballast to make up for any under-loading) are essentially always operating with the same load, but have to operate over an extremely wide variety of different speeds (a factor of four or more in variance) with severe efficiency concern at all of them, they represent a truely unique engineering question, seldom discussed in commercial applications. Consequently, there are relevantly few pieces of literature which address the present question directly. (Happily, not zero) However, there are plenty of instances where the relevant physics and trade-offs are explained in depth to address related, but not identical questions.

5 The difference between nuclear and conventional propulsion

Nuclear submarines vary quite remarkably from conventional submarines because of the means by which they generate their power. Because of the extremely high energy density in enriched uranium or plutonium, the reactors on board nuclear submarines generate an abundant supply of energy. Most submarine reactors are reportedly capable of generating between 25 to 50 megawatts (MW) of power, though Russian submarines have hundreds of megawatts of power available (2017).

In contrast, the Collins Class Submarine’s main motor is rated at less than 6MW, with designs for the future submarine appearing to be only slightly larger (Patrick 2015). It is fair to say that in terms of maximum power ouput, nuclear submarines could have something like 5-10 times as much power at their disposal, and their **peak** output.

The difference between the peak-powers of the submarines significantly understates how different the designs are, because the difference in the total amount of energy stored and available for use in a voyage or dive is vastly greater. A nuclear submarine might have literally millions of times more energy at its disposal, it is practically unlimited for all intents and purposes on a given voyage. Consequently, wheras a nuclear submarine might regularly conduct transits at or near it’s peak power, a diesel electric submarine would probably transit at less than half the speed which it could manage at a sprint, (and use less than a quarter of the energy, as discussed earlier) and on patrol it might be operating at a tenth of the maximum speed, and use maybe just 1% of as much power on propulsion. In this situation, the amount of power that is drawn for lights, CO2 scrubbing, washing, cooking, heating, as well as the electronics driving the combat systems (the ‘Hotel Load’) might well become significant, and even be as larger or larger than what is required for propulsion.

Consequently, the difference between the power output a conventional and a nuclear submarine might regularly operate at could be even quite a bit larger than the maximum amount of energy that they can deliver to their propulsion systems.

Perhaps more significantly for power-design of nuclear submarines is a little-discussed phenomenon called Xenon poisoning, which affects nuclear reactors when they shut down or lower their power significantly. When Uranium or Plutonium atoms split (or fission) into two smaller isotopes atoms, a variety of different radio nucleides (unstable variants of atoms) are produced. Two of these are Xenon-135 and Iodine 135. Iodine is produced much more often, and decays into Xenon-135, which a half-life of about nine hours. This Xenon has a very special, perhaps unique role in reactors, since they very easily captures the free neutrons which cause the continued fission reactions in Uranium or Plutonium which drive the reactor. As such, Xenon is known as reactor ‘poison’ since it can kill the reactor’s reactivity in very high doses.

This high neutron-capture from Xenon means that it has a duplicitous relationship with the reactor’s power level. At high levels of reactor power, lots of Xenon-135 and Iodine-135 are produced by the fission process. The high presence of Xenon reduced the reactor’s reactivity. On the other hand, there are lots of neutrons

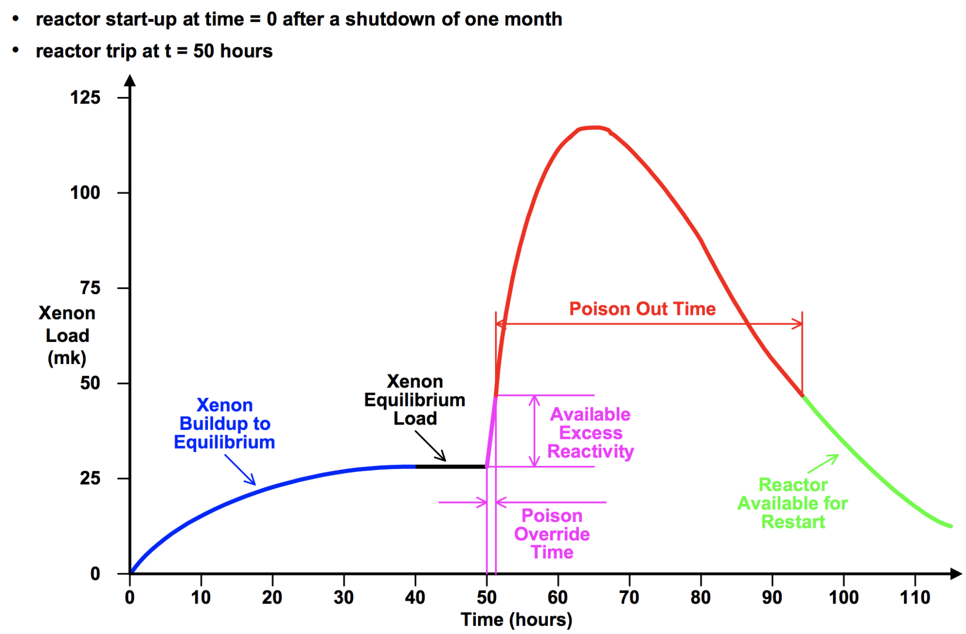

Figure 1: , Figure 2: Xenon poisoning effect following shutdown from

available to 'burn off' the Xenon (which absobs the neturons to become a different isotope). This keeps the total level of Xenon in check.

The situation becomes much more complicated when the reactor undergoes a sudden change in power output. If the power is lowered dramatically and suddenly, the production of Xenon continues quite rapidly for some time due to the decay of the large stock of Iodine-135. With less neutron flux available to 'burn off' the Xenon, the Xenon levels spike, and push down the reactor's reactivity. Unless the reactor is quickly raised back to relatively high power (~60%) quite quickly (an hour or less), the Xenon levels become so high that the reactor will have to be shut down, otherwise extreme (and dangerous) measures would be required in order to keep the reactor going. (This is essentially what lead to the Chernobyl Explosion (2009).) A fuller discussion of Xenon poisoning can be found in (Garland 2005), which demonstrates key concepts related to the poisoning effect shown in Figure 2. And you can see that in the Introduction.

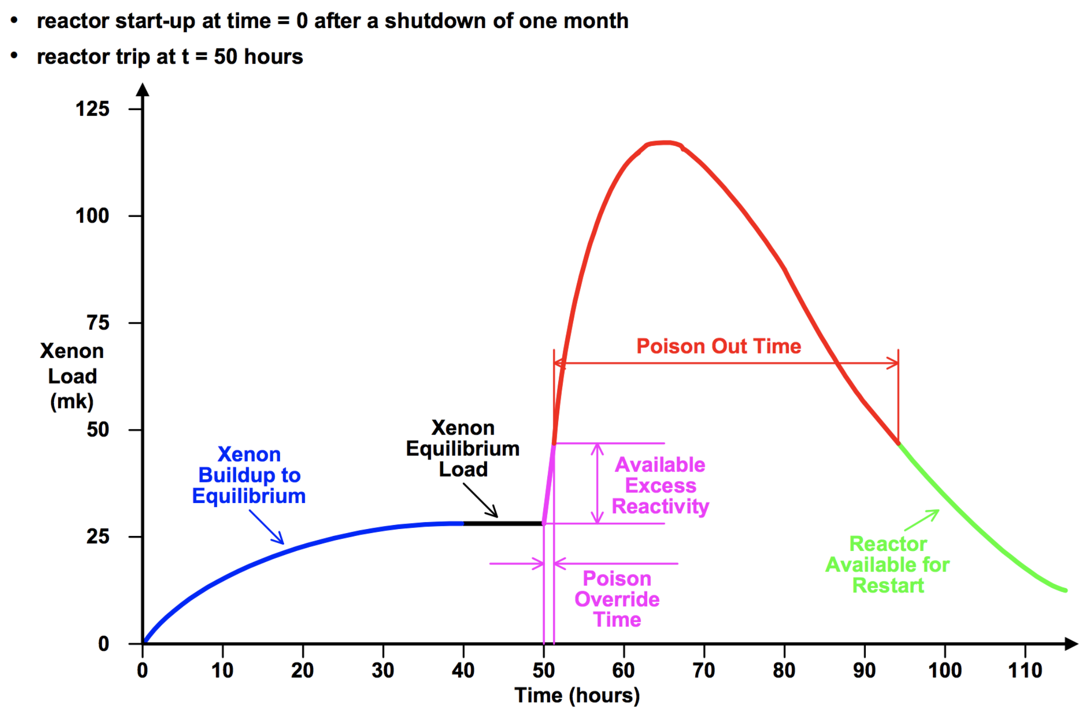

Figure 2: A prototype of the Job Information dialog @garland2005

Consequently, nuclear reactors aren't well suited to rapid fluctuations in power, particularly dramatic reductions in power, as these can lead to instability in the reactor core. If the reactor is shut down in order to avoid such dangerous circumstances, it generally cannot be started again until Xenon levels have fallen again, which can take a couple of days. Obviously this is never desirable for a military vessel, and hence is avoided at almost all costs.

This effect has a dramatic impact on nuclear submarine design, since much of their design is oriented around being able to comfortably disperse large amounts of excess power, rather than with conserving it. For the propulsion system, this actually makes having an inefficient propulsor at low speeds a considerable advantage. Since the reactor will likely need to dispose of excess power, particularly during ramp-down, an inefficient propulsion system actually provides a useful power sink. Since any excess power will have to be disposed of by some other means (normally by pumping more water to remove the power as the heat) inefficiency at low speeds has no penalty, and probably a marginal benefit, since it will reduce overall demand for additional systems. Provided the excess turbulence inside the pumpjet isn't too noisy, wasting energy through the propulsor is useful.

It should also be noted that a nuclear reactor's aversion to sudden reductions in power would also have a substantial impact on the design of a submarine's combat system, and it's demand on the Hotel Load. For the same reason, a high Hotel Load, or power-hungry Combat System, could actually be advantageous, as it helps to set an elevated 'floor' for power requirements, reducing the scale of fluctuations in overall power demand from the reactor due to changes in propulsion speed.

6 Some essential concepts

6.0.1 Conservation of Energy

This is perhaps one of the most fundamental and well-established principals in physics. The essential idea is that energy can move or change in form, but it isn't ever created or destroyed. Machines, plants and animals all derive their energy from a particular other source, which can be measured and evalutated to establish the limits of energy available. Plants collect energy from sunlight falling on their leaves. Humans (as well as combustion engines) capture the chemical potential energy in organic matter, and release it by combining it with oxygen. Hydro-electric power plants turn the gravitational potential energy of water stored at a height into electricity.

Conservation of energy has a particularly relevant embodiment in fluid flows, which is given it's primary expression in Bernoullis equation. It says that the total energy in a connected body of fluid is constant, though it can change in form between kinetic energy (movement), gravitational potential energy (it being elevated) the heat energy in the fluid, and the pressure of the fluid.

In different fluids, the dynamics of how energy moves between one and another change. For example, in gases, heating up a confined piece of gas will increase it's pressure, or if it is unconfined, increase its volume. This is particularly important for understanding gas turbines. In the case of a liquid, however, all the molecules are in close contact, and hence can't increase in volume or pressure substantially except by the creation of steam. As such, in the absence of large amounts of cavitation, the terms in the relationship which are most important for our consideration are the relationships between pressure, and kinetic energy, and gravity.

In the case of most waterjets which propel surface vessels, the water is lifted from the bottom of the hull at the intake to the pump, which is generally incorporated inside the hull. This increase in gravitational potential coincides with a slowing down of the water relative to the vessel-speed. Since the jet in such vessels is generally ejected at the same height as the pump, this potential is never regained, and is technically a loss, however at high speeds such a loss is small relative to the total power ouput.

6.0.1.1 Venturi Effect and Flow Diffusion

In the case of submarines and torpedoes the water doesn't undertake a change in height, since intake and nozzle are generally all in line with the central axis of the submarine or torpedo. As a consequence, the key relationship in Bernoullis equations is the relationship between the liquids velocity, and its pressure. The consequence is that when water moves through a pipe (duct, or shroud) it's pressure is inversely related to the square of its velocity. This means that when a liquid is forced to to travel through a narrowing pipe, it's pressure necessarily decreases as the velocity increases. This is a simple embodiment of the Venturi effect. The inverse process is where a pipe increases in volume, and the flow is forced to slow down in order to fill the wider area, and the pressure correspondingly increases. This is a process called 'diffusion', and is important to achieving high pressure levels in many types of water pumps, including those which will be particularly relevant for pumpjets for watercraft propulsion (Waterjets 1997).

6.0.1.2 Energy waste and efficiency

The conservation of energy also has useful implications for how the efficiency of systems is thought about. In particular, because energy is conserved, identifying inefficiencies in a system necessarily involves identifying where energy goes to doing tasks which aren't useful for the intended purpose. A perfectly efficient system won't do any work that isn't for the intended purpose. In the case of analysing the efficiency of propulsion systems, the relevant 'work' is almost always related to moving water backwards to produce thrust. Moving water in directions other than backwards, including random turbulent flows which wind producing heat rather than thust, are two examples of wasted energy. Noise in the water also reflects energy which is wasted.

6.0.2 Boundary Layer

When water or any fluid flows with some speed relative to another solid surface nearby, there is some layer adjacent to the surface in which the speed of the fluid is diminished relative to the main flow. At a microscopic level, there are some molecules of the fluid on the surface which will be effectively static relative to the surface. The layer of fluid that joins the gap between the static surface, and the part of the flow which is moving at the full flow speed, is called the boundary layer. Exactly how thick the boundary layer is, and how the fluid moves in the boundary layer, is extremely important for consideration of efficiency of fluid flows over and around solid surfaces.

6.0.3 Turbulent and Laminar Flow

6.0.4 Pressure, Thrust, and Momentum

6.0.5 Cavitation

6.0.6 Flow separation

7 What tech are we talking about? The core relationships between pumps, jets, ducts, and propellers, and all the different things we call them, their parts, and combinations

8 Propulsive performance of the pumpjet, or decelerating ducted propeller

8.1 Efficiency Relationships, and various curves

8.2 Practical and recent evidence of efficiency relationships

9 Results of numerical simulation

10 Acoustic Considerations

11 Conclusions

References

Carlton, John. 2007. "Marine Propellers and Propulsion." Elsevier. http://www.nuceng.ca/br_space/2017-09_4d03_6d03/misc_files/xenon_poisoning.pdf.

Garland, Bill. 2005. "Elementary Physics of Reactor Control Module - Fission Product Poisoning" 3. Nuclear Engineering (Originally from McMaster University). http://www.nuceng.ca/br_space/2017-09_4d03_6d03/misc_files/xenon_poisoning.pdf.

Liang, Lee Hong. 2014. "The Economics of Slow Steaming." Seatrade Maritime News. http://www.seatrade-maritime.com/news/americas/the-economics-of-slow-steaming.html.

Patrick, Rex. 2015. "The Driving Factor in the SEA 1000 Choice." Asia-Pacific Defence Reporter. https://corporate.siemens.com.au/content/dam/internet/siemens-com-au/root/aunz-defence-solutions/apdr-october-2015-issue-future-submarine.pdf.

Sanguri, Mohit. 2012. "The Guide to Slow Steaming on Ships." Marine Insight. https://www.marineinsight.

com/wp-content/uploads/2013/01/The-guide-to-slow-steaming-on-ships.pdf.

Waterjets, Hamilton. 1997. "Jet Torque." Hamilton Waterjets.

2009. "Chernobyl Accident Appendix 1." World Nuclear Association. http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/appendices/chernobyl-accident-appendix-1-sequence-of-events.aspx.

———2017. "Nuclear Powered Ships." World Nuclear Association. http://www.world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-powered-ships.aspx#ECSArticleLink0.