Efficiency

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1 Introduction

The purpose of this paper is to investigate the suitability of the pumpjet propulsor technology selection for Australia's future fleet of submarines. Amongst this considerable controversy surrounding the submarines, this particular technology choice deserves special attention. Much has been made of the significance of the pumpjet in the DCNS (now Naval Group) bid for the submarine, to the extent that it has been claimed that the pumpjet rendered propellers obsolete (*The Shortfin Barracuda Bloack 1A*), and features extremely prominently in the all the marketing and literature. It seems to be accepted knowledge that the proposal from Naval Group (formerly DCNS) was selected because of its acoustic superiority (Stewart 2016), with the pumpjet apparently comprising the jewel in the crown.

The selection of the DCNS bid to design the future submarine attracted considerable attention and controversy on a number of fronts. The choice of the pumpjet, and the question of efficiency at low speeds, has been touched on briefly in various informed discussions (Stanford 2017) (Davies 2017). However, it has remained the case that even extremely well-informed commentators reluctant to quantify and qualify the plausible scale of this trade-off, and what it might mean strategically and tactically for the submarine. Everyone knew it was an issue, but no-one confident enough in the scale of the impact (or even at transit speeds the direction of the impact (Davies 2017)) to make it clear whether it mattered. Even the head of the progam to build the submarine acknowledged an improvement in dived endurance would be possible with conventional propellers (*Size of new submarines locked in* 2017), which seemed a clear acknowledgment that some trade-off was acknowledged, even by the strongest advocates of the pumpjet. But despite this, the chiefs of DCNS and SEA 1000 both remain adamant that the pumpjet was an "integral part of our bid" (Nicholson 2017b) and that it can be efficient "across the entire speed range" (Nicholson 2017a).

Having done my higher education in physics, and spent considerable time considering military maritime technology running a small start-up defence company I found seemingly unresolved series of exchanges regarding the pumpjet choice particulaly curious. As is commonly quipped, including in defence circles, it can be reliably assumed when it comes to technology choices "there's no free lunch in physics". Whilst all technologies steadily improve, and new ones continuously emerge, it's inevitably the case that when significant technology switches are made, some trade-offs are necessary. In the case of the pumpjets, the trade-offs what might have been expected appeared obvious, and probably unavoidable to some extent to all those experienced in maritime systems: it would have lower propulsive efficiency, particularly at low speeds.

It's definitely true that efficiency isn't everything in military technology. In recent years I was heavily involved in designing a small speed-boat and a medium-weight torpedo for naval combat, and in both cases I selected a waterjet or pumpjet for those purpose. Pumpjets, or some kind of "decelerating ducted propeller" (explained in detail later) suited very well the sorts of speeds and operational circumstances that they were required to operate in, which were well over 30kt. However, having made that selection, and on several occasions wrestled with adapting the boat to alternative purposes, (such as mine warfare, including the towing of heavy sweeps and decoys) I found myself continually balancing the inclination to design a better, more specialised tool for each job, with the desire to compromise performance consolidate capability into a multi-role, more flexible capability. The trade-offs inherent in propulsion systems, and the relative efficency of jets at high speeds and propellers at low speeds was a familiar encounter.

The development of this line of inquiry into of the full substance of this paper has come about not due to my own intrigue, but largely due to the determination and interest of Gary Johnson. Through mutual networks in industry and academia we discovered that we had both been intrigued by the technology choice, and considered it of potential significance to Australia's national interest. Australia is fortunate to have citizens so concerned with national interest to so substantially invest in research to advance public debate. Unless he had commissioned me to write it, there is no way that I would have been able to make the sustained and deliberate inquiry which the topic required to reach a useful level of quantification and confidence to meaningfully inform debate.

I should hasten to add that my expertise in this area is derived largely from an academic background whithin a different field of physics (particle physics), which enhanced only my aptitude for understanding and analysing physical concepts, paired with a substantial exposure to the relevant disciplines and industry from a commercial perspective as an entrepreneur developing new products. I don't claim to be an authority, but reasonably capable of grasping the works and words of those who are.

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. This paper doesn't seek to advance the technical field with any new research or insight. It aims only to bring together as neatly and simply as possible those concepts and results which are neccessary and sufficient to give the appropriate weighting to this question.

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, and more thorough discussions of those topics which are relevant, but not essential to the question at hand.

It should be noted that the technical fields involved here are vast and rapidly evolving. 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. If other subject matter experts have additional or better insights into the topic than those presented here, I would welcome their further comment and contribution to debate.

However, the existence of unknown developments and advances does not mean that realistic approximate bounds and limits of technologies cannot be found from public inquiry. Scientific discovery and technical tends to confirm many of the best discoveries are actually built-upon and confirmed, rather than simply sweep them aside 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 within which that field will operate. My research into this topic has confirmed that this is certainly the case in the relevant arts of hydrodynamics and turbomachinery, where a number of canonical works from the middle of last century are still very frequently referenced in the most modern literature for outining the foundational principals.

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 confidence (often broad principals or relationships which determine trade-offs) and those things which we can't (the precise embodiments in present design). 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.

2 Executive Summary

The choice of the pumpjet propulsion system is quite probably the most significant new technology inclusion for Australia's future submarines. Unlike other modern technolgoies such as Air Independent Propulsion and Lithium Ion Batteries, which are either in service or entering service in multiple other navies, no other navies have have adopted pumpjet technology for their conventional sumbarines, which is currently only used by nuclear submarines (()coorey2016).

Despite acknowledging that the pumpjet may have an adverse impact on dived endurance (*Size of new submarines locked in* 2017), Naval Group justifies the superiority of the pumpjet in the following terms: "In a confrontation between two otherwise identical submarines, the one with pump jet propulsion always has the tactical advantage." No further explanation of this superiority has been provided in detail, but it is widely held that the pumpjet offered acoustic advantages which were highly regarded by those Australians who were responsible for selecting the design partner (Stewart 2016).

The comparison between two otherwise identical submarines (though not necessarily limited to engaging just each other in combat), provides a useful and suitable framework for evaluating a single significant technology choice, where most other significantly novel or new technologies were apparently excluded from consideration (Stanford 2017). The conclusion of this report is that the following statement can be made with confidence:

In a comparison between two otherwise identical submarines, the one with the pump jet will always have a lower dived endurance, a lower dived range, a worse indiscretion ratio, a lower overall endurace, and a lower overall range, than the one with a conventional propeller. This will confer a substantial tactical and strategic advantage on the conventionally propelled submarine in a very broad range of operational scenarios.

Whilst it is broadly acknowledged that propellers have superior efficiency at lower speeds, but jets might have higher efficiency at higher speeds, the precise point of cross-over seemed unclear in public debate. One informed commentator suggested that the crossover point was likely to be below or near the transit speed of the submarine, and that the pumpjet may offer enhanced range and endurance over the whole mission profile as a consequence (Davies 2017). This report finds no evidence of a pumpjet of the type used on submarine ever being recommended as superior for efficiency in general, and even closely related technologies for more commecial use not advocated below 25kt. During my research I encountered domain experts confident that a pumpjet could simply not feasibly be superior to a suitable propeller at speeds below 18kt. Evidence of propellers remaining generally superior to waterjets and pumpjets in the speed ranges up to and even over 30kt is abundant. Consequently, the possibility of some cross-over point leading to any kind of range or endurance advantage relevant for a conventional submarine can be safely ruled out. The basis for claims made by public officials to the contrary, such as those by Rear Admiral Sammut (Nicholson 2017a), must be called into question.

This report also explores in some detail the theoretical concepts that drive the limitations of pumpjet performance at lower speeds in comparison to propellers. Enduring and fundamental principals of momentum theory provide robust limitations on the circumstances where a propeller's 'ideal efficiency' might be improved by the addition of a duct/or shroud, one type of which constitutes the transition to a 'pumpjet'. These principals stronly support the the notion that pumpjets will not and indeed cannot suddenly overcome their efficiency disadvantage at low speeds by means of technical ingenuity or innovation.

Furthmore, a particular hydrodynamic phenonemon called 'flow separation' can be identified as the primary cause of the pumpjet's declining efficiency at very low speeds. Put simply, the duct provides an additional hurdle or barrier though which the water must pass when moving through the propulsor. At very low waterspeeds, this additional resistance is sufficient to stop some of the flow progressing through the jet, creating unsteady eddies and vortices which sap energy from the system, but produce no thrust, driving down efficiency to zero at very low flow-rates.

The design of the pumpjet for military purposes, namely the reduction of acoustic signatures effectively mandates that this must be the way that pumpjets work. The act of slowing the water down is necessarily equivalent to the act of raising its pressure. It is this elevated pressure at the point where the blades to their work on the water which enables the blades to avoid cavitation (the rapid expansion and collapse of small voids or bubbles in the water) which is very large source of noise underwater. Maintaining this advantage to the same level necessitates a duct design which slows water down to the same extent. The act of slowing water down when it's already going slowly is what causes some of it to stop, which is when flow separation occurs.

In order to assess the probable magnitude of the impact of this reduction in efficiency at low speeds, a numerical model was developed, based on known principles of physics, and publically available information relating to the likely technologies involved in the future submarine. The most important and variable assumptions - the efficiency curves of the pumpjet and propeller - were taken from a recent study lead by world-leading engineering companies, supported by the US and Royal Navies, comparing closely related propulsion systems (Giles et al. 2010). Knowing that the systems would not be identical to the propulsors on submarines (the precise design of which is obviously secret), additional curves varying from these assumptions were also modelled in all directions, and the combinations combined and tested.

The model has been made available publically in the form of a web-app, so that alternative assumptions, including alternative efficiency curves may be tested by the interested parties.

The model in its central assumptions was able to achieve very realistic results, which were consistent with other public estimates of performance parameters of conventional submarines and their known characteristics **??**. A variety of different assumptions regarding the hotel load, battery density and different combinations of efficiency curves were tested. The central assumption values showed that a submarine with a conventional propeller had a very substantial advantage in terms of range and endurance across the entire speed range. This advantage reached a proportional maximum at around 6kt of over 60%. However, in nominal terms, the greatest differences occurred at slightly lower speeds. Under central assumptions, the propeller submarine had an advantage in submerged range of some 200nm at 5kt, and approximately a two-day advantage in dived endurance at 4kt.

The full range of plausible efficiency curves exhibited a significant efficiency advantage right through transit speeds. Central assumptions suggested that this would result in the overall range of a submarine being enhanced by approximately 50% with the use of propellers instead of a pumpjet. None of the scenarios suggested it was likely that this range advantage would be any less than 20%. Given the significant emphasis that has been repeatedly placed the unique requirements for range and endurance for Australia's submarine, this raises substantial questions about suitability of this technology to meet Australia's needs.

The model was used to test a wide range of different assumptions. A further key result of the study established the sensitivity of the difference to a range of assumptions regarding hotel load, and battery energy density. This showed that the difference between the two systems was made substantially larger with smaller hotel loads, and larger stored electical energy (as might be achieved with lithium-ion batteries), and these two effects combined to give some particularly startling results. Circumstances where the *difference* in dived range and endurance between the two systems in terms of range and endurance exceeded the *entire* dived range and endurance achieved by many modern conventional submarines frequently arose.

The model demonstrated clearly that all of the most pronounced advantages in dived range and endurance occurred at speeds around 3-7kt, generally within plausible speeds achievable with modern AIP systems. The addition of AIP was briefly considered which revealed that a difference in dived endurance of the order of one month, or thousands of nautical miles, would likely have emerged between the two propulsion systems.

The consequences of flow separation also has acoustic consequences, which this report explores. The vortexes and eddies which are created by flow separation tend to be unsteady, and shed periodically into the main flow. This results in pressure fluctuations inside the shroud and more intense, unsteady large-scale types of turbulence occurring as these vortices are ingested into the rotor blades. These effects are are likely to cause some accoustic signature which becomes lower in frequency as the submarine slows down further and the vortexes become larger, and shed more slowly. This is in contrast to early stages of cavitation, which would be high frequency at when bubble sizes are small, and move to lower fequencies as speed increases and bubbles expand. Lower frequencies are of particular significance because they tend to propagate further, and would be less effectively shielded by the duct.

It remains plausible that in the absence of cavitation the noise generated in the propulsor by such flow separation is not loud enough to be of significant tactical concern. However, it is extremely unlikely that at some very low speeds, where conventional propellers experience no cavitation and enjoy steady, smooth flows over the blades, that a pumpjet could actually have a lower acoustic signature, even in terms of radiated noise. Flow separation demands that two or three times as much energy is wasted by a pumpjet creating and destroying these unsteady vortexes than a propeller would require to create equal thrust. Consequently, the claim that pumpjets are generally acoustically superior should be treated with some caution. This claim has strong grounds wherever a conventional propeller might experience cavitation, such as at higher speeds. But at some very low speeds it is unlikely to be true.

Overall, it seems unlikely that the full range of consequences of pumpjet choice have been fully comprehended by the Australian government. The scale of the probable impact on range and endurance is quite probably so substantial that it is difficult to see how such a performance penalty is consistent with the government's stated aim of acquiring a regionally superior submarine.

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

Perhaps the most important relationship to understand to comprehend the operation of submarines is the relationship between speed and drag . This is important 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 to movement. 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 in the case of ships, 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.

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

[1]

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, pp. 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. Fortuitously for submarines, the square law for

[1]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 where 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.

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. [2] 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. Even engineers and manufacturers of propulsion systems tend to be far less confident in making quantitative claims about the performance of their own systems in extreme off-design conditions, since normally decisions affecting system choice are made based on some threshold of performance change which occurs much closer to the nominal design speed or load.

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 (total drag force at any given speed), 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. However, there are plenty of instances where the relevant physics and trade-offs are explained in depth to address related, but not identical questions.

[2] The physics described above would say 16 times, but some reduction due to the reduction of surface area from planing might offset this.

4 The difference between nuclear and conventional propulsion

4.1 Power and Energy

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 (*Nuclear Powered Ships* 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 than diesel-electric submarines would, even at their peak output.

However, 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 widely regarded as 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. This has considerable consequences for the design of all of the submarine systems, including the propulsion system.

4.2 Xenon poisoning and low power limitations

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 quickly into Xenon-135 (which has a half-life of about nine hours), and it is this process which produces the majority of Xenon in the reactor. This Xenon has a very special, perhaps unique role in reactors, since they very easily captures the free neutrons which trigger the continued fission reactions of 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. But another process works in the opposite direction which offsets this, since there are lots of neutrons 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 changes suddenly 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 (*Chernobyl Accident Appendix 1* 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 1.

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.

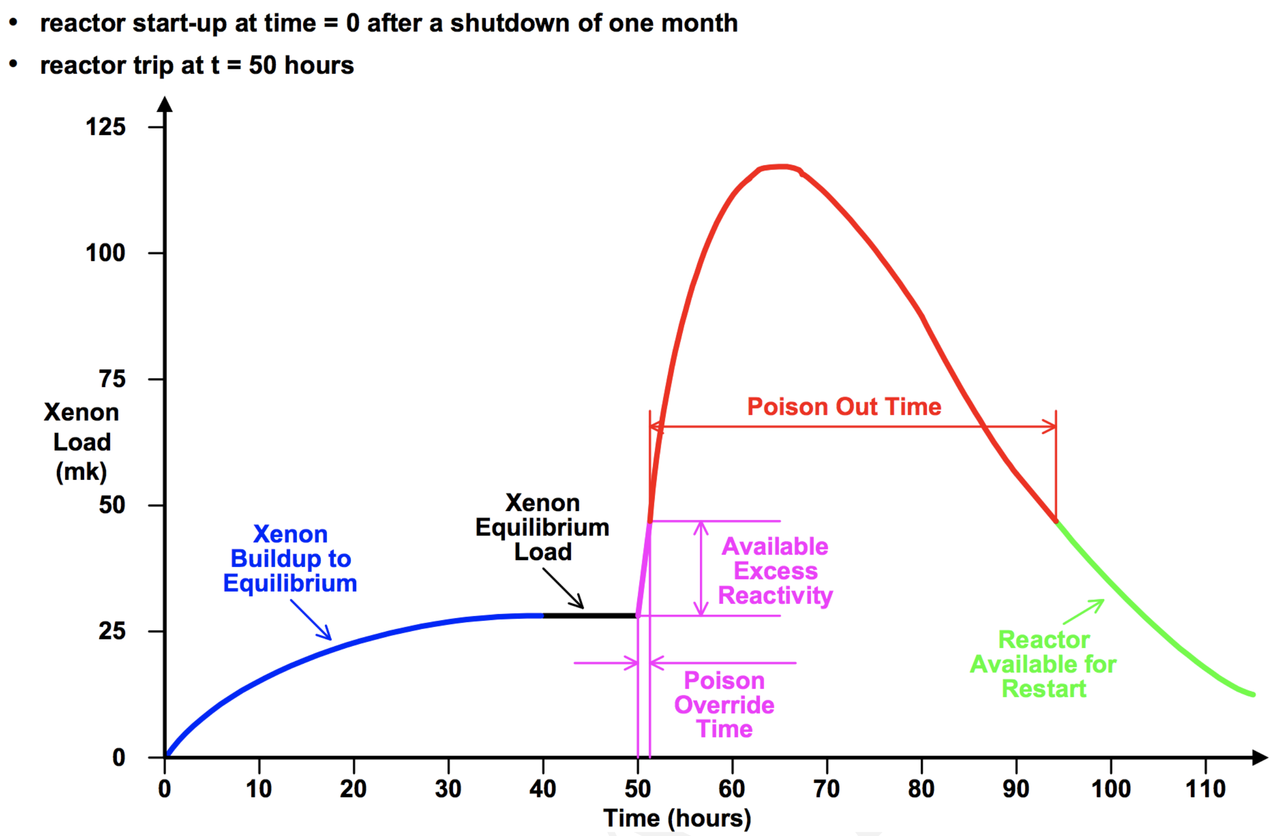


Figure 1: Xenon poisoning effect following shutdown from (Garland 2005)

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 such as pumps to remove the excess heat. Provided the excess turbulence inside the pumpjet isn't too noisy, wasting energy through the propulsor is useful whenever there is an ample surplus, which could be the case whenever operating noticeably below top speed. Whilst reactors can reach considerably lower power outputs safely in when there are low levels of Iodine and Xenon in the stocks are low (after a smooth ramp-down) the requirement to reduce power gradually means that when speed is reduced suddenly (relative to the 9-hour half life of Xenon 135), for example on arrival in theatre or a higher threat area, this high surplus power will be unavoidable.

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.

4.3 Recent Commentary

Some efforts have been made to 'debunk' such suggestions that nuclear submarines effectively have "unlimited" power (Autret and Costello 2016), with the leaders of the DCNS's bid at the time making some effort to suggest that the needs and characteristics of nuclear and diesel-electric submarines "drives the same system design". They make three comments to justify this claim. The first is that the large submarine proposed by DCNS for Australia uses as much or more power for the hotel load at the most frequently used speeds. Assuming the authors are referring to speeds between patrol speeds and approaching transit speed, the subsequent analysis will show that this fact may be true, particulalry in the presence of the pumpjet. However on its own this doesn't constitute an argument worthy of any consideration. One might equally argue a glutton can be relied upon not to eat too much at dinner because he eats a dinner sized meal at afternoon tea.

The authors of this piece seem to imply that the relatively high impact of hotel load at patrol speeds is linked to the high cost and weight of the nuclear reactor, and hence this contributes to the desire to minimise hotel load. Given the way that the square law drives drag as discussed earlier, driving a cube law for power, there is no chance at all that the hotel load has any bearing on the reactor power capacity required. The last few knots of top speed would demand ten times over the power required for hotel load, as can be seen in Figure 41.

One more plausible argument is worth consideration, namely that a safety requirement to be able to operate on batteries without the reactor drives a need to minimise hotel load. For all the reasons discussed above, it's completely implausible that the reactor would ever be shut down volunarily during operations. One would think that the sorts of emergencies or accidents which would cause a reactor are likely to also mean that the reactor can't be restarted. However, it is plausible that through the development of some instability, perhaps through an unknown fault or dramatic power reductions of the type which I described should be avoided, it might be the case that the reactor would need to be shut down, but could plausibly be restarted. However, as discussed above, the restart would need to occur either within minutes, or probably wait for a couple of days.

This puts some serious constraint around type of contingency that needs to be planned for in a reactor shutdown event. It might be presumed that surfacing and remaining surfaced for a couple of days is likely to constitute an end to combat operations for a submarine that was located in theatre, presumeably through enemy action. However, the implied alternative remaining submerged and continuing combat operations, even at low speeds will essentially necessitate replicating the full power demand of any diesel-electric submarine until such a time as the reactor can be restarted. This fact is emphasised by the DCNS claim that hotel load exceeds propulsive power at patrol speeds. As we can gather from other public estimates of submarine submerged endurance (Buckingham, Hodge, and Hardy 2008), roughly a couple of days is a very significant fraction of the entire dived endurance of a diesel-electric submarine, perhaps 50%. It is difficult to imagine that nuclear submarines carry nearly 50% of the battery load of equivalently sized diesel-electric submarines, in addition to the reactor, simply for safety purposes.

Consequently, it seems much more likely that the sort of battery-requirements that are necessary for this kind of safety system are not closely linked to a full operational hotel load, but some substantially reduced survival load. As discussed in later sections, many of the most energy intensive systems in the hotel load could readily be switched off in an emergency to save power, if saving power was what was required to get through the emergency, including the combat system. It is difficult to imagine what sort of emergency might require a reactor to be shut down, that wouldn't also justify shutting down essentially every other component of normal hotel load which could plausibly be delayed for a couple of days.

If it was known that the reactor couldn't be restarted after the poison-out period, the mission would need to be aborted in any case, and some kind of rescue sought. Even a hundred of tonnes of batteries embarked wouldn't change this reality, unless the submarine was literally at the entrance of a home port. It seems much more likely that the safety requirement for batteries on a nuclear submarine is most likely to be framed around maintaining key life support systems (CO2 scrubbing for example) for sufficient time to enable some hope for a seach/rescue mission to rescure the crew, in the likely case that the kind of emergency which shut down the reactor was the kind of emergency which meant the submarine might not resurface, such as the case of the Russian nuclear submarine, the Kursk.

Claims that the power management imperatives of nuclear submarines and diesel electric submarines are even remotely similar at low speeds are generally implausible. Nuclear submarines will have unconstrained energy reserves, and a vast surplus of spare power capacity when ever operating below top speed. The dynamics of reactor management dictate that generally avoiding large fluctuation in power, and strictly avoiding sharp and dramtic reductions, will be dominant considerations in a nuclear submarine's power output. To put things simply, the characterisation that nuclear submarines have "power to burn" is generally sound, and would only ever be challenged when the submarine is travelling at flank speed, or the reactor is shut down due to a (presumeably near-catastrophic) emergency.

5 Basics of Ducted Propellers and Pumpjets

It's easy to be somewhat confused by the many different names which seem to be associated with related, or similar systems. Between pumps, pumpjets, water-jets ducted or shrouded propellers, or impellers, there is plenty of grounds for some confusion In this section, I aim to clarify in simple terms what the important differences between distinctly different systems are, and where some terms are used somewhat interchangeably without doing any great violence to the concepts underlying. Appreciating where the fundamental as opposed to superficial differences lie is important to understanding subsequently the limitations of different systems.

5.1 Propellers

Perhaps the best starting point is the most basic, and oldest of the systems which we're considering: the basic screw propeller. A propeller uses a number of tilted blades attached to a central hub to sweep around a disc in the water, and accelerate a column of water passing through the disc. Due to the slant of the blades, water on the back sides of the blades is pushed astern, and reduced pressure on the front faces pulls more water from ahead to replace it. As such, it accelerates a column of water, which necessarily is contracted in circumference after the point of acceleration.

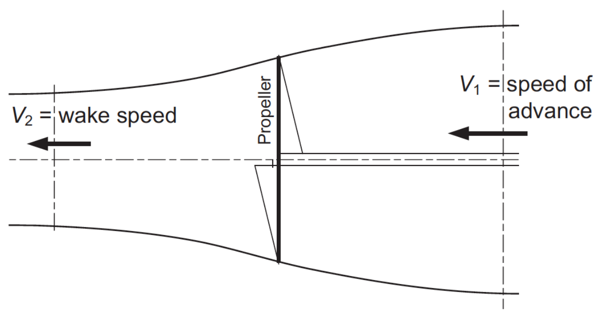


Figure 2: Propellers generate thrust by accelerating a column of water, as shown in (Molland, Turnock, and Hudson 2011, p. 247)

A comprehensive description of the development of the propeller can be found in Carlton 2007. Here I won't elaborate on beyond describing some essential features and characteristics with which one ought to be familiar, primarily for the purpose of comparing different propellers and understanding their evolution into the systems such as pumpjets.

Most propellers will have between three and seven blades. In general they are shaped as an aerofoil, with the convex side being upstream, just as the convex side of a plane wing is above, in order to generate lower pressure and lift as it moves through the air. The blades tend to be twised so that they have a higher angle of attack closer to the hub, and lesser closer to the extremities, so that those faster moving sections push their respective parts of the water column at an overall similar speed. The are often also thinner towards the extremities, and will be swept backwards as if dragged by their rotation through the water (skew) and also dragged by the ship's movement throug the water (rake). Whilst the degree of all these characteristics is highly variable for different applications, these are a few of the commonly referred to characteristics which can be varied in order to optimise performance for any given application.

5.1.1 Pitch

Perhaps one of the most important characteristics of a propeller is its pitch. The pitch represents the distance that a blade section would travel forward if it carved its way around a helix through one full rotation. It is intuitive to think of as something akin to the angle-of-attack of the propeller blade to the water, however this is technically misleading as the movement of the water-column incoming to the blade, as well as the speed of rotation, also have a significant bearing on what the actual angle of attack of the blade ends up being. Whilst technically pitch is a distance (measured in meters), it is often expressed and used in formula as a ratio of the diameter of the propeller, to give it a unitless equivalent, as is common in the description of many characteristics of propellers and propulsion systems.

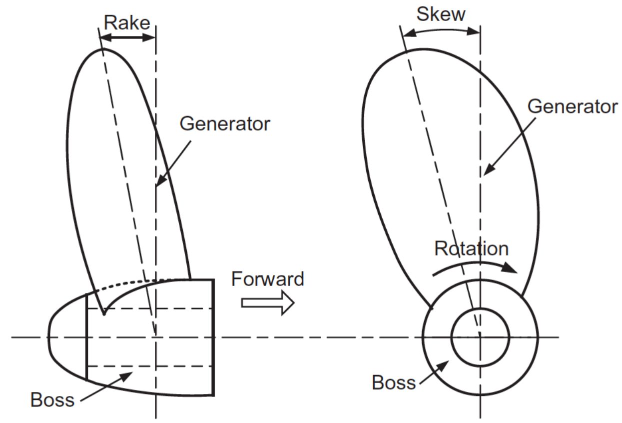


Figure 3: The development of a boundary layer (Molland, Turnock, and Hudson 2011, p. 262)

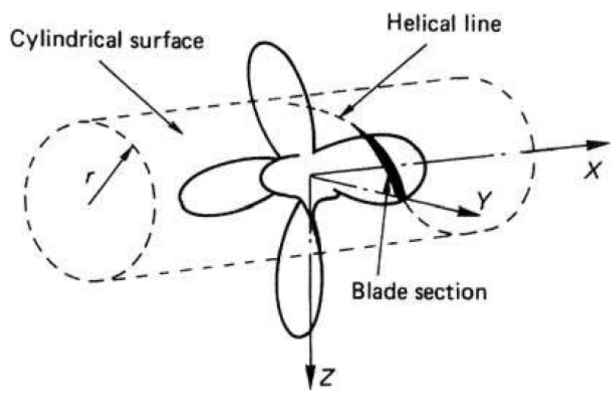


Figure 4: A blade section of a propeller traces a helical line around a cylinder as it is rotated (Carlton 2007)

The selection of the exact blade selection that is used to define pitch must be specified as being at some fraction of the radius from the centre, given the tendancy for the blades to twist. This distance is calculated to be the 'moment mean' or a technical derived effective average, which tends to lie between 0.6R and 0.7R. A thorough discussion of pitch can be found in Carlton 2007, pp. 35-37.

Pitch is of particular importance to the discussion the efficiency of propeller and propulsor design because its optimal choice tends to vary considerably with the different loads which a vessel is intended to operate at, which can also relate to a vessel's design speed. It is for this reason that a considerable number of vessels actually have variable pitch propellers. Whilst considerably more complex, expensive, and heavier than a traditional fixed-pitch propeller, the ability to vary the pitch of a propeller assists considerably, particularly when the amount of load (resistance) a vessel is expected to face varies considerably. Controllable pitch propellers also have advangates in terms of manouverability, since the pitch can be reversed and hence reverse thrust can be produced, without requiring the direction of the power coming from the engines to be reversed. This has advantages for ferries which undertake frequent docking manouvres in confined spaces (Diesel and Turbo 2017, Lewis 1988).

5.1.2 Pitch and the Advance Ratio

Pitch is also an extremely important concept to understand because it relates closely to the way that a propeller's 'open-water efficiency' η_O is expressed in charts, as well as the advance ratio J that usually comprises the x-axis in such charts.

This chart also shows two other closely related dimensionless coefficients, the torque and thrust coefficients (K_Q and K_T) which we shall not dwell on here. However, it is important to note that a number of different lines are expressed on this sort of chart, which represent different versions of the same propeller, with only the pitch

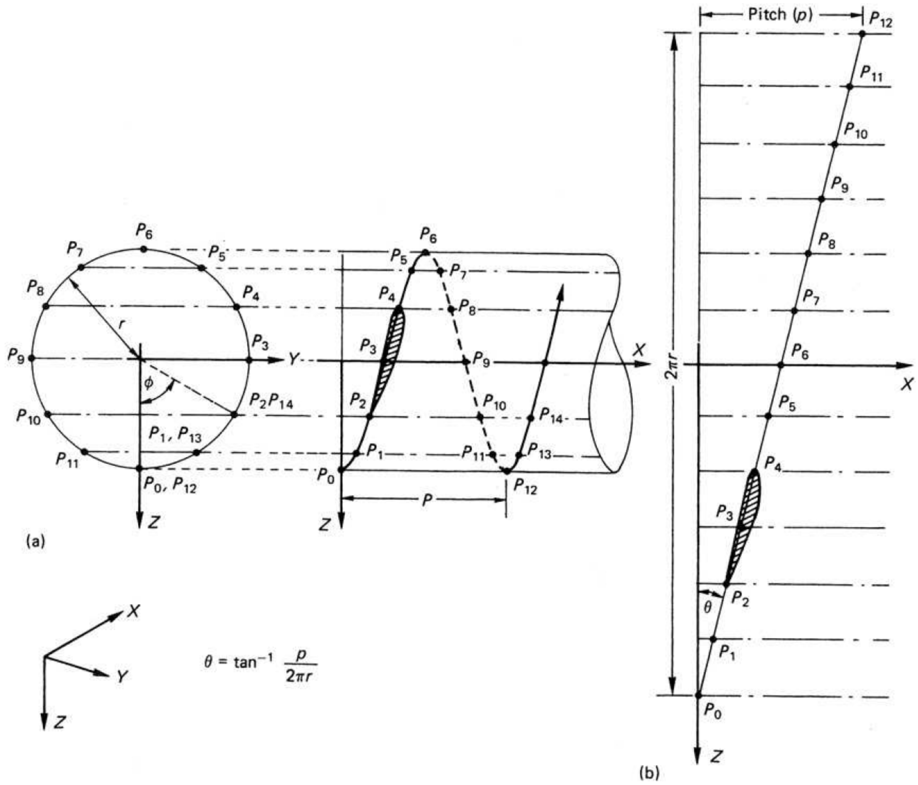


Figure 5: The definition of pitch is the distance traveled by a blade section along a cylinder, as given in (Carlton 2007)

(expressed in its dimensionless form as P/D) being different in each case. The x-axis, J, also warrants a clear definition:

$$J = \frac{V_a}{nD} \tag{2}$$

Where V_a is the speed of advance of the propeller, or the speed at which water arrives at the front-side of the propeller, and n represents the rate of the propeller's rotation (revolutions per second) and D is the propeller's diameter. For fullness of understanding it is also worthwhile to note here that V_a does not correspond directly to the vessel's speed of travel, though they are related. To some extent, a vessel moving through water will always draw water in its wake along with it, which means that in the wake (where the propeller tends to operate to some extent or other) the water incident on the propeller will arrive at a lower speed than that implied by the ship speed (Diesel and Turbo 2017, p. 15). Another key distinction for the consideration of jets later on is that the speed of advance does not necessarily incporate the movement of water due to the movement induced by the propeller (or duct) itself, which is a distinct effect to that of the wake field. In Lewis 1988, p. 213 V_A is used specifically to denote the undisturbed stream velocity, since the role of certain ducts can be to accelerate or decelerate the stream prior to the water arriving at the blades of the propeller.

One may also note from the previous figure that for each line representing a given pitch, the efficiency falls precipitously towards zero around the point where J reaches P/D. This is because this extreme of the curve represents a circumstance where the propeller is rotating, but not actually moving any water, since it is moving through the water at about that speed which corresponds to the exact helical path defined by the pitch being traced. This represents circumstances where a propeller encounters effectively zero load. This might be the case when a eases it's power, and the momentum of the ship temporarily keeps the ship moving without the propeller exerting much or any net thrust, or where alternative propoulsion sources (sails, or other propellers) are keeping a speed higher than what the propeller actually has push backwards on water to maintain. Since drag due to friction scales with velocity squared, very low speed do correspond to increasing advance ratios for a given propeller size, as would increases in propeller size for a given speed and pitch ratio. In practice however, under self-propuslion

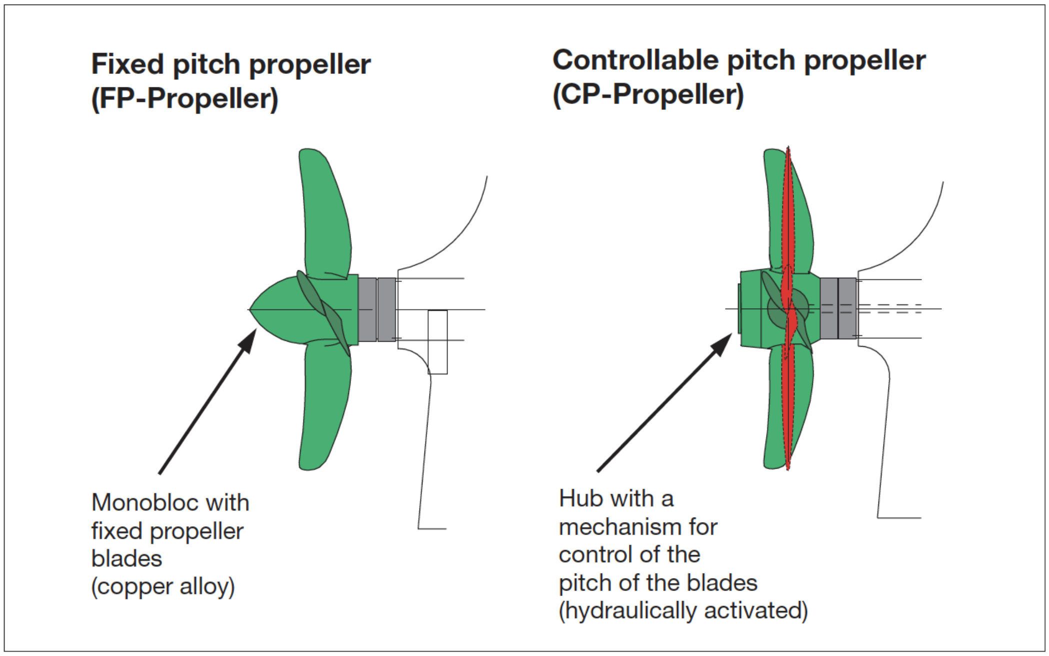


Figure 6: Controllable Pitch Propellers (CP Propellers) allow the pitch of the blades to be varied. Image credit: (Molland, Turnock, and Hudson 2011)

conditions for open propellers, slowing down towards does not elevate the advance ratio far enough past beyond peak efficiencies for overall efficiency to fall very far, as can be seen in Figure 28

A closely related concept here is the slip ratio, which is a measure of the difference between the pitch (the distance the blade section would travel if it traced a perfect helix for one rotation) and the actual distance that the blade did advance through the water. This is neatly defined and shown in a diagram in 8.

It can be seen from the diagram of the open-water efficiencies that there is some desirable non-zero slip ratio for a propeller. The other end of the spectrum, where efficiencies also fall off toward zero, represent circumstances where the propeller is simply spinning in the same place in the water. In this case the slip ratio is one. This represents a circumstance known as 'bollard pull' where a vessel is simply exerting force against an immovable object or infinite load. Whilst the very low efficiencies here could represent a case of a propeller that is simply too small for the task it is trying to achieve, it is actually a significant and important circumstance to consider for propellers on working vessels such as tugs or trawlers, which exert large forces at very low water-speeds. Measurement of the thrust generated in bollard pull, and the power required to achieve this thrust, is still an important metric for such vessels, but the definition of 'useful work' for normal propulsion requieres the thust to be excerted over some distance travelled.

5.2 Ducted Propellers

A ducted propeller is a propeller in any kind of tubular shroud, casing or nozzle. Ducted propellers fall into two categories, one of which is referred to frequently and interchangeably as a pumpjet. The two types are called the accelerating type (also known as a Kort Nozzle, after a company that made them popular in the 20th Century) and the decelerating duct. The names describe the different effects that each type of nozzle have on the flow speed of the water at the point where it meets the propeller (which is also called an impeller, particularly when associated with decelerating ducts, or pumpjets).

A detailed description of the essential differences between the two can be easily demonstrated by diagram, which show a simple comparison an acelerating and decelerating duct, which have the shape of the aerofoil section which comprises the duct inverted. [3]

[3]It should be noted that some designs attempt to strike a balance between efficiency and cavitation performance of accelerating and decelerating ducts for certain purposes, and in such cases the duct shape might not be so clearly contrasted (Abdel-Maksoud, Steden, and Hundemer 2010). But for the purposes of explanation, as well as optimisation for military purposes, the distinction between the two will generally be quite clear, and in practice ducts will still tend to decelerate the flow on approach to the impeller unless specifically

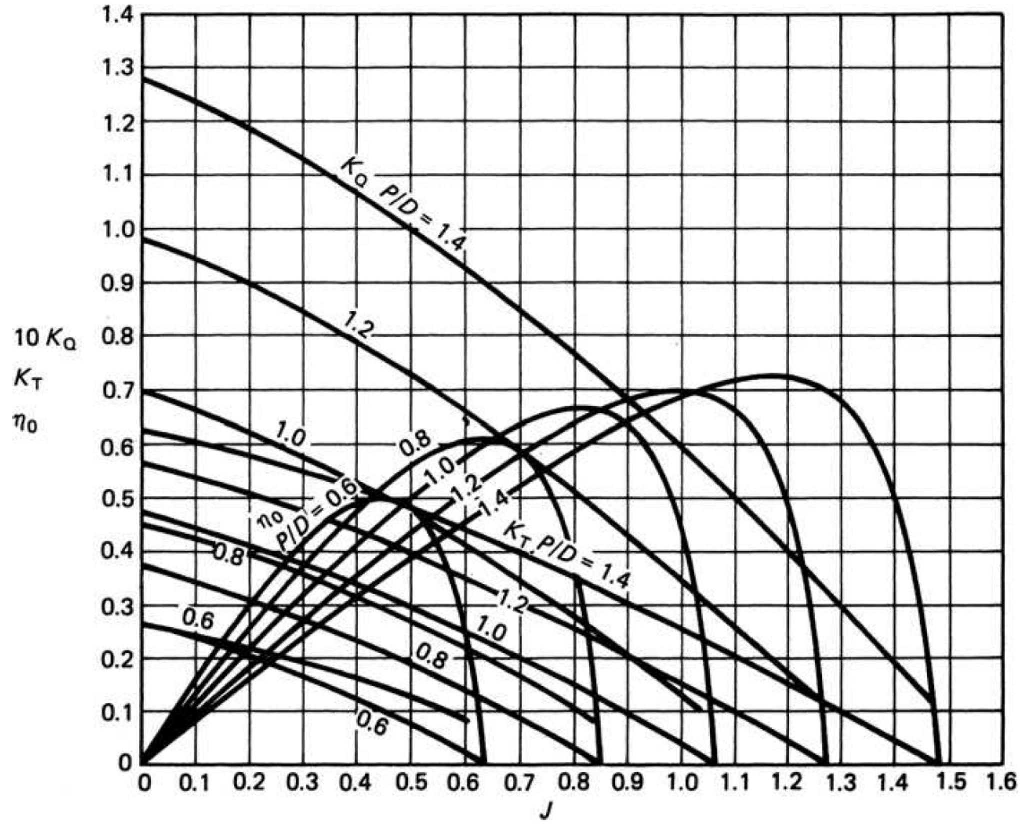


Figure 7: A typical chart showing open water efficiency of a propeller, in this case a Wageningen B5-75. Image: MARIN

A consideration of what happens to the flow as it moves through each type of duct helps to demonstrate how the acceleration and deceleration effects are achieved. In the case of an accelerating nozzle, the area through which the flow must pass contracts prior to the water arriving at the impeller. In the decellerating case, the available area contracts after the water has passed the impeller. In some cases, a degree of diffusion is actually incorporated ahead of the impeller, whereby the area actually of the flow actually expands ahead of the impeller, which slows down the flow and increases its pressure according to Benoulli's principal (Wislicenus 1973).

5.2.1 The Accelerating Duct

Accelerating ducts are most commonly used by vessels which have to operate at high loadings at very low speed, such as tugs, barges, or trawlers. In those circumstances, relatively small vessels need to exert considerable forces against substantial loads, at very low water-speeds. Also, in these circumstances, the practical size of a propeller might be constrained, since operating an optimally sized propeller might increase the complexity of machinery required to deliver the power to so low a hub in the water, and it might also be difficult to arrange for the thrust to be directed substantially against the centre of drag of the vessel.

The effect of the nozzle in these circumstances actually increase the optimal efficiency of the propeller, when operating at very low water-speeds but high thrusts (low advance ratio), since the pressure reduction on the inside of the nozzle induced by the movement of the water through the nozzle actually produces a net thrust forward, since the interior face at the opening of the nozzle is necessarily angled forward. This has the effect of distributing the suction force across a larger area, which now includes the interior of the nozzle. An equivalent way of describing the same effect is that the nozzle causes the water to be accelerated more gradually, over a longer distance, by inducing it to move more quickly as it passes through to the entrance. As a broad generalisation, more gradual or gentle actions tend to involve lower overall losses to turbulence, and hence the efficiency of the propeller can be increased.

shaped to narrow in the opening.

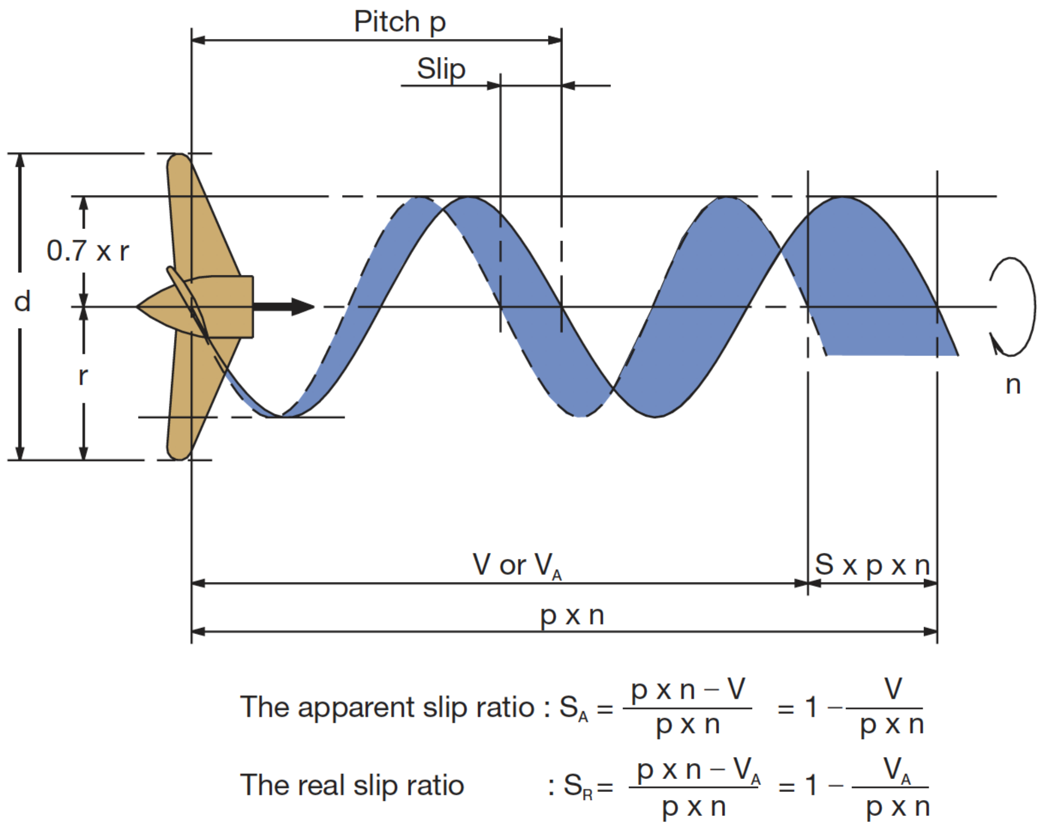


Figure 8: The slip ratio of a propeller. Image credit: Diesel and Turbo 2017

A further means by which the efficiency of a propeller can be increased is through the reduction of the turbulence created by the blade-tips passing through the open (static) water at high speed. Since the two sides of the blades have low and high pressure on them respectively, at the tips where the two faces meet, there there is a tendancy for water to 'spill' from the high pressure side the the low pressure side, creating a vortex which leads to unwanted turbulence. It is also around this vortex that blade tip cavitation tends to occur. By limiting the movement of water around the outside of the blade tip by having a tightly fitted shroud, losses due to this particular type of tubulence, and the onset of this type of cavitation, or the vortices that occur even when cavitation does not, can be diminished.

However, it is important to note that the existence of an accelerating duct by no means eliminates all cavitation. In fact, given that the static pressure at the impeller is necessarily reduced by an accleratint duct, the propensity for cavitation other surface of the propeller is generally increased. In many circumstance cavitation can and does still occur in ducted propellers near the blade tips at design loads (Moulijn 2015).

A detailed explanation of the means by which the ideal efficiency of propeller can be improved can be found in Lewis 1988, pp. 213-222, as well as other texts on marine propulsion, such as Carlton 2007. A substantial work exploring the efficiencies of a range of accelerating and decelerating ducts can also be found in Oosterveld 1970. A common feature of these extensive studies also show that for ducted propellers, including accelerating ducted propellers, the advantage in terms of efficiency is overall restricted to low waterspeeds. At higher waterspeeds, the drag induced by the water-movement over the exterior of the duct begins to increase substantially, and the net thrust on the duct becomes negative. When the exterior of the duct experiences relatively little water velocity, but the interior experiences a great deal more, the greatest advantages of an accelerating duct are realised. Furthermore, in general these models do not incorporate the effect of flow separation, which is acknowledged as a possibility on both the exterior and interior of ducts, which can dramatically reduce efficiency performance (Oosterveld 1970, p. 20, Lewis 1988, p. 214).

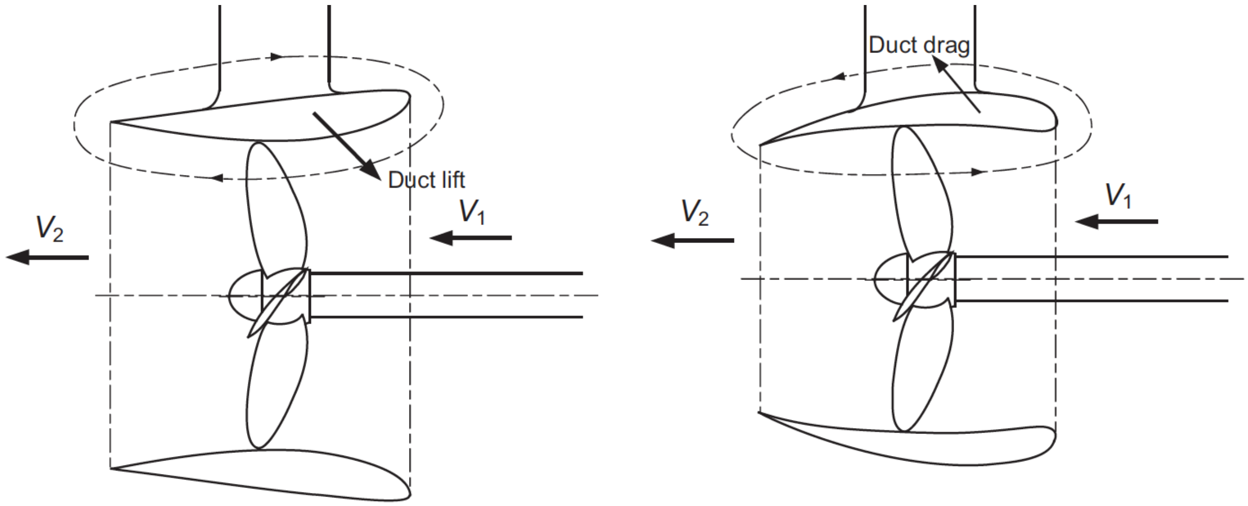


Figure 9: The two types of ducted propeller, accelerating (left) and decelerating (right) as shown in (Molland, Turnock, and Hudson 2011, p. 249)

5.2.2 The Decelerating Duct or Pumpjet

Decelerating ducts necessarily produce a negative thrust, since the process of raising the pressure of the water about the impeller (equivalent to slowing it down) necessitate reducing its kinetic energy and consequently momentum. In a wide range of literature introducing the fundamentals of ducted propellers and water-jets, or discussing their more modern development there is universal acknowledgement that the choice of a decelerating duct is generally made for the avoidance of cavitation for specialised (generally military) purposes, rather than for the achievement of increased efficiency (Carlton 2007, Oosterveld 1970, Molland, Turnock, and Hudson 2011, Haimov et al. 2010, Lewis 1988).

In order to achieve a reduction in cavitation, however, care must be taken in the design of a decelerating duct. Since the negative thrust produced by the duct must necessitate additional work being done by the impeller, there can be circumstances where the additional loading of the impeller out-weighs the impacts of elevating the pressure around it. Oosterveld 1970, pp. 24-25 provides a more thorough derivation of the circumstances in which this can be reliably achieved, which generally include larger blade area ratios or with more rows of rotors for higher loading, or circumstances where the loading of the propeller is quite low. This creates an inevitable and necessary tension between optimisation of a duct for propulsive efficiency and reduction of cavitation, which will be returned to in Section 5.2.3.

It is perhaps most relevant at this point to further clarify the distinction between the different names for related or similar systems. In Carlton 2007, p. 17 pump jet is described as an ”interesting development of the classical ducted propeller”. Oosterveld, in his thesis on ducted propellers also states with regard to the decelerating duct ”This ducted propeller system is the so called pumpjet” (Oosterveld 1970, p. 8). Other authors give separate treatement to ducted propellers and pump jets, though the systems they describe are essentially similar in terms of composition, advantages, and physics (Lewis 1988, p. 288).

In other definitive literature on the design of pumpjets (Henderson, McMahon, and Wislicenus 1964) the difference between a pumpjet and a propeller is a described as being that ”the stream of flow through the pumpjet is made to depart from the ”natural” or free-stream sufrace that bounds the flow though a standard propeller.” According to the diagrams and the subsequent description it is clear that the definition embraces quite exactly the distinction between an accelerating duct, and a decelerating duct, namely that the flow is slowed at the point it encounters the impeller, where as in a free situation the free stream would contract and accelerate at this point.

The addition of some new parts such as stator blades (to straighten out the flow) and other possible features which make the propeller system more like pump or turbomachinery components might be associated with systems more commonly referred to as pumpjets than ducted propellers. Not all decelerating ducts have stators, but the impact of the duct on the stream will remain. The key concepts behind the operation of these systems, however, remains essentially similar in their nature and design intent. In the presence of a duct propellers might be advantageously shaped differently, including maintaing a larger chord lenght right to the shroud, rather than tapering as open propellers tend to in order to lessen vortices and cavitation on the extremities. However, there is

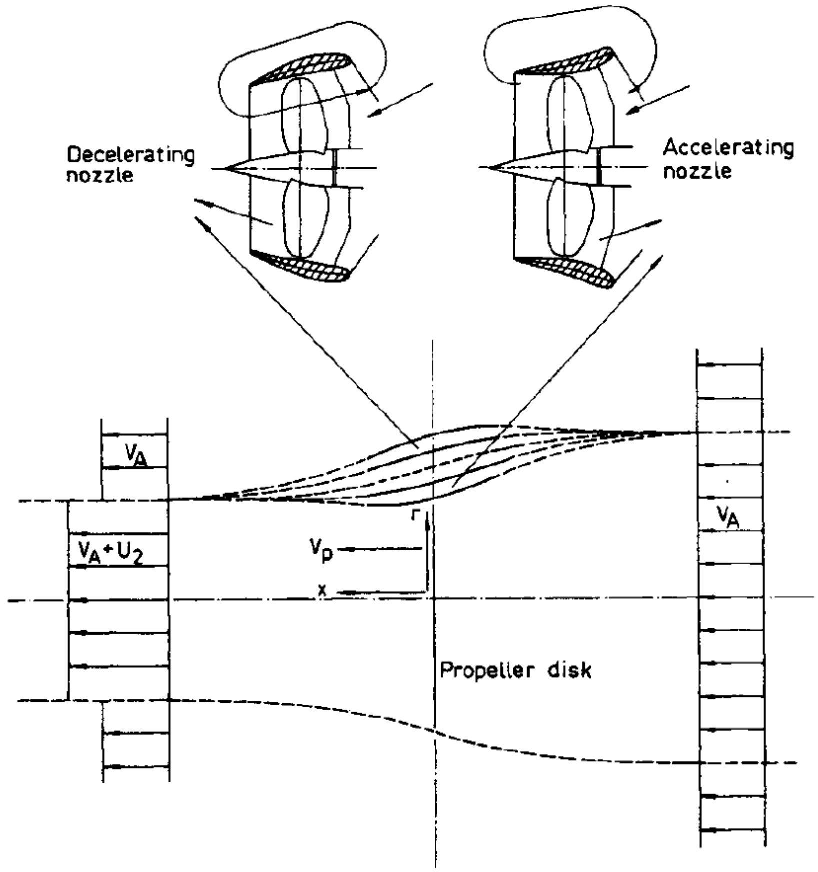


Figure 10: The streamlines of flow through different duct types (Lewis 1988, p. 214)

not to my knowledge any single defining physical characteristic which the transition to the name 'impeller' implies, which woud not be effectively equivalent to specialised propellers for decelerating ducts. In systems tending to be described as pumpjets or waterjets hubs tend to be larger, blade-numbers higher, twist, skew and rake lower. No definitive transition point seems to be accepted as having great significance. Most commonly literature will refer to a 'rotor', a more general term which could encompass both propellers and impellers.

5.2.3 Waterjets

The use of the word waterjet, as opposed to pumpjet, has a tendency signify that the jet expelled from the shroud or pump is situated above the water, which is desirable in very fast-moving surface vessels which attempt to minimise their contact with the waters surface, including high-speed planing hull vessels, including pleasure craft. The physics of the two systems, however, are closely related, with the very noticeable exception of the absence of flow considerations for water on the exterior of the duct considerations for waterjets. However, the physics relating to the impeller and stator blades or (turbomachinery) designed to add energy to the flow are generally extremely closely linked, though a larger variety of diffeent pump types can be chosen for waterjets which might differ more significantly from the natural evolution of a propeller to an axial-flow pump. Many of the essential equations which govern the efficiencies and cavitation performance of pumpjets and waterjets are of the same or extremely similar form, as can be seen in detailed discussions given to both, by similar authors (Wislicenus 1973, Henderson, McMahon, and Wislicenus 1964). There are, however, plenty of instances in recent literature where this distinction regarding the ejection of the jet above and below the waterline is not maintained, and waterjets and pumpjets seem to be used interchangeably (Abdel-Maksoud, Steden, and Hundemer 2010), or systems are described as 'submerged waterjets' (Buckingham, Hodge, and Hardy 2008).

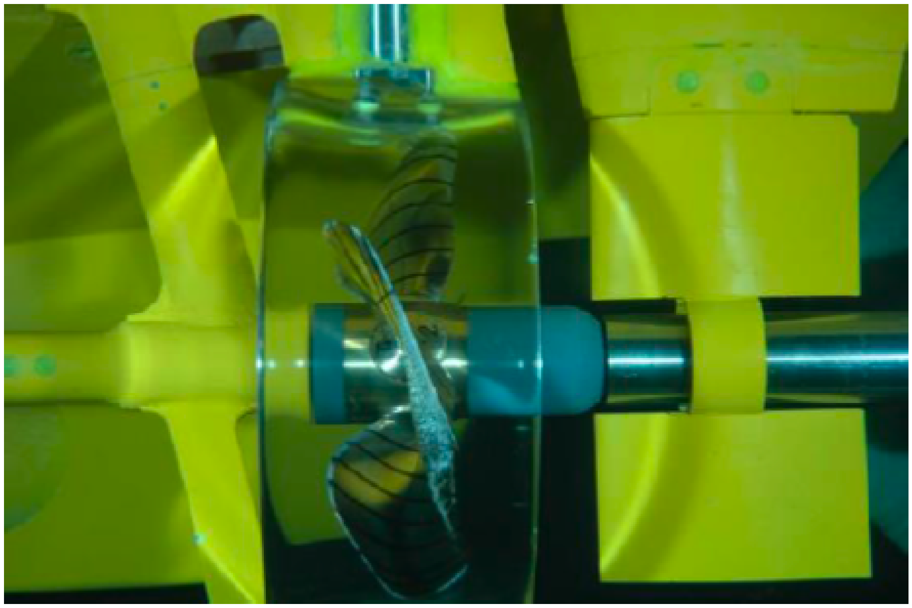


Figure 11: An example of the cavitation occurring at the blade tips of a ducted propeller. Image credit Moulijn 2015

5.3 Pump Types

There are broadly three categories of pump types for water which are used for propulsion. The first is called an axial-flow. In such a pump, the water has work done on in by blades which push the flow in the same direction to the axis of the blades rotation. This is what a decelerating ducted propeller comprises. The blades of the rotor push the water from the front, to the back, in the same direction as the craft moves, by blades that turn about an axis that is also oriented in that direction. These types of pumps are generally best for handling very large flows of water, with relatively less head (energy added) per amount of water flowing through, and are consequently generally desired for propulsion systems, where moving water at high velocity, rather than elevating it to high pressure, is the end objective of the system.

The contrasting system is that of a radial or centrifugal pump. In one of these systems, work is done on the water by spinning outwards, from close to the axis of rotation to the extremity. In such a case, the axis of the rotor is actually perpendicular to the direction of flow of the water exiting the pump. The pumps are generally favoured for pump systems which need to add quite a large amount of head, mostly in the form of pressure, to a given amount of flow. Consequently they are desirable for fire pumps, and or other systems which have to raise water to a high pressure, including lifting water up to great heights. However, centrifugal pumps were originally the type of pump used in the first waterjets created by Hamilton (Waterjets 1997), and are still used in some waterjet applications today, for example in ouboard waterjets (*Jet Drive*).

The third major class of pumps are called mixed-flow pumps, because these types of pumps involve the water having work done on it whilst flowing in both the axial and radial directions. In overall appearance, they tend to reasonably closely resemble that of an axial flow pump, since the axis of the rotor is parallel to both the direction of water intake and outlet. However, the water is also accelerated in an outwards direction by the impeller, by means of the hub expanding (and the outer shroud also expanding) in that section where the rotor does work on the water flow. The outwards flow is subsequently deflected back towards the axis by the shape of the shroud contracting towards the nozzle, and the hub tapers to a point in this section also. The main difference between these can be seen in Figure 15.

The physics of of the fluid flows through the impeller of a mixed-flow pump are quite different to that of a pure-axial pump (the flows must be modeled in three rather than two dimensions), and blade design necessarily changes somewhat to accomodate this type of change. However, the core limitations and physics surrounding duct design before and after the impeller remain in place for mixed-flow pumpjets, with the primary additional consideration being that the pump section of the duct will tend to need to be somewhat more bulbous in shape to accommodate the larger hub. As such, differences in the pump efficiency (how well the impellers add energy to the flow) at any particular flow rate might not represent a large impact on the overall efficiency of the propulsor, as the losses due

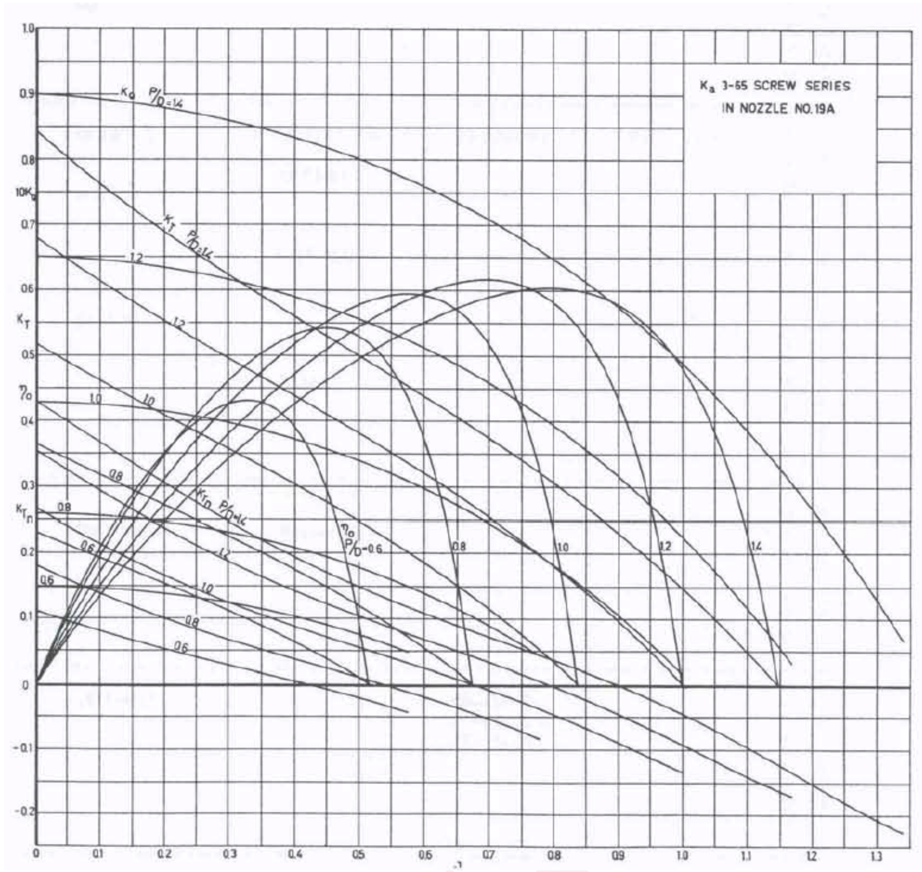


Figure 12: Accelerating ducts produce a net positive thrust at low advance ratios, but a net negative thrust at higher advance ratios as the drag on the nozzle exterior increases. Image credit:Open-water test results of Ka 3-65 screw series with nozzle no. 19A (Oosterveld 1970)

intake duct and nozzle will comprise separate and independent considerations, quite independent of the efficiency of the pump design.

Mixed flow pumps also can experience flow separation or stall in just the same way that this occurs in pure axial-flow pumps **??**, and the similar design considerations (such as optimal flow rate) impact the extent to which this occurs. Similarly, the design considerations for reduction of cavitation in mixed-flow pumps tend to be similar, including increasing blade area, and similar efficiency trade-offs are also generally found (Waterjets 1997)

Mixed flow pumps can have a variety of different degrees of radial flow over the impeller, and a variety of different designs are found in the pumps in waterjets which vary from pure axial to mixed-flow designs. This is because the optimal efficiency of mixed-flow pumps tend to lie between the optimal efficiencies of axial and centrifugal pumps, across an intermediate range of flow requirements. Many waterjet manufacturers offer a combination of both pure axial and mixed-flow designs for various applications, and often considerations other than efficiency, including machinery size and shape, can be even more significant than pure efficiency considerations. Detailed discussions of the differences between pure axial-flow and mixed-flow pumps can be found in Wislicenus 1986.

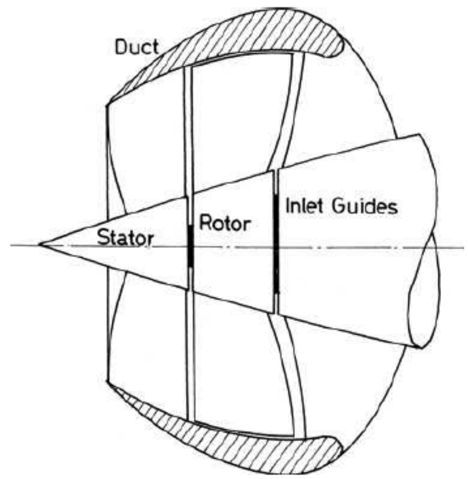
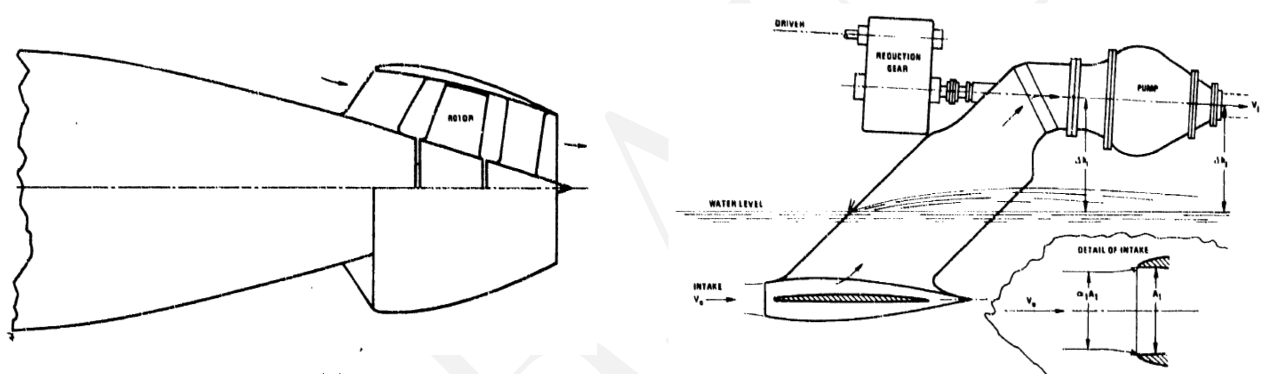


Figure 13: In Carlton 2007 the pump jet is described as a development of a classical ducted propeller, with the noticeable addition of a stator



(a)

(b)

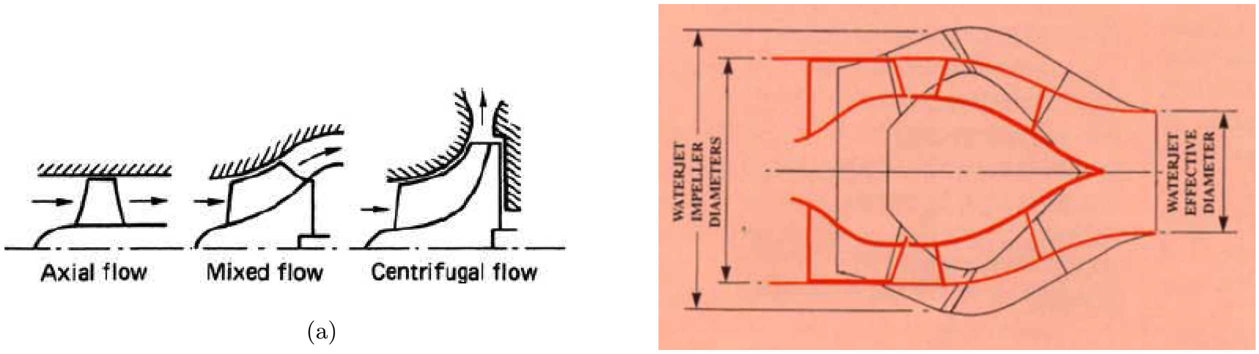
Figure 14: A comparison of a pumpjet (a) and waterjet (b) as given in Wislicenus 1973

6 Constraints on the efficiency of pumpjets at low speed

6.1 Recent Commentary

There has been already some attention given to the probable efficiencies of pump jets at low speed. Recently Andrew Davies published a piece in the The Strategist (ASPI) arguing that the pump jet may actually save fuel at transit speeds (around 8kt) and overall improve the endurance of the submarine, despite likely having lower efficiency at low speeds such as patrol speed (Davies 2017). This argument relies on pumpjet efficiency still overtaking that of propellers at what is considered a relatively low speed for many applications. As Andrew acknowledges, further quantification of the likely efficiency is required, as the particular chart which he cites is not quantified. This section aims to identify as far as is reasonably possible from public literature how the efficiency of a likely pumpjet for a submarine might perform in quantitative terms, relative to a propeller.

There has also been questions put in parliamentary hearings regarding the pump jet (Patrick 2017), and responses from public officials to such questions indicate that some of the literature provided to support such lines of questions was dated, and that the state of the art may have advanced considerably since this time. Whilst the statement that the state of the art is much advanced is obviously true in the case with marine propulsion as with most sciences, it is also equally true that new advances tend to confirm, rather than annul, many of the works that have been previously undertaken. To the extent that modern literature still supports the overall constraints and bounds provided by some of the foundational earlier works, a great deal of useful information can still be



(a)

(b)

Figure 15: Mixed flow pumps push the water partly outwards as the water flows through the impeller blades, in a part-way step towards a fully centrifugal or radial flow, as shown in (a) from Carlton 2007. Different hub shapes can induce different levels of radial flow or axial flow in the pump, as seen in (b) from Waterjets 1997

obtained from earlier works. In particular, the foundational theories, often derived from well-established principals of conservation of momentum, energy, as applied by the likes of Bernoulli and Euler, are as well respected and deeply depended upon today as they were centuries earlier when they were first arrived at. It is noteworthy that some of oldest works, such as those by Wislicenus and Henderson, are still amongst the most frequently cited in the most recent of papers.

6.2 Modern literature and results

Abundant modern works, including those which involve experimental validation of theoretical results also clearly confirm that restrictions on the efficiency of waterjets are enduring, and give us a clear starting-point for consideration of their probable orders of magnitude, and likely transition points indicating at what speeds pumpjets might become advantageously more efficient. It should be noted however, that relatively little literature focuses on the performance of propulsive systems far far outside of their intended design speeds, which tends to be far higher than the patrol and transit speeds of diesel electric submarines. Fewer still tend to express their work in terms of ship-speed, instead adopting the convetion of using dimensionless ratios so that work done on one system can be readily translated into different combinations loads, pressures, speeds and sizes. However, from a few notable studies exist which provide important reference points. (Further interpretation of the what we can lean from the trends expressed in dimensionless coefficients will be discussed later.)

A 1995 Japanese experimental study on the performance of a waterjet demonstrated a close experimental fit to a theoretical relationship which sees the propulsive efficiency of the waterjet fall to zero with craft velocity, with significant declines in efficiency commencing just under 10m/s, or somewhere around 18kt (Fujisawa 1995).

In 2015 an Australian team including staff from the Australian Maritime College and Incat published results of an experimental study comparing the use of waterjets and propellers for medium-speed ferries operating in the 20-30kt speed range (Mustaffa Kamal et al. 2015). This study explicitly set out to establish the cross-over point for where propellers become more efficient than jets, since Incat was interested in pioneering highly efficient medium-speed vessels, after having considerable success in very high speed catamarans. It is again acknowledged as given that at lower speeds propellers are more efficient than waterjets. The study found that propellers were considerably more efficient over the entire speed range tested, often by a factor of two in terms of transport efficiency.

Both of these previous studies confirm the general and widespread assumption that jets are known to be more efficient at high speeds, and propellers at lower speeds. They also suggest that differences in efficiency could be very large, of a factor of two or more, including at speeds well over a submarine's transit speed. However, care must be taken making precise quantitative comparisons, since such experiements involved jets which expelled into air (waterjets) as opposed to remaining under water (pumpjets) do have at least one significant difference in their makeup, though their internal pump mechanisms may often be similar. Specifically, pumpjets would experience drag on the exterior of the shroud/duct, which waterjets would not, however waterjets are likely to have longer intake ducts, which might involve larger duct losses than pumpjets. Given that these factors might affect efficiency, and the overall design of the nozzle considerably, more direct comparison with fully submerged jets should be sought to make more direct comparisons.

At IMARESTS 10th International Naval Engineering Conference, a paper was presented by BMT Defence and

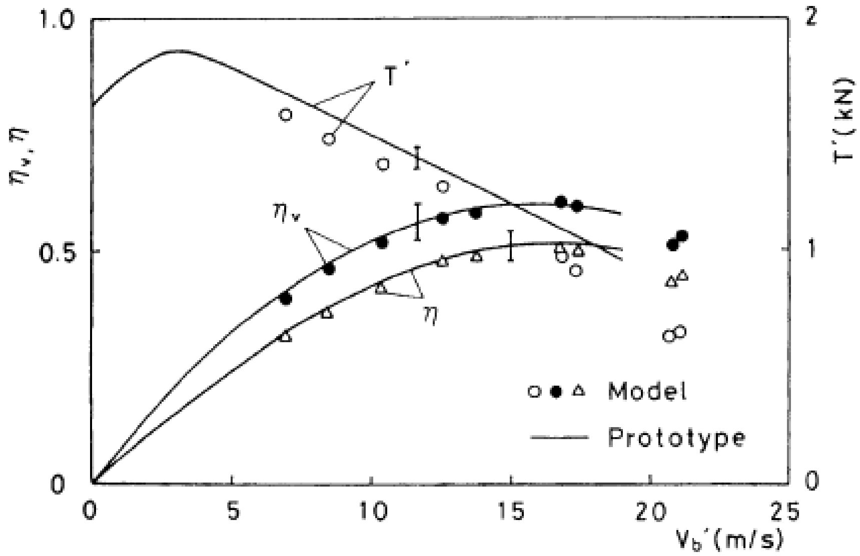


FIGURE 7 Propulsive performances of waterjet systems in relation to craft velocity V_b'.

Figure 16: A graph from a Japanese study of waterjet efficiency shows efficiency rapidly declining below craft velocities of 10m/s, in accordance with theory. (Fujisawa 1995)

Rolls Royce (Giles et al. 2010), outlining a proposal for 'fully submerged waterjets' to be used on future surface ships in order to achieve better acoustic performance, particulalry for an anti-submarine warfare role. The jets comprise a mixed-flow pump coupled to an electric motor, and have been both extensively modelled and also tesed in demonstrator vessels. These may be a closer representation of the performance characteristics achievable by submerged pumpjets, since shape of the intake and shroud more closely resembles the shape of a pumpjet that might be found on a submarine. Importantly, this work focuses specifically on the performance of the jets as a function of ship-speed, including identifying possible crossover points.

The paper makes no effort to justify the selection of choice of jets on the efficiency of the propulsion system, instead focussing on improved acoustic performance, and potential machinery space-saving advantages. The vessel under consideration would require 250 tonnes more fuel with jets find than with propellers, the jets would require more power to reach equal waterspeed to a conventionally propelled craft right up to 30 kt. In the case of this analysis, modifications to the hullform in order to accommodate the jet (which are likely to be more substantial for a surface ship than a submarine) also have an impcat on the resistance offerd by the hull. This also has an interaction with the different shape of the propulsors, which alters the required level of delivered (effective) power to achieve a given speed, in addition to the considerations of how efficiently the propulsor generates that effective power. The paper states: "This is an encouraging result for a first iteration as the AWJ-21 arrangement has not been fully optimised and, hence, there is further prospect of reducing the shaft power for this form. If the power could be reduced by 5% (e.g. by fur ther improving the waterjet/hull fairing), then the AWJ-21 vessel would be better at all speeds above 25 knots." This statement, however, is made in reference to the hullform needed to accommodate the jet, rather than the jet propulsion efficiency itself (Giles et al. 2010). As the propulsive efficiency curves given in the study show, the propulsors themselves are considerably further from reaching parity, still separated by about 10% at 25kt.

The paper also provides specific curves for the efficiency of the propulsor as a function of vessel speed, which demonstrated that the waterjet efficiency was lower than that of conventional propellers throughout the speed range, but declined particularly precipitously below speeds of 10kt. At 5kt, the propeller was more than twice as efficient as the waterjet. This study has been used to directly inform the 'central' efficiency curves assessed in this analysis.

It appears from recent examples in the literature that there is no evidence of jets approaching the same efficiency

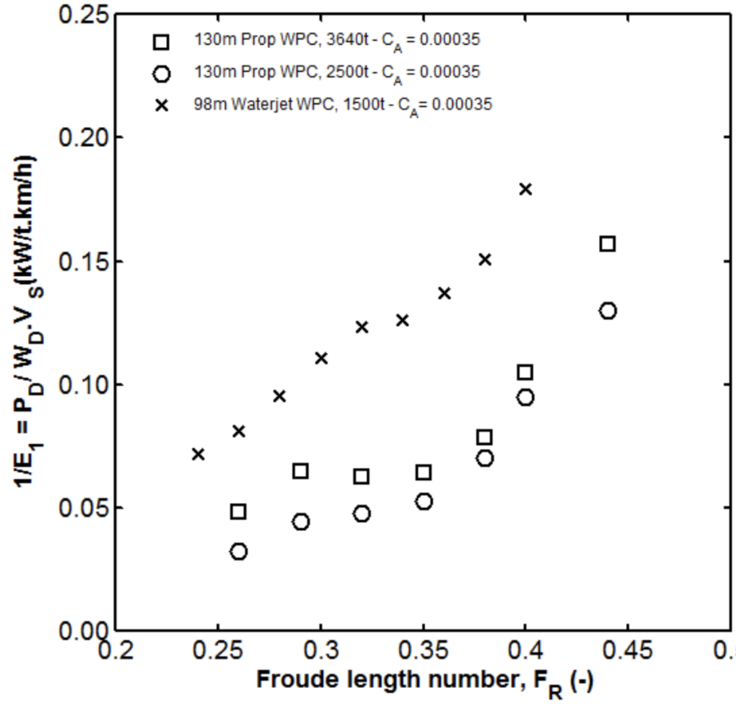


Figure 14: The transport efficiency versus Froude length number. The results for the propeller driven catamaran were extrapolated using the ITTC 1978 method.

Figure 17: An Australian experimental study aimed at determining the crossover point for the efficiency of jets and propellers in the 20-30kt range revealed much higher power was required across the entire speed range (Mustaffa Kamal et al. 2015)

as propellers at speeds as low as 10kt. Indeed, there seems to be considerable evidence that jets of most kinds suffer substantial efficiency penalties relative to propellers in this regime, and that this is understood and accepted as an inevitable design trade-off to be made. In the case of a submarine, which might spend nearly 100% of its time travelling at 10kt or less, this disadvantage (as opposed to less than 35%, as assumed for a surface ship in Giles et al. 2010) would become extremely substantial, which will be quantified in later sections.

Moreover, recent literature seems to confirm that efficiency of pumpjets fall off precipitously towards zero the closer that the vessel speed comes to zero. This strongly suggests the existence of some fundamental constraint in the physics of the operation of jets, which recent advances in technology seems not to have overcome. To more firmly establish the extent to which adaptation or plausible improvments in technology could or could not change this trend, it is worthwhile considering the theoretical limits that are presented by the physics. This should further limit the range of error that might be made in estimating realistic bounds of performance for a system which we do not have precise design specifications for.

6.3 A simple theoretical explanation

Pumpjets are necessarily low in efficiency at very low speeds because they attempt to get the water to do multiple things. They don't just accelerate a water colum. They first slow it down (increasing its pressure), then add pressure to it, then accelerate it. When the total amount of energy embodied in the incoming water stream, and the total amount of energy you want to add to the water both get very small (as they do at very low speed) there simply isn't enough energy to do all things at once to all of the water. The energy penalty inflicted by using the additional devices becomes very large in proportion, and part of the water doesn't do all the necessary things for the jet to work. In essence, if you try to slow down something that's already going slowly, it tends to stop That's exactly what happens in jets operating at very low flow-rates, when flow separation, also known as stall when it occurs between the blades, begins to take place. When there isn't enough energy to move all the water through

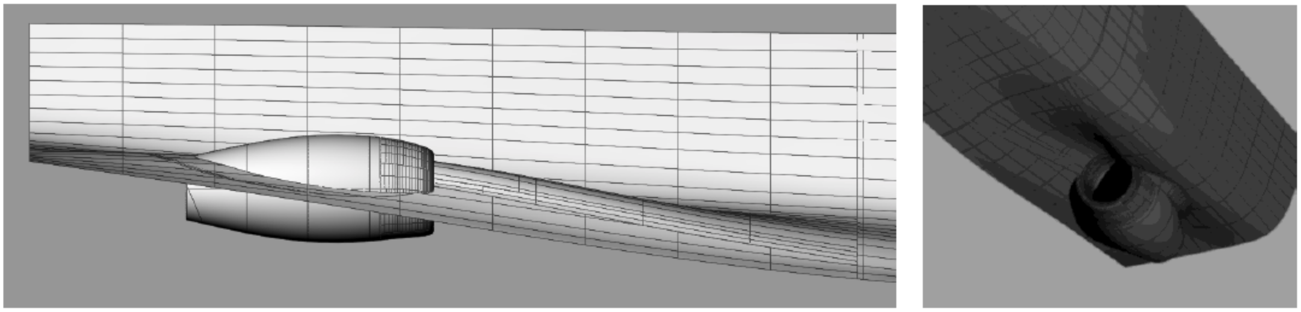


Figure 18: The 'fully submerged waterjet' proposed by BMT and Rolls Royce for military surface craft may more closely represent the duct shape used on submarines than waterjets that release above the surface. (Giles et al. 2010)

the pressure-hurdles imposed by the duct, only some of it moves, and the rest spins in place.

There are other some fundamental limitations on the peak efficiency that can be achieved by jets based on simple calculations of ideal efficiency from momentum theory, which are discussed in Section 6.4. They also provide enduring, reliable limitations on the extent to which ingenuity or design changes might be able to improve the efficiency of jets at low speed. But the primary reason why jet efficiencies decline towards zero at low speed is to do with flow separation (Fujisawa 1995), which is what occurs when the assumptions inherent in momentum theory's analysis of an 'ideal' actuator disc start to break down.

The conditions which lead to flow separation in a pumpjet can be relatively simply explained in terms of conservation of energy, and conservation of mass. Conservation of mass requires that as a pipe or duct expands, the flow through it necessarily slows down, in order to occupy the large volume, in proportion to the new cross-sectional area. Conservation of energy requires that it increases in pressure, and defines a very specific relationship between the pressure increase and the change in velocity, which is determined by the shape of the duct. That relationship says that the static pressure increase is inversely proportional change in velocity **squared**, as given by Bernoulli's equation, which was discussed in earlier sections. As a result, at high speeds, the total energy of the system is dominated by its velocity, but at very low speeds the static pressure is much more significant.

It also means that for any given change in velocity, the static pressure changes also, but doesn't change as much as the velocity change. The consequences for this pumpjets are and inevitable, since the geometry of the duct is inevitably fixed. At very high flow rates, the expansion of the area ahead of the impeller creates an adverse pressure gradient, as the water must slow down to fill the greater area. This adverse pressure gradient is larger at higher speeds, the proportions aren't linear, hence the the speed is much much larger, due to the square relationship, and flow is consistent (though still turbulent) throughout the entire cross-sectional area of the duct.

At low speeds, the same effect leads to detrimental effects. The adverse pressure gradient is much reduced, but the velocity is much much $(much)^2$ reduced. The pressure gradient is necessarily constant across the entire area radial area of the duct, but the drag due to the boundary with the duct itself will necessarily be greater closer to the walls in the case of the intake of the duct. For this simple reason, as the flow rate decreases, some point is reached where the flow adjacent to the walls actually reverses, and the flow becomes separated.

The same phenomenon is also prone to occur near roots of the blades of the rotor (Henderson, McMahon, and Wislicenus 1964, p. 15). Necessarily, the blades of the rotor are doing work on the fluid, so unless the impeller is in a region of considerable contraction, pressure will necessarily have to increase significantly through the blades, providing an adverse pressure gradient, which again must be constant radially. Since closer to the hub the velocity of the blades through the water is lower, the blades tend often to also be longer and deflect the flow even more in order to do the same amount of work on the fluid. With the longer surface over which the fluid must travel, as well as greater angle of deflection, flow separation is prone to occur here too. The physics will be exactly analogous to that of the separation on the inside of the duct intake, except the pressure gradient will be provided by a different source (the rotor doing work), and the surface (the blade roots) will also be different. This will also mean that the direction of rotation of the vortices will be different, and the location also close to the middle of the jet, instead of the outside.

As can be seen in Figure 21, the duct of a jet is designed to operate by deflecting the flow away from the natural path that would occur for a propeller, which would accelerate the stream over its blades directly, with the flow necessarily contracting with the acceleration as shown in Figure 2. Instead, pumpjets tend to use some

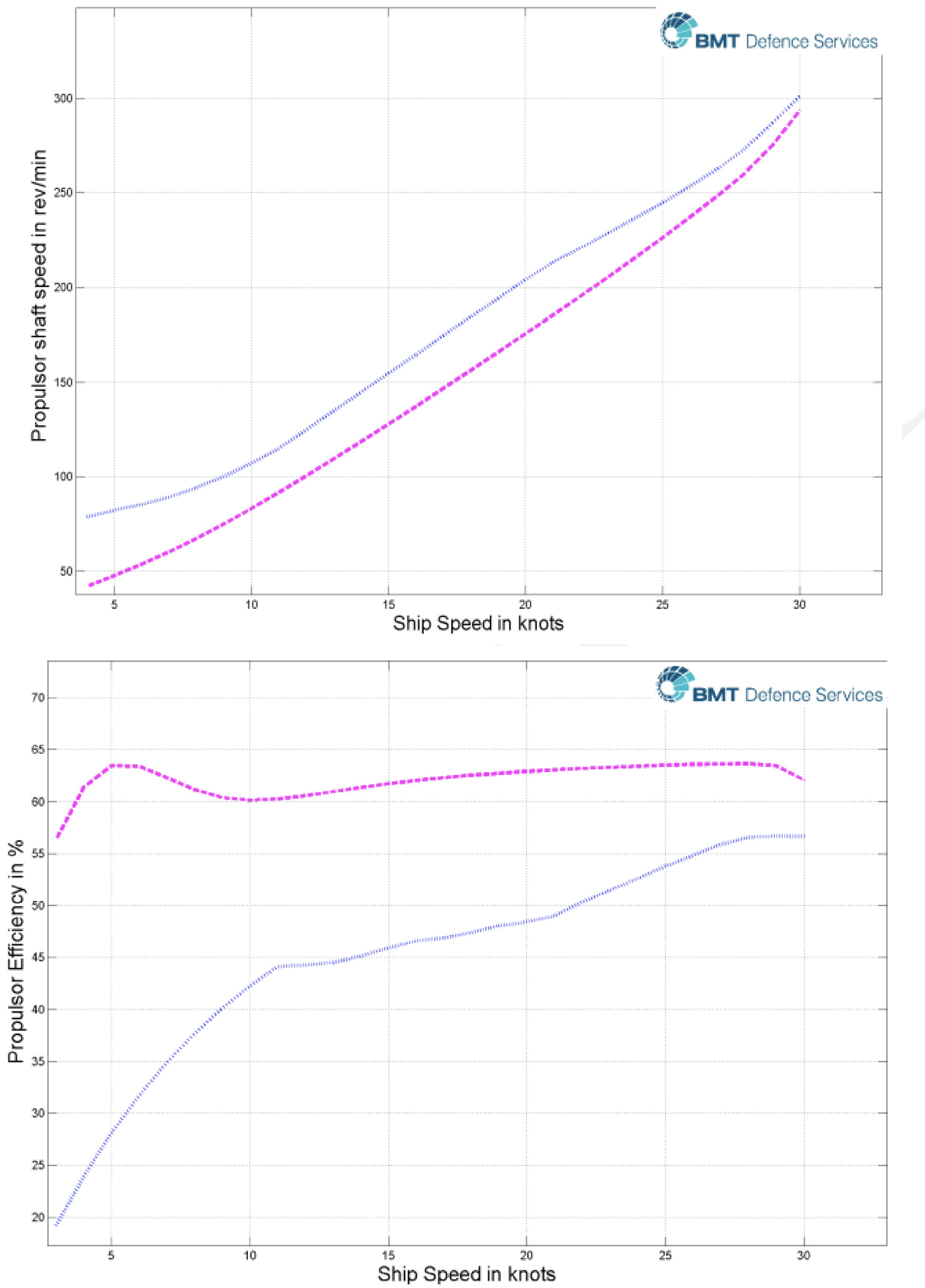


Figure 19: Studies on submerged waterjets for military surface craft currently show that the efficiency of jets decline sharply below 10kt (Giles et al. 2010)

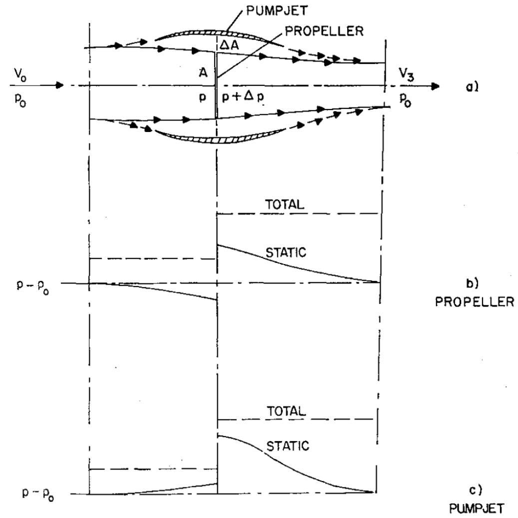


Figure 20: The effect of the duct is to deflect the flow away from the streamlines of an open propeller, elevating the static pressure at the stator blades by slowing the flow down.

moderate expansion of the flow in advance of the impeller (diffusion) in order to raise its pressure, and reduce its velocity. (Allowing the blades to do work on the water at lower speeds and higher pressure is the essence of what reduces cavitation.) The blades then do their work on the liquid, further raising its pressure. The duct allows this pressure then to be converted back to kinetic energy, as the water accelerates to move through the contracting area in the nozzle. This difference in the shape of the flow, and the consequent impacts on the static pressures, are demonstrated in Figure 20 taken from McCormick and Eisenhuth 1963.

Consequently, the geometry of the duct defines a pressure gradient in the intake and through the nozzle. The greater the difference in the cross-sectional areas, the greater the total magintude of the pressure differential that will occur, as necessitated by conservation of mass. The same amount must go out as came in. As the area through which it passes changes, the velocity much change so that the flow rate remains constant, otherwise cavitation will occur. The rate at which the areas change (how rapidly they expand and contract along the axis) will determine the gradient. Making the pressure change as smooth as possible is an important aspect to jet design in order to minimise flow separation.

Figure 22 shows a jet operating at very low speed. The adverse pressure gradient combined with the drag forces of the boundary layer are sufficient to bring the flow to a stop and reverse it, as shown by the arrow size reducing, and changing direction in the diagram. This occurs very close to the inner surface near the opening of the duct, and potentially also between the blades of the rotor, beginning the roots (Henderson, McMahon, and Wislicenus 1964, p. 15). Flow separation necessarily sees additional energy expended in the kinetic energy of the additional vortices and turbulent flows created, which don't result in the creation of thrust, which demands a change in the net momentum of the liquid in a backwards direction. Consequently, the degree and extent that it occurs necessarily and inevitably reduces the efficiency of the propulsor. As the flow rates slow further, the areas of flow separation will become larger, effectively reducing the intake area of the jet, and further degrading efficiency.

Flow separation also tends to lead to unsteady flows, with vortices periodically being shed into the main stream as they are speed up or change shape, and then ingested by the impeller and stator blades. As can be seen by the diagram in Figure 22, regions abound which are adjacent to or behind flow blockages or reversing flow, where considerable turbulence and unsteady forces would exist. These effects also have acoustic consequences, which will be discussed in Section 9.

It is worthwhile noting that the diagrams in Figures 21 and 22 do not include a hub for the sake of simplicity. In practice, the cross-sectional are of the pumpjet naturally only includes that aread between the hub and the duct, and in the case of many pumpjets, particularly those on the ends of torpedoes or submarines, the hub may include/incorporate the tapering tail of the body, for example in Figures 13 or 14. Particularly in Figure 14, the appearance of the inner side of the shroud to roughly follow contraction of the hub or body gives the optical appearance of very little diffusion or contraction of the flow occurring, as the one dimensional separation might

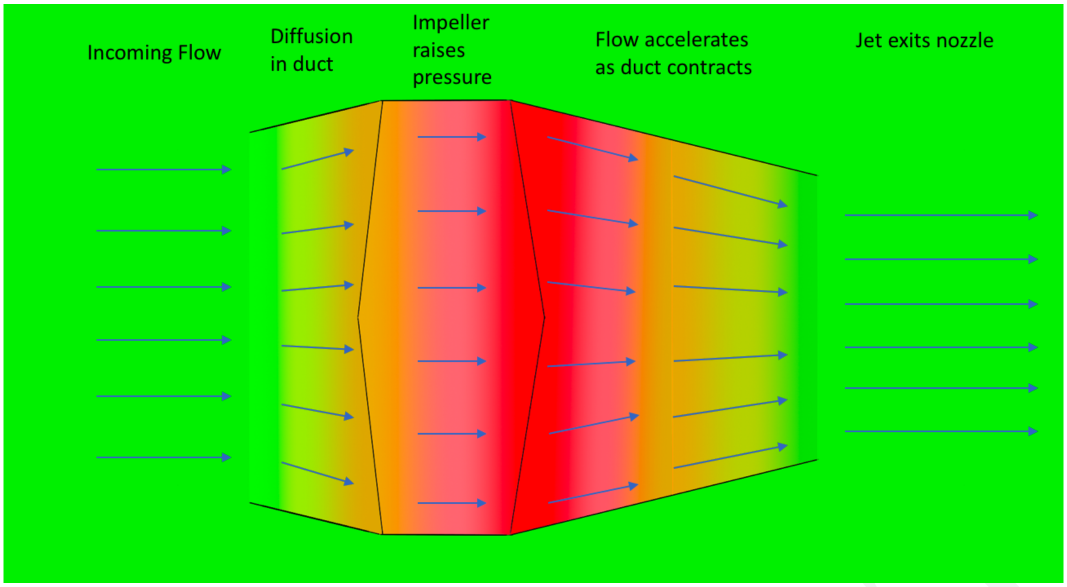


Figure 21: At high flow rates the water has sufficient velocity (indicated by arrow length) to overcome the adverse pressure gradients created by the duct shape, shown by the change from green to red. After the impeller has added further pressure to the water, the water accelerates out of the contracting nozzle through the favourable pressure gradient (red to green) to produce a jet, reaching equal pressure to outside at the exit

seem to be roughly constant, or even expanding in places where I have earlier explained it generally contracts. It is important to consider the impact of the second dimension on the actual effective area. Since area of a disc follows πr^2, the impact of the contraction of the hub will be dramatically larger when it is large than it will be when it is small.

Consequently, the contraction of the outer shroud at the very end of the duct will dominate the final taper of the hub, and actually lead to substantial restriction of the flow. Similarly, where the body or hub is quite substantial and also tapering steadily, keeping the duct intake parallel to the axis of the body for a small distance, or even just tapering it proportionally less than the hub, can still result in a considerable expansion in the area, and considerable diffusion. The example in Figure 13 shows a case of extremely sharp flow diffusion on the intake, probably more than what is practially realistics to avoid flow separation, even at quite high speeds. It is important to recognise that this simple relationship with r^2 generally means that even moderate changes in terms of diameter, which is what we tend to observe when looking at images and diagrams can actually amount to much more substantial changes in velocity, and hence pressure, which drives the effects described in this section. A side-by-side comparison of the geometries and flow-lines likely in the case of pumpjet or propeller is give in Figure 23, from to help illustrate this point.

6.4 Trade-offs and Limitations on Improvements

Having established that the inevitable decline of a pumpjets efficiency towards lower speeds is driven by the increasing occurrence of flow separation, some consideration ought to be given to the potential scope for the effect to be improved or negated by design changes, or otherwise mitigated with other improvements in efficiency. Here I have found considerable help from well established literature, many including various old declassified technical reports funded by the US Navy, many of which are frequently cited in the most recent literature as laying out the enduring frameworks for the modern discipline.

It is clear that the optimisation of a system for minimising cavitation, and hence improving acoustic performance, is a separate and independent design requirement to that of optimising a system for propulsive efficiency. These two design requirements can be found either to be in tension, or alignment, in different regimes. At high speeds, where cavitation tends to have severe impacts on propulsive efficiency of open propellers, and high mass-flow (which leads to good efficiency) can be achieved through compact ducts and pumps, pumpjets offer very good performance on both metrics. Hence, in this regime the two design requirements tend to align relatively well in favour of pumpjets. However, in very low-speed, low-load environments, where cavitation effects are negligible, and larger areas need

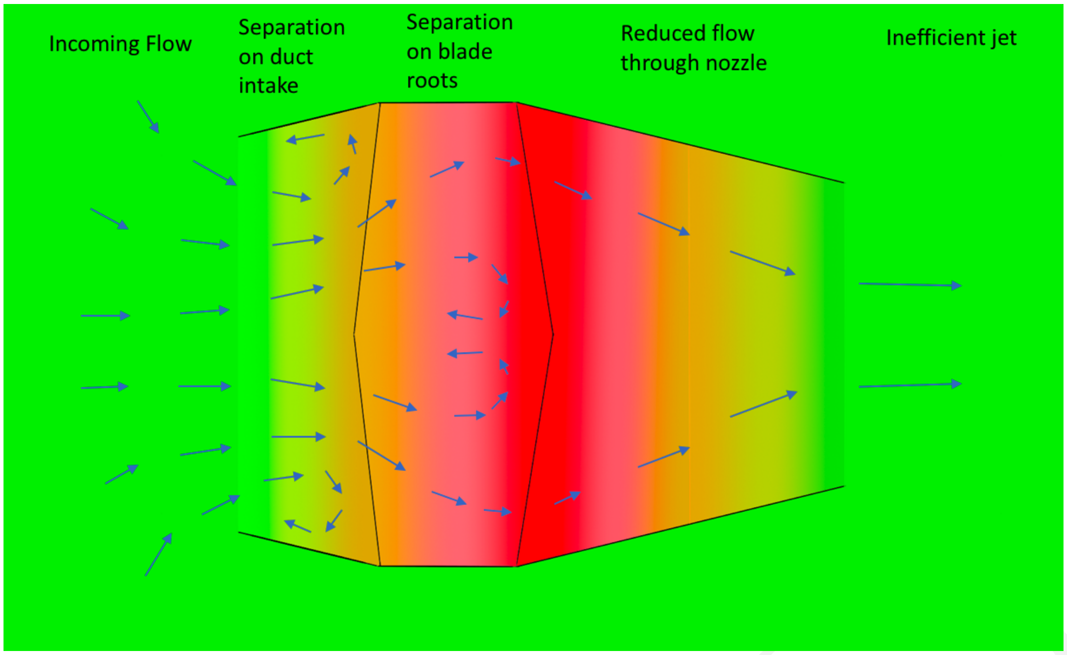


Figure 22: At low flow rates the water has insufficient velocity to overcome the adverse pressure gradients created by the duct shape, and flow separation begins to occur on the duct intake, and between the blades beginning near the roots (stall). Flow through the jet would be unsteady, with excessive energy expended creating vortices and turbulence that results in little thrust.

to be engaged achieve good mass-flow and efficiency, the two design requirements align relatively well in favour of an open propeller. In a variety of regimes (including at quite high speeds), the two requirements find themselves in tension and needing to be balanced (Gearhart and Henderson 1966).

For this particular consideration, two questions are of paricular importance. The first is where the clear transitions in the regimes will tend to lie, with respect to the probable requirements of a conventional submarine. The second is what drives the tension between those design requirements in the intermediate regimes, and whether it is a fundamental or inescapble tension in the laws of physics, or simply a technical hurdle which imminent improvements in the state of the art are likely to overcome by engineering improvements or innovation.

The answer to the first question, as discussed in earlier sections, seems to be that the operating speeds of a submarine tend to lie far below the probable levels where pumpjets are even remotely comparable to waterjets for efficiency. In my research I have found no evidence of waterjets being advocated for speeds less than 30kt, and for pumpjets for speeds less than 27kt. Having consulted with leading academics in the field, I've had it strongly confirmed that a pumpjet will always be less efficient than a propeller at speeds under 18kt. In later sections I will address further the acoustic comparisons at low speeds where flow separation will begin to occur, for instance below 10kt.

The answer to the second question is that the tension between acoustic and propulsive performance at intermediate speeds and loadings is driven by foundational physical requirements. That is not to say that optimal means of balancing those requirements will not still be found, and improved, as the art advances. However, it does mean that significantly adapting using known variables that can be changed to favour one design requirement are unlikely to yeild large improvements without some trade-off being made to the other.

The reason for this trade-off occurring can be quite simply attributed to the nature of the shroud, or duct, which surrounds the the rotors of the propulsor, and the effect it has on the flow. If the duct acts to increase the pressure at the rotor, (which reduces cavitation) it necessarily must slow the flow at/around the rotor, which necessitates produceing a negative thrust on the duct. The system as a whole produces a positive thrust, becuase the impeller or rotor pushes a larger positive thrust, but the duct necessarily produces a negative thrust. As the speeds get lower, and the thrust required gets much much lower, this negative thrust becomes proportionally more significant, as described later.

Put another way, the work required to slow the water down, then speed it up again, becomes a gradually greater

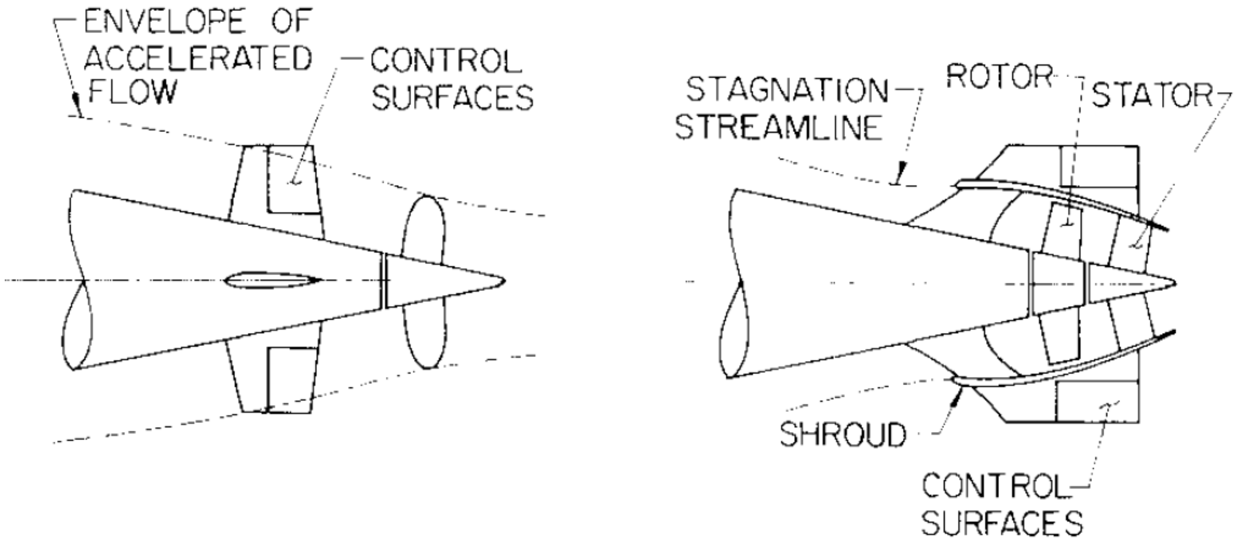


Figure 23: At the end of a tapering body the impact of the contracting hub will be much larger near the intake than near the tail, making the degree of diffusion ahead of the impeller, as well as contraction of the flow in the nozzle after it, much larger in impact than it appears by looking at the external shape. Credit Gearhart and Henderson 1966

penalty the the slower the water is coming in, and the less you actually want to speed it up. If the water is slowed enough by the duct to effectively stop, then the impeller must do the work of speeding it up (sucking it into the duct) before the duct slows it down, before the impeller raises its pressure, and the pressure accelerates it out of the nozzle afterwards, immediately reducing even the ideal efficiency to 50% (Lewis 1988, p. 277). Compared to simply accelerating the water in one simple push, as a propeller blade does in an unconstrained flow, the efficiency penalty is substantial, and larger in proportion at low speeds.

6.5 The impact of duct loss on an ideal propeller

Derivations of the 'ideal' efficiencies are frequently made for propellers and jets using basic conservation laws (momentum theory) which consider simple acceleration of some column of water as actuated by a disc representing the impeller or propeller. A fuller description of these equations can be found in most standard texts (Lewis 1988, p. 131). These methods are computationally simple, and allow simple upper-bounds to be be set for efficiencies achievable for given designs under certain conditions, without considering the pottential impact of other more complex effects such as skin friction over the blades, potential flow separation, or cavitation. As such, they can be easily relied upon to constrain the overall plausible range of values that can be achieved from universally applicable inputs, such as the velocity of water going into a duct, and the velocity of water exiting a nozzle.

Such methods are used in Wislicenus 1973, pp. 8-14 to construct an 'ideal' jet efficiency that applies to waterjets and pumpjets. Whilst I won't repeat the full expansion here, a fundamentally important early conclusion of the derivation is the distinction between 'useful work' and the total energy expended. Since the rate of change in momentum is known to be necessarily equal to the force generated, and increasing momentum change (hence thrust) can be achieved either accelerating more mass, or accelerating mass to higher speeds. Given that energy embodied in a flow is proportional to it's velocity squared, but its momentum only to its velocity, a necessary and inevitable consequence is that some energy is always wasted in accelerating a fluid to a higher velocity than its surrounds.

This is expressed in the equation which represents 'ideal jet efficiency', which is directly equivalent to 'ideal propeller efficiency' using momentum theory of propeller action:

$$\eta_j = \frac{1}{1 + \frac{\Delta V}{2V_0}} \tag{3}$$

The inevitable consequence of this relationshiop is that efficency approaches unity when ΔV (the change in

Figure 24: The outer shape of pumpjets on the aft end of torpedoes or submarines, such as this one on the French Triomphant class on which the Barracuda's jet will be based, may understate the degree of deceleration that the duct achieves. Credit silence_hr 2016

water of the water between entering and exiting the system) relative to V_0 approaches zero. Intuitive embodiments of this relationship are (equivalently) that efficiency is maximum when the least force is exerted on any given bit of water, which might be when negligibly small work is being done (extreme low speed) or when such a large mass of water is acted on that it barely needs to be pushed at all. This relationship would lead to the conclusion that infinitely large propellers or jets are always desirable from an efficiency perspective. This of course isn't practical to build, and also doesn't hold when taken to the etremes the effects of the drag on the propeller blades, or duct, are taken into account. Infinitely large systems would increase the total weight, as well as having significant surface drag when moving through the water, all of which are neglected in this 'ideal' consideration.

In Wislicenus 1973, pp. 8-14, Wislicenus expands the relationship in the case of the jet to incorporate terms to represent some of the inevitable adjustments that would occur in the case of pump jets and waterjets, particulalry the duct head loss (K) (fraction of energy required to push the water through the duct), as well as the additional drag on the outside of the propulsor (ΔT). This leads to an adjusted efficiency relationship, which still neglects any losses due to pump efficiency, or change in height of the jet (which is added for consideration for waterjets, but not relevant here).

$$\eta_j = \frac{1}{1 + \frac{\Delta V}{2V_0} + K\frac{V_0}{2\Delta V}}(1 - \frac{\Delta T}{T}) \tag{4}$$

The conclusion of the analysis, and the plotting of these results for certain possible values of K and ΔT is: "Its outstanding characteristic is that this efficiency approaches zero rather than unity for $\Delta V/V_0 = 0$, even for small duct losses".

Wislicenus also acknowledges Wislicenus 1973 another author, Brandau, who makes a different assumption about the relationship between the duct loss and water velocity (Brandau 1967) in his derivation (along with another thorough discussion of potential and ideal efficiencies), who produces a different peak efficiency point, but retains a similar overall shape featuring efficiency falling very rapidly to zero at low values of $\Delta V/V_0$, and contrasting this with the ideal propeller, which approaches unity in this low regime.

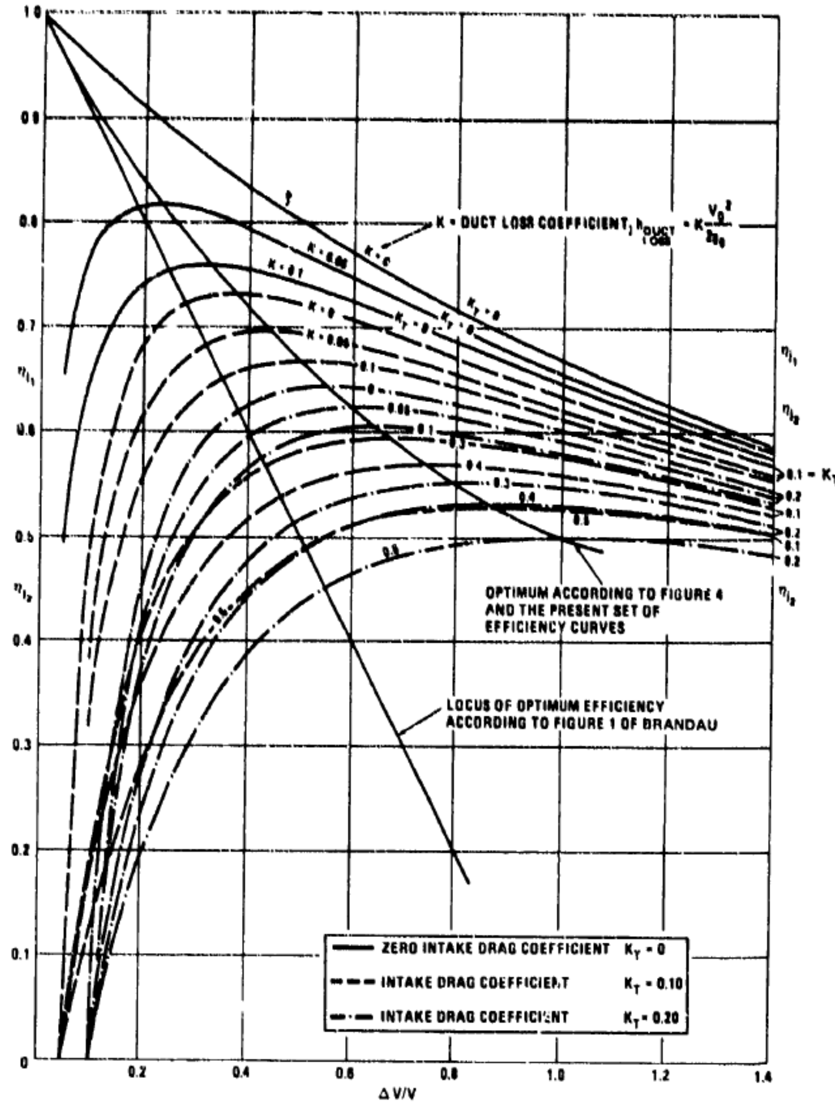


Figure 5 Jet Efficiency Corrected for Duct Losses and for Intake Parasite Drag

Figure 25: Ideal jet efficiencies sharply appoach zero at low values of $\Delta V/V_0$, where as ideal propeller efficiencies without a duct $K = 0$ approach unity. Credit: Wislicenus 1973

Charts such as these are generally used with dimensionless ratios on the axes (such as $\Delta V/V_0$) to allow the most general solutions to be used to solve for any given particular vessel size, speed, or loading requirement which might be required, these confusing to many readers unfamiliar with hydrodynamics. For the avoidance of any confusion, it is important to note that the value for $\Delta V/V_0$ for a given vessl and propulor may tend to increase with increasing waterspeed of the vessel, however one cannot rely upon this particular value diminishing towards zero at very low speeds, as it does for related by different metrics. In an idealised circumstance, the flow rate increases directly with vessel speed. Given that the force produced scales with ΔV, which at constant values of $\Delta V/V_0$ increase in proportion to (if, in the idealised circumstance, vessel speed is equal to V_0), an increase in thrust can theoretically match the V_0^2 requirement imposed by drag without any change in $\Delta V/V_0$. However, in practice the water encountered by the propulsor is slowed by the wake field, and so the drag encountered by the vessel may increase faster than velocity of the water entering the intake, an effecnt which is likely non-linear with vessel speed. So whilst the trend with regards to vessel speed can be known with regards to the graphs in **fig:PumpjetEfficiency.png** a direct translation of the x-axis used to vessel speed at any given point is difficult prove without additional system information. One might generally infer that the sorts of declines in efficiency observed as vessel speed discussed in recent literature correspond with movement towards very low values of $\Delta V/V_0$, though it is possible that alternative derivations have been used, or that the phenomenon known to occur in practice (such as flow separation) aren't adequately captured by such ideal equations derived from momentum theory in order to make a direct translation into real-world application.

For context, the equations developed by Wislicenus are used for the purposes generally of selecting the ideal propulor diameter, which can be made larger in the case of a propeller to access higher ideal efficiencies. This is an opportunity which is constrained in the case of jets because the efficiency diminishes at very low values of $\Delta V/V_0$. This is quite a different constraint to other "practical" considerations as some have suggested, such as weight, or space constraints. Open propellers may advantageously choose to lower their values of $\Delta V/V_0$ as low as 0.1 in order to obtain ideal efficiencies (Wislicenus 1973). This still provides a hard limit on potential improvements that can be attained for a pumpjet that has non-zero duct loss.

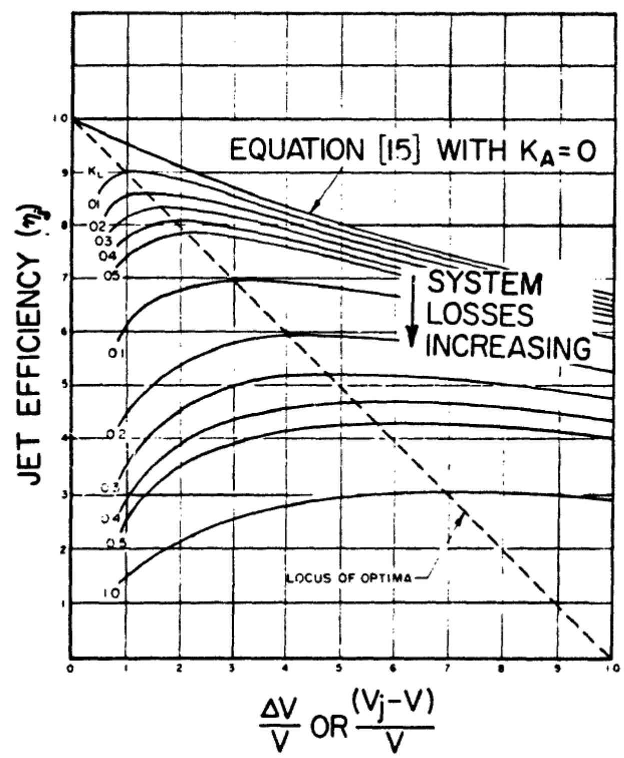


Figure 1 - Effect of System Losses on Optimum $\frac{\Delta V}{V}$

Figure 26: Alternative derivations of ideal jet efficiency also show sharply declining efficiency for low values of $\Delta V/V_0$ Credit: Brandau 1967

The structure of these curves is found to be overall quite similar for both pumpjets and waterjets, though the probably values for the losses incurred in the intake duct, or on the exterior of the shroud, are obviously different (Wislicenus 1973, pp. 13-14). Similar efficiency shapes can be found for discussions focussing explicitly on underwater pumpjets (Henderson, McMahon, and Wislicenus 1964, p. 13). It should be noted that the theoretical efficiency derived by these general equations is consistent both in derivation and results with those produced by other authors (Lewis 1988, p. 227).

Care should be taken, however, to note that different graphs for efficiency can be produced which have different variables on the x axis. For example, Molland, Turnock, and Hudson 2011, p. 247 a graph of ideal efficiency of a pump jet is shown using the speed of advance divided by the jet speed, or V_1/V_2. Given that the x axis used in the previous charts used $\Delta V/V_0$, which would be related to $V_2 - V_1$ in this case, this has the effect of reversing the effective direction of the chart and changing its shape. In this case, for a fixed jet and vessel design, high-speed operations will be towards the left of the chart, and the precipitous decline in efficiency will occur as speed declines to zero, along with thrust, toward the right of the chart, which can be known to correspond to waterspeeds declining to zero at $V_1/V_2 = 1$.

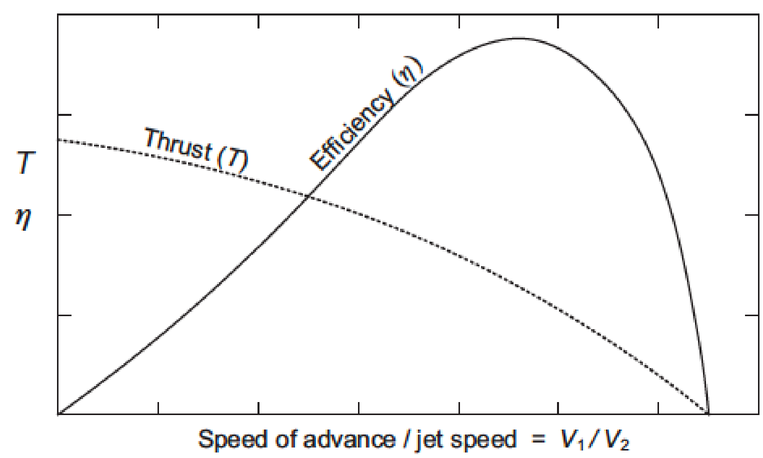


Figure 27: Other modern reference texts might demonstrate jet or propeller efficiencies with different x-axes, effectively reversing the way the graph should be understood for a single system operating at different speeds. Credit: Molland, Turnock, and Hudson 2011

These types of charts correspond more closely in orientation and trend that the very frequently used x-axis unit $J = V_a/nD$ when showing efficiency curves for both propellers and ducted propellers (such as used in Figure 7) are of a similar orientation to the chart shown in the figure above. The left side of the chart will correspond to the highest number of rotations for a given amount of progress through the water. For vessel of fixed load, and a propeller of fixed geomtry, this will correspond to a propeller facing the higest drag force due to the vessel moving at the highest speed.

Readers may observe that the efficiency for all propellers also decline to zero at the other end of the spectrum, most sharply at a point where J equals or exceeds the pitch ratio of the propeller. As discussed earlier, these correspond to cases where the propeller is slicing along its helical path without exerting any force to move water backwards, or when the slip ratio is zero. In this circumstance, the rotation of the propeller would not push any net water backwards, and simply act as a paddle-wheel needlessly spinning water. Such circumstances are unlikely to occur to a significant degree unless a vessel was decelerating, or experienced some other force to assist its propulsion. It is possible that at extremely low speeds a propeller could somewhat descend to the right of optimal advance ratio, when very dramatically reduced load was encounterd because of the extreme low speed, as might be suggested by the slight reduction in propulsive efficiency of the propeller below 5kt in the BMT study. These losses of efficiency, however, could never supercede those of a decelerating ducted propeller or jet, which has the shroud which necessarily imposes an **additional** drag to the watercolumn in excess of any other resistance faced by the rotor. This effect can be seen clearly even or an accelerating duct, as shown in 29.

It should be clear from the above analysis that the efficiency of a pumpjet falling towards zero with a vessel's waterspeed is an enduring and foundational result of basic physics. The addition of negative thrust on a decelerating duct, no matter how small, requires that efficiency must decline at some point with with blade loading, in contrast

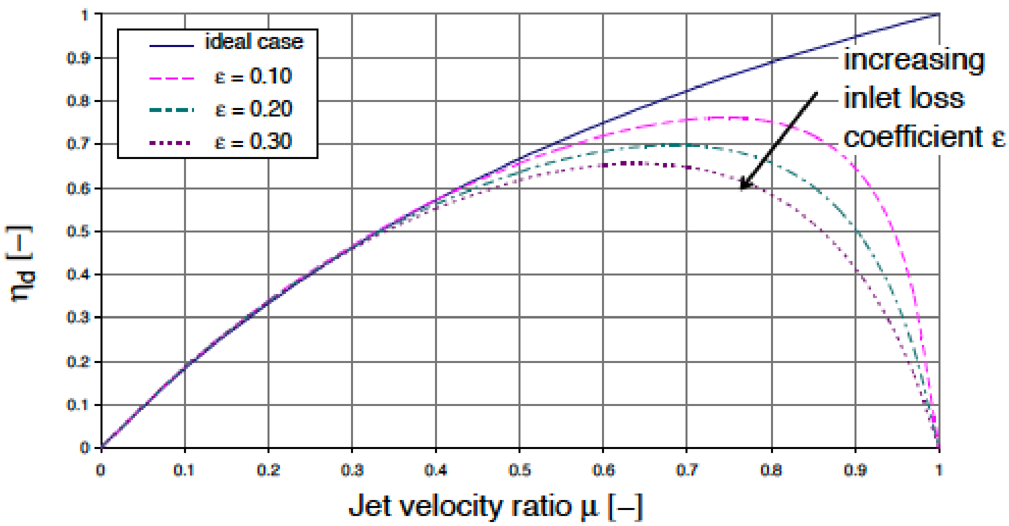


Figure 28: Another graph representing efficiency as a function of the ratio of jet velocity to incoming velocity, which shows efficiency declining at low thrust (to the right). The impact of increasing duct losses can be clearly seen, as opposed to the 'ideal' propeller without a duct. Credit: Bulten 2006

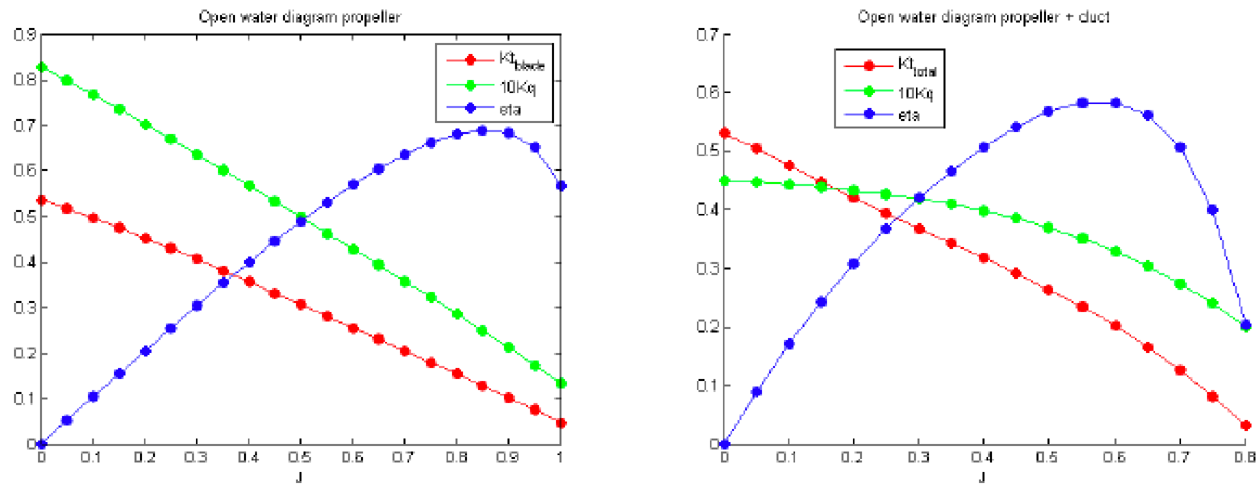
with an ideal propeller which rises to unity. This explains the overall shape given by the the mysterious unquantified chart cited by Andrew Davies (Davies 2017) and Access Economics (Stanford 2017) shown 30, and is also consistent with the shapes plotted by more recent studies as shown above, and those presented in other modern publications studying the use of pumpjets (Giles et al. 2010) and waterjets (Fujisawa 1995).

In terms of establishing plausible peaks and cross-over points, the study undertaken in Giles et al. 2010 probably provides a sufficient indication as to the current state of the art in the relevant technologies. Whilst this effort focussed on a surface vessel rather than a submarine, the study was undertaken with the backing of military customers with support and testing facilities (the US Navy), and involved two major companies who are world leaders in maritime engineering (BMT) and waterjet manufacture (Rolls Royce). Even if further technical advances through design refinement were possible, as the authors alude to, the cross-over point in terms of efficiency might be brought down to 25kt. The claim that the crossover point lies anywhere near the transit speed of a convetional submarine (8-10kt) appears implausible. In discussions with leading world experts involved in the development of advanced ducted propellers (including those involved in citations) I was told that a pumpjet could not be more efficient than a propeller below 18kt, confirming this conclusion.

With the optimum efficiency of a jet probably being no greater than 60% or 70% at its peak efficiency according to many theoretical and experimental studies (Lu, Pan, and Sahoo 2016), which would quite probably lie considerably higher in terms of waterspeed even than 18kt. These facts, along with the inevitable decline of efficiency towards zero as waterspeed also declines, offer a suitably constrained set of plausible efficiency curves may be investigated numerically, as will be done later in later sections.

6.6 An assessment of scope for improving the efficiency of a pumpjet at low speeds

Before continuing to assess the impact of the likely efficiency curves of pumpjets relative to propellers, it is worthwhile considering what the known literature about the theory of pumps, jets, and turbomachinery might tell us about the potential for a radical advance which make might substantially improve the shape of the curve at very low speeds. Whilst the field of propulsor design is no doubt complex, and I will not attempt to be exhaustive in detailing all of the potential design considerations which might make an improvement. However, the pursuit of reasonably comprehensive confidence is aided by the the scale of the gap which probably needs to be closed to make pumpjets comparably efficient to propellers at the relevant speeds. Minor adjustments and the improvement of small or marginal effects, of which there might be many, will clearly not help in shifting the efficiency peak of a jet from over 25kt to under 10kt. In other words, this gap will not be closed or noticeably reduced by 'tuning'.



(a) Ka4-70 propeller **(b) Ka4-70 propeller + 19A duct**

Figure 29: Even the addition of an accelerating ducts substantially reduces efficiency of propellers at very low loadings, or for constant loads, low speeds. Maximum attainable efficiency is also reduced. Their benefit lies in the bulging of the curve at low advance ratios (higher loads). Credit: Willemsen 2013, p. 6

Quite substantial redesign of core characteristics (like mass flow) would be required, which would necessitate a cycle of redesign and tuning virtually all other aspect of the entire jet, as illustrated by numerous guides to the design of such systems (Bruce et al. 1974, Furuya and Chiang 1988, McCormick and Eisenhuth 1963, Henderson, McMahon, and Wislicenus 1964). As such, I will only consider those parameters which could plausibly be altered quite substantially, where the consideration of larger changes make the likely limits or trade-offs quite clear.

6.6.1 Increase mass-flow by widening area of intake

Perhaps the most obvious means by which one might attain substantial increases in efficiency is to increase substantially the mass flow rate. This is derived from a fundamental relationship, as expressed earlier in the representation of ideal propeller and jet efficiency (prior to the consideration of any drag or other losses) which was given in the earlier equation. Since excessive velocity differences result in more energy expended than momentum changed, as given by momentum theory and basic mechanics, doing work on a large body of water, rather than working harder on more of it, is generally desirable from an efficiency perspective. Considering what the appropriate mass-flow should be at design speeds is generally the first thing that is specified to occur in all design processes for pumpjets, and good example of which is in Henderson, McMahon, and Wislicenus 1964, pp. 6-7.

As noted in Henderson, McMahon, and Wislicenus 1964, the key constraint of this variable is that increasing the diameter of the pumpjet necessarily leads to an increase in the surface (including the external suface) of the shroud. The increased drag that this induces must be deducted from the thrust that the pumpjet produces, or effectively increasing ΔT as given in earlier equations. In this respect, there is "no free lunch" to be had in expanding the size of the intake. As Henderson et al. conclude, for this reason the diameter of a pumpjet tends to be about 15% or 20% smaller than that of a corresponding propeller, whereas the diameter to have equivalent mass-flow, highlighting the tension set up in pumpjet design with their earlier observation that "if the cavitation resistance of the blades is to be improved with no reduction in thrust and the same rate of flow through the propulsor, the pump jet rotor must be larger than that of the propeller." (Henderson, McMahon, and Wislicenus 1964, p. 1)

It should also noted that in order to substantially increase the opening area of the propeller, the difference between the velocity of movement at the blades nearer to the root (close to the hub) and the extremities of the blades increases substantially. In order for equivalent work to be done on all of the water distributed radially across area of the impeller, quite a different blade shape might be required, in order to provide a higher deflection of the

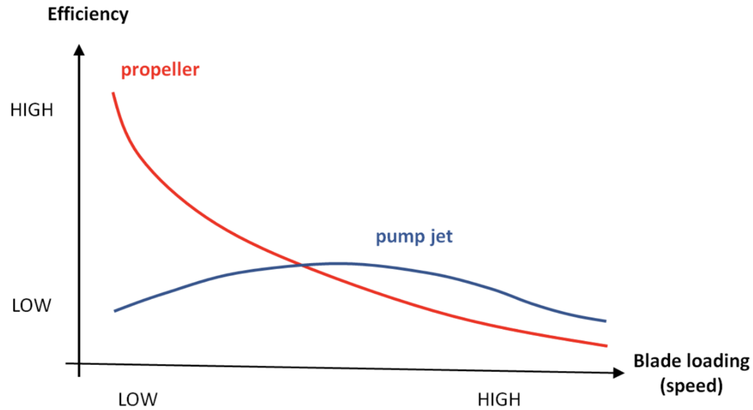


Figure 30: The mysterious efficiency comparison chart which has been doing the rounds in the Australian debate probably quite reasonably reflects theoretical physical limits of 'ideal' pumpjets and propellers. Credit: Stanford 2017

water close to the root. In these areas, there is increase probability of flow separation occurring, where the velocity of movement of the water across the surface is insufficient to overcome the pressure gradient required to move over the blades. (In a pump, the pressure necessarily increases as work is done on it.) Or, since there isn't enough pressure exerted on the whole of the water column to overcome the resistance imposed by the duct, not all of the water moves forward, and some starts to move backwards. This leads to flow separation, or stall occurring close to the blade roots, which dramatically diminishes the efficiency of the system. A further discussion of this effect can be found in Henderson, McMahon, and Wislicenus 1964, pp. 15,27, Bruce et al. 1974, pp. 807,8012, Wislicenus 1973, p. 185, McBride 1979, p. 60 and many other related texts. This is a general problem that affects a range of axial-flow turbomachinery, particulalry operating in off-design conditions, and will present a general concern for the design of a new pumpjet Wislicenus 1986, p. 185, Li et al. 2013.

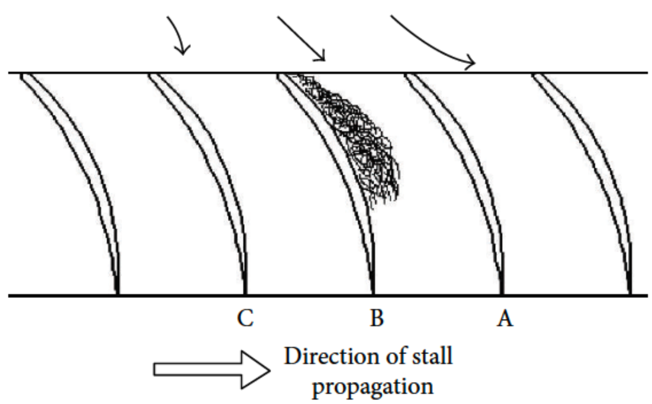


Figure 31: Flow separation, or stall, can occur when the flow over the blades of a pump slows too much, as shown in Li et al. 2013

It is possible to limit the variation of deflection between the blade tips and roots by simply expanding the size of the hub. However, this necessarily reduces the effective frontal area that is available to receive the mass-flow, which necessitates further expansion of the outer diameter, and a very substantial increase in the weight of the system. In addition, expansion of the hub will necessarily increase the total surface area relative to the mass flow, including by increasing the amount of tapering required after the stators in order to prevent risk of cavitation occuring around the tail the hub. Consequently, increasing the area is not plausible without also increasing duct loss to some degree, consistent with the earlier observations from Henderson, McMahon, and Wislicenus 1964.

Increasing the frontal area of the intake also is necessarily linked to the advance ratio of jet. Since low advance

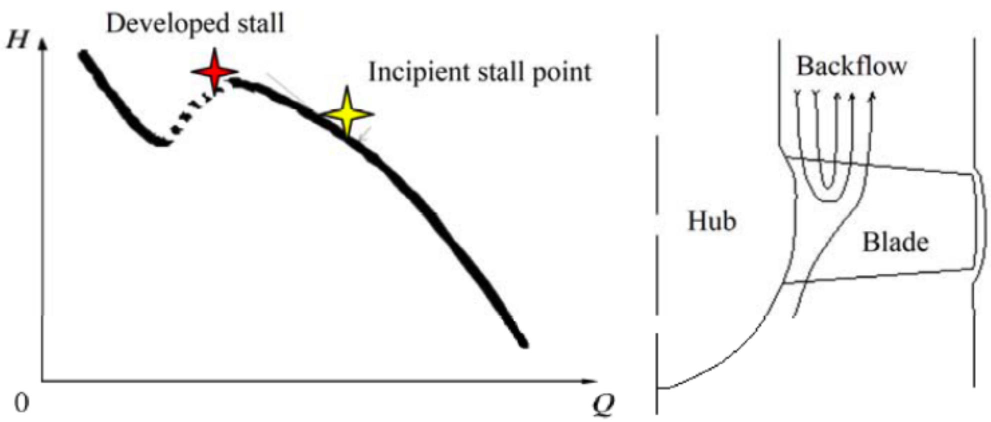


Figure 32: Stall results in water flowing backwards near the hub of the blades at low flow rates, as shown in Li and Weijun 2014

ratios correspond to higher shaft speed for a given forward velocity, increasing the thrust produced for a given rotation (by widening the jet area) necessarily results in higher advance ratios, since more work is done on the water for a given rotation. However, this also necessarily results in poorer cavitation performance of the jet, since higher blade velocities relative to the water flow result in necessarily increased propensity for cavitation. A detailed discussion of this can be found in Gearhart and Henderson 1966, but similar tensions can be readily found in most other pieces of literature, including Henderson, McMahon, and Wislicenus 1964, Wislicenus 1973.

Given the fundamental nature of the flow-rate and intake area to the design of pumpjets, and the great lenght of time for which they have been understood and discussed as a crucial design input for a waterjet, it is altogether implausible that some large increase in intake area can be achieved without incurring necessary and unavoidable tradeoffs.

6.6.2 Reduce degree of diffusion (i.e. switch to accelerating duct) to reduce negative thrust from duct

A further means of reducing the negative thrust produced by a duct may involve significantly reducing the degree of diffusion, or compression that occurs in advance of the rotor, since the process of diffusion necessarily slows the water and produces negative thrust. However, this amounts to transitioning towards an accelerating duct, or Kort Nozzle. Whilst nozzles of this type have been known to improve the cavitation characteristics of a propeller by enclosing the tips (which often tend to cavitate first), their ultimate function is to actually decrease the pressure at the blades of the propeller under higher loadings. Consequently, they necessarily increase the propensity of other types of cavitation to occur across the blade-face, including bubble, cloud and sheet cavitation. As such, these types of propellers are not considered for the military purposes which require an absolute minimum of noise to be created. Transitioning to an accelerating duct signify a shift away from a pumpjet, and necessarily be in direct tension with the need to minimise cavitation for acoustic considerations.

In addition, whilst it is often demonstrated that for a given propeller under certain load conditions (high loading), the addition of an accelerating duct can considerably improve efficiency, all of these situations have generally been in the context of vessels which are designed for a relatively high thrust, low waterspeed situation, when propeller size is necessarily greatly constrained. This is the case fishing vessels, or for tug boats, which need to impart significant thrust to a vessel dozens or hundreds of times their own size. Mounting a propeller the equivalent size of the vessels they mean to push, however, would be excessively heavy, arranging a mount and power drive that would keep the entire propeller submerged, and not have the effect of flipping the boat backwards or sideways when rotated hard, would be effectively impossible, without proportionally increasing the size of the tug. Furthermore, in most circumstances these propellers are still designed to operate with some cavitation, even if the extent of it is reduced by the presence of the duct (Haimov et al. 2010).

In other words, the use of highly loaded propellers in such applications is actually particular to design constraints that are unlikely to be present for a submarine, which can position the propeller at the tail of its body, directly behind its centre of mass and drag, and consequenlty have freedom about the optimal size of the blades. It is well known that a duct cannot improve the performance of a low-loaded propeller which would be the situation for a slow-moving vessel with unconstrained propeller size. Authoritative references in the literature include Oosterveld

1970, who calculates the minimum thrust coefficient C_T (a measure of loading) for an accelerating duct to improve a propellers performance to be between 1 and 2, as shown in 33.

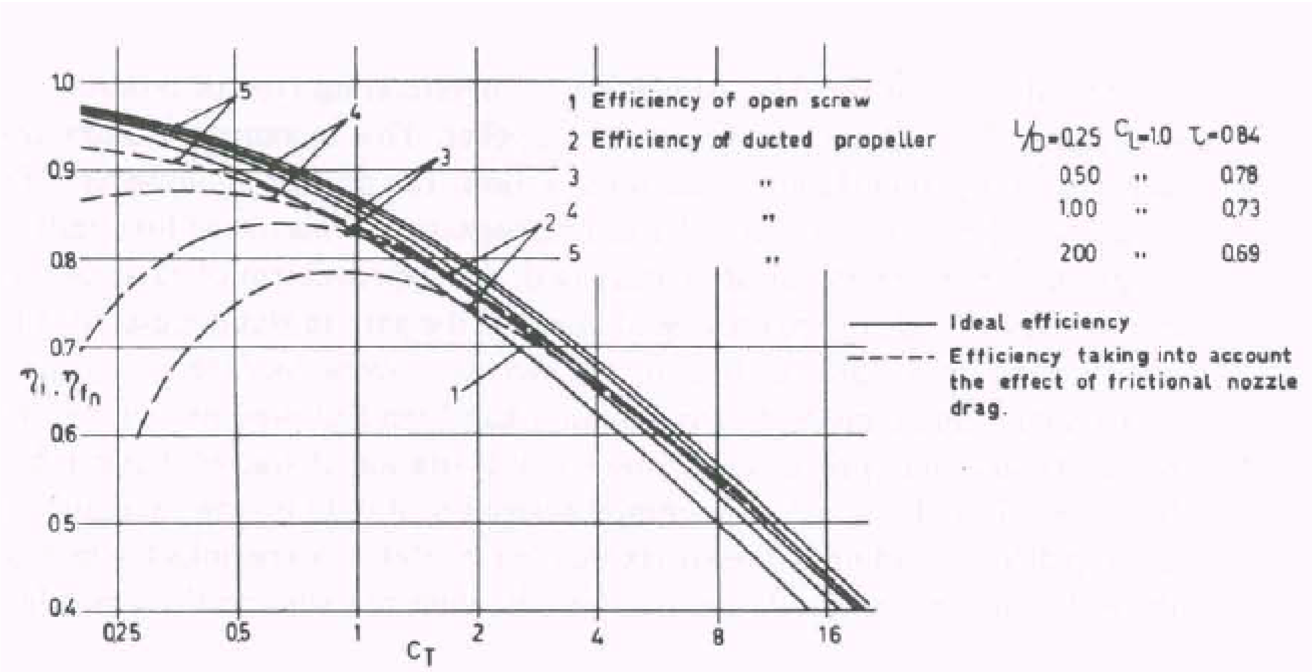


Figure 33: Calculations of 'ideal' efficiencies of accelerating ducts (neglecting drag) in Oosterveld 1970 show that a duct can only improve the efficiency of a propeller if it is loaded above a certain degree, and that longer ducts produce better improvements in 'ideal' efficiencies

A parallel design change in the switch away from the degree of deceleration in the duct would be the reduction of the nozzle contraction after the rotor. For waterjets and pumpjets of all sorts, based on fundamental disc actuator theory, the degree of this contraction of the flow area has also been long identified as a means to increase pressure at the rotor, and hence decrease cavitation, but at the direct expense of efficiency (Van Terwisga 1996, p. 14).

Numerous efforts to find suitably compromised duct shapes exist, but even advanced modern designs still exhibit declining efficiency at low speeds, as well as some cavitation during operations at design loads, which still tend to imply relatively high speeds, for example 27kt in 34 . Consideration of accelerating duct designs for a military submarine would be extremely unlikely, and be a profound departure from any existing pumpjet designs.

6.6.3 Reduce shroud length to decrease drag on duct

The reduction of the length of the shroud in order to reduce drag presents another possible means to lower the duct resistance, as shown and discussed in Oosterveld 1970, pp. 21-25. The fundamental difficulty with greatly shortening a duct, however, is that it requires that any changes in the shape and with of the water column be accomplished much shorter distance for the duct to achieve its desired effect, which means that generally it has to achieve less of it. This means that very low duct lenghts achieve less of an efficiency improvement to the ideal efficiency of a propeller, in those circumstances where they can achieve an improvement (accelerating ducts at high loads), as discussed above.

If more aggressive shape changes are attemped in a limited space, the deflections of flow and pressure gradients become much more extreme. This leads to a far greater propensity for flow separation to occur. This can happen inside the duct ahead of the stator, particulalry when any degree of diffusion occurs in order to elevate static pressure at the blades, or any kind of direction change is required as in the case of waterjets. Unlike waterjets, pumpjets also have the potential for separation on the exterior surface, which is an additional concern in the design of duct Henderson, McMahon, and Wislicenus 1964, p. 13. Given the role of the duct is to change the speed of the flow at the impeller relative to what would occur in its absence (in particular to decelerate it) separation might tend to occur on different surfaces in different operating conditions, depending on the relative pressure gradients

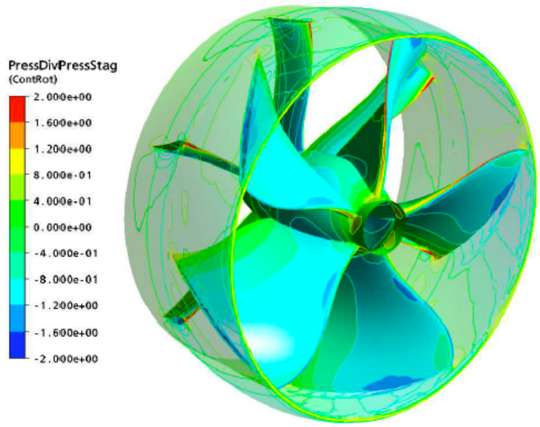


Figure 20: Pressure distribution on the final fine-optimised geometry.

(a)

Figure 30: Cavitating behaviour for the 2nd geometry (seen from astern, portside).

(b)

Figure 34: (a) Extensive work has been done exploring compromise designs for decelerating ducted propellers (pumpjets), including with very modest deceleration in the intake, limited shroud taper, short duct lengths, or essentially incporate some of the advantages of accelerating ducts. (b) TAt optimally efficient conditions (corresponding to 27kt) such designs still exhibit some cavitation. Credit: Abdel-Maksoud, Steden, and Hundemer 2010

and velocity ratios they experience at different speeds and loads. This substantially complicates the challenge of designing a duct that performs well across a wide speed range. This is illustrated for the case of a waterjet in Bulten 2006, p. 20. Equivalent complexities occur in pumpjets operating in low speed ranges (2-6kt, where flow separation occurs ahead of the impeller, inside the shroud. In the case of an accelerating duct, this phenomenon is also observed on the outside of the shroud at high advance ratios (the equivalent of low speeds and low loads) as shown and discussed in some detail in Willemsen 2013.

In addition, the substantial reduction in the length of the shroud, both ahead of and behind the rotor, will also have the substantial effect of diminishing any acoustic sheilding which the duct may achieve.

6.6.4 Summary remarks on potential for redesign of pumpjet for low-speed conditions

Overall, while the parameter-space for the alteration of marine-propulsors is large, the parameters which would allow for very dramatic rather than minor changes to propulsor efficiency at low speed are relatively few. The major ones include increasing the width of the intake, decreasing the length of the duct, and decreasing the pressure inrease at the blades achieved by the duct. In short, it involves evolving the pumpjet back towards a propeller. None of these changes could be effected to a substantial degree without some inevitable trade-off in terms of the cavitation performance of the system at higher speeds.

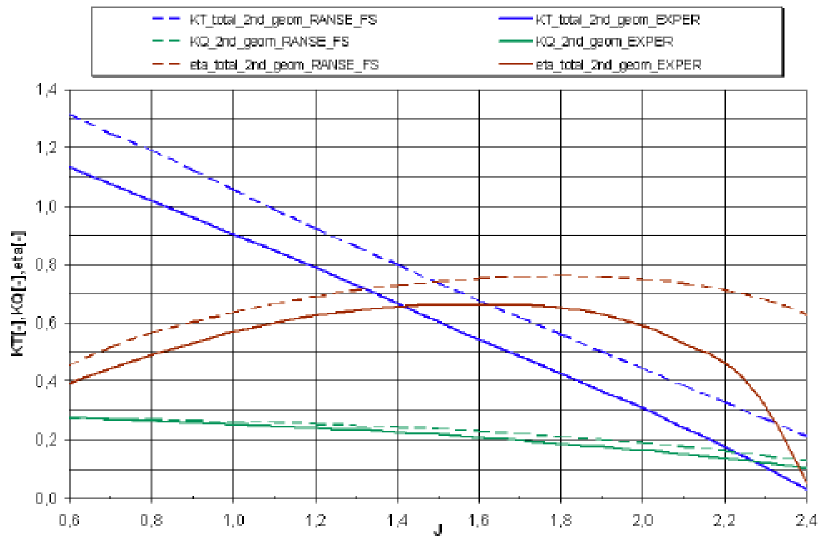


Figure 29: Measured and calculated (fullscale) hydrodynamic performance for the 2nd geometry.

Figure 35: In experimental testing such designs still exhibit sharply falling effiency at high advance ratios, or low speed. Credit: Abdel-Maksoud, Steden, and Hundemer 2010

7 Model Structures and Assumptions

7.1 Mathematical Structure

The core of the model rests upon the assumption that drag increases with the square of the velocity of the submarine. This is a widely used assumption for fully submerged objects subject to turbulent flows (Wislicenus 1973, p. 5), (Davies 2017), as also discussed in earlier sections. Given that the amount of work done (energy consumed) by a system is equal to the distance over which it acts, which scales with speed also, we assume that the Effective Power P_E (also known as Towing Power) required for propulsion to meet a given speed v can be given by Equation 5, where C_d represents a drag constant.

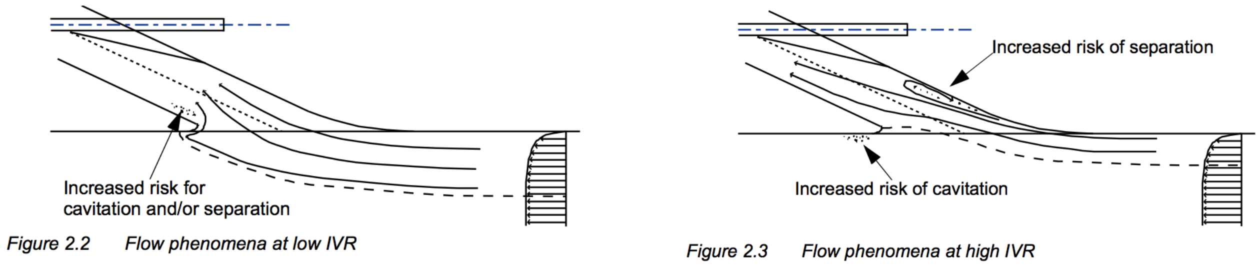
$$P_E = C_d v^3 \tag{5}$$

The power drawn by the propulsion P_D is assumed simply to be the by the Effective Power divided by propulsive efficiency at any given speed η_v as given in Equation 6. Using a plausible efficiency assumption and total power required, Equation 6 can be used to solve for the constant C_d. Other efficiency factors, such as the efficiency of electric motors or hull efficiency factors are assumed to be either relatively small, or essentially similar between submarines which might be conventionally powered but with a jet or propeller being the main point of difference. Hence the total power consumed by the submarine is given by Equation 7.

$$P_D = \frac{P_E}{\eta_v} \tag{6}$$

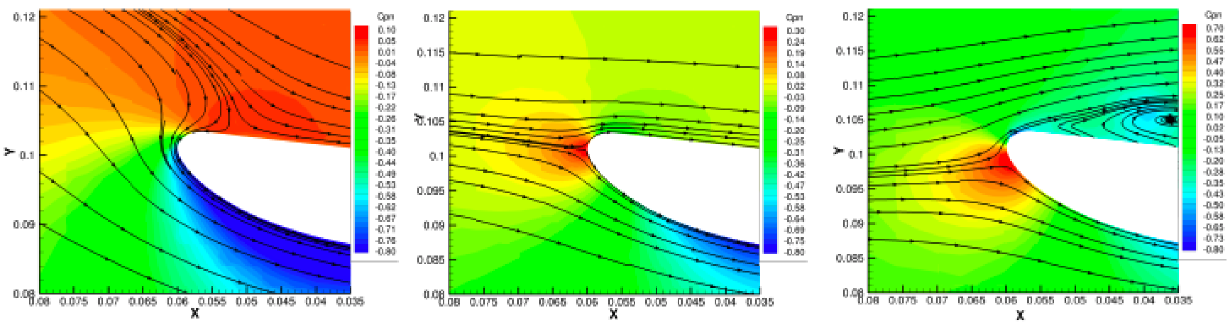
$$P_T = P_D + H \tag{7}$$

With this relationship defined across the speed range, it is elementary to calculate the time that a given speed could be sustained based on a finite energy store (endurance) and the distance covered in this time (range). This provides the fundamental structure that underlies the model which is used to assess the dived range and enurance of conventionally powered submarines, without using air independent propulsion (AIP).



(a) (b)

Figure 36: (a) A an intake may experience risks of flow separation even at low speeds (Inlet Velocity Ratio) on some surfaces due to certain flow deflections being more severe. (b) A an intake may experience risk of flow separation on different surfaces at high speeds (Inlet Velocity Ratio) where other flow deflections are more severe. Source: Bulten 2006



(a) J=0.20 **(b)** J=0.50 **(c)** J=0.80

Figure 37: Flow separation occurs at on the outside of an accelerating duct at high J values, which corresponds to low loads, or speeds. For high J values, the pressure reduction on the inside of the duct, creating positive duct thrust, can be seen. Source: Willemsen 2013, p. 73

7.2 Efficiency Curve Assumptions

In order to begin to model the likely impact of propulsion system choices on system peformance characteristics such as dived range and endurance, it is necessary to adopt some plausible curves indicating likely levels of efficiency across the operating speed range, in this case assumed to be up to 20kt.In this case, three possible curves have been selected for each system, representing a high, low, and central assumption for each, with peak efficiency for the propeller at about 65% at near 5kt, and jet efficiency around 27% at the sames speed.

The central assumption has been taken in both cases from the study undertaken by BMT and Rolls Royce, as in Giles et al. 2010, and indicated in 18, since this represents the most direct comparison made as a simple function of waterspeed, with comparable technologies. It is probable that the pumpjet of the submarine will be a purely axial-flow pump, as opposed to a mixed-flow pump, but this difference in turbomachinery is unlikely to result in a substantial loss of propulsor efficiency, as discussed in Section 5.3. Having the outflow of the waterjet released entirely underneath the surface (as opposed to just above it, in the case of most waterjets) certainly removes the most substantive difference that might drive significant changes in the flow-rates, diameters, and other significant determinants of the machinery characteristics that might normally distinguish different types of pumps. In addition, the intake duct may be somewhat longer, increasing duct losses, but the degree of diffusion in the duct may be lower, reducing the adverse pressure gradient. In other words, it is plausible that different individual components may incur quite different levels of certain types of losses, but it is unlikely that the overall efficiency profile of the system as a whole is dramatically altered assuming competent design, since an enclosed intake controlling the waterspeed at the impeller, and contracting nozzle beyond will remain common features of both. Indeed, it is difficult to imagine why the US Navy, having already attempted a pure axial-flow pumpjet directly in place of propellers

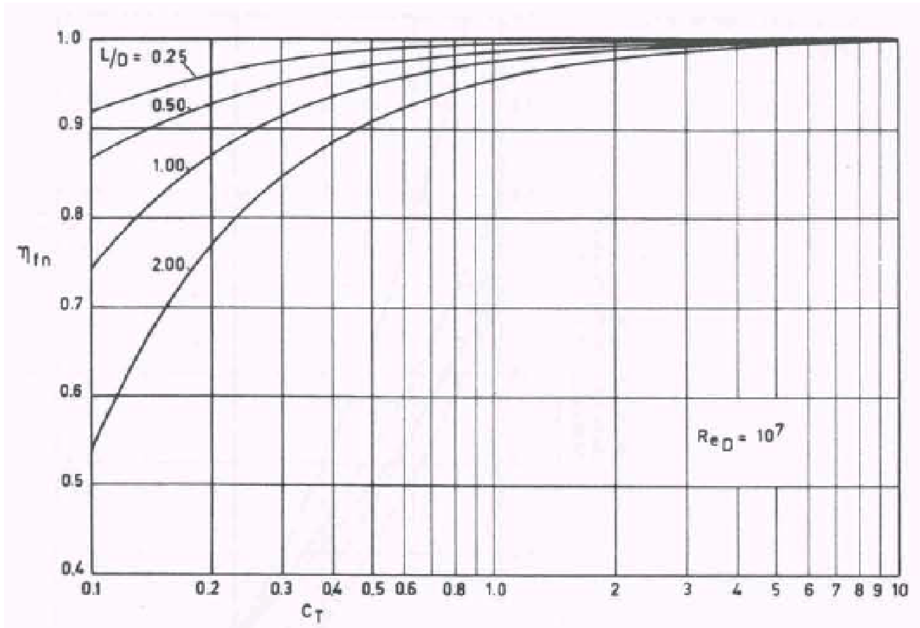


FIG. 10. Efficiency factor due to frictional nozzle drag of ducted propeller.

Figure 38: Dramatically reducing the length of a duct relative to its diameter (L/D) as shown in Oosterveld 1970 can reduce its drag, which has the most significant impact at low thrusts or speeds.

for similar ship for the same purpose (reduction of cavitation-induced noise for Anti-Submarine Warfare) in 1965 (Harvie 1965), would support a study 40 years later using a pump type that was expected to have substantially reduced efficiency at the intended operating speeds.

Small design difference between the propellers used on submarines and surface ships may also exsit. It is probable that the the ship propeller would have five blades, where the submarine would likely have seven or nine. However, being for a warship designed to travel at similar speeds to those that a nuclear submarine might, with relatively unconstrained propeller size, the impact of the propeller difference here are is still likely to be very small relative to the contrast with jets.

Overall, however, its considered that having an experimentally verified curve comparing very similar technologies as a direct function of waterspeed, on vessels attempting to optimise for the same characteristic (reduced noise induced by cavitation) provides a far more certain basis for comparison than attempting to derive efficiency curves *ab initio* using theortical dimensionless factors corresponding and our best estimate of a more likely precise design.

Variations from this central line have been made with consideration for some plausible trade-offs errors, which are intended to be indicative of magnitude possible unknowns in system design and their likely impact. In the case of the 'high' pumpjet assumption, it is assume that a substantially larger intake area has been chosen in order to achieve higher efficiencies at lower speeds, at the cost of peak ideal efficiency, which might be realised not too far above 20kt for such a design. The low assumption for the pumpjet is still represents higher efficiencies at equivalent speeds than those given in Fujisawa 1995 for a waterjet. It is assumed that for both the central and low pumpjet curves, peak efficiency would not be achieved until a speed considerably above 20kt. All of the efficiency curves reflect a smaller decline in efficiency than the indicative assumption used by Andrew Davies, namely that efficiency might reduce by a factor of four between transit and patrol speeds, if those speeds also differed by a factor of four Davies 2017.

The higher assumption curve used for the propeller approaches a maximum of just under 72%. This performance would not be implausible if a specialised propeller was adopted specificially to deliver peak performance at around this speed. Advanced flexible composite propellers, such as those used by the German submarine builder TKMS (Durrant 2017), are able to achieve very high efficiencies, as well as delayed onset of cavitation, by allowing the blades to deform in certain ways to adapt to their specific degree of loading (Young and Liu 2007). Such propellers have been observed in experiment to have propulsive efficiencies above 70% (Young 2007). In this case I have assumed that this design necessitates the trade-off of steadily declining efficiencies over 10kt, considerably below the speed for which most open propellers are optimised. Given the ability for composite propellers to adapt their shape as loads increase, it is actually likely that the performance curve in this case is actually far broader. However, assuming a trade-off in this case also facilitates a scenario whereby the efficiencies of a propeller and jet actually cross over at around 18kt, which is relevant to consider, since experts in discussion have ruled out the possibility that a jet could be more efficient at lower speeds than this.

The lower propeller curve shows efficiency still increasing up to around 65% at 20kt, which might be consistent with a propeller optimised for conventional ship speeds, but probably not likely for a specialised submarine propeller. For all propeller curves, sharply declining efficiency has been assumed at very low speeds, (2kt or less), in order to reflect the dip seen below 5kt in the efficiency curve seen in Figure 19, assuming that this is driven by the decline in efficiency shown in Figure 29 at advance ratios approaching 1. This has been exaccerbated beyond realistic levels in the case of the the low propeller assumption line for the sake of testing sensitivity more dramatically to some losses in this regime. It is unlikely that a state-of-the-art submarine propeller would not be able to attain maximum efficiencies between 5 and 15kt, unless some other significant factor not discussed in this paper affects propellers in these regimes. At very low speeds, some small but sudden changes in efficiency may be possible in either direction, particularly as complex effect with multiple overlaid effects take place, for example increasing laminar flow over the propeller blades leading to lower frictional losses, but potentially greater separation. However, on balance, the low propeller curve is considered relatively unlikely, but useful for investigating sensitivity to errors or adjustments.

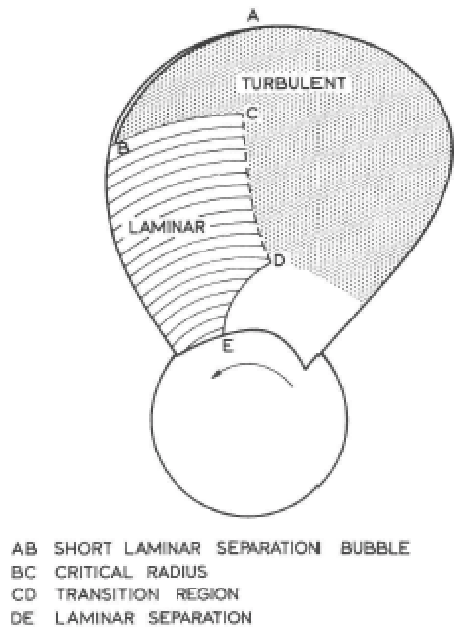


Figure 39: At very low speeds changes in regimes such as an increase in laminar flow over the blade section could lead to small changes in efficiency, perhaps explaining the distinct rise at low speeds for the properller at 5kt in Figure 19

These efficiency curve assumptions are shown in Figure 40.

7.3 Hotel Load Assumptions

It is also required that some assumptions are made about the hotel load, or the power which the submarine requires which doesn't go to propulsion. We might assume that this is in the order of 100kw, as suggested in Martinez 1995 though official sources of information are scarce. It is also likely that the actual hotel load varies considerably as different systems are switched on and off, some of which might be discretionary in combat scenarios (e.g. hot water for washing), and others (such as the combat systems) might have increased demand during crucial phases of combat operations. It is important to note that the combat system that has been selected for Australias FSM, the AN/BYG-1, is designed for a nuclear submarine, and is reportedly consumes considerably more power than other

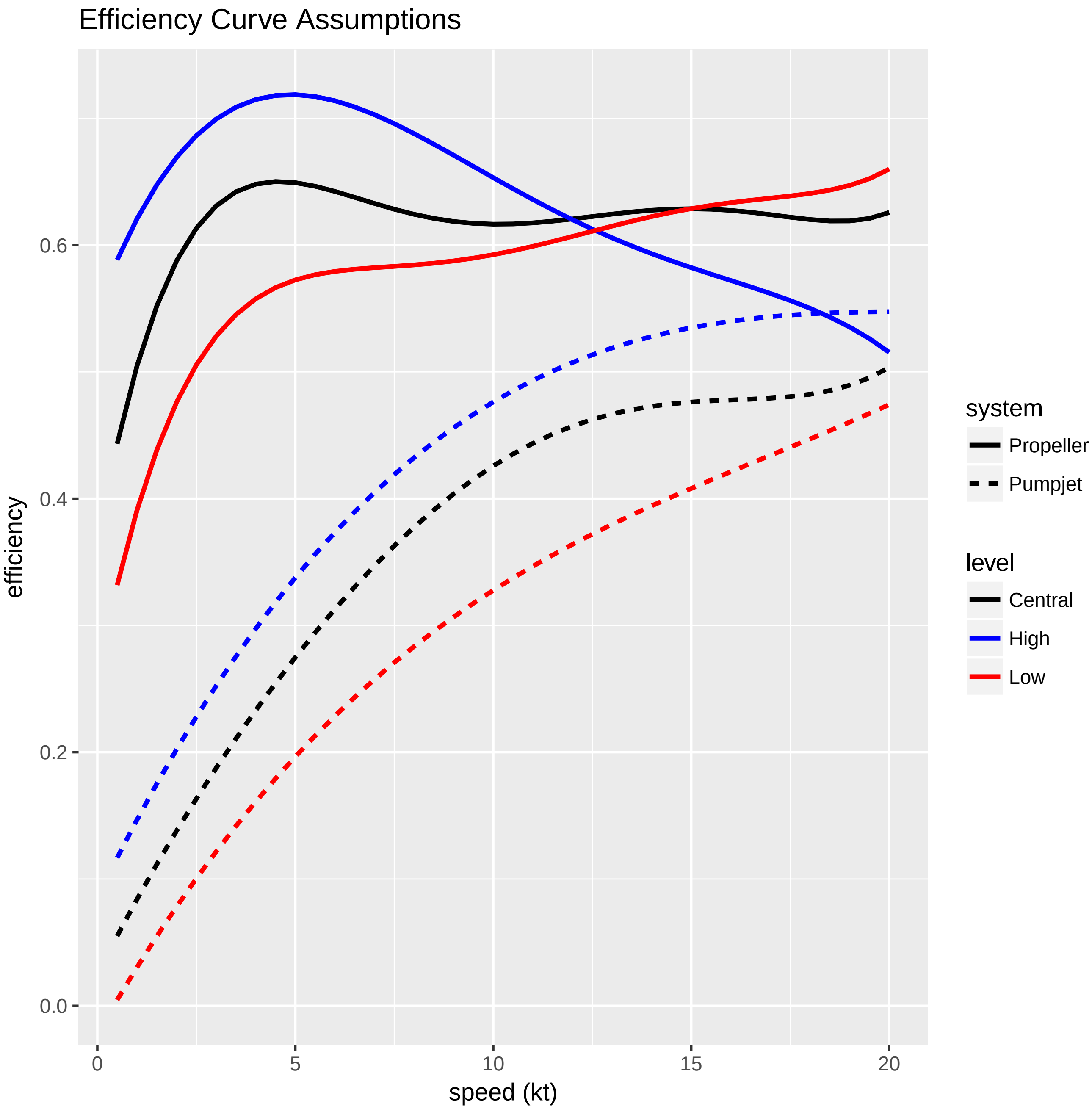


Figure 40: A range of possible efficiency curves for pumpjets and propellers to be modeled

systems Muir 2015, apparently even in the order of 100kW more. Patrick 2011. Consequently, the actual hotel load experienced might vary considerably, and as such the model used in the app allows the hotel load assumption to be varied, in order to test sensitivity to this parameter. A flat 100kW hotel load is used as a starting assumption in the initial calculations in this paper, and some sensitivity analysis is given at half and double this power, to give an indication of the impact of plausible alternative energy demands dependent on operational circumstances, and choice of combat system.

7.4 Battery Assumptions

Since the purpose of the task at hand is to assess dived endurance only, this model focuses on a single energy store simulated by a total embarked mass (battery bank) and an energy density of those batteries. Since the SEA 1000 project has elected not to use lithium electric batteries, the energy density of the batteries can be assumed to be that of lead-acid batteries, which are known to be in the region of 30-50Wh/kg (Watt-hours per kilogram). Taking a central figure and converting this to Megajoules per kilogram (MJ/kg) we assume 0.14MJ/kg to be the effective energy density of lead acid batteries for our test submarine's purposes. This parameter can be adjusted easily for sensitivity testing, and in our case this will be adjusted to half, and double this energy density, noting that lead-acid batteries become much slower to charge as their charge level passes 80%, and consequently it may be the case that only 50% of their available capacity might be genuinely available for tactical purposes (Briggs 2016).

It is worthwhile considering that alternative types of battery may be on offer for submarines. In particular, lithium ion batteries have been selected by Norway in a selection process which happend almost concurrently with Australia's (Ohff 2017a), and would probably have been on offer to Australia if they had been sought. Precise energy density of these batteries is not publically available. For domestic uses such as handheld electronics or solar power applications, lithium ion batteries may have 3-5 times the energy density of lead-acid batteries (O'Connor 2017). However, the actual useful density of lithium ion batteries can vary widely depending on different chemistries and designs. It might be assumed that for very large battery banks (such as submarines) where the stability of the battery bank is of critical importance, maximum density migth be sacrificed in favour of additional safety systems, such as increased monitoring, as well as spacing and insulation barriers between cells, in order to prevent thermal runaway in one cell leading to a catastrophic fire. The realistic energy density advantage that might be obtained as been suggested to lying closer to a factor of two or slightly less (Greenfield 2016).

The total embarked load of the batteries is not a well-known public figure, though it is likely to be several hundred tonnes in order to provide the likely desired levels of dived endurance. It has been suggested publically that the approximately 700 tonnes might be required for the Shortfin Barracuda (Ohff 2017b). This would appear to be quite a large fraction of the plausible payload of a submarine, even of over 4000 tonnes displacement, given that a great deal of the potential displacement will be taken by the thick steel involved in constructing a pressure vessel (probably at least a thousand tonnes per submarine) (Jean 2017). 500 tonnes of batteries has been assumed as a nominal figure for these purposes. Given that the mass of batteries embarked has only a direct and linear relationship with the dived range and endurance, no sensitivity testing will be undertaken on this variable. Proportional changes to the energy density of the batteries will have equivalent effect for the purposes of measuring the impact on performance. Consideration of likely impacts on space, and hull-resizing, and associated drag are beyond the scope of this paper.

7.5 Drag Coefficient of Hull

In the online version of the web-app, alternative reference points or known facts relating a given power output to a speed can be used in order to solve for this constant C_d. For instance, one might assume (as done by Davies 2017) that the hotel load might match the propulsive demand at some given speed, for some given hotel load. However, given that the precise hotel load is generally not known and highly variable, and the potential for the different systems to have widely varying propulsive efficiencies at low speeds, this method is subject to very wide error margins.

Given that any known power consumption level and speed match can be used as a reference, I have chosen instead to use the probable power consumption at top speed, both of which we have some indication of, and given that propulsive efficiencies of the two systems are likely to be much closer at this speed, there will be less error in likely comparisons between different design concepts. It is known that the a early German designs for a plausible submarine for SEA 1000 included a 6MW electric motor (Patrick 2015), and the Shortfin Barracuda of Naval Group is often referred to as having a 7MW electric motor (Ohff 2017b) (Coates 2016), with top speeds ”¿20kt”. Given the nature of increasing drag at high speeds, it seems unlikely that top speeds will be very far above 20kt. Hence, in this model we have assumed that 20kt will be obtained with the ouput of 6.5MW.

Considerable confirmation that these assumptions are realistic can be made by assessing the endurance of the submarines under the model with other known reference points. For the central curves, we obtain a dived endurance betwen 60 and 100 hours for both systems at 5kt, reflecting nearly exactly the range of other public estimates of dived enurances endurances which other modern diesel-electric submarines operating only with batteries (Buckingham, Hodge, and Hardy 2008, p. 3) at around 4kt. Given that somewhat larger submarines might be somewhat assisted in this respect because their overall volume/surface ratio is slightly higher, this gives confirmation that the model is overall quite realistic in its magnitudes at the most important speeds. The sames sources also suggests that the same submarines achieve endurances of around 1-2 hours at 20kt, which also confirms that the relationship in our model linking differnt speeds is also in agreement with other models.

8 Results and Discussion

8.1 Power Demand

As part of the calculation of results for each pair of efficiency curves, the power requirements of each respective component (propulsion for the two respective systems, as well as effective power required, and hote load) can be plotted to ensure that realistic results are obtained, which is important for selecting plausible values for the constant C_d. For the central efficiency curves, we can show the resultant power curves for the the assumed values of battery load, energy density, and hotel load, as seen in Figure 41.

It can be seen here that one of Andrew Davies assumptions, regarding hotel load matching propulsion power demand at patrol speeds, might match quite closely with our assumptions at a patrol speed of 4kt for the case of a pumpjet. It also shows the remarkable impact of the square law on power demands, particularly their effect at low speeds. At just a few kt, an entire submarine might be propelled by a power level comfortably produced by a large family car. This gives further explains why it is that efficiencies of propulsion systems aren't routinely discussed at dramatically lowered speeds. Even for jets which have efficiencies which decline much faster than those we've assumed (for example in Fujisawa 1995), the reduction in power demanded falls substantially faster than efficiency. Consequently, at low speeds nothing dramatic occurs to make the declining efficiencies of consequence to operators. It is often still more economical for such vessels to travel very slowly, well outside the ideal performance range of their propulsion systems, simply because of the drag on the hull.

Overall, this chart is consistent with expectation, and confirms that a plausible value of C_d has been selected under these assumptions.

8.2 Central Results

The plots comparing the resultant endurance and range calculations across the speed range considered are in Figures 42, 43, 44 and 45. In all cases, the comparison for the central efficiency curves have been replotted centrally, in order to highlight varience under each of the different assumption comparisons.

It is clear that under the central assumptions, the declining efficiency of the pumpjet has a very significant impact on range and endurance, particularly at speeds around 4-8kt. It might be noted that under the central assumption, the propeller system achieves 138 hours of dived endurance at 4kt where the pumpjet only manages 91 hours dived endurance at this speed. Consequently, at a likely patrol speed, the difference amounts of almost exactly two days in dived endurance. One might presume that such a difference is of some considerable tactical significance. In order to match the propeller's dived endurance, the pumpjet submarine would need to slow to 2.5kt.

The phenomenon manifests itself in a very substantial reduction in the overall range that can be achieved submerged, and a difference between the speed at which maximum range can be achieved. Under central assumptions, the propeller driven submarine can reach over 540nm at any speed between 4 and 5kt. The pumpjet driven submarine reaches over 360nm between 3 and 6kt. A difference of 180nm dived range would presumeably be of considerable tactical significance.

8.3 Sensitivity of Curve Selection

As can be seen from the comprehensive comparison in Figures 42, 43, 44 and 45, the shape of curves selected has very different levels of impact at different speeds. Key observations include how small the impact of efficiency variation to either curves tends to be at very low speeds (under 2kt). This is due to hotel load becoming clearly dominant at such speeds. The relative difference between the lines also diminishes somewhat towards higher speeds. More striking, however, is the very dramatic reduction in both range and endurance at higher speeds. At a speed of 20kt, a propeller driven sumbarine might manage to remain dived for 3.6 hours according to these assumptions, where a pumpjet driven submarine might manage just under 3 hours. A difference of about half an hour would presumeably be of less tactical significance. At any speed above 10kt, neither submarine would be able to remain dived for much more than 24 hours (25.4 hours for the propeller system, 18.3 for the jet).

It should also be noted that these results, and those around 8kt, can also provide some insight into likely snorting intervals and indiscretion ratios. As given in Patrick 2015, submarines tend to carry diesel power capacity that approaches their main motor power. Whilst the difference between the two systems still appears very significant at these speeds, it appears that if transits occur in the region of 8-10kt, snorts might occurr roughly daily, and last a number of hours. The indiscretion ratio during commute of the jet system would be significantly impaired

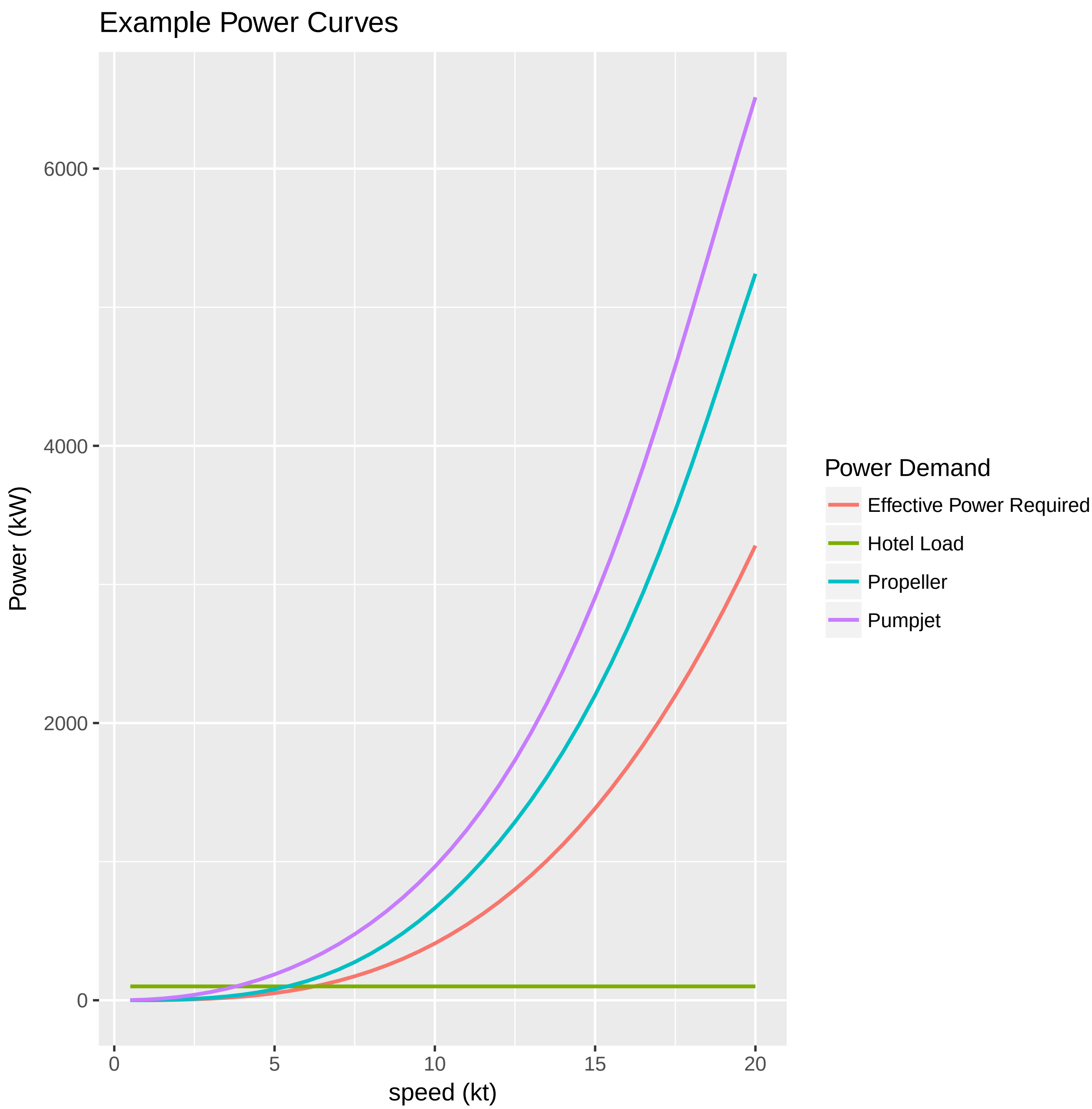


Figure 41: With central assumptions, a pumpjet powered submarine reaches 20kt with 6.5MW of delivered power. Hotel load matches propulsion power demand around or below 5kt.

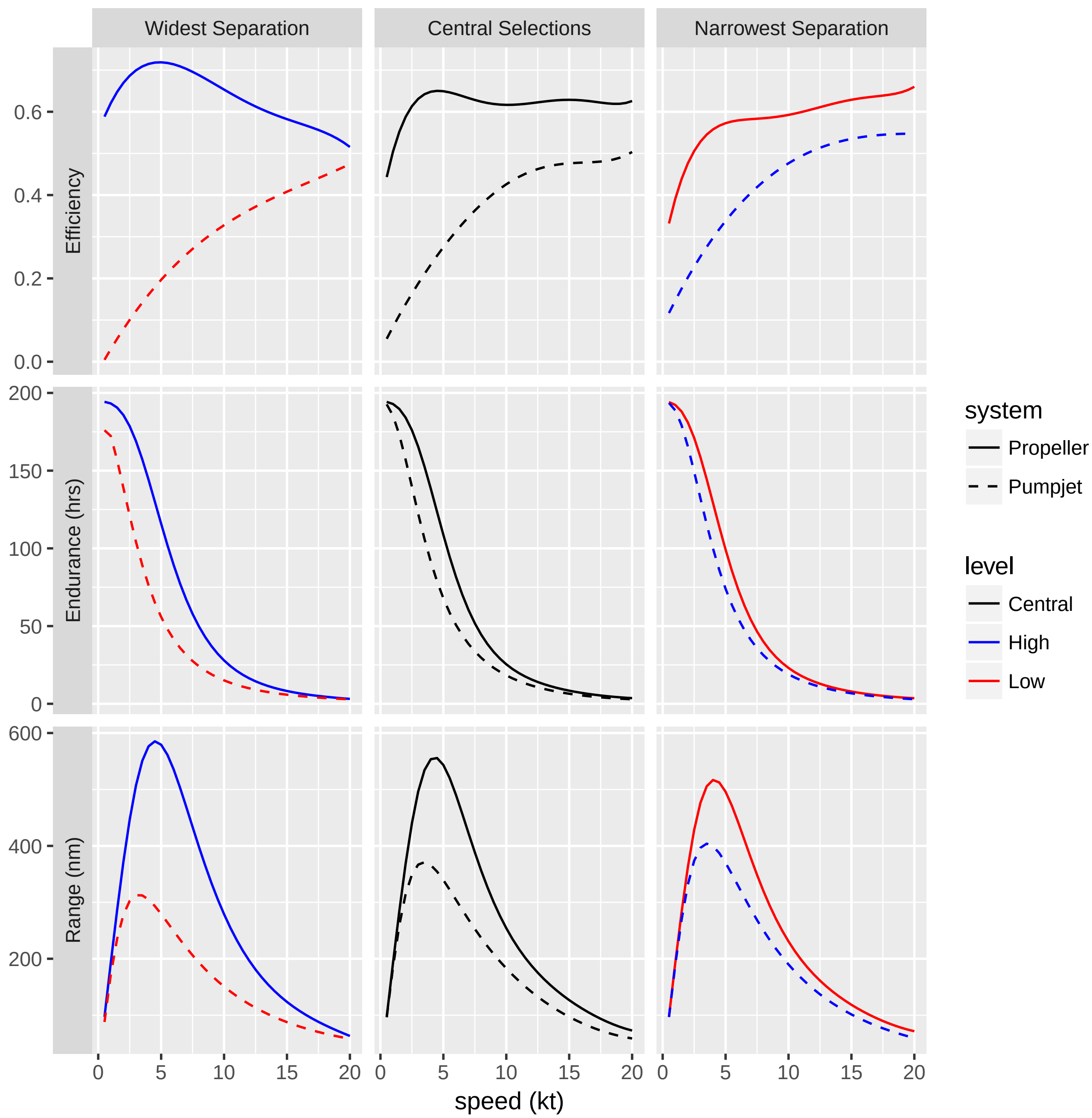


Figure 42: The most extreme and central assumptions are compared

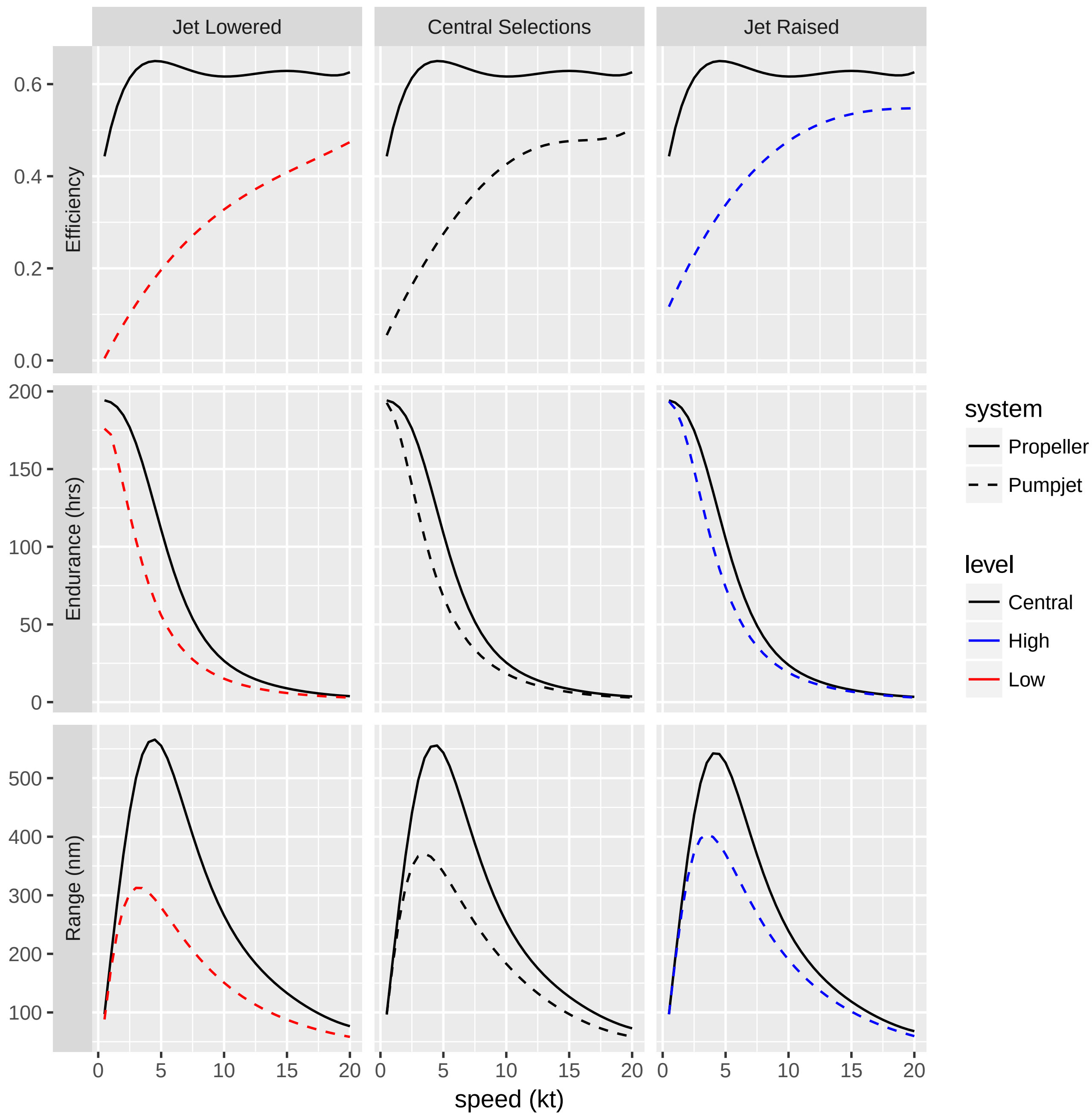


Figure 43: The impact of different jet efficiency assumptions compared to the central propeller curve shows wide variance

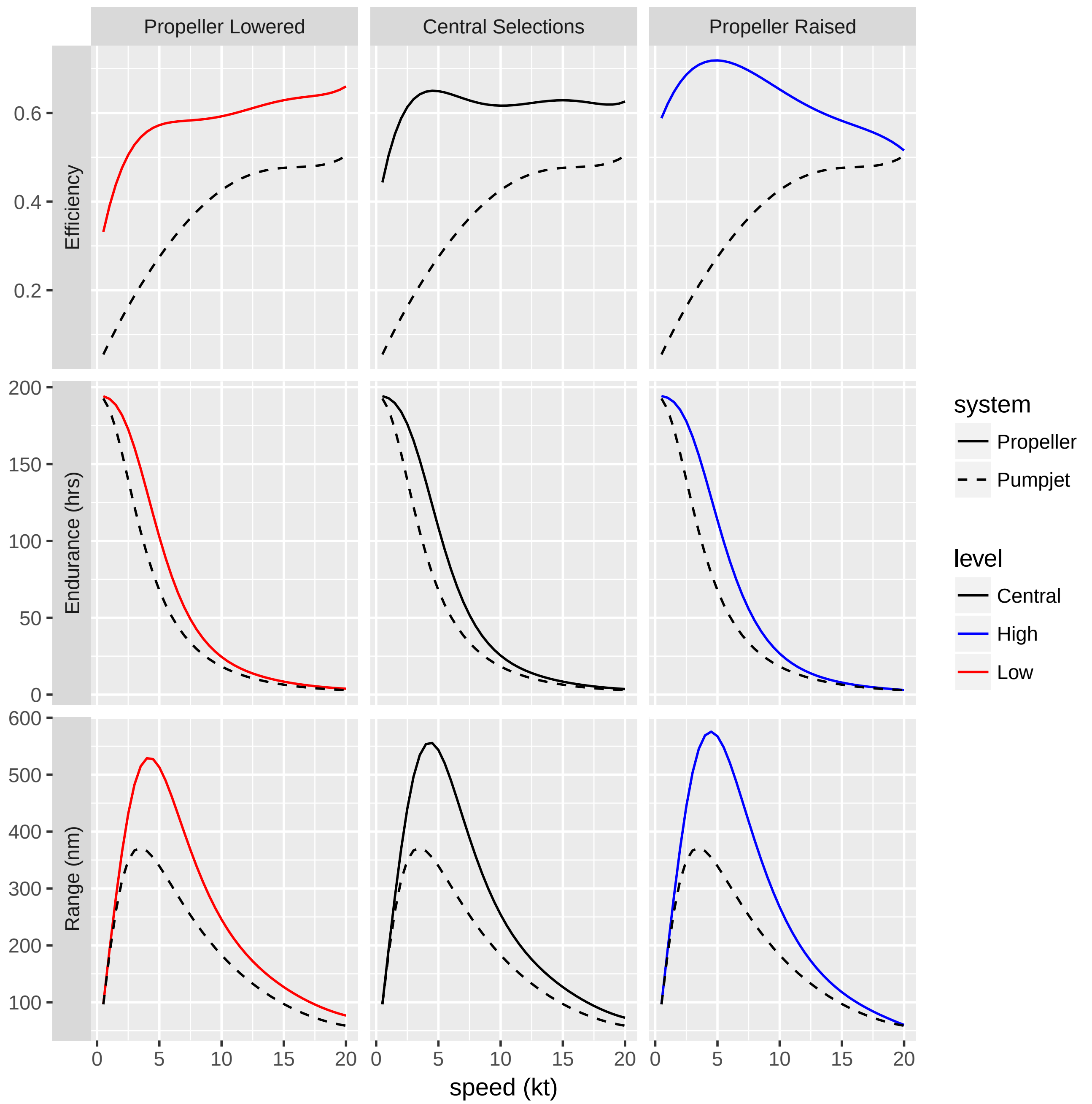


Figure 44: The impact of different propeller efficiency assumptions compared to the central pumpjet curve shows less variance

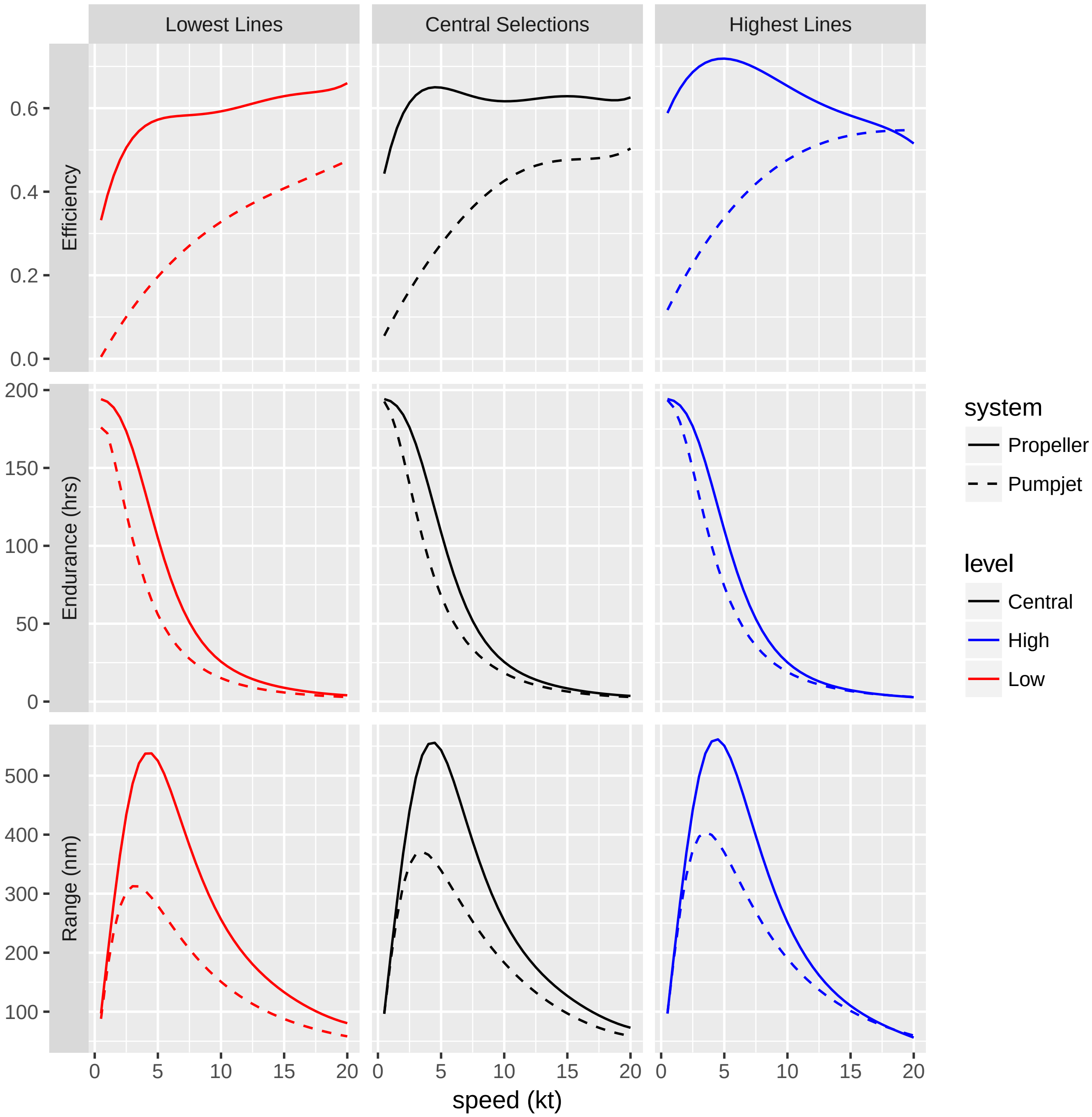


Figure 45: Comparing the lower and higher lines for both systems together

given the substantially larger power demands at transit speeds, though a detailed calculation and comparison lies outside the scope of this paper.

It seems extremely clear from these conclusions that the general results confirm very strongly that the impact of the propulsion system is likely to be of the greatest importance in the speed range 3-8kt, where propulsion power is more significant relative to hotel load, but excessive drag does not prohibit significant dives.

A further feature of the results is that the relative difference in performance is much more sensitive to changes in the efficiency of the jet at the relevant speeds, owing to their larger proportional impact at low efficiencies. Whilst a smoothly declining efficiency curve from around or over 50% at 20kt to zero at 0kt might seem moderately well defined, the precise path taken, particularly the exact level around 3-8kt, is of great importance, substantially more than plausible variations in the propeller curve. This can be seen in an overlaid plot of the proportional differences in total power demand (hence endurance and range) for the different pairs of curves as in Figure 46.

The proportional change in overall power requirement (directly determining both range and endurance) shows that in the central scenario a propeller driven submarine would have more than 60% advantage in terms of range and endurance around 5-6kt. It is interesting to note that the proportional change is greatest slightly above the speed where maximum range is achieved, and the point of peak advantage moves steadily towards higher speeds as the difference in efficiency between the systems increases.

As can be seen, even compared to the central propeller curve, choosing a jet efficiency curve somewhat lower than the central assumption means that the peak difference immediately jumps to over 100%, or effectively allow a propeller powered submarine to achieve double the range and endurance of a pumpjet powered submarine at those speeds. It is interesting to note that these speeds in include those speeds which might lie near the maximum speeds that could be sustained by Air Independent Propulsion (AIP) systems (Stanford 2017, p. 100). Consequently, it is likely that a conventional submarine that used pumpjets might only achieve a fraction of the dived range and endurance enhancements generally expected on propeller powered submarines which employ this technology, as will be discussed later.

The proportional improvements will also be effective rough guides to the likely impact on indescretion ratios and overall range.[4] Near patrol speed almost all scenarios show a difference approaching or exceeding 50%, which will have a material impact on indescretion rates during all combat operations.

Perhaps surprisingly, the impact at transit speeds is still quite significant, with no scenarios showing less than 20% advantage around 8-10kt. The sensitivity to pumpjet efficiency here is also very high, with three scenarios showing an impact of over 70%. Given the likelihood that a submarine's average speed over its range is likely to be dominated by its transit speed, this indicates that the choice of a pumpjet propulsion system will also result in a substantial reduction in the overall range of the submarine, quite probably in the range of between 25-50%. This would require the embarkation of significantly larger volumes of diesel to meet minimum range requirements, and also contribute to higher running costs.

8.4 Sensitivity to Hotel Load

As can be seen in Figure 47 the difference between the two systems is very sensitive to changes in hotel load, both in proportional and nominal terms. The impact of halving the hotel load from 100kw to 50kw more than doubles the *difference* between a pumpjet and propeller dived endurances, from around two days to well over four days at speeds between 2.5 and 3.5kt. In the context of a submarine which might have a nominal dived requirement at patrol speeds in the order of several days, this suggests that extremely large gains can be made by reducing hotel load. Increasing the hotel load has the noticeable effect of pushing the speed of largest difference to higher speeds, and substantially reducing the total difference. If the hotel load was doubled to 200kW, the middle efficiency curve pair would still see a difference of nearly a day between the two systems, or around 19.5 hours at speeds of 4.5-5 kts.

The difference between pumpjet and propeller propulsion systems in terms of range tends to be found at slightly higher speeds, though this point also moves towards higher speeds as hotel load increases. With a reduced hotel load of 50kw, the difference between the two systems in the middle scenario is about 370nm for speeds 3.5-4.5kt, substantially greater than the 200nm around 4.5-5.5kt at a hotel load of 100kW.

Changes in the effective battery energy density will have the same effect as having larger masses of battery stored. They equivalently impact the total amount of energy available for consumption before recharging batteries while snorkeling. There is therefore no shift in the proportional impact on range and endurance due to this factor,

[4] Additional considerations including the size and efficiency of the diesel engines and generators must be included for proper analyses of indescretion ratios, which will not be given here.

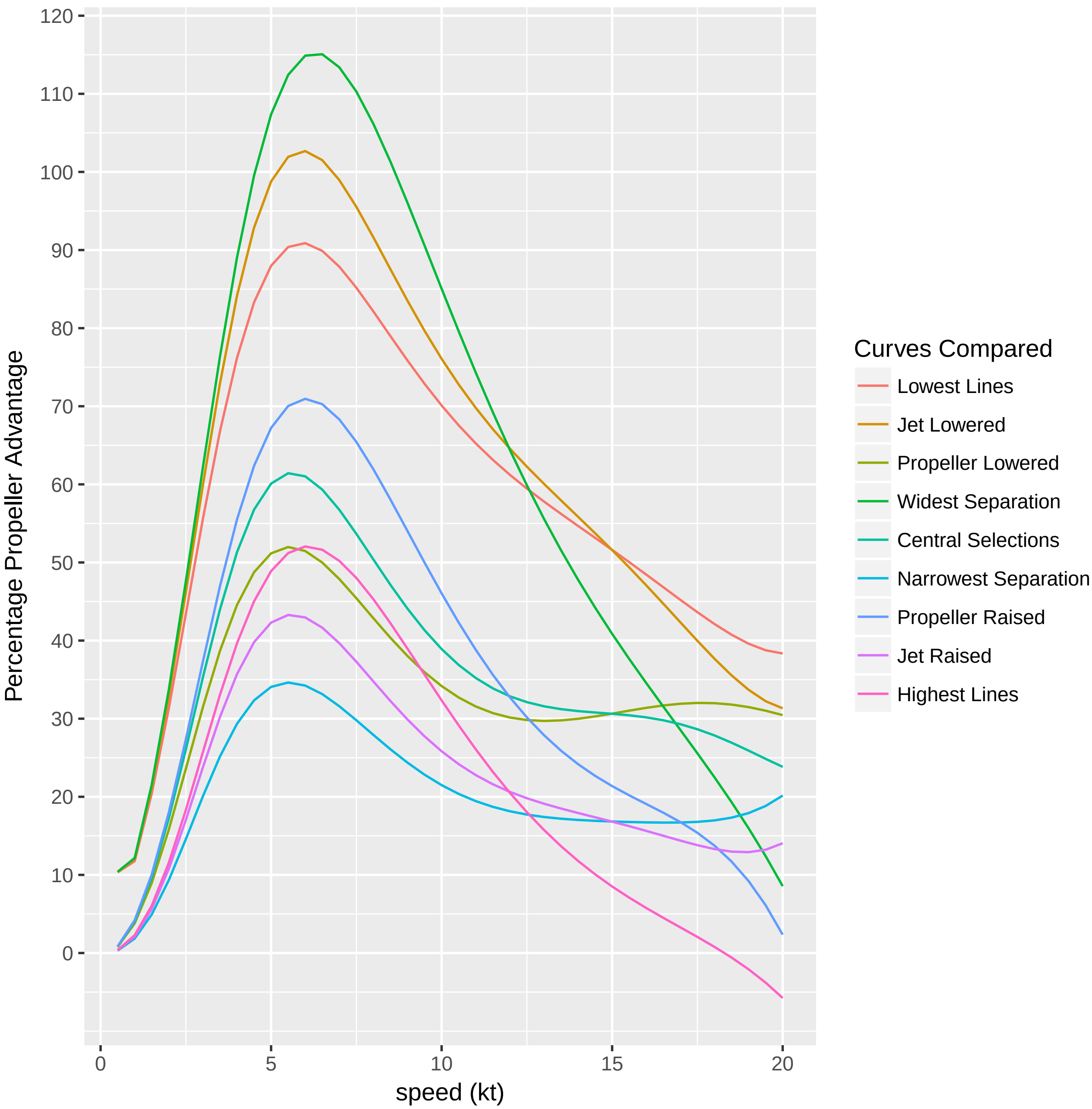


Figure 46: The most proportional differences between the propeller and pumpjet performances for a range of assumptions

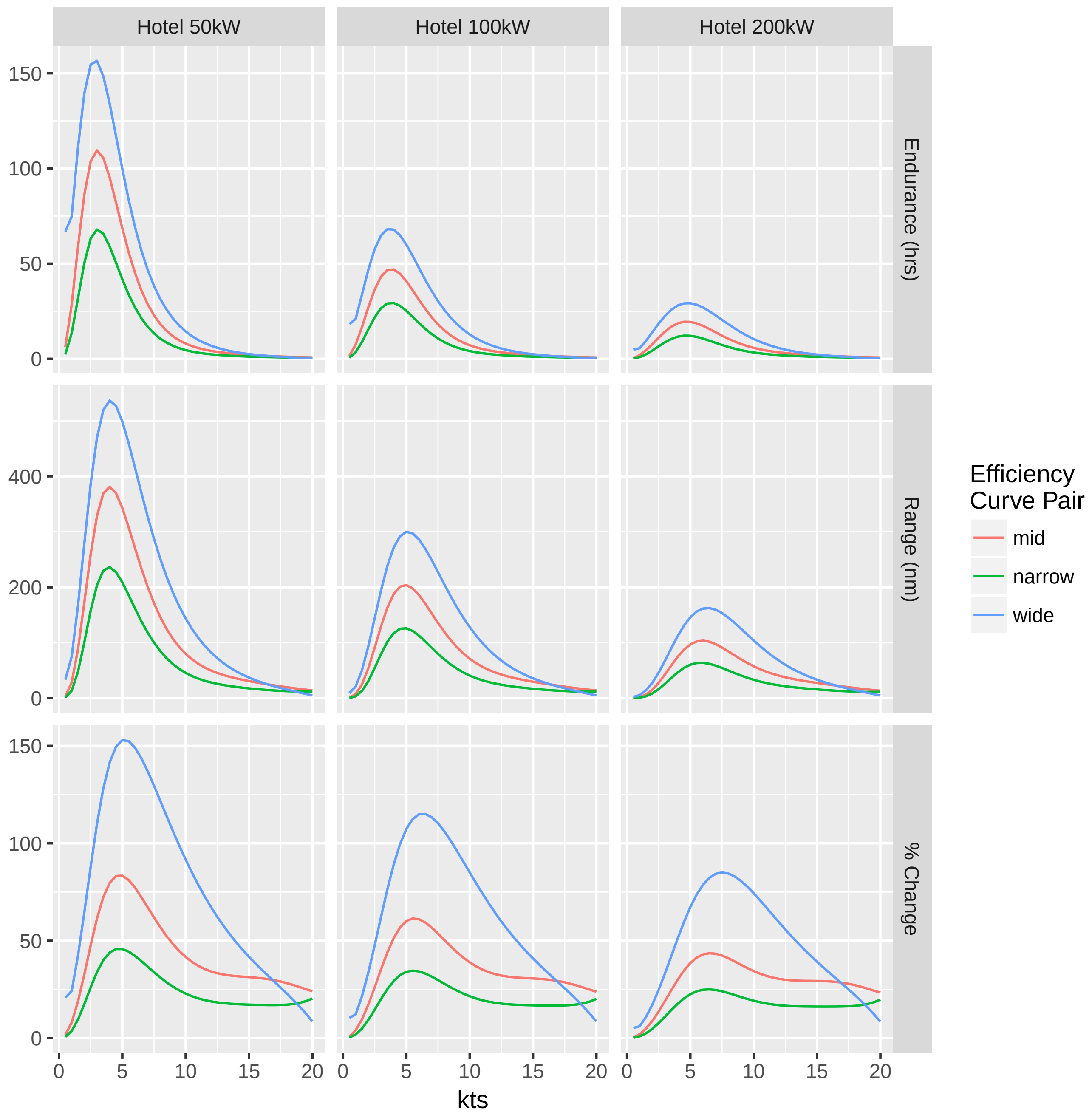


Figure 47: The impact of the propulsion system efficiencies are very sensitive to changes in the hotel load, including as a proportion.

as can be seen in the lower graphs in Figure 48. The nominal impact, however increases directly and linearly with the total energy stored.

The results in nominal terms are striking in their magnitude. In terms of enduracy, doubling the stored electrical energy, for example by adopting lithium batteries, increase the *difference* between the two systems under the central efficiency curve assumptions to nearly four days (93 hours) at 4kt. Given that most modern, capable submarines are estimated to only be able to achieve dived endurances between 60 and 100 hours on batteries at 4kt (Buckingham, Hodge, and Hardy 2008) this cannot be dismissed in terms of its tactical significance. Even under the efficiency curve assumptions representing the narrowest spearation considered, the difference in this case would be 59 hours, almost equal to the estimated dived endurance of a Type-214 operating without AIP.

In terms of submerged range, the same proportional impact is also extremely significant. Doubling the energy stored inceases the *difference* between two otherwise identical submarines to over 400nm under central assumptions at 4.5kt. That's a larger distance than the width of the Java Sea, the most central body of water in the Indonesian Archipelago, or most of the length of the Malacca Strait. The tactical significance of such distances are not likely to be lightly dismissed. If far smaller amounts of energy are embarked, the nominal differences reduce to perhaps 100nm, in direct proportion to the reduction of the submarine's dived endurance. This is still a non-trivial distance in terms of it's tactical signicance, and comprises a substantial fraction of the dived ranges of most non-AIP submarines. It still represents a significant difference in operational terms, equal approximately to the width of Hainan Island, or neraly twice the length of the Sunda Strait.

It is also clear that increasing the hotel load has a greatly diminised impact on the proportional differences between the systems at higher speeds. At very high speeds (e.g. 15kt) changes in the hotel load have almost no impact in proportional terms to the difference, which lies at about 30% in all cases for the central selection of curves. At 9kt, in the region where transit speed is likely to occur, increasing the hotel load by a factor of four (from 50kW to 200kW) only decreases the advantage of the propeller from 48% to 38%. Therefore one might say near certainty that any difference between efficiency around these patrol speeds is likely to have a substantial impact on the overall range of the submarine, with differences of much less than 30% quite unlikely, irrespective of other changes in the submarine design or operation circumstance.

Only brief consideration is given here to the impact of Air Independent Propulsion, which has substantially higher energy densities possible even than Lithium, and also amounts to the addtional embarkation of greater mass. The volumetric energy density of the feedstocks to modern AIP systems (liquid oxygen and methanol) is estimated to be approximately ten times greater than that of lead-acid batteries (Davies 2016), around 4.5MJ/L. Given the greater mass embarked, and additional studies suggesting that at constant speeds they might extend the dived endurance of a modern submarine from around 60 hours to over 1000 hours (a factor of roughly sixteen) (Buckingham, Hodge, and Hardy 2008) an approximate estimation of the the direction and magnitude of this impact may by scaling up energy density by this factor. This would amount to adding three further frames to the right of Figure 48, with the energy density being doubled in each successive frame. This would plausibly (under the central line selections) amount to more than a month of dived endurance *difference* between AIP inclusive submarines with propellers or pumpjets, amounting to thousands of nautical miles of continuously submerged travel. This difference would also now be material in terms of the overall range of the submarine amounting to a further 15-20% reduction in the submarine's overall range.

8.5 Sensitivity to Battery Changes

Changes in the effective battery energy density will have the same effect as having larger masses of battery stored. They simply directly impact the total amount of energy available for consumption before recharging batteries while snorkeling. There is therefore no shift in the proportional impact on range and endurance due to this factor, as can be seen in the lower graphs in Figure 48. The nominal impact, however increases directly and linearly with the total energy stored.

The results in nominal terms are striking in their magnitude. In terms of enduracy, doubling the stored electrical energy, for example by adopting lithium batteries, increase the *difference* between the two systems under the central efficiency curve assumptions to nearly four days (93 hours) at 4kt. Given that most modern, capable submarines are estimated to only be able to achieve dived endurances between 60 and 100 hours on batteries at 4kt (Buckingham, Hodge, and Hardy 2008) this cannot be dismissed in terms of its tactical significance. Even under the eficiency curve assumptions representing the narrowest spearation considered, the difference in this case would be 59 hours, almost equal to the estimated dived endurance of a Type214 operating without AIP.

The in terms of submerged range, the same proportional impact is also extremely significant. Doubling the energy stored inceases the *difference* between two otherwise identical submarines to over 400nm under central

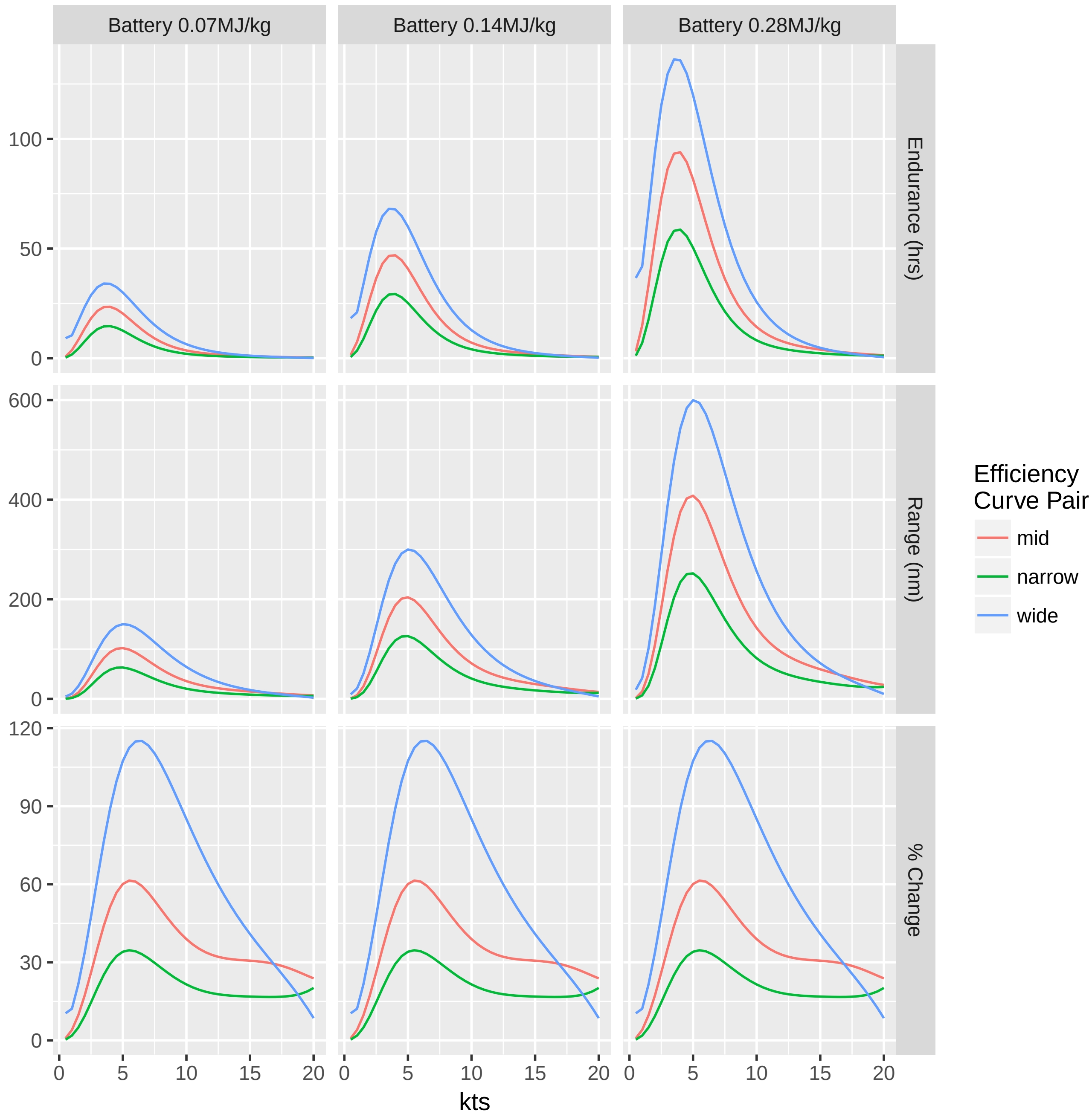


Figure 48: The impact of the propulsion system efficiencies are extremely sensitive to battery energy density (or load) though proportions remain fixed.

assumptions at 4.5kt. That's a larger distance than the width of the Java Sea, the most central body of water in the Indonesian Archipelago, or most of the length of the Malacca Strait. The tactical significance of such distances are not likely to be lightly dismissed. If far smaller amounts of energy are embarked, the nominal differences reduce to perhaps 100nm, in direct proportion to the reduction of the submarine's dived endurance. This is still a non-trivial distance in terms of it's tactical signicance, and comprises a substantial fraction of the dived ranges of most non-AIP submarines. It still represents a significant difference in operational terms, equal approximately to the width of Hainan Island, or neraly twice the length of the Sunda Strait.

The singificant range of different energy density values tested here reflect quite plausibly some of ranges of different energy levels available in operation. For instance, as has been discussed (Briggs 2016; Greenfield 2016), lead acid batteries may well only be able to practically utilise about 50% of their total energy stores for tactical operaions, unless operating in a very low-threat environment and undertaking very slow charging to reach the maximum full charge is possible. In addition, the plausible improvement in enery density of lithium batteries may well be in the order of a factor of two in practice (Greenfield 2016), though theoretical limits of the chemistry suggest much higher may be possible (Davies 2016).

Only brief is given here to the impact of Air Independent Propulsion, which has substantially higher energy densities possible even than Lithium, and also amounts to the addtional embarkation of greater mass. The volumetric energy density of the feedstocks to modern AIP systems (liquid oxygen and methanol) is estimated to be approximately ten times greater than that of lead-acid batteries (Davies 2016), around 4.5MJ/L. Given the greater mass embarked, and additional studies suggesting that at constant speeds they might extend the dived endurance of a modern submarine from around 60 hours to over 1000 hours (a factor of roughly sixteen) an approximate estimation of the the direction and magnitude of this impact may by scaling up energy density by this factor. This would amount to adding three further frames to the right of Figure 48, with the energy density being doubled in each successive frame. This would plausibly (under the central line selections) amount to more than month of dived endurance *difference* between AIP inclusive submarines with propellers or pumpjets, amounting to thousands of nautical miles of continuously submerged travel. This difference would also now be material in terms of the overall range of the submarine amounting to a further 15-20% reduction in the submarine's overall range.

With such massive differences between the performance of the two systems emerging with the presence of the AIP, it is difficult to see how one could realistically consider a pumpjet as being competitive if a direct comparison were made.

8.6 The interaction of hotel load, battery energy density, and efficiency curves

It is interesting to observe how the the combination of changes to the hotel load and battery density interact when altered together, as shown in Figure 49. To the extent that each of these effects contribute to increasing or decreasing the relative difference between the systems, the two clearly combine in a multiplicative fashion.

Where battery density and hotel load are both reduced, the proportional change has a much higher and sharper peak at around 5kt, reaching an 83% peak at 4.5kt under central assumptions. For high hotel load and battery density, the porportional impact is lower at a higher speed, at 43% at 7kt. However, it is intereting to note that the nominal impact of each of these different scenarios is somewhat more similar in magnitude for both endurance and range. For low hotel load and battery store, the endurance difference peaks at 54 hours at 3 kt, and range difference peaks at 190nm at 4kt. For raised hotel loads and battery stores, the difference is shifted to higher speeds and broadened somewhat, with a difference of 39hours at 4-5kt, and 200nm at 5-6kt.

The most striking feature of this figure however is the impact on the submarine's performance when hotel load is lowered, and battery density is raised simultaneously. Here the two factors combined have a proportional impact of around 80% improvement for the switch to propellers under central assumptions, and over 150% in the scenario of widest separation. However, in nominal terms, this impact is even more significant, with central scenarios showing a *difference* of over 200 hours between the two systesm under central assumptions at 3kt, and a range difference of over 750nm. These differences are extremely large, representing plausibly double the expected total ranges and endurances of existing modern diesel-electric submarines. Even if such large changes in hotel load and battery capacity are not simultaneously likely these sensitivitiesquite clearly demonstrate how even modest shifts in both hotel load and battery energy density might combine to have very significant impacts on the appearnce of the pumpjet and propeller comparison. For instance, a hotel load that reduced by 30%, and a battery energy density increase of 40% could plausibly have the impact of doubling the nominal differces between the performance of the two propulsive systems.

This sort of extreme sensitivity ought to have a significant bearing on how the overall performance specifications of the submarine are defined, as seemingly incremental changes to hotel load and electrical energy stores are likely to substantially magnified, or muted, by the choice of propulsion system.

8.7 Indiscretion Ratios

Indiscretion Ratios represent the fraction of time that a submarine must spend on the surface snorting (running diesel engines) in order to maintain a constant speed. In order to calculate the Indiscretion Ratio, it is necessary to know how much power the diesel engines are able to generate when running while snorting, and how much energy (net of any efficiency losses, hotel load, and power drawn to maintain propulsion) can be directed to recharging the batteries. Reliable information regarding the arrangement of engines, generators is not generally available in the public domain. However, from Patrick 2015, it can be seen that credible submarine designs might include diesel engines that have a total capacity in the region of 85% of the maximum power output of the main motor. Assuming that there are some necessary losses in the generation and recharging process, and plausibly some increase in the hotel load for the operation of additional systems, fur the purposes of this assessment it is assumed that while snorting approximately 5MW might be available to meet propulsion and normal hotel load requirements, and any surplus can be directed towards charging batteries.

The fraction of time required to charge the batteries to a given level at a given speed, relative to the amount of time that the batteries could sustain the submarine at the same speed, then results in an indiscretion ratio. For similar assumptions to those used for central scenarios, including that hotel load is 100kW, 500tonnes of batteries are embarked, and the energy density of the batteries is that of lead-acid at 0.14MJ/kg, the results for the different efficiency curves considered for the two propulsion systems can be seen in Figure 50. It should be noted that since the precise machinery choices for the likely submarine cannot be known with great confidence, the indiscretion ratio levels here at any given point have high uncertainties attached. However, the relative difference between indiscretion ratios at different speeds (the shape of the curve) as well as the difference between the two systems, should be closely resemblant of a real comparison of otherwise identical submarines, even if the level is somewhat shifted.

The graph in 50 shows that very low indiscretion ratios, below 5%, could be plausible for either system at very low speeds under 3kt. However, these very low indiscretion ratios do not last for a significant range of speeds for the pumpjet system. Whilst for a propeller driven submarine, such very low rates of indiscretion last up to around 6kt, pumpjet propelled submarines are likely to start to see their indiscretion ratios start rising significantly after 4kt. In the region of transit speeds, around 8-10kt, the difference between the two systems becomes clear and substantial.

It should be noted that these plots only extend to 13kts, in contrast to previous plots which extend to 20kt. Since the propulsive power required to reach higher speeds can consume effectively all the power produced by the diesel engines, and then even exceed it at some speeds, the indiscretion ratios calculated by the method above become extremely large or negative, and don't assist in useful comparison.

Figure 51 demonstrates the difference between the two otherwise idendtical submarines' indiscretion ratios as a function of speed, and also what this difference represents as a proportion of the indiscretion ratio at that speed for the submarine as a propeller. It can be seen here that the indiscretion ratio is generally somewhat less sensitive to variation in hotel load than calculations for range and endurance. (Indiscretion ratio is also independent of energy density of the batteries, and hence will not be compared.) However, increasing the hotel load does still have the impact of somewhat diminishing the peak difference between the two systems, and moving the point at which the proportional difference peaks to higher speeds. Where the penalty of the pumpjet on a submarine with a hotel load of 50kW might have the largest impact at 5kt, it the difference would probably be greatest at 6kt and 7kt for a sumbarine with hotel loads of 100kW and 200kW respectively.

The magnitude of the difference is also substantial. For the central efficiency curve and hotel load assumptions, the pumpjet would cause a sumbarine to increase the time spent snorting for by over 60% between 5kt and 7.5kt. One would expect that this would be of considerable tactical consequence. These graphs also demonstrate that the difference does not diminish at higher speeds, infact it begins to increase again above 10kt, as the power required for propulsion begins to consume much of the power generated by the diesel engines, and the efficiency difference strongly impacts the size of the diminishing surplus available for charging. It is also clear that the sensitivity to the selection of efficiency curves remains quite strong in this case. It is clearly plausible that in a range of circumstances the pumpjet could double the time spent snorting. However, the difference between the lines representing the pair of central efficiency curves, and the narrowest separation, is noticeably smaller, and the impact of chaning hotel load on these lines is also proportionally diminished. As such, it might be said with considerable confidence that the most likely impact of the pumpjet on indiscetion ratios at any speeds over 4kt will around 40% or higher. It would be extremely unlikely that the penalty induced by the pumpjet at speeds of 5kt and above would be any

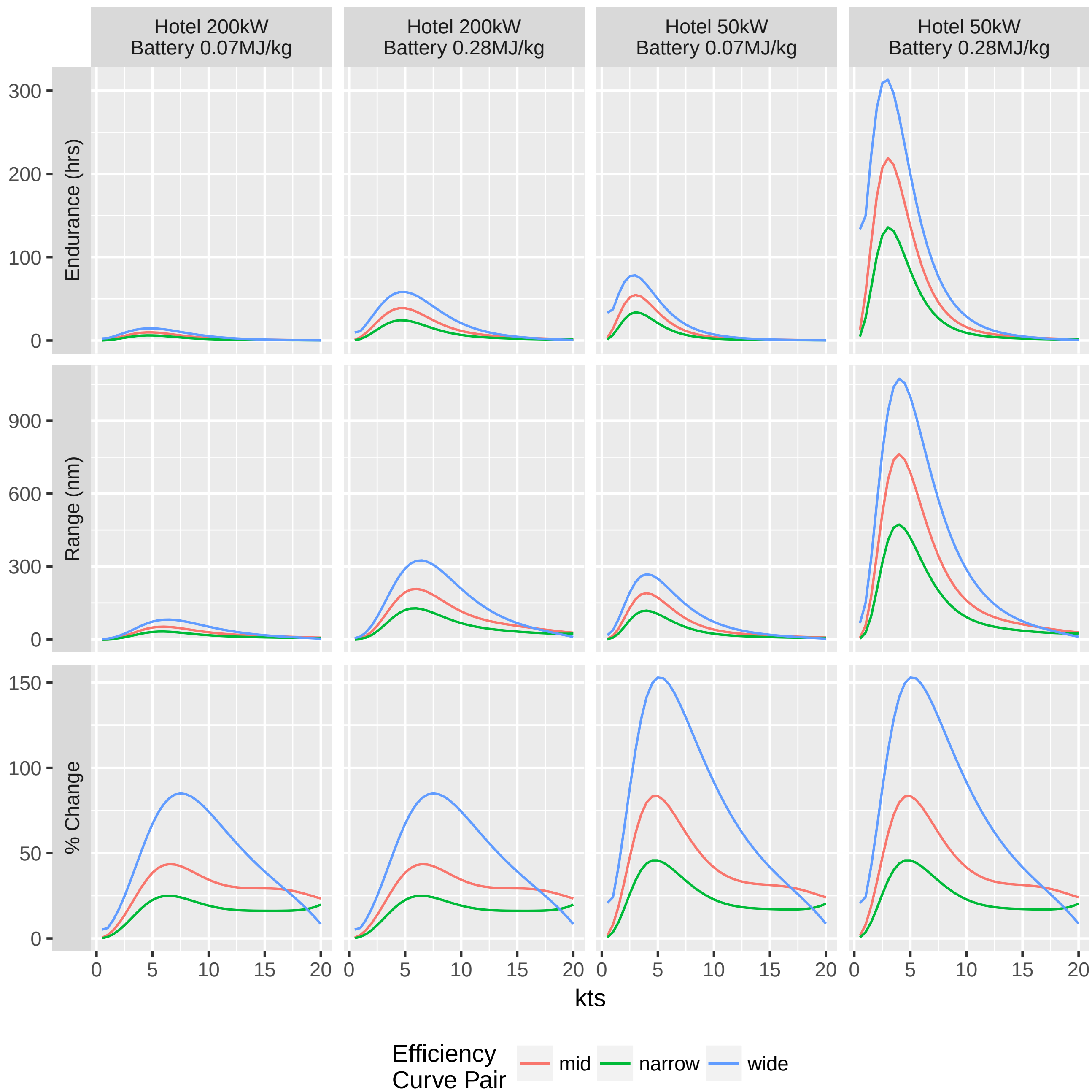


Figure 49: Specifying low density batteries and a high hotel load dramatically reduces the proportional and nominal impact of propulsion system efficiencies at low speeds

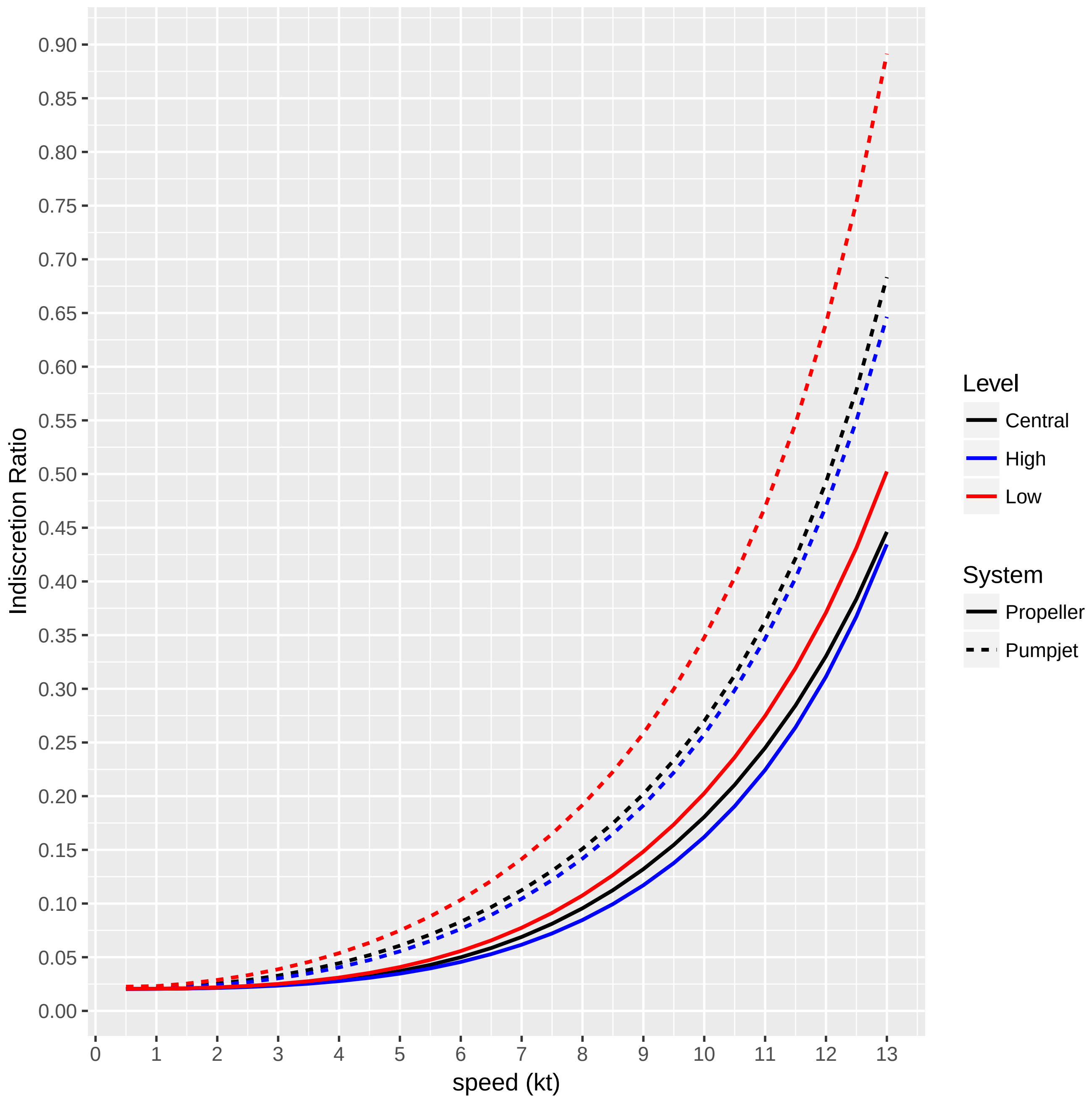


Figure 50: Some calculation of plausible indiscretion ratios show that the pumpjet would substantially increase the amount of time spend snorting

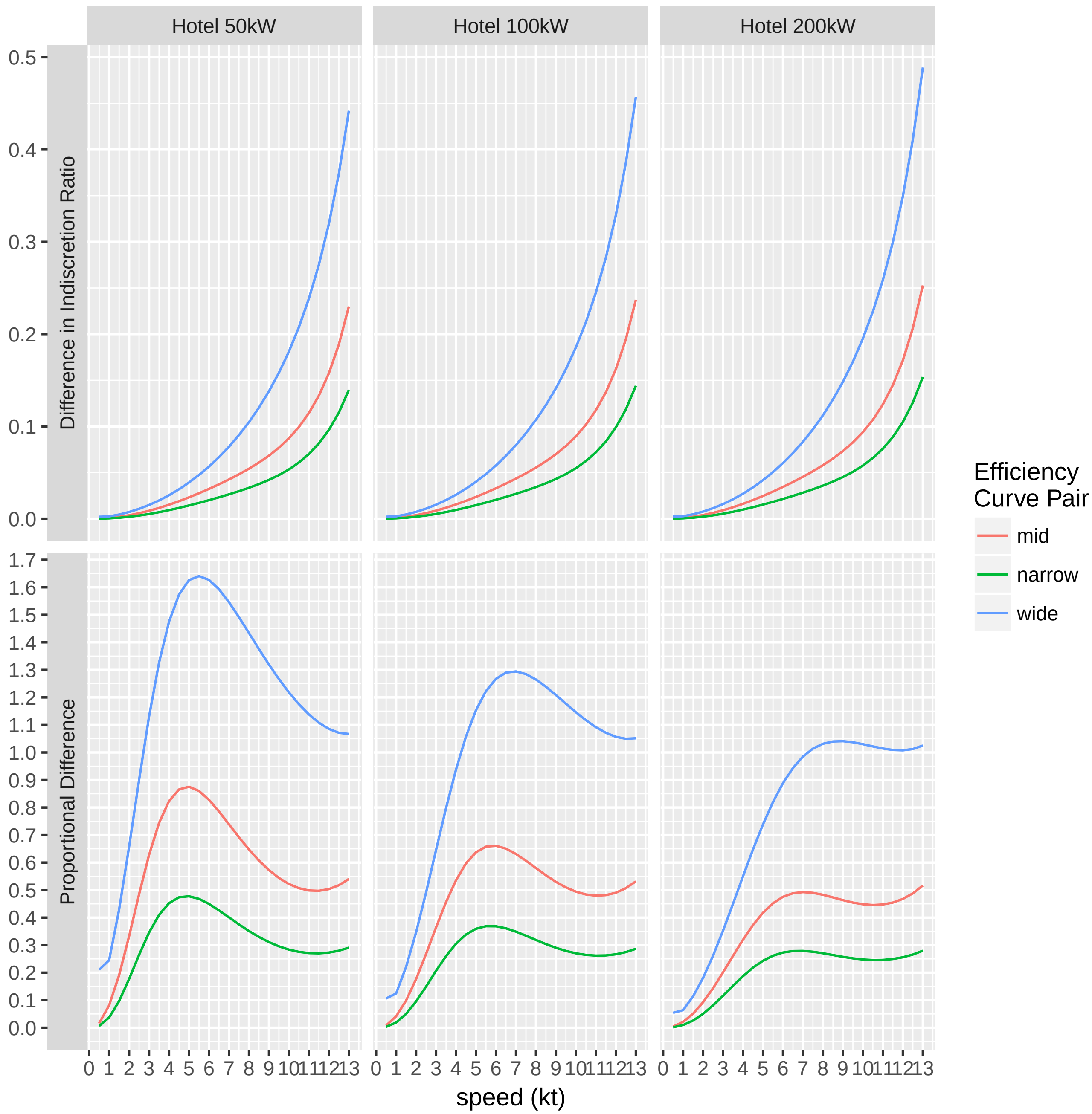


Figure 51: The additional indiscretion ratio necessitated by a pumpjet, and this difference expressed as a proportion of the indiscretion ratio of a propeller driven submarine. Sensitivity to hotel load is not as great as for endurance or range calculations.

less than 25%.

9 Acoustic Considerations

9.1 The importance of cavitation inception

It is generally considered that the existence of cavitation of any sort will tend to dominate the acoustic signature of any vessel that doesn't produce any machinery noise by relying on all-electric drive as a conventional submarine would when dived (Giles et al. 2010, Harvie 1965). Its quite possible that during the period when a submarine is snorting, or running its diesel engines, these sources of noise would be a more substantial and distinctive acoustic signature than small amounts of cavitation on the propulsion system if it were to occur, owing in particular to the low freqency of diesel engines.

Other sources of noise hydrodynamic noise, such as the turbulence produced in the boundary layer of the flow over the hull, or parts of the propulsor, will still contribute to overall noise and some signature, but it will tend to be significant smaller in magnitude. This owes to the essentially incompressible nature of water. Without compression, even very relatively intense votices or tubulent flows will not propagate very much noise, if the water remains perfectly solid. All of the 'round and round' can't achieve much 'in and out', which is what results in propagated noise. This obviously doesn't hold true in compressible fluids, such as air, as one would observe noticing the intense noise produced by hand-dryers, aeroplanes, jet engines etc. It also doesn't hold true *within* a turbulent flow underwater. If you were to put a sensor inside a turbulent flow, the rapid movements would result in continual and significant pressure fluctuations, hence noise. But at a distance, these fluctuations tend to substantially cancel out. The larger the scale of the eddies and vortices, the further noise might propagate, and also the lower the frequencies of resultant noise might be, which makes noise propagate further. Likewise, larger caviation voids will tend to emit lower frequency sound aswell, as can be observed from the boiling of a kettle.

As a result, when dived, it might be reasonably assumed that the complete elimination of all sources of cavitition will be the primary objective of acoustic signature management. This is neatly put in Gearhart and Henderson 1966, p. 88: "The occurence of cavitation in a propulsor results in a degradation of the propulsor operating characteristics if extensive amounts of cavitation exist, and in significant noise when minute amounts occur. As a result, the performance requirements of a submersible weapon system specify that the occurence or inception of cavitation be avoided below certain operating depths." One might consider that a submarine's 'tactical silent speed' would most probably correspond to the speed at which it can operate safely below the point of any cavitation inception.

The precise point at which cavitation inception occurs, what type of cavitation it is, and where it occurs on the blades is a complex science, with considerable work being continually undertaken to validate theoretical models. A good overview of the some of the science can be found in reference Kuiper 1981. Still today, similar techniques such as paint tests and visual observations are validate models and theory. However, despite the inherent complexity about predicting the precise point in time and space of onset, and the respective impact on efficiency and acoustics, several broad relationships are known to hold well, and can be relied upon to characterise the most significant trends that determine when cavitation will be more likely to occur, which is generally driven by the diffence between the vapour pressure of water and the local static pressure.

9.2 Impact of speed on cavitation

Perhaps the most significant determinant of the pressure deviations on the propulsion system is how hard the propellers have to push on the water at any given point. In general, the harder the propellers push, the larger is the required pull on some opposing edge or side. It is these pressure reductions, on the suction side of the blade, where sheet cavitation generally starts to occur. To think of it simply, the water isn't able to rush to fill the gap left behind by the propeller fast enough. However, at some point cavitation also occurs on the pressure side of the blade, as the impact of the leading edge breaking the water leads to sever local pressure drops just behind the leading edge.

Whilst a range of very particular and intricate phenomena may be at work, perhaps the largest and most dominant trend at work will be that pressure differentials across the blade must necessarily increase with increase thrust. The blade velocity relative to the oncoming stream is also a close indicator, which will be closely related for an open propeller. Consequently, since the thrust required for self-propulsion increases with velocity squared, the propensity for cavitation occur will necessarily tend to follow this relationship also. As such, modest changes in speed can have a big impact on the degree of probability of cavitation occurring. Halving your speed will roughly reduce local pressure fluctions by a factor of four. Consequently, even for non-specialised propellers, there is generaly some low speed for which no cavitation occurs, though almost all propellers in major surface vessels experience some cavitation at the speed they are designed to do their work at.

9.3 The impact of depth on cavitation

It is also crucial to understand that increasing depth necessarily increases the static pressure throughout a propulsion system. As such, the speed at which cavitation starts to occur will necessarily be a function of depth. Approximately every 10m of water adds approximately the equivalent of an atmosphere of pressure. As such, the static pressure a system experiences at 10m depth will be half that experienced at 30m (since the air in the atmosphere comprises the first atmosphere of pressure). Consequently, diving deeper will necessarily increase the speeds one can achieve without any cavitation occurring 52.

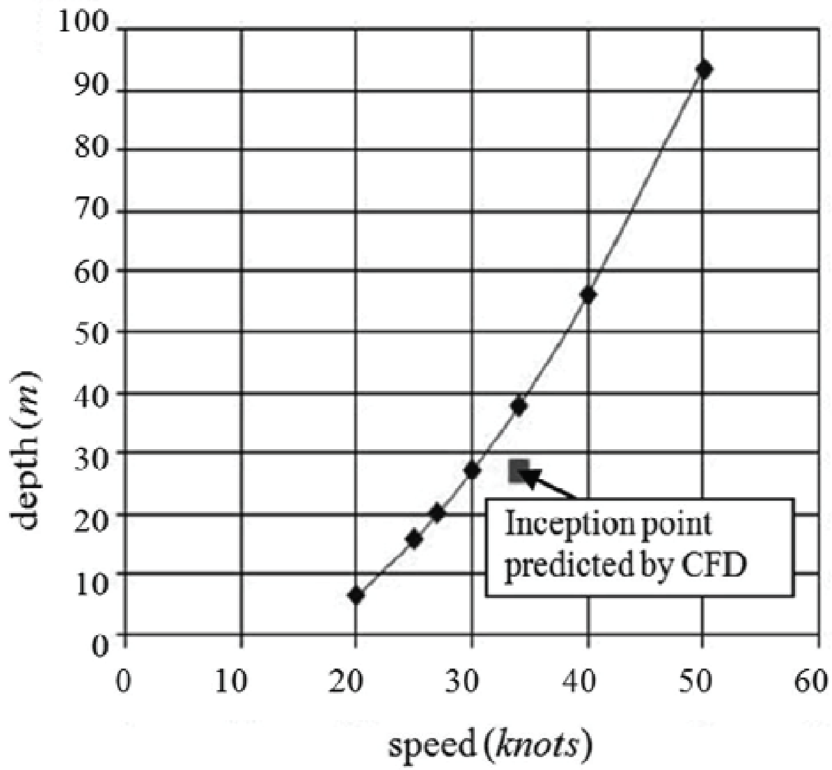


Figure 52: Increasing in depth improves the speed achievable before cavitation begins to occur, as shown in the case of a torpedo (Suryanarayana et al. 2010)

The interaction of these two relationships can be expressed in a general form in figure 53, which has been generated using an approxiate numeric model. As can be seen here, at very low speeds, modest changes in depths can achieve considerable additional surplus pressure in order to prevent cavitation. However at much higher speeds, since the pressure diffential scales with the square of the velocity travelled, far greater additional depths are required to achieve sufficient excess static to supress cavitation for a give further speed increase. Whilst certain system parameters such as the blade area and design (or duct design) will have a significant impact on which curve a particular system lies upon, the overall trend of a parabolic cavitation free "bucket" prevailing at low speeds and large depths will generally be robust. This is confirmed by the close resemblance between the curve shapes found by an experiment on a torpdo in Figure 52, and the numerical model found in Figure 53.

It is noteworthy also that the vapour pressure of water is an important component in the equations that describe the conditions for cavitation to occur. It is generally given that when the local static pressure falls below the vapour pressure, cavitation occurs, though known exceptions to this do exist. Given that temperatures also affects the vapour pressure of water (warmer water is just a little closer to boiling) this does have an impact on the cavitation inception point. However, at plausible temperatures the impact is small. The difference between the vapour pressure of water at 10 degrees and 30 degrees is approximately 3 kilopascals. Diving just 10m deeper adds over 100 kilopascals to static pressure. In many circumstances, altering your speed by a couple of knots will have an even larger impact on local pressure reductions. Consequently, the impact of temperature on the inception of cavitation is essentially negligible. The difference between inception contours in 20 degree and 30 degree water are given by the difference between the black and red-dashed contours in Figure 53.

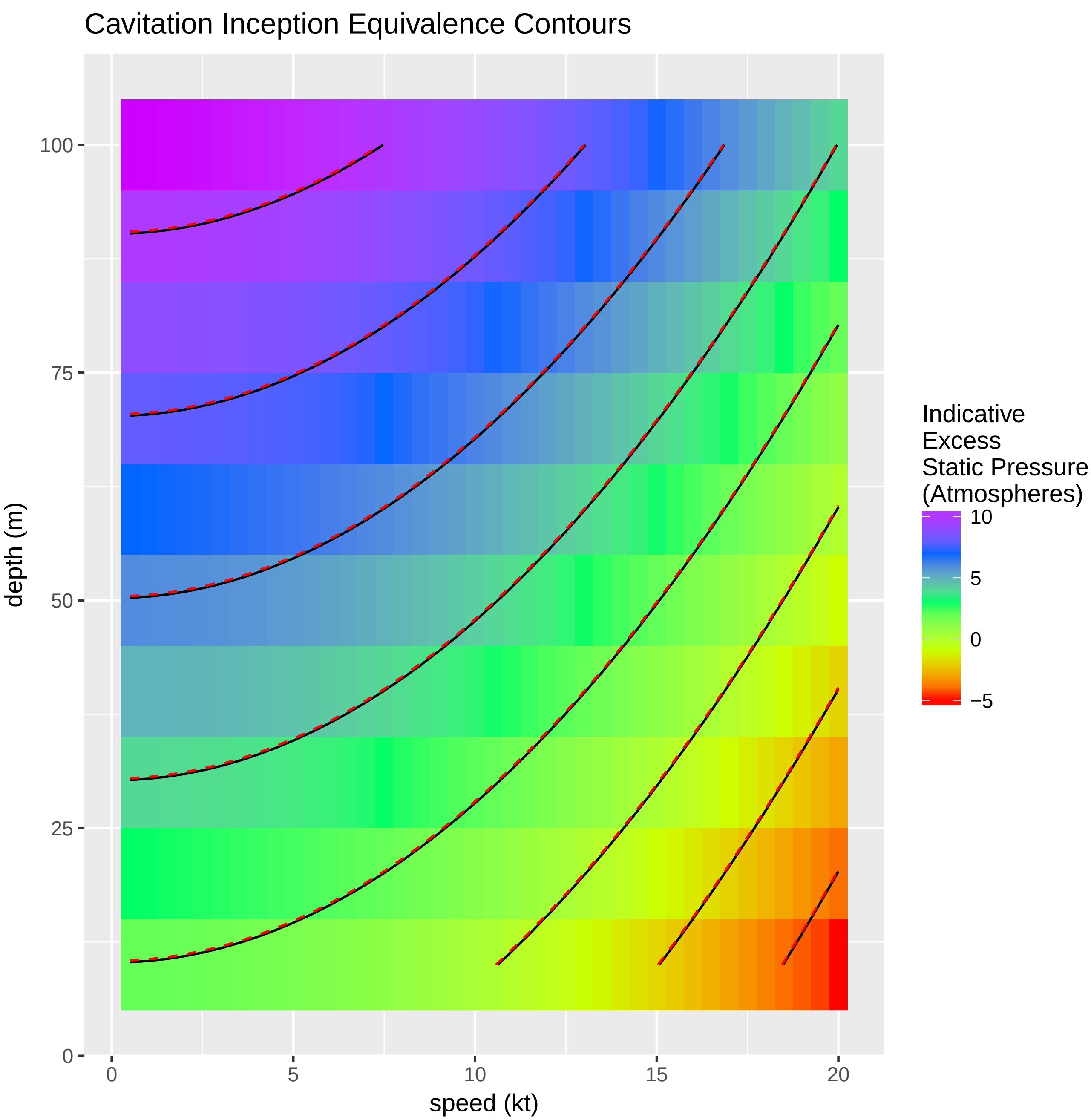


Figure 53: Contours showing plausible lines of plausible equivalent cavitation inception

9.4 The significance of flow separation

The addition of a duct will necessarily lead to flow separation occuring on the inside of the duct opening at some very low speeds which correspond to high advance ratios when load remains constant. Flow separation tends to lead to vortex shedding, which means that inconsistent flows (vortices) are then ingested into the blades of the impeller. This effect is well known and documented. A good example is shown on the exterior of an **accelerating** duct at $J = .8$ in Willemsen 2013.

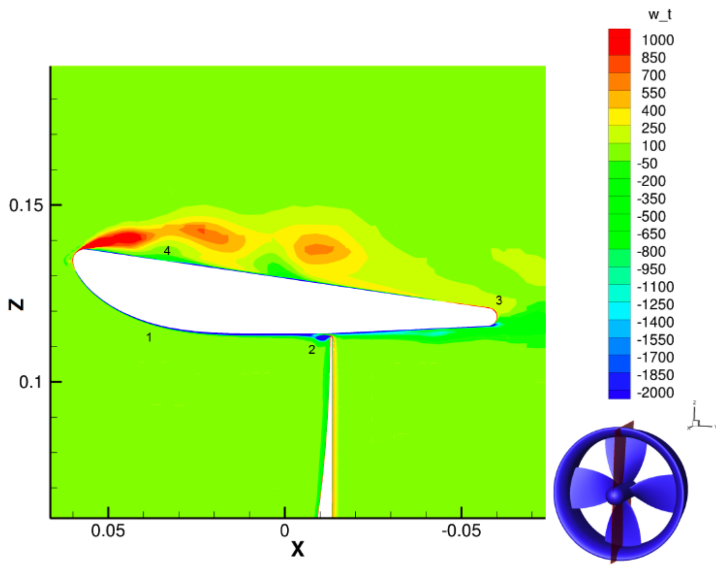


Figure 54: Vortex shedding following a flow separation leads to eddies being released unsteadily into the main flow stream, as shown here on the exterior of an accelerating duct. In the case of decelerating duct (pumpjet), duct shape is inverted, leading to the vortices being shed into the impeller blades. (Willemsen 2013)

Whilst at very low power levels or at good depths, it is quite plausible that this doesn't result in any cavitation, which would normally be a likely occurrence if the blades are operating closer to their design power and such such vortices were shed into the intake. However, given the inherently unpredictable and unsteady nature of such vortex formation and shedding, this phenomenon would increase the risk of cavitation occurring unexpectedly in marginal conditions. In addition, in the absence of cavitation, the sudden and changing pressure gradients over the blades would dramatically increase the overall pressure fluctuations and turbulence level that occurs within the propulsor. This would necessarily increase the overall levels of noise generated. It is plausible that the noise is of sufficiently low level that it is not considered a significant compromise of stealth. However, it is almost certainly untrue that that pumpjet actually generates less noise overall than a propeller at very low speeds.

9.5 The impact of duct shielding

The presence of the duct around the impeller may also have the effect of preventing the noise from being effectively radiated away from the propulsor. This may well result in substantial reductions in some types of noise being radiated away from the propulsor in certain directions, which may have given rise to the consistent qualification of 'radiated' being used to descrive the type of noise which differentiated the French submarine bid (Stewart 2016, Davies 2017, Ohff 2016), including by the designers of the submarine (Autret and Costello 2016). This is a secondary effect, quite separate to the avoidance of cavitation, which might be seen as an acoustic advantage in circumstances where cavitation might not be expected to occur on either type of propulsor. It is highly likely that this is the effect which is relied upon to sustain claims that a pumpjet is generally acoustically superior to a propeller, including at low speeds.

It should be noted here that shielding effects might comprise the combination two distinct and seperate physically phenomenon: reflection and damping. Noise tends to be reflected very effectively off hard, smooth surfaces representing the boundary between mediums of very different density (such as steel and water). Changes in density which are gradual, often representing soft, squishy, or broken surfaces tend, to have the effect of absorbing sound, where the acoustic energy is converted to heat or degradation of the material, rather than reflecting it. Given the significance of increased drag on any surfaces within the propulsor, it is highly unlikely that any attempt at damping is made within the pumpjet. However, it should be noted that some pumpjets have been constructed with a hollow design, in order to reduce weight (Harvie 1965), which would reduce the thickness of solid steel, though offer some potential opportunity for damping. Overall, damping is increased in its effectiveness at low frequencies by allowing it to occur over larger distances, corresponding to the sound's increased wavelength, leading to increased thickness of the transition substance or damping material. Consequently, effective damping within the propulsor itself is unlikely to be attempted, or limited to medium and higher frequencies, probably suited to reducing noise from normal surface flow turbulence and very early onset cavitation.

The ability of a thin layer of material to reflect noise is also highly frequecy dependent, and also dependent on mass of the shield layer. As the material becomes thinner and thinner, a hard shield layer will tend increasinly to transmit rather than reflect the noise, a phenomenon that increases as the amplitude (loudness) of the noise increases, and frequency decreases. Denser materials are more effective at reflecting sound, as more energy (pressure) is required to excite the same movement in the material. Consequently, the effectiveness of a shield depends on both its thickness and density. There is therefore some tension inherent in the design of a shield where thickness and total weight are constrained. A thicker layer solid steel will be very effective at reflecting sound, but have negligible absoption or damping. A hollow between two thin layers will offer some potential for a soft daping material to be inserted, but at the cost of reflection.

It is most likely that little or no damping or absorbing layer is attempted within the body of the shroud, since increasing the duct thickness above hydrodynamically determined optimum profile is likely to have a detrimental impact on efficiency. Constructing a large components from thing pieces of steel, and still maintaining an optimal shape to the precision required for housing powerful turbomachinery like the impeller is also likely to involve considerable construction risk and complexity. Hence the shielding effect is most likely to dominated by the reflective characteristics of the duct, which would seek to internally reflect noise back into the turbulent flow, where sound waves would be increasingly convoluted, and somewhat absorbed through the eventual transition to small-scale turbulence and heat.

The degree to which the total noise generated is reflected internally will also be shape-dependent. A more concave inner surface, will increase the extent of internal reflection. Such a design would be consistent with higher degrees of diffusion in advance of the impeller, and greater nozzle narrowing after it, which is consistent with higher pressure elevation at the impeller (hence improved cavitation characteristics) but higher negative duct thrust, leading to even poorer efficiencies at low speed. Substantial alteration of duct shape on account of efficiency considerations at low speed are therefore necessarily going to have some impact on the degree of effective shielding that a duct can afford.

9.5.1 Directional Dependence

Two important qualifications must be made regarding shielding. The first is that its impact is highly directionally dependent. The pump jet requires openings at the front and back to allow water in and out. Only noise that is reflected internally sufficient to be largely absorbed is effectively shielded. The larger the areas of the intakes and outlets, the narrower the effective shielding will become. Consequently, design changes to make the pump more efficient at low speeds, which may include expanding both the inlet and outlent, and diminshing the difference between them, will necessarily be at the expense of diminishing effective width of the shielding 'belt' around the propulsor.

When the submarine is travelling at high speeds, and there is significant flow through the propulsor, the impact of waterspeed through the propulsor might have the additional impact of diminishing the radiation of noise in the forwards direction, in the same way that sound tends tends not to travel well up-wind in air. However, at very low speeds this effect would be greatly diminished, and possibly not relevant.

It should further be noted that in the underwater environment sound can be made to reflect in a variety of directions simply with differences in temperature, salinity, movement of water bodies, as well as off plenty of nearby underwater objects, including the ocean floor and objects on it. This phenomenon generally serves to make the art of underwater acoustics complex and unpredictable, and generally contributes to the difficulty of precisely locating a submarine, even when some signature is detected. However, it also means that direction-dependent reductions signature do not reliably translate to overall reduced probability of detection.

9.5.2 Frequency Dependence

It ought further to be noted that the effectiveness of acoustic shielding is also highly dependent on frequency. Much lower frequencies are very hard to reflect, and absorb, as can be easily observed in a house with a home-cinema, where lower frequencies emitted by the subwoofer will tend to affect many surrounding rooms, where higher frequency sounds might be substantially muffled by interceding walls. The same acoustic effects are at work in underwater acoustics.

This has an important consequence for shielding for pumpjets at very low speeds because of the occurrence of flow separation and vortex shedding. In the absence of flow separation and cavitation at very low speeds the most substantial sources of sound would be the turbulent flow over surfaces of in the propulsor. This noise will tend to be relatively white and high in its frequency owing to the very small length-scales of the eddies and vortices in such turbulence. The steel shroud would be very effective in reflecting such high frequency noise. Under acceleration or higher loads, the very instances of cavitation woud also be relatively high frequency, as the voids or cavities would be small at first. These sounds might also be very effectively reflected by the shroud, and consequently diminished.

In contrast, flow separation results in the creation of vortices of a dramatically larger scale than occurs with normal turbulence in a boundary later, and hence would tend to generate noise of a much lower frequency. In addition, as the flow rates slow even further, these vortices are likely to become larger in size, even if lesser in intensity, resulting in further reduction in the frequency of noise generated. The rate at which the vortices shed from the surface and impact the impeller will also result in another acoustic signature. Again, at lower flow rates, these vortices will tend to develop and shed more slowly, lowering frequencies further.

Consequently, whilst for certain types of noise which tend to become both louder and lower in frequency with increasing speed (cavitation), flow separation provides a contrasting characteristic, in that it is likely to decrease in frequecy with decreasing speed. As lower frequencies tend to propagate much further in open water, this could have a significand adverse impact on the total acoustic signature of the submarine, even if the flow separation doesn't lead to any cavitation.

The foregoing consideration suggests that the acoustic signature of a jet-powered submarine might not reduce steadily with speed all the way to stationary movement. It is plausible that there could be some elevated propulsion signature at very low speeds due to flow separation, and that the submarine's optimal acoustic signature when moving is actually at some slightly higher speed, where smoother flow through the propulsor can be achieved. However, given that the amplitude, frequency, and combined impact of those two characteristics cannot be accurately evaluated without substantial further work and more detailed system knowledge, it is also possible that the increase in other noise (including hull flow noise and other machinery) at elevated speeds offsets the improvement in the smoothness of the pumpjet's operation. It is still quite likely the overall level of noise radiated by the pumpjet, including under conditions when flow separation occurs, is still considered to be sufficiently low in amplitude as to not be of significant tactical consequence. However it is highly unlikely that the accoustic signature of the pumpjet is actually superior to that of an open propeller at very low speeds, when cavitation occurs for neither system, but substantially increased turbulence including flow separation must neccessarily occur for the pumpjet.

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Appendices

A Some essential concepts

A.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, as given in Equation 8. It says that the total energy in a connected body of fluid with no additional work being done on it is constant (C), though it can change in form between kinetic energy (movement, $\frac{1}{2}\rho v^2$), gravitational potential energy (it being elevated, $\rho g z$, relevant for liquids, less for gas) the heat energy in the fluid (not shown, not relevant for incompbressible fluids), and the pressure of the fluid p.

$$\frac{1}{2}\rho v^2 + \rho g z + p = C \tag{8}$$

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. In the case of submarine pumpjets, located on the end of the hull and parallel to the axis of the submarine, this effect (and the term gz) are not relevant.

A.1.1 Venturi Effect

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 equation 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 what underlies the Venturi effect.

A.1.2 Flow Diffusion

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, particularly elevating static pressure levels in order to prevent cavitation (Waterjets 1997; McCormick and Eisenhuth 1963; Bruce et al. 1974).

A.1.3 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, though the significance of the acoustic signature is not necessarily indicative of the magnitude of energy wasted.

In general terms, energy waste in propulsion systems will result in turbulence (moving water in random chaotic patters, where the energy soon becomes smoothly distributed as heat) and acoustic energy that is propagated away. Flow separation incolves the creation of larger-scale vortices and eddies, which might be considered as a special case of turbulence, since the length-scale of the unsteady flows is much larger than that of normal turbulence, for instance in a boundary layer.

On important consequences is that whilst increasing creation of noise, flow separation, or turbulence necessarily represent greater amounts of energy wasted, some increase in any given one does not neccessarily indicate the reduction of efficiency of the entire system, as larger amounts of energy may be being saved through reduced wastage through another means, or vice versa. For example, a squeaky join on a car might make a lot of noise, and it will represent some loss of kinetic energy. However, the brakes can be applied and absorb vastly larger amounts of energy, essentially silently.

Furthermore, efficiency of a system is necessarily given by the a ratio of useful work to total energy expended. Some trends which show increasing levels of energy wasted might be outweighed by larger increases in the overall amount of productive work being achieved. Pumpjets, which generally tend to require highly turbulent flows, and even more turblent flows at higher speeds, still can become more efficient as speed inceases, as the amount of useful thrust produced increases even faster. So, despite the wasteful round-and-round movements increasing with speed, the increase in productive front-to-back movement improves even faster, and total efficiency rises.

A.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. In particular, a boundary layer can be either turbulent or laminar in nature, and can transition to turbulent flow after a short distnace of laminar flow, as shown in Figure 55.

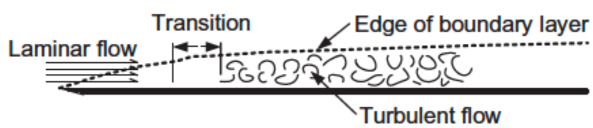


Figure A1.6. Boundary layer development.

Figure 55: The development of a boundary layer as shown in (Molland, Turnock, and Hudson 2011)

A.3 Turbulent and Laminar Flow

The way that fluids move relative to a surface can one of either two methods. In 'laminar flow' all the fluid moves in one direction in an smooth and orderly manner, with very little mixing between the layers of fluid travelling at different speeds.

The alternative is 'turbulent flow', where the fluid moves around in unpredictable swirls and circles as well as moving overall in an predominant direction. There is considerable mixing between all the different layers, and the average speed remains relatively constant in the flow, with the exception of the flow immediately adjacent to the wall, or in the boundary layer. Becuase turbulence involves a lot of movement that is not overall in one productive direction and contributing to thrust, it necessarily leads to some loss of energy from the overall thrust. Once the swirls and movements become smaller and smaller, the energy winds up simply as heat in the fluid.

The likely point of transition between a flow being turbulent and laminar can be given by unitless number called the Reynolds Number, which is determined by a fluids velocity, viscoscity, density, and a characteristic length-scale

(a) Laminar (b) Turbulent

Figure 56: A simple comparison of laminar and turbulent flows from (*Laminar Flow* 2017)

over which the flow occurring. A fuller discussion of these important concepts can be found in *Laminar Flow* 2017.

Turbulent flows in gasses can be extremely noisy, since those fluids are compressible. Consequently, the rapid and intense ciruclar movements result in a lot of oscillatory compressions against the surrounding air. Consequently things like jet engines, vacuum cleaners, hand-dryers, and other devices that create rapid movements in gasses tend to be quite loud, including at some distance.

In essentially incompressible fluids, the random changes in pressure and velocity which are involved in laminar flow tend not to generate nearly as much noise in the surrounding liquid outside the flow. Because the fluid is incompressible, all of the random 'round and round' movements don't amount to much 'in and out' movement, which is what creates the pressure waves which result in propagated noise. Consequently, whilst turbulent flows do inevitably generate some noise, the amount of noise generated is dramatically greater in the presence of cavitation, where a void opens up in the water, and vastly more 'in and out' movement is able to occur.

A.4 Cavitation

Cavitation is the rapid expansion and collapse of a void, or bubble in water. Put technically, caviation occurs when the local static pressure (pressure in the rest frame of the fluid) falls below the vapour pressure of the fluid (pressure at which the liquid will start to boil).

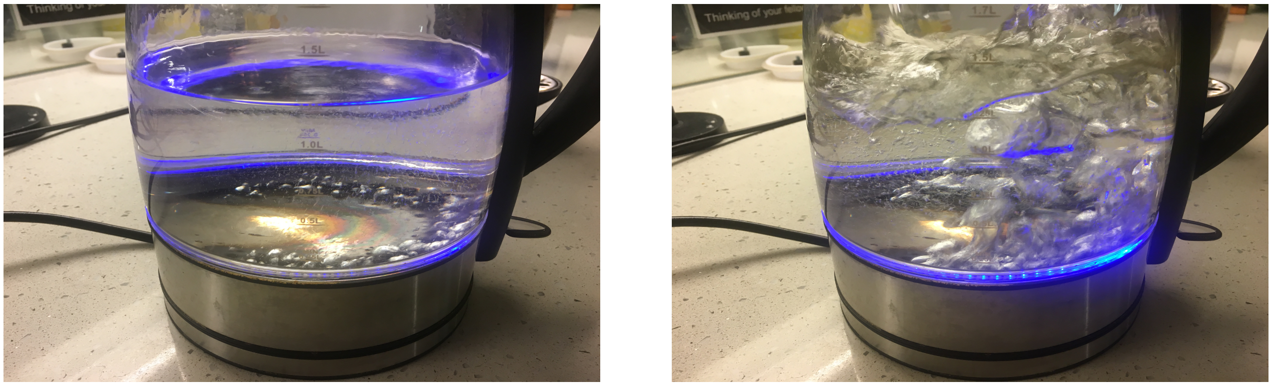
To try to conceptualise how it occurs in the context of propulsors, one might imagine what happens when something moves very fast through water. The front side of the object pushes the water forward, but on the back side the water has to push in to fill the space left behind. If theres not enough pressure to push the solid water in fast enough, a gap opens up, with just a few gaseous water molecules (steam) inside the cavity. (This is also described as water boiling at low pressure.) However the gap doesnt stay around for long. Soon the water catches up, and the bubble implodes with a pop, leaving only very tiny bubbles as a result, which you can see in the wake of almost any boat or ship moving at speed. Whilst some energy turns to heat (the remaining steam in the tiny bubbles) some is propagated away as a sound-wave generated by the implosion.

A watching water boil in a glass kettle gives a quick and intuitive insight into the occurrence of cavitation. Quickly after the kettle starts heating, a considerable noise can be heard, which corresponds to the commencement of cavitation on heating element. At some local point for a moment in time, there is enough energy for the water present to boil. It tends to be on rough surfaces or in the presence of some impurity that cavitation will occur first (in the blackened part of the surface in this case.) However, whilst the bubbles on the bottom can be seen plainly on the bottom, they collapse almost straight away again, and leave only a tiny bubble of stable steam circulating in the water. It is the rapid expansion and collapse of these bubbles that causes the noise of a kettle, long before it has boiled.

It is only when the water is all at a much higher temperature that the bubbles remain their full size for long enough to detatch and rise all the way to the surface, a process we typically think of as boiling water. It is worthwhile noting that the sound emitted at this stage is much softer and lower than the early onset of cavitation. Larger bubbles result in lower frequencies of sound being emitted. Even at higher temperature, the rougher parts of the surface provide the points where all the cavitation originate.

Cavitation is extremely important in the study of ship propulsion, since it's occurrence in particular circumstances can lead to substantial losses of efficiency, as well as damage to the propeller and related appendages. It is particularly important for submarines, since the expansion and collapse of these bubbles tends to lead to the creation of noise which is often far larger, and more distincly characteristic than other turbulent disturbences in the water when no cavitation is present. Consequently, the onset of cavitation can be thought of as a distinct threshold in terms of the acoustic performance of propulsive system.

Despite cavitation necessarily representing some energy being wasted generating unwanted noise in the water, some cavitation inevitably occurs around most propulsion systems operating at full power. In plenty of cases, the consequences for efficiency are relatively small, as they tend to be dominated by other efficiency considerations



(a) (b)

Figure 57: (a) Cavitation bubbles form and collapse creating noise and some tiny bubbles long before boiling occurs. (b) Only at very high temperatures do the bubbles endure at full-size in the water and reach the surface.

in imparting thrust. Put another way, the savings that can be gained by minimising wastage to turblence can outweigh the losses incurred by having some cavitation occur. In most cases, propellers are designed to work with a certain extent of cavitation for optimum efficiency under working loads (Shin, Regener, and Andersen 2015). Cavitation also occurs to a considerable extent within the jets of most high-speed surface vessels, but doesn't necessarily have a particularly bad effect on their overall efficiency at their intended speed levels. It is generally only within very specialised military circumstances when the absolute avoidance of cavitation supercedes other concerns for efficiency, and require the elimination of all cavitation entirely (Molland, Turnock, and Hudson 2011), (Lewis 1988). These circumstances include the design of submarines and torpedoes.

In certain special cases, particularly supercavitating propellers or surface-piercing drives, high levels of cavitation can be higly advantageous for efficiency. However these represent specialised designs, generally only for very high speed vessels, where acoustic concerns are negligible, and are of little concern for this particular endeavour.

Cavitation can occur in a number of different ways at different points and forms on or around the propeller. It is common for cavitation to occur first near the out extremities of the propeller, where the blades are moving at the highest velocity relative to the water-flow. Cavitation tends to spread across the back of the blades in a sheet (sheet cavitation), since the back side of the blades are generally the areas of most depressed pressure, though it can also occur in places on the back side of the blades, where the dynamics of the water moving around the blade can produce points of near the edges of significantly reduced pressure. On surface vessels cavitation tends to occur most when the blades are closes to the surface, where the pressure is lowest.

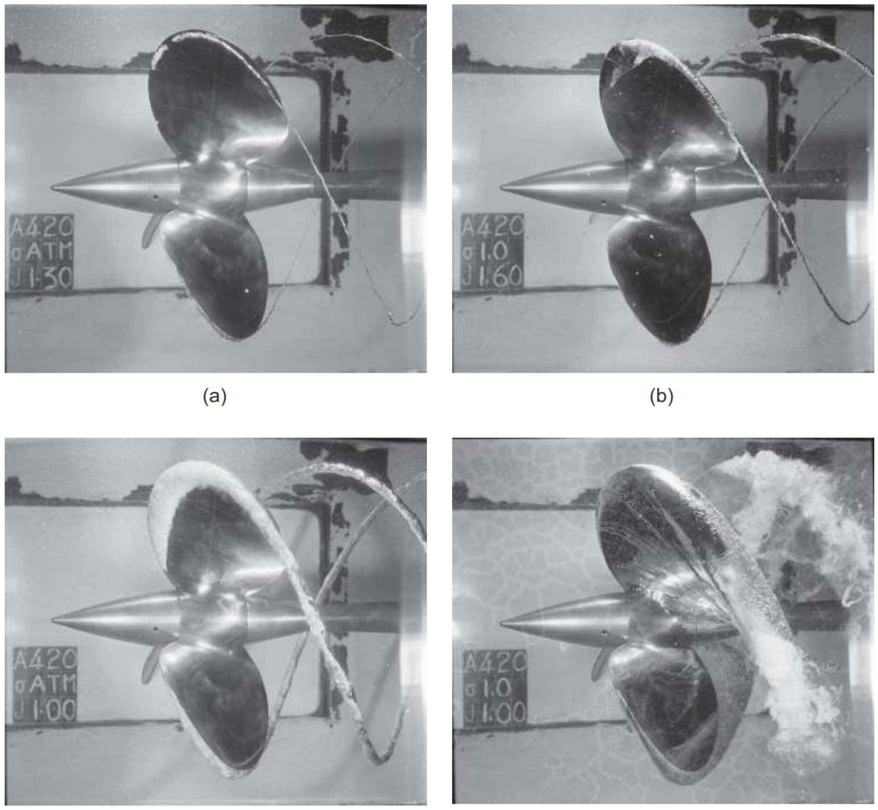
A.5 Pressure, Thrust, and Momentum change

A few simple related concepts make up the foundations for many of the simplest and enduring theoretical models (Momentum Theory, still widely and routinely used to model 'ideal' propeller efficiencies by considering the propeller simple disc (Carlton 2007, p. 169)) and other quite intuitive concepts which migth be more readily grasped in understanding propulsors.

Thrust is a force, measured in Newtons, which is generally used to refer to the forces acting on a vessel or object by its propulsion system to move it forward in the water. Generating thrust is consequently a key objective of any propulsion system.

Pressure is a measure of force divided by an area over which it is applied. Pressures are necessarily applied to some extent over all of the surfaces of any object, including due to the atmostpheric pressure of air. In considering the efficiency of propulsion systems for solid bodies, thrust is always the consequence of some **net** pressure difference on different sides and surfaces of an object. For instance, on a propeller blade, the rear-facing side of the blade is the side that pushes the water backwards, and hence has a raised pressure on its surface. Being generally backwards facing this acts to push the propeller forwards. This pressure acts equally to push water backwards, as well as to push the propeller forwards. Importantly, the forward-facing side of the propeller will expereince a lowered pressure, which also serves to pull water backwards, and suck the propeller forwards. It is the sum of all the pressure differences on the propeller that result in a net force.

Importantly in hydrodynamics, it is important to consider the possibility of other forces being generated other surfaces which may have an impact on the movement of the vessel. In the presence of the hull, water being drawn



(a) (b) (c) (d)

Figure 12.29. Development of cavitation; Emerson Cavitation Tunnel. Photographs courtesy of The University of Newcastle upon Tyne.

Figure 58: Cavitation frequently occurs first at the extremities, then spreads inwards across the blad face, as shown in (Molland, Turnock, and Hudson 2011)

by the propeller can cause pressure changes on other surface of the vessel which may assist or impede producing a net positive thrust. Submerged jets represent a particular case in point. A famous home experiment suggests that one compare the thrust (backwards pressure) experienced by someone holding a garden hose creating a jet of water when it is in the air, as opposed to submerged in a pool of water. When submerged, the backwards pressue appears dramatically reduced. In fact, this phenomenon is due to a the water-jet drawing adjacent water with it under-water, the movement of which exerts a negative pressure on the outside of the nozzle, conteracting the pressure exerted on the inside of the nozzle. This effect represents one of the important distinctions between the jets which release their water below or above the water-line, and generally means that underwater jets have much lower jet velocity ratios than those released over water.

It is also an important law of physics that force or thrust is equal to the rate of change of momentum. Put simply, the speed at which one speeds something up, or the increasing amount of something which begins to move, is always equivalent in magnitude to the thrust that is produced. Since momentum is a vector, this simple law requires that the momentum change has to net out to one particular direction in order to produce a net thrust, which provides the core principal for Momentum Theory as it applies to propeller and jets. Circular movements necessarily are cancelling, and produce no thrust. It is useful to recall however that this principal is simply another complete, alternative way of measuring the consequences of the net pressure differences discussed earlier. The total rate of change of momentum in the system which is induced as a conseqence of the pressure differentials on all sides of the propulsor must necessarily be equivalent to the total net force that is produced. For the garden hoze in the pool or bucket, the jet rapidly entering the liquid in one direction necessitates new flows of liquid in other directions, reducing net moment changed. This new liquid movement will exert pressure reductions on the nozzle surface surface, which reduce the net momentum change affected by the entire system. These net forces, and net momentum change are necessarily equivalent and equal in effect. Consequently literature seeking to optimise propulsion might discuss analysis referring to both of these effects or phenomena, and neither are in conflict.

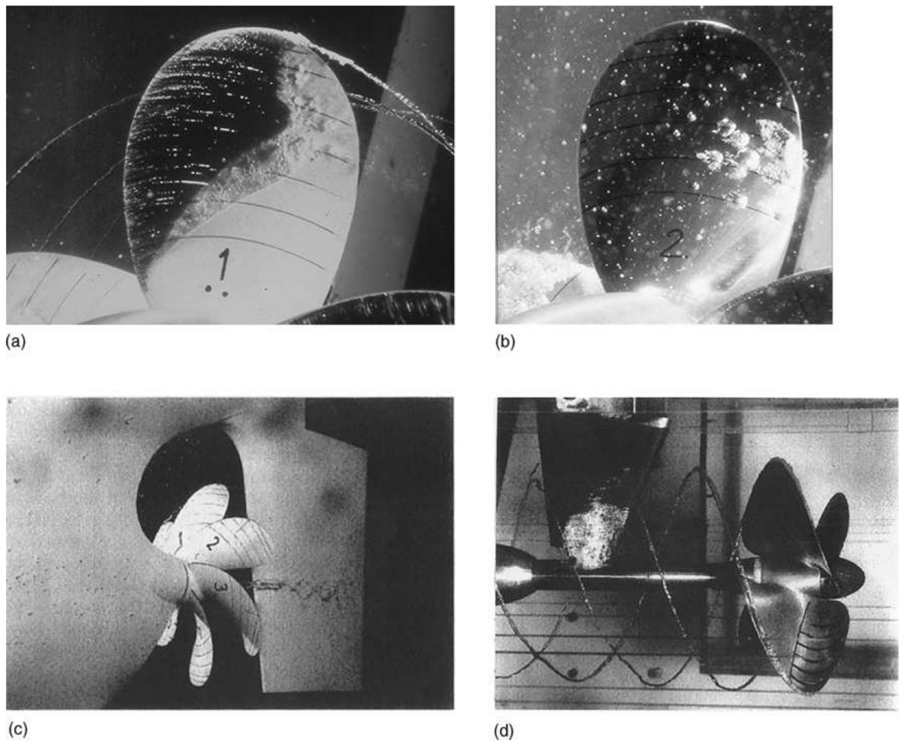


Figure 9.9 Types of cavitation on propellers (MARIN): (a) sheet and cloud cavitation together with a tip vortex; (b) mid-chord bubble cavitation together with a tip vortex and some leading edge streak cavitation; (c) hub vortex cavitation with traces of LE and tip vortex in top of propeller disc (Courtesy: MARIN) and (d) tip vortex cavitation

Figure 59: Different types of cavitation can occur on different parts of the propulsion system as shown in (Carlton 2007)

Full and proper derivations of many of the thrust equations for different propulsion systems from these principals can be found in plenty of authoritative works, including Lewis 1988, Carlton 2007 and Molland, Turnock, and Hudson 2011.

A.6 Flow separation

Flow separation refers to a circumstance when the flow over a surface separates entirely from the surface, and a new eddy or votex is formed where the flow actually moves in the opposite direction to the dominant flow. It is of particular significance in hydrodynamics because it can lead to substantial losses of efficiency, as energy is diverted into the kinetic energy of the eddy or vortex, which is unproductive. It tends to occur near the surface of aerofoils with high angles of attack, or in the blades of turbomachinery including diffuser or mixed-flow pumps and ducted propellers operating in off-design conditions, including low flow rates (Li et al. 2013), parencitebakker2006, parencitemcbride1979, parencitewislicenus1986.

In order for flow separation to occur, a fluid must be moving against an adverse pressure gradient, which simply means that the static pressure (pressure in the rest frame of the fluid) is increasing in the direction of movement, which means the flow is slowing down as it moves, unless new work is being done on it. At the boundary layer, where the flow velocity is already reduced due to drag forces experienced near the surface, the adverse pressure gradient can be enough to reverse the flow altogether. In this case, the fluid flows in reverse near the surface and forms a vortex, and the main flow becomes separated form the surface by the votex.

In addition to the necessary loss of efficiency, flow separation can often tend to result in unsteady flows, with the vortices periodically being shed into the flow (Molland, Turnock, and Hudson 2011, p. 480). If this occurs ahead of the blades of a propeller or impeller, such disturbances to the flow can lead to instances of cavitation when otherwise a steady homogenous flow might be well below the cavitation inception point, and can be consequential for the acoustic performance of the system, particulaly if such shedding resonates with characteristic frequencies of any of the machinery.

Flow separation tends to occur earlier for laminar boundary layers than for fully turbulent boundary layers.

Figure 60: Flow separation occurring over the top of an aerofoil in a wind tunnel. Image courtesy of Deutsches Zentrum fuer Luft- und Raumfahrt e. V. (DLR)

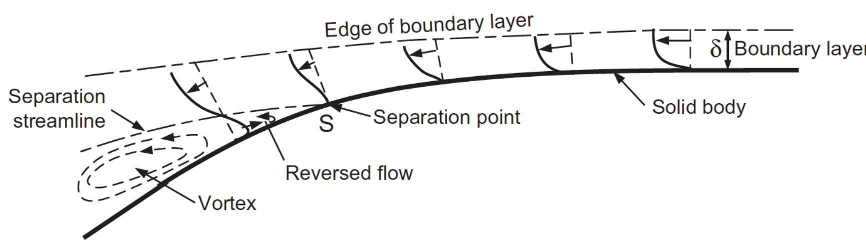


Figure 61: Flow separation involves flow reversal near a surface when a fluid is moving against an adverse pressure gradient, as shown in (Molland, Turnock, and Hudson 2011)

Consequently, some systems are able to become more efficient by deliberately inducing turbulent, where the benefit from reduced friction in the laminar boundary layer is outweighed by the cost suction induced by the larger wake field created by earlier flow separation. This is the reason that golf balls have dimples, and tennis-balls have fur, to enable them to fly further. The impact of the increased surface area, and more turbulent flow over the surface, is exceeded by the reduced wake field (trailing area where the flow is totally separted) behind the ball.