# Evaluation of Engine Systems in Non-Nuclear Submarines for the United States Navy

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This report compares the effectiveness of non-nuclear submarines powered by the diesel-electric system and by the Stirling engine system according to the criteria of stealth, cost, mobility, endurance, and efficiency.

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*Title page picture taken from *SUBSIM Review* [Online], "Alternative Fueled Subs" by Frank Kulick, July 14, 2002 from the World Wide Web: http://www.subsim.com/ssr/frank1.htm.

## Executive Summary

The United States Navy has plans for constructing many new nuclear submarines over the next decade. These submarines, while extremely effective throughout the Cold War, may no longer provide the Navy with the mobility, stealth, and cost effectiveness that it desires. For these reasons, non-nuclear submarines may soon replace their nuclear brethren in the production line and the question arises as to what type of non-nuclear submarine such replacements will be.

Submarines powered by diesel-electric systems with battery-driven propulsion are quiet beneath the surface, but require a noisy recharging process if battery power runs out. They can reportedly reach underwater sprint speeds around 25 knots and dive to depths of about 400 meters. Construction costs $250 million and maintenance adds significantly more. At over 40%, engine efficiencies are relatively high, allowing diesel-electric submarines to stay submerged for over a month.

Stirling engine submarines provide quiet propulsion underwater with no need for noisy battery recharging. They are limited to a speed of 20 knots submerged and can reportedly dive below 450 meters. They cost $100 million to build and rarely require engine maintenance. Submerged endurance lasts several weeks running on Stirling engines with astounding efficiencies of 50% or more.

Despite their slower speeds, Stirling engine powered submarines provide more stealth, almost equal endurance, and higher engine efficiencies at a significantly reduced cost.

# Introduction and Problem Statement

The United States Navy's fast attack nuclear submarines comprise the most feared fleet of weapons vehicles ever built, but significant advances in non-nuclear propulsion technology over the last few decades raise the question of whether the military should augment its nuclear submarine fleet with now equally effective and dramatically less expensive non-nuclear submarines [1].

The Navy significantly scaled back its nuclear submarine production after the Cold War ended, but still plans to build and deliver four new submarines, estimated to cost $1.65 billion each, before the year 2006 [2]. Nuclear submarines are often extremely large and therefore have limited maneuverability in shallow water, where they can quickly become "sitting ducks." They require compact nuclear reactors to generate steam to power the submarine. Even with modern technological adaptations, these reactors make a lot of noise, reducing the stealth ability of the submarines. And there is, of course, the question of what to do with the nuclear waste on decommissioned submarines, a problem that because of national and international criteria has no good solution to date [3].

In comparison, modern non-nuclear submarines cost only $100 to $300 million. Most versions run on noisy diesel engines on the surface, but use extremely quiet battery-driven electric motors while submerged [1]. Others run on silent Stirling engines that may also recharge the submarine's batteries. All are significantly smaller than bulky nuclear submarines and thus can enter tight spaces and perform more specialized missions. As with nuclear submarines, their time spent continuously underwater is limited primarily by the crew's need to resupply food and oxygen at the surface [4].

These reasons all seem to point the Navy's submarine fleet's future towards non-nuclear alternatives. As Robert G. Williscroft, Navy Editor of DefenseWatch, states concerning non-nuclear replacements, "More than twice the muscle for half the cost is a no-brainer."

## Purpose, Scope, and Methodology

The purpose of this project was to recommend the best engine alternative for use in Navy non-nuclear submarines while considering the specifications it would need to gain approval from the Navy. The engine systems considered for use in these ships are the modern diesel-electric system and the Stirling engine system.

The alternative solutions were evaluated according some specific defense, mechanical engineering, and business criteria put forth in textbooks and on commercial, government, and military Internet sites: stealth, mobility, cost, endurance, and efficiency.

In order to evaluate the diesel-electric system and the Stirling engine system as suitable motor power choices, Scott's Engineering Consultants (SEC) acquired information from textbook materials, Internet searches, and library research. SEC established the need for assessment when non-nuclear submarines were discovered on the Internet to be in current production overseas and American implementation was hypothesized. Logistic information on submarine stealth was gained through commercial Internet sites of submarine contractors and through online government data. Cost figures were found on an international submarine market analysis website and in Navy articles published online. Endurance information was acquired through library research as well as submarine contractor Internet sites. Theoretical and actual efficiencies for the two types of engines were obtained from mechanical engineering textbooks and library materials.

## Organization of the Report

The remainder of this report is divided into five sections. The first section, Alternative Solutions, describes in detail the two engine options considered by SEC. The second section, Solution Criteria, defines the criteria that were used to evaluate the diesel-electric system and the Stirling engine system. The third section, Evaluating Engine Alternatives, assesses the motor options according to the criteria. The fourth section, Conclusions, explains how the Stirling engine system better meets the criteria over the diesel-electric system. The report finishes with a list of recommendations for implementing the conclusions.

## Alternative Solutions

Scott's Engineering Consultants decided to evaluate the diesel-electric system because the majority of the world's non-nuclear submarines already use some version of it. The Stirling engine system was chosen because of the high stature it recently has gained in the Royal Swedish Navy. Other non-nuclear options were for the most part not available.

### Diesel-Electric System

Rudolf Diesel designed the first diesel engine in 1892 with the intention of outperforming standard gasoline engines. He succeeded and even today, diesel engines can produce more power at higher efficiencies than ordinary gasoline engines.

His design became known as the Diesel cycle and consists of four processes (ignition and combustion are considered to be only one process) as shown in Figure 1 below:

a. Intake of air through a valve as the piston lowers in its cylinder.
b. Compression of the air at a ratio between 15:1 and 25:1 as the piston pushes upward.
c-d. Injection of diesel fuel into the compressed air in the piston cylinder. The heat of the compressed air is enough to light the fuel spontaneously and combustion of the fuel and the consequent expansion of the gases in the cylinder force the piston downward.
e. Outtake of exhaust gases through another valve as the piston pushes upward and completes its cycle [5].

The high efficiencies of the diesel engine are a direct result of the high compression ratios it holds. Compression ratios in typical gasoline engines are only half of what diesel engines can withstand. This increase in compression also leads to more power, the reason why most large shipping trucks have diesel engines. Because only air and no fuel is compressed, diesel engines do not experience knocking as gasoline engines can, keeping them quieter and increasing the usable lifespan.

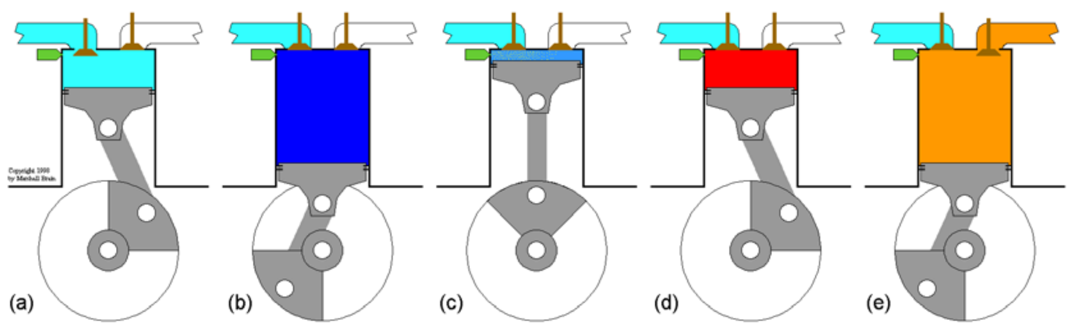


**Figure 1: The diesel engine as it undergoes (a) intake of air, (b) compression, (c) fuel injection and ignition, (d) combustion and expansion, and (e) removal of exhaust. The green device attached to the left side of the cylinder is the fuel injector [5].**

Submarines use diesel engines on the surface and while snorkeling to provide substantial propulsion power through the water. During their runtime, they are also charging the submarine's onboard batteries, which are a primary source of power and propulsion when submerged. Because fuel is ignited intermittently in diesel engines, they tend to be quite noisy. In contrast, the battery motors are significantly quieter and therefore are used when the submarine is in hostile territory.

## Stirling Engine System

Submarines use a variation on the two-piston Stirling engine. All Stirling engines have external combustion and are divided into two sections, the cold space and the hot space, with a device called a regenerator in between. Figure 2 below illustrates the four processes that a Stirling engine passes through in each complete cycle:

a. Isothermal compression as the cold space piston begins its downward stroke and the hot space piston finishes its left stroke.
b. Constant volume heat addition as the working fluid passes through the regenerator causing the cold space piston to finish its down stroke and push the hot space piston rightward.
c. Isothermal expansion forcing the hot space piston to finish its right stroke (this is where Stirling engines get their power) and the cold space piston to start moving up.
d. Constant volume heat rejection through the regenerator pushing the cold space piston upwards and pulling the hot space piston to start its left stroke.

To ensure isothermal compression and expansion, any heat generated by these processes is transferred into the walls of the surrounding cylinder, which are maintained at the constant space temperature. Heat is either added or absorbed by the regenerator as the working fluid passes through it in the constant volume processes [6]. This unique device is therefore essential to the Stirling engine as it provides a means for storing energy until it is needed later in the cycle.

In submarines, Stirling engines use helium as the working fluid and create a hot space by burning oxygen and diesel fuel in an external pressurized chamber. The pressure in this combustion chamber is higher than the pressure of the surrounding seawater, allowing the minimal exhaust products to be discharged and dissolved overboard without the use of a noisy compressor. The required oxygen is stored in cryogenic tanks in liquid form while the diesel fuel is simply contained in standard gas tanks [7].

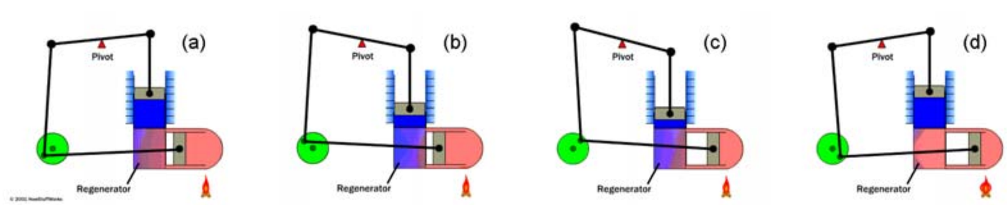


**Figure 2: The Stirling engine as it undergoes (a) isothermal compression, (b) constant volume heat addition, (c) isothermal expansion, and (d) constant volume heat rejection [8].**

# Solution Criteria

Commercial, government, and military websites devoted to attack submarines as well as various engineering textbooks provided SEC with specific defense, mechanical engineering, and business criteria in order to evaluate and recommend the best choice of engine for Navy non-nuclear submarines. For clarity and simplicity, the criteria are listed in order of importance.

## Stealth

An essential attribute of modern submarines, a submarine's stealth derives from its ability to submerge and remain hidden underwater [9]. Sound travels faster and further in water than it does in air, and with today's modern technology it is possible that any small noise may be picked up by an enemy ship. Since the motors are by far the noisiest piece of equipment on submarines, minimizing their vibrations and sound is essential. When evaluating stealth, how well a submarine can hide and how long it can hide for are both taken into consideration.

## Mobility

Non-nuclear submarines are limited in the amount of fuel they can carry for power generation. This amount of power stored on board is essential to how fast and how deep a submarine can go in open waters. Depth and speed are of obvious importance to the Navy for the purpose of evading enemy vessels.

## Cost

Cost is defined primarily by the amount of money required to purchase a submarine, but can also include the amount of money spent on its operation, maintenance, and repairs. Maintenance issues are foreseen and fixes are made to avoid further problems whereas repairs correct damage that was not expected. Engine lifespan is considered important because of potential replacement costs. Cost estimates are given a lower priority than may be expected because the consumers of non-nuclear submarines are almost always national governments of moderate size countries whose defense budget can allow for more expensive vehicles. All published figures are given in United States dollars.

## Endurance

Submarines typically remain at sea for several months at a time and could potentially have a need to be submerged that entire time. Endurance measures the length of time in consecutive days or weeks that a submarine can safely stay beneath the water. Maintenance, repair, and crew needs could all render a situation unsafe underwater and require the submarine to surface and possibly return to port. Potential crew needs include supplying food and oxygen, scheduled breaks, and medical attention.

## Efficiency

Engine thermal efficiencies are mechanically defined as input to output energy ratios and are expressed in terms of percentages. They have a direct effect on how much fuel an engine requires to run, how much power it produces, and how much waste or pollution it creates. Higher efficiencies can lead to more stealth, lower costs, and higher endurance.

# Evaluation of Engine Alternatives

This section evaluates the diesel-electric system and the Stirling engine system according to the defense, mechanical engineering, and business criteria defined above.

## Diesel-Electric System

### STEALTH

As stated in the introduction, modern diesel-electric submarines are very noisy while operating their diesel motors. They are, in fact, so noisy that running a diesel engine in hostile territory is considered suicide because all enemy submarines and most enemy ships most certainly will pick up the submarine's location. For this reason, diesel-electric submarines use their diesel engines only when surfaced or in friendly waters and use their battery-driven motors when the threat of combat is near. Because these battery-driven motors have few moving parts, their vibrations are minimized and their operating noise is very low.

However, batteries on submarines eventually run out of power and must be recharged using the noisy diesel engines. In such a way, diesel-electric submarines are limited in the amount of time that they can remain quiet and hidden. With modern technology this limitation has been minimized, though. Some of the newest diesel-electric submarines reportedly can travel 3,000 miles underwater at a speed of four knots, inferring quiet transport for more than a month [10]. Still, a diesel-electric submarine must recharge its batteries at some point and it is this limitation that lowers the vessel's stealth significantly.

### MOBILITY

Non-nuclear submarines do inherently lack some of the speed of their nuclear brethren, typically averaging 15 to 20 knots at top speed as opposed to the 25 to 30 knots top speed of a nuclear submarine. But modern technology appears to be bridging this gap. The Germans have developed a diesel-electric submarine, the TR 1700, that has a published underwater sprint speed of over 25 knots. While the TR 1700 can obviously not hold this speed for very long, the statistics do prove that it can outrun a nuclear submarine attack at least long enough to provide itself some means of escape.

Submarines may also have no choice but to seek escape in the depths of the ocean. One new diesel-electric vessel made in Germany has a published maximum depth of 380 to 400 meters [11]. Another German model currently in the production stage will supposedly be able to dive to a depth of over 400 meters [12]. Beyond these depths, the severe water pressure can cause sustaining damage to a submarine's hull and engine and possibly immobilize the ship altogether. Even with slightly lower depth ratings, diesel-electric submarines ability to move quickly underwater make it a very mobile vessel overall.

### COST

A new diesel-electric submarine reportedly costs approximately $250 million to build with variances coming due to the number and types of custom fittings purchased [1]. Once in operation, non-nuclear submarines such as diesel-electric vessels can complete a mission for costs that are typically about one third of those of surface ships [13]. And while advances in technology have cut down on the amount of maintenance required on diesel-electric submarines, the cost and frequency that are required still remain significant figures.

Because of their numerous moving parts and constantly high internal temperatures and pressures, diesel engines do have a limited lifespan. Expected lifespan for automotive diesel engines is 5000 hours [14] but because of their greater size and care, submarine engines typically can last up to 28 years in this application (nuclear submarines may exceed 30 years). Diesel-electric engines are therefore certainly a worthwhile investment, but their initial cost and regular maintenance expenses are still comparatively high.

### ENDURANCE

The newest diesel-electric submarines, as reported above, potentially have the ability to stay submerged for over a month and can even travel beneath ice [13]. During this time underwater, the mechanics onboard the submarines are called upon to conduct routine maintenance, such as oil changes, on the diesel engine. Any maintenance issues that cannot be handled at sea are typically few and far between and can be dealt with when the submarine returns to port, so there is little reason to doubt such published timeframes. A month is a relatively long period of time, but not so long that other submarine models of a similar kind cannot match it.

### EFFICIENCY

In 1896, Rudolf Diesel proudly displayed an engine that had a theoretical efficiency of 75%, by far the highest such value in the world at the time [15]. The actual efficiencies in today's heavy-duty diesel engines, such as the ones found in submarines, can get close to a respectable 40%. The diesel engine industry believes that current engine efficiencies can be increased to between 50 and 55% with some research and changes [16]. (To put these numbers in a little better perspective, the engines found in automobiles typically run at efficiencies around 25%.) Such improvements would cut a submarine's fuel expenses, allowing them to run for a longer time at sea and become more affordable. Still, it is unlikely that any diesel engine will match the remarkable efficiencies of the Stirling engine.

## Stirling Engine System

### STEALTH

Kockums, a Swedish engineering company, has designed a state-of-the-art Stirling engine system for use in submarine propulsion. Because Stirling engines have relatively fewer moving parts and no intermittent internal combustion of gases, they seldom have torque variations and therefore can optimally run vibration-free and silent. This lack of noise makes the infrared signature of Stirling engine submarines very low, meaning the submarine is harder to detect by enemies utilizing infrared methods [4]. The combustion that does take place occurs in a separate chamber where the pressure is kept higher than the surrounding seawater pressure, allowing the relatively little amount of exhaust products to be dissolved in seawater (no bubbles) and discharged out of the submarine without the use of a noisy compressor [7]. The system also offers an alternative to battery power, which in turn eliminates the requirement for noisy battery recharging, as is the case with diesel generators. Thus, Stirling engine submarines easily gain an overall advantage in stealth over diesel-electric submarines of the same kind.

### MOBILITY

Stirling engines are designed to produce constant power over a long period of time. Their pistons tend to be "pulled" more than "pushed" as in conventional engines, resulting in somewhat limited power production. At top speed, Stirling engine submarines are typically capable of 11 knots on the surface and 20 knots below water. These speeds typically will not be sufficient to outrun most nuclear submarines and many conventional submarines as well.

Stirling engines are still able to dive relatively deep under water, though. The Stirling Engine Society estimates a limit of 450 meters for the Swedish Navy's HMS Gotland class based on the statistics of its predecessor. This maximum depth parallels that of the newest conventional submarines, although it lags significantly behind nuclear submarines, which were designed to operate in the deep open waters of the ocean. So while Stirling engines gain many advantages as a result of their unique design, their lack of speed shows that mobility is not one of them.

COST

Despite the specialized materials that must often be used in their construction, submarines with Stirling engines can be produced for approximately $100 million [1]. They are readily available for implementation in both new and currently operating submarines and are proven in operational service. Operating costs run slightly higher than conventional submarines because of the necessary use of liquid oxygen as part of the fuel. Stirling engines require little maintenance, however, because they have few moving parts and no internal heat to burn off the oil lubrication. One engine currently in use with cryocoolers has a published operating life of over 50,000 hours [18] and another engine ran in a lab for more than 90,000 hours without stopping [14]. Still the lifespan of a Stirling engine submarine is only around 25 to 30 years, but for less than half the cost of any submarine system, the Stirling alternative is extremely cost effective.

ENDURANCE

The use of Stirling engines coupled with modern advances in technology has led to the increased submerged endurance of non-nuclear submarines. According to Kockums, "a Stirling submarine can extend the amount of time submerged from days to weeks." The submarine is limited primarily by the amount of liquid oxygen stored onboard. However, were this supply to run out, the motor could still be run as a type of diesel engine and the vessel would remain a functional conventional submarine. In addition to these prospects, because the Stirling engine is an external combustion engine, only a sufficient heat source is needed for it to operate. In very drastic situations, the crew could burn almost anything to keep the motor running, increasing the survivability onboard a Stirling engine submarine. Overall, these submarines have very similar submerged endurance times to those of diesel-electric models.

EFFICIENCY

The idealized Stirling cycle is very similar to the Carnot cycle, recognized by mechanical engineers to yield the highest theoretical efficiency possible. Ideal conditions are not present on submarines, however, and so actual efficiencies must be considered. Efficiencies around 50% are typical for well-designed engines, and 70% efficiency is considered to be the maximum achievable value [6]. These values are impressive considering again that most automobile engines run at 25% efficiency. Just its theoretical efficiency alone shows that the Stirling cycle and systems based on it have the potential to be extremely efficient.

## Conclusions

Based on the evaluation of engine alternatives using the solution criteria put forth by defense, business, and mechanical engineering sources, SEC has reached the following conclusions concerning the implementation of an engine system into a non-nuclear submarine.

1. Implementing a diesel-electric system gives the submarine quiet battery-driven propulsion beneath the surface, but requires the batteries to be recharged by running the noisy diesel engine. The newest diesel-electric submarines are reportedly capable of underwater sprint speeds around 25 knots and can dive to depths around 400 meters. On average, they cost $250 million to build. If need be, they could potentially stay submerged underwater for a month or more. Diesel engine efficiencies, 75% theoretically and 40% realistically, are relatively high compared to the common internal combustion engine.
2. Using a Stirling engine system provides a non-nuclear submarine with quiet propulsion underwater and eliminates the need for noisy to battery recharging. Stirling engine

submarines are limited in propulsion to only 20 knots when submerged but reportedly can dive to an estimated depth of 450 meters. They are relatively inexpensive for an attack submarine, costing only $100 million to purchase and requiring little engine maintenance over their lifetime. Submerged endurance can last up to several weeks, being limited only by the amount of liquid oxygen fuel that is stored onboard. The Stirling engine has very high efficiencies, running at 100% theoretical and 50% actual, that have not been and may never be surpassed by another engine.

Taking all the criteria into consideration, the Stirling engine system will provide better results in non-nuclear submarine performance as illustrated in Figure 3. Choosing to implement a Stirling engine system such as the ones designed and manufactured by Kockums will benefit the United States Navy for several reasons. The advantages of Stirling engine systems over more conventional diesel-electric systems are as follows:

- More stealth through quieter, longer lasting propulsion
- Significantly lower cost of acquisition and operation
- Higher maximum and actual engine efficiencies

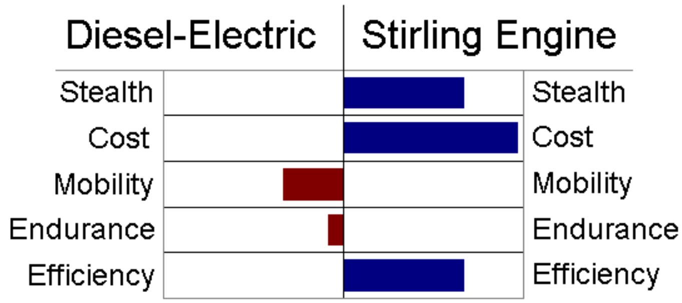


**Figure 3: Evaluation of the diesel-electric system vs. the Stirling engine system in non-nuclear attack submarines according to each of the specified criteria.**

## Recommendations

In order to increase the effectiveness and decrease the cost of its non-nuclear submarines now and in the future, Scott's Engineering Consultants recommends that the United States Navy use Stirling engines as propulsion systems in the retrofitting of old submarines and the construction of new ones. In order to implement this recommendation, SEC suggests the following:

1. Reconsider the budget for submarine construction a few years ahead and replace on paper a few of the planned nuclear submarines with several Stirling engine alternatives.
2. Begin construction of Stirling engine powered submarines.
3. Decommission several non-nuclear submarines that have been in service for over twenty years.
4. Decommission several nuclear submarines that have been service for over thirty years.
5. Commission and launch the new submarines with Stirling engine propulsion (perhaps alongside the one or two nuclear submarines that were under construction at the same time).

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