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Can Russian Strategic Submarines Survive at Sea? The Fundamental Limits of Passive Acoustics

Eugene Miasnikov[a]

Deep reductions in the strategic nuclear arsenal of Russia raise very important questions about the survivability of its strategic forces. The Start I and II treaties will increase the role of Russian sea-based strategic missiles in providing assured deterrence relative to its land- and air-based forces. In this article, estimates are made, based on information available in the open technical literature, of the upper limits of the ranges at which Russian SSBNs can be detected by U.S. attack submarines. In particular, it is shown that it is implausible that U.S. attack submarines would be able to trail covertly Russian SSBNs on a day-to-day basis in their patrol areas in the Barents Sea, the Sea of Okhotsk and the Marginal Ice Zones of the Arctic, provided that Russia applies advanced submarine silencing technologies and that the strategic submarines are properly maintained and operated.

INTRODUCTION

Nuclear arms have been the means of deterrence between the United States and the Soviet Union. However, with the end of the Cold War and the establishment of new sovereign states on the territory of former Soviet Union, of which only Russia (and possibly Ukraine) is going to remain a nuclear weapons state, it is necessary for both the United States and Russia to reevaluate the roles of their nuclear weapons and to correspondingly change the structure of their strategic nuclear forces.

The tables in appendix 1 reflect the current process of strategic nuclear disarmament. Under the START Treaty, both sides are required to reduce

a. Research Associate, Center for Arms Control, Energy and Environmental Studies, the Moscow Institute of Physics and Technology.

their arsenals to about 8,000 warheads each by the year 1998. The START II treaty, signed in January 1993, will produce much deeper cuts, down to 3,000 to 3,500 warheads for each side by the year 2003. It is possible that the implementation of these reductions could be accelerated and even deeper cuts negotiated.

These deep reductions raise important questions about the future of both countries' strategic forces. First, how should the remaining nuclear warheads be deployed? The START II Treaty, although it does eliminate land-based multiple warhead missiles, largely leaves it up to each country to determine where and how they should deploy their nuclear arms. A second and related question is how the survivability of this smaller number of weapons can be assured if the relations between the two countries deteriorate, perhaps becoming similar to what they were during the Cold War.

Historically, the strategic nuclear forces of both countries have consisted of a triad of land-, sea- and air-based weapons. The submarine launched ballistic missiles (SLBMs) play a particularly crucial role, since they are widely viewed as being able to survive even a surprise first nuclear strike, and, therefore, as providing a guaranteed means of nuclear retaliation. The role of SLBMs will become even more important after all MIRVed land-based missiles have been eliminated by the START II Treaty, and by the year 2003, SLBMs could account for half of the total strategic warheads on each side.

Can SLBMs really be relied on to be secure against all possible measures an adversary might take? Unlike the situation for their American counterparts, the answer to this question may not be obvious to Russian policy makers, due to a number of technological, geographical, and historical factors. The technology of nuclear submarine building in the Soviet Union has in many respects not been as advanced as in the United States. In particular, Soviet submarines have been noisier and thus more vulnerable to detection methods based on acoustical principles, which are the most important means of submarine detection.[1] Another factor is that the United States has prominent geographical advantages, and has been able to deploy submarine detection and surveillance systems at the strategically important passages between the internal seas of the Soviet Union (the Barents Sea and the Sea of Okhotsk) and the open ocean.[2]

On the other hand, the new generation of Soviet submarines is much quieter than its predecessors and is therefore substantially less vulnerable to the detection capabilities of U.S. anti-submarine warfare (ASW) forces.[3] In addition, following the START reductions, all of the remaining Russian SSBNs (see appendix 1) will be armed with very long range missiles and thus will be able to target most of the United States from ocean areas adjoining the Russian coast.[4]

What then is the threat to Russian SSBNs patrolling in their home waters (the Barents sea or the sea of Okhotsk), where any enemy who attempts to operate in these waters would face very strong Russian air and sea defenses? Aside from a possible deterioration of the military capability of the Russian Navy because of economic difficulties,[5] there may exist several potential threats to these submarines. First, the United States may deploy underwater surveillance systems near Russian SSBN bases that would allow them to covertly track Russian SSBNs.[6] Second, an unforeseen breakthrough in U.S. reconnaissance capabilities, such as the development of a satellite sensor capable of detecting submarines from space, might occur.[7] Third, and clearly the most real and immediate threat, is that U.S. attack submarines, using passive acoustic detection, could covertly detect and trail Russian SSBNs.

There is another reason why this third threat is the most important. Even if the first or second threats were to materialize, the only mean of preemptively destroying a missile submarine in its home waters would be a use of an attack submarine. Such an attack submarine could possibly detect and trail an SSBN, and, after having received a proper order, could kill the SSBN before it could launch its missiles.[8] This potential threat could grow as the number of Russian SSBNs rapidly diminishes while the number of US attack submarines decreases less rapidly.[9]

This article does not attempt to provide a complete and definitive answer to the question of whether or not Russian SSBNs are vulnerable to foreign attack submarines. The objective of this article is evaluate, under various environmental conditions, the range at which an attack submarine might be able to detect a Russian SSBN. A complete assessment of SSBN vulnerability would need to consider not only the deployment of covert surveillance systems or the possibilities of technological breakthroughs in non-acoustic detection, but also the possibility of continuous covert trailing[10] of SSBNs by attack submarines. However, if in a given set of environmental circumstances, the detection range of a U.S. attack submarine against a Russian SSBN is too low to provide a reasonable search rate or allow reliable continuous covert trailing, then this would mean that in these circumstances, Russian SSBNs may be considered as a secure option for nuclear arms deployment.

The results presented here can be considered to be reasonable estimates. The detection range against a submarine is a key parameter in the planning and execution of a strategy and tactics of anti-submarine warfare (ASW) operations,[11] and precise information about the performance characteristics of SSBNs, such as the amount of noise they produce, is not available in unclassified sources. However, it is possible to assess the vulnerability of SSBNs with their noise level as a parameter as well as to make informed estimates of the plausible range of values for this parameter. The calculations presented here clearly show that, at currently achievable levels of submarine silencing, and assuming proper SSBN operation, passive acoustical means are ineffective for detection of strategic submarines in Russian SSBN deployment areas such as the Barents sea or the Arctic.

FORMULATION OF THE SUBMARINE DETECTION PROBLEM

In the following, for brevity, we will not make a distinction between different types of submarines, since the conclusions of this article are applicable not only for SSBNs, but for all kinds of submarines. The most important of the modern sensors used by submerged submarines are based on acoustical principles.[12] These sensors (sonars) can operate in both passive and active modes. However, as a rule, active operation gives away the presence of the submarine and deprives it of its covertness, a very important tactical advantage of a submarine. For this reason, active sonars generally are used only in certain situations (such as before surfacing, or in order to better determine a target's location before launching a torpedo attack). In what follows, we will only consider passive sonars.

A submarine is an underwater vehicle that generates sound and this sound can, under certain circumstances, be observable at quite large ranges by underwater sonars. When this occurs, it may be possible for a distant sonar operator to determine that a detected acoustic signal is from a submarine. It may also be possible to estimate the location, speed, and direction of motion of the detected submarine. And if the observed sonar signal is of sufficiently high quality that it can be correlated with previously collected intelligence data, it may even be occasionally possible to make an informed guess about what type of submarine is generating the signal.[13] In the following analysis, we focus on the *detection* problem, i.e., whether or not the sonar operator is able to detect the presence of a submarine.[14]

There are a number of factors that influence the detection range for a given submarine target. In order to formalize the problem and to obtain quantitative estimates of the detection range, the following terms are usually introduced:

Source Level

The source level (*SL*) is the intensity of the target submarine-generated sound, measured in a one Hz bandwidth at a distance of one meter from the submarine in the direction of the receiver. The *SL* is measured with respect to a reference intensity, generally (and in this paper) that of a plane wave with an rms pressure of one microPascal.

Transmission Loss

Transmission loss (*TL*) is the loss of sound intensity as the sound travels from the target submarine (actually from the *SL* reference point one meter from the target) to the receiver.

Noise Level

The noise level (*NL*) is the oceanic and man-made background noise at the receiver with respect to the reference intensity of one microPascal.

Receiving Array Gain

The receiving array gain (*AG*) is the improvement of the signal-to-noise ratio provided by the use of a given sonar array compared to a single receiver of the array.

Detection Threshold

The detection threshold (*DT*) is the level by which the submarine signature must exceed the noise in a one-Hz bandwidth in order to obtain a specified probability of detection and of false alarm.

The terms above are expressed in decibels (dB).[15] The range at which it is possible to detect a submarine depends on the acceptable size of the transmission loss, which can be estimated from the passive sonar equation:[16]

$$TL = SL - NL + AG - DT$$

In the following analysis, we will estimate the range of variability of each of these factors and then use these estimates to determine possible detection ranges in Russian SSBN patrolling areas, namely, in the North Atlantic and North Pacific (the deep ocean case), in the Seas of Barents and Okhotsk (the shallow waters case), and in the Arctic.

BACKGROUND FOR ESTIMATING THE DETECTION RANGE AGAINST SUBMARINES

Detectable Features of Submarines

The sources of submarine-generated sound include vibrations of the submarine's hull, machinery noise (engines, rotating and vibrating shafts), cavitation[17] noise and pressure waves produced caused by the rotation of propulsion screws, and hydrodynamic noise from the turbulent flow of ocean water along the hull of the submarine.[18] This combination of sources results in a noise spectrum that is an uninterrupted continuum of sound pressure levels that is punctuated by acoustic lines at well defined frequencies. The most important source of these acoustic lines, which are called "tonals," is vibrating and rotating mechanical equipment inside the hull of the submarine. Such vibrating equipment causes the hull of the submarine to resonate and produce sound in the surrounding water. As a rule, the presence of these lines is the most important factor in submarine detection, since they can be seen even when the source submarine is moving slowly (so that its cavitation noise is low).[19] This feature of the spectrum allows the effective application of narrowband processing. (See "Criterion for Distinguishing a Signal in a Noise Background" on page 97.) The basic idea of this technique is that the signal level and the noise level are compared in a narrow band which contains most of the energy of a tonal.

There are many similarities between the basic characteristics of the acoustic spectra of surface ships and submarines. For surface ships, the frequency range where tonals can occur is restricted to frequencies below one kHz.[20] These tonals may stand out from the cavitation spectrum by factors ranging from less than 10 dB up to about 20 dB. Typically, the cavitation spectrum is a continuum, peaking between 50 and 100 Hz and, at frequencies above 100 Hz, the continuum part of the source level decreases approximately inversely proportional to the square of the frequency.[20]

Unlike commercial surface ships, very substantial efforts are made to design, construct and operate submarines so that they will have very low acoustic outputs. Rotating equipment mounted in the hull of a submarine is precision machined, balanced, and sound-isolated at great effort to reduce the amplitude of vibrations that are transmitted to the hull. Care is taken to sound isolate steam lines, pipes, and decks from the hull, and to design propellers that produce minimal acoustic signal as they push the submarine through the water. In addition, submarine operators are trained to operate their ships in ways that will minimize the possibility that they will be detected.

For example, since the noise produced by a submarine increases when it maneuvers, or when propellers cavitate, great care is typically exercised to operate submarines in ways that minimize the need to maneuver or to take actions that will cause propeller cavitation.[21] Submarine crews also learn to maintain equipment in ways that minimize the increased noise output that naturally occurs as equipment in a submarine wears and becomes out of balance.

The lower limit of a tonal bandwidth can be estimated to be about 0.1 to 1 Hz.[22] The bandwidth of a tonal depends on the nature of the vibrating equipment that generates the sound, and on the motion of submarine. The longer a submarine moves at constant speed, and the more stabilized the vibrating equipment is, the narrower will be the bandwidth of tonals emitted by the submarine. In addition, because high frequency (thousands of Hertz [Hz]) equipment vibrations are much easier to isolate from the hull of a submarine than vibrations of lower frequency (tends to hundreds of Hz), tonals emitted from submarines tend, on the average, to be stronger at low frequencies than they are at higher frequencies.

The rare submarine noise data that can be found in the open literature,[23] indicates that at low frequencies, the source level of World War II submarines was between 120 and 140 dB at speeds of six to 10 knots (see figure 1). Of course, the technology of submarine quieting has greatly advanced since that time. Given the lack of specific data on the source level of modern SSBNs, we will use the models of source level spectra shown on figure 1.[24] In these models, the source level of "noisy," "quiet" and "very quiet" submarines are 140, 120 and 100 dB respectively at a frequency of 30 Hz. It is reasonable to assume that the source levels at 300 Hz are 10 dB lower.

Transmission Loss

The transmission loss, representing the loss of the intensity of a sound wave as it spreads from a source to a receiver along a sound channel, is determined by the propagation geometry, bottom and surface reflections and water absorption.[25] The influence of these factors will be different for various environments.

We will consider the case where both the source and the receiver are at a depth of less than 500 meters. This case corresponds to a situation in which an attack submarine is "hunting" an SSBN.

At distances large compared to the size of a submarine, the submarine can be considered to be a point source of sound producing a spherically spreading sound wave whose intensity diminishes inversely with the distance squared.

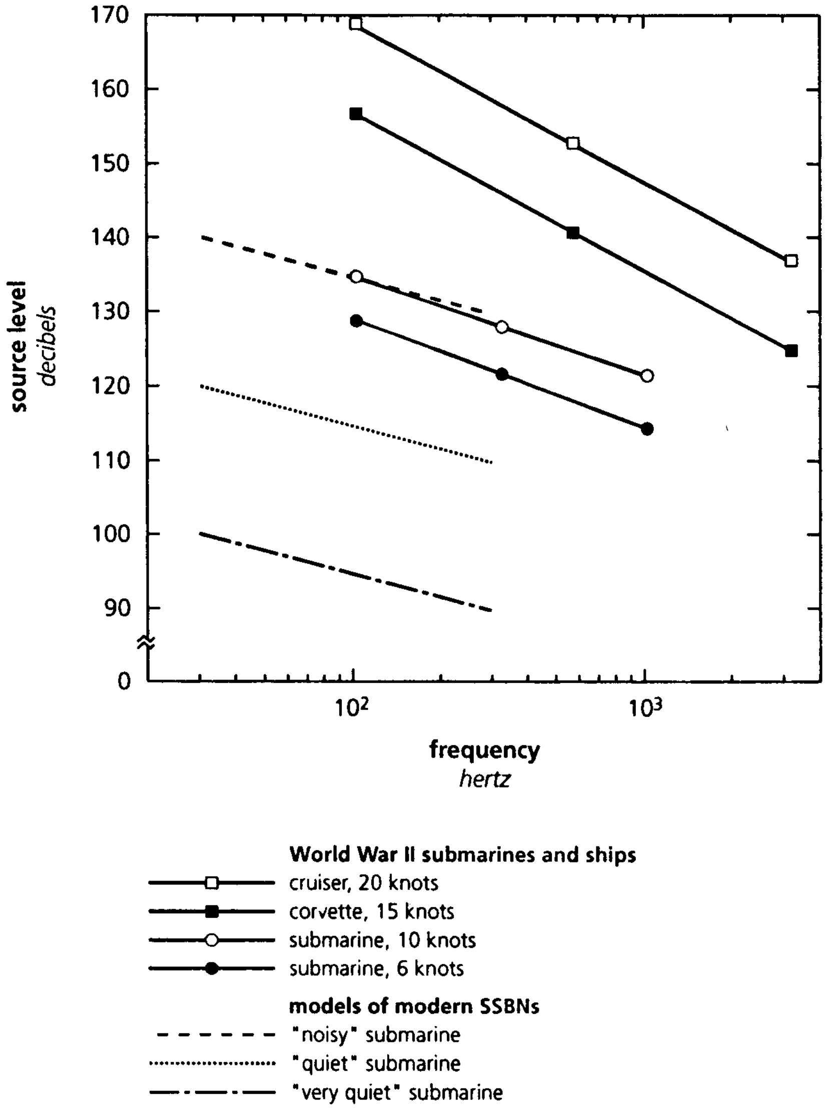

Figure 1: Source levels of World War II submarine and ships, and models of source levels in modern SSBNs. Data are taken from R.J. Urick, *Principles of Underwater Sound* (McGraw-Hill, 1983) pp. 346, 350.

So the loss increases with distance as $20 \cdot \log_{10}R$ (in dB, R is expressed in meters). At short ranges, there is a nearly straight-line path between the source and the receiver and thus the transmission loss is determined by spherical spreading (although it can be modified by interference effects due to surface reflections).

In general, sound energy in the ocean does not propagate in a straight line. The speed of sound in the water depends on the local temperature, salinity and pressure, which are typically horizontally uniform but change strongly in the vertical direction. The sound rays are refracted as they pass through layers that have different physical properties (and therefore different sound speeds), and are bent toward the layers having lower speed. As a result of these effects a large part of the sound energy generated by a sound source in the ocean gets directed into so called "sound channels," located at the depths of minimum sound speed. Since the sound energy trapped in these channels spreads cylindrically rather than spherically, the sound intensity diminishes inversely with the range from sound source, rather than inversely with the square of the range. In the open ocean, the sound speed is typically at a minimum at depths of one to four kilometers, and the corresponding channel is called a deep sound channel.

Normally, a surface mixed layer (a layer with a constant temperature versus depth) exists in an ocean or sea. Such a mixed layer results in the formation of a sound channel near the surface (a surface sound channel). The presence of a sound channel is one reason why sound spreading transforms from spherical into cylindrical spreading as the distance from the source increases, with the loss becoming proportional to $10 \cdot \log_{10}R$. Cylindrical spreading may also exist in shallow waters if the sound rays reflect from the surface and the bottom with small losses.

The distance at which spherical spreading transforms into cylindrical spreading can vary from several H (depth of the water) to many H depending on the water depth and on the vertical profile of the sound speed.

The geometric spreading is the primary mechanism of transmission loss at distances less than one kilometer. For all situations, the loss due to spreading at 100 meters is 40 dB. For deep waters, the loss at one kilometer is about 60 dB, but it is a bit less for shallow waters, since the spreading regime has changed over into cylindrical spreading by this distance (see figures 2 and 3).

The transmission loss depends strongly on the presence of a surface channel as the distance between a source and a receiver increases. If the mixed layer is deep (it is typically deeper in winter than in summer) and the surface wind is not very strong, the surface channel is a good sound conductor. Otherwise, the sound rays scattered by the bottom may make a large contribution to

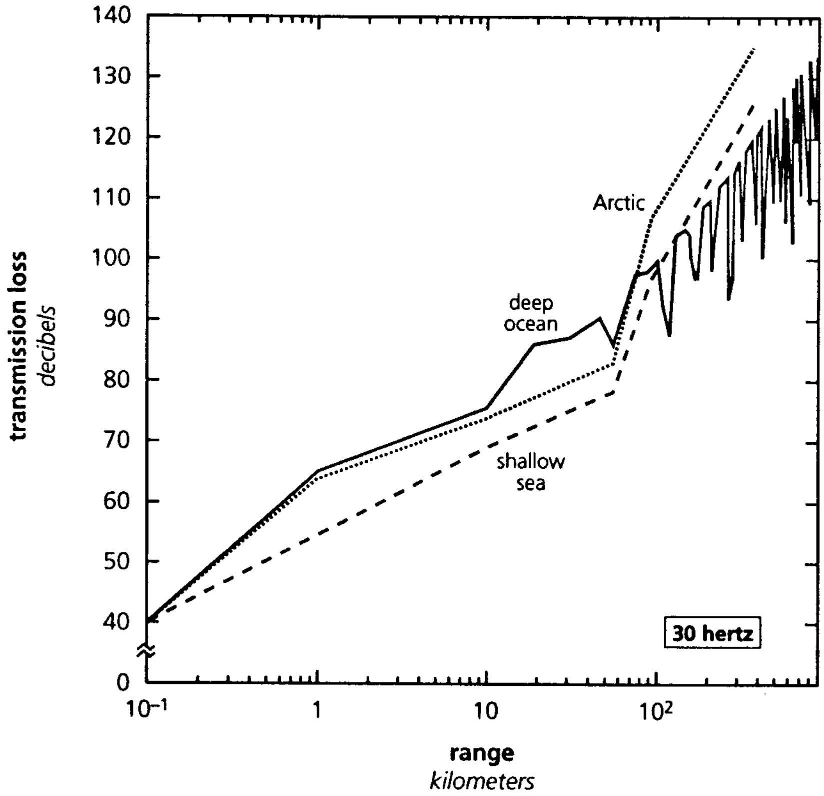

Figure 2: Transmission loss for the frequency of 30 Hz at submarine patrolling areas.

the received signal. This kind of sound spreading prevails in the absence of a mixed layer.

The nonstraight propagation of sound rays through the deep sound channel produces such phenomena as convergence zones (zones of sound focusing) and shadowing zones that have important implications for submarine detection.[26] For example, in deep oceans, convergence zones can produce gains of between 5 and 20 dB. It is the presence of such convergence zones that makes it possible to achieve detection ranges of over 1,000 kilometers.

As a rule, in a shallow waters, the transmission loss at a distance of several dozens of kilometers is less than the loss in the deep ocean because of multiple reflections from the surface and the bottom.

In the Arctic, the transmission loss at several dozens of kilometers is greater than in deep or shallow ice-free waters for two reasons. First, as the

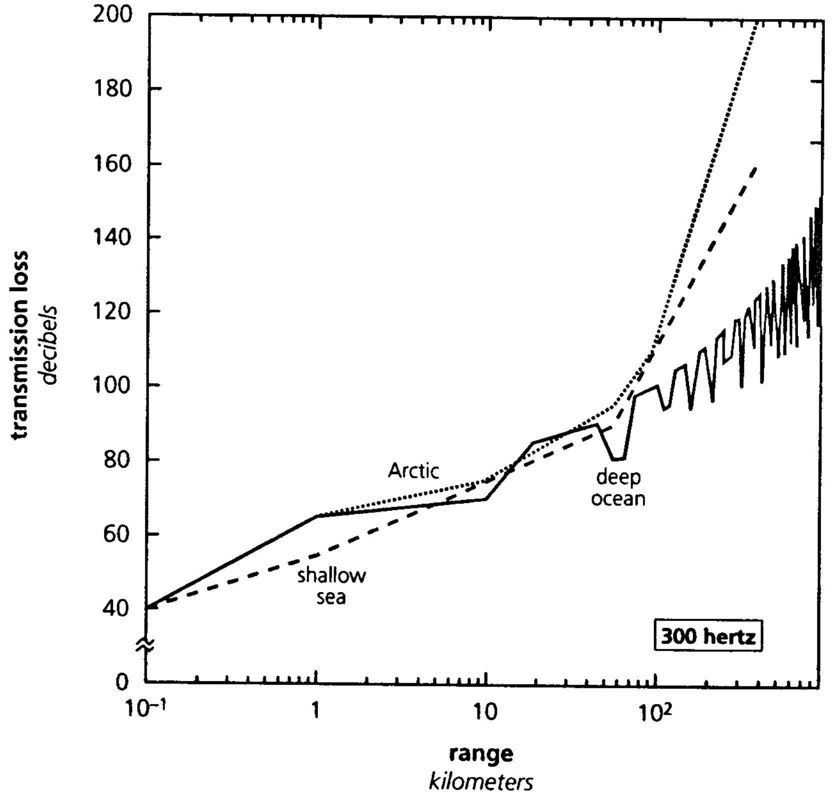

Figure 3: Transmission loss for the frequency of 300 Hz at submarine patrolling areas.

sound rays spread they undergo more surface reflections because of the much stronger positive vertical gradient of the sound speed profile in the Arctic. Second, the character of under ice surface roughness is such that the sound energy loss per reflection is high even for relatively low frequencies of 100 to 1,000 Hz.[27]

As a rule, transmission losses increase with increasing frequency in the deep ocean and Arctic. The reasons for this are higher absorption and higher loss per surface or bottom reflection at higher frequencies. The exceptions to this are in surface channels and shallow waters, where the optimum propagation frequency is between 50 and 1,000 Hz.[28]

Noise Level

In order to detect the presence of an acoustic signal emitted by a submarine it is necessary to be able to distinguish between the submarine generated signal and the noise background caused by external (due to environmental conditions) or internal (flow noise of hydrophones, nonideal signal amplification and processing) noise sources. We consider here only the unavoidable and fundamental restrictions that are imposed by noise generated by the environment. These are the wind generated noise level and the distant shipping noise level at the submarine's depth (here assumed to be 500 meters). The detection range against submarines may also be limited by other factors, such as the flow noise of hydrophones when the hunting submarine moves through the water.[29]

At very low wind speeds, the noise level in deep waters exceeds 55 dB at a frequency of 30 Hz (see figure 4), and it exceeds 50 dB at 300 Hz.[30] At these frequencies, the lower threshold of ambient noise in deep oceans is limited by distant shipping, since at low and moderate wind speeds, even light distant shipping can create much higher noise levels than does the wind.

In shallow waters, the wind generated noise level is usually 10 to 15 dB higher than it would be in a deep ocean for the same wind speed conditions because of the greater number of bottom and surface reflections.[20] The noise due to distant ships will rarely be important beyond 100 kilometers, and therefore, shipping noise is dominant only at places with high traffic. This is in sharp contrast to the situation in deep ocean waters, where the noise of shipping can spread over thousands of kilometers. An analysis of data on typical noise level spectra for shallow waters[30,20] leads to the conclusion that at wind speeds of one to 20 meters per second (m s^{-1}) (4 to 72 kilometers per hour), the total noise level varies between 70 and 90 dB at 30 Hz and between 60 and 80 dB at 300 Hz.

The origin of noise in the Arctic is very different from that in waters free of ice. The noise in the Arctic is the result of environmental factors on the ice, such as wind blowing over sea ice, and the cracking and the ridging of sea ice.[27] The noise in the Arctic is highly variable.[30] In the central Arctic, there are very quiet periods of time during which the noise level drops to 40 dB at 30 Hz and to 30 dB at frequencies near 300 Hz. On the other hand, during periods of ridging activity, the maximum level of noise can reach 100 to 110 dB near marginal ice zones (MIZs).[31] As a rule, the noise level is higher in MIZs than in the central Arctic. For example, data on seasonal noise variability measured in the Beaufort Sea (on the periphery of the Arctic) never show noise levels less than 60 to 65 dB at a frequency of 32 Hz or less than 35 dB at 1,000 Hz.[32]

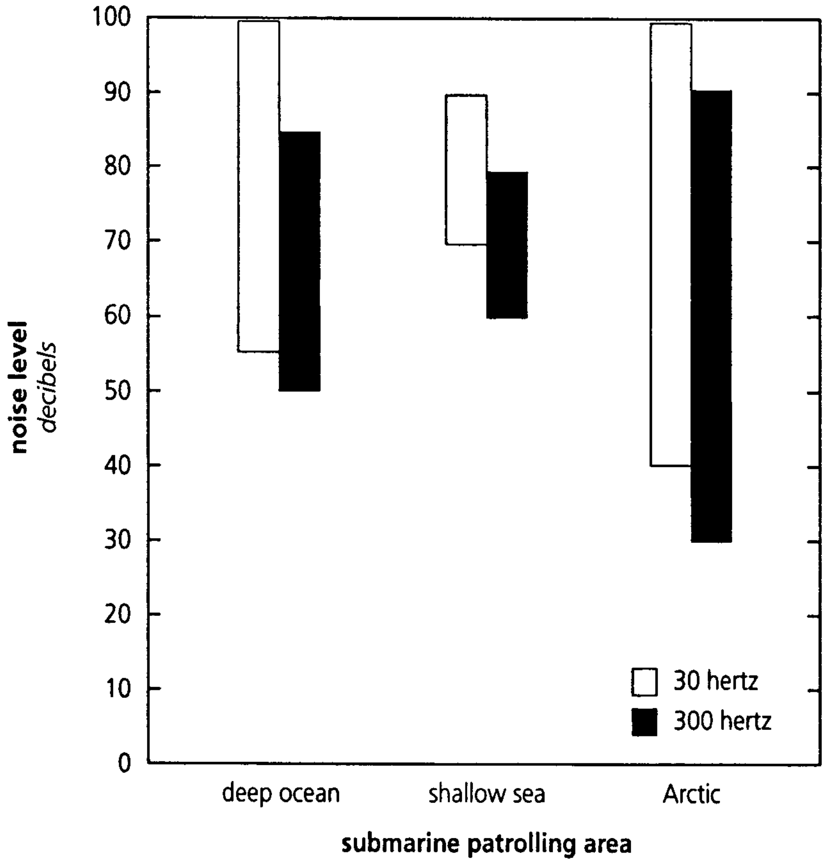

Figure 4: Range of noise level variability for frequencies 30 and 300 Hz at submarine patrolling areas.

Performance Characteristics of Submarine Sonars

A submarine sonar system consists of sensor arrays fixed on or in the hull as well as ones that are towed behind the submarine. As a rule, the fixed and towed arrays of a submarine are part of a unified sonar system with a single data processing system. For instance, the BQQ-5 sonar system (used on U.S. Los Angeles class submarines) includes a BQS-13 bow sonar array (1,241 type TR-155E/BQ hydrophones placed on a sphere with a diameter of approximately four meters), a hull-mounted conformal array probably about 60 meters long (104 DT-76 type hydrophones) and a TB-16/BQ or TB-23 towed array.[33] The TB-16 acoustic towed array consists of 50 hydrophones and is 75 meters long, towed on a cable 830 meters long. The more effective TB-23 array consists of 98 hydrophones and has a total length of 1,220 meters (this includes the towing cable, probably about 830 meters long).[34]

The signal gain produced by arrays of multiple receivers can be explained in the following way. Assume that the source is far from the receivers so that the received sound wave can be considered as a plane wave. Since the locations of the receivers and the wave frequency are known, we can add the signals at each receiver in phase. When this is done, the total output signal will be N^2 times greater than the output signal level at each separate receiver, where N is number of receivers in the array. On the other hand, the noise level will only increase proportionally to N if the noise signals are uncorrelated at the receivers. In fact, this is equivalent to the situation when there is a single receiver and the signal integration time is increased N times. Thus, for a perfectly coherent signal and incoherent noise, the signal/noise ratio increases proportionally to the number of receivers, and we get for the array gain:

$$AG = 10\log_{10}N$$

Estimates of the maximum array gains that can be achieved with the BQQ-5 submarine sonar arrays are shown on figure 5. Two fundamental factors restrict the maximum achievable array gain.

First, the noise signals received by two hydrophones are also added in phase if the distance between the hydrophones is less than the correlation length of the noise. In the best case, the noise correlation length will be equal to half of the noise wavelength.[30] Therefore, when the size of an array is restricted to be comparable with (or less than) the wavelength of the signal received (as in the case of a submarine's fixed sonar)[35], the array gain will be severely limited. As figure 5 shows, at a frequency of 30 Hz, the main restriction is the size of the arrays, and for the types of arrays we are considering here, the array gain will not exceed 12 dB. As can be easily seen, the fixed sonar is inefficient at frequencies below 200 Hz, where submarine machinery tonals are the strongest. This is the reason why towed arrays of receivers are used.

The second restriction on the array gain is due to the fact that as the length of an array increases, the signal received at its two ends becomes more uncorrelated. The coherence length (the distance between two receivers at which the correlation coefficient of the received signal is equal to 0.6)[36] depends on the character of the sound spreading and on the distance between the source and the receiver. Typically, it is larger when there is a single path from the source to the receiver[37] (for example, in convergence zones of deep water propagation) and smaller for multipaths.[38]

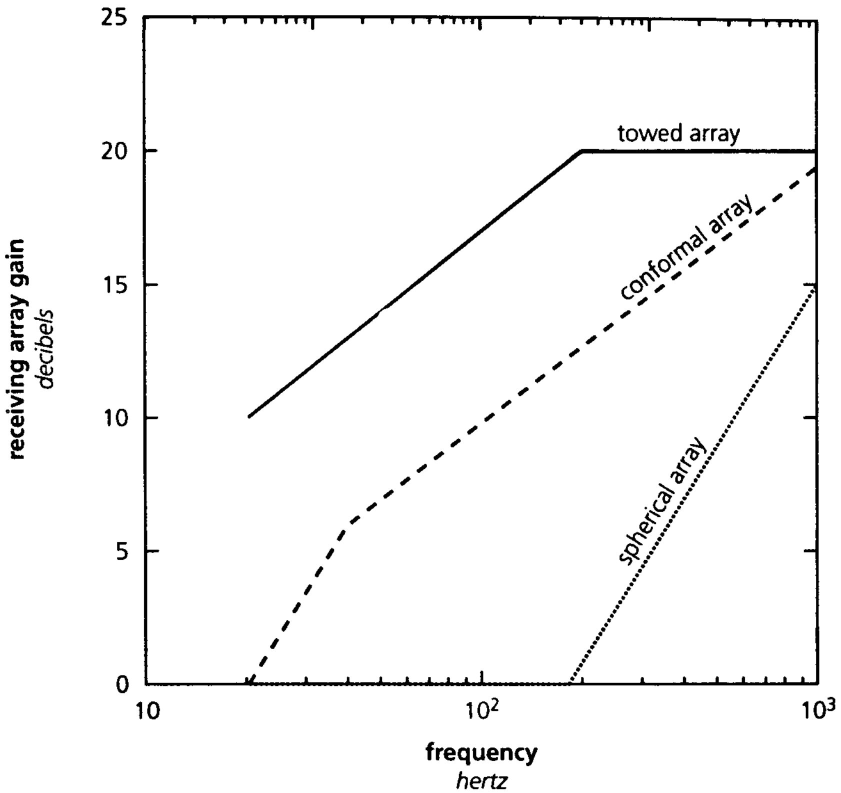

Figure 5: Maximum receiving array gain for BQQ-5 sonar of Los Angeles class submarine at low frequency.

At a frequency of 300 Hz, the array gain is primarily limited by the maximum correlation length of the signal and only in the best circumstances (in particular, in convergence zones) will array gains as high as the 20 dB shown in figure 5 be achievable.

Criterion for Distinguishing a Signal in a Noise Background

When narrowband processing is used, the signal is processed by a narrow filter centered at the frequency of the submarine tonal. The sonar operator watches, on a display screen, a signal that is proportional to the received level of sound in the filter bandwidth.[39] In the absence of a target submarine, the sound received is essentially background noise and the distribution of sound pressure levels is determined by a probability density function. In order to

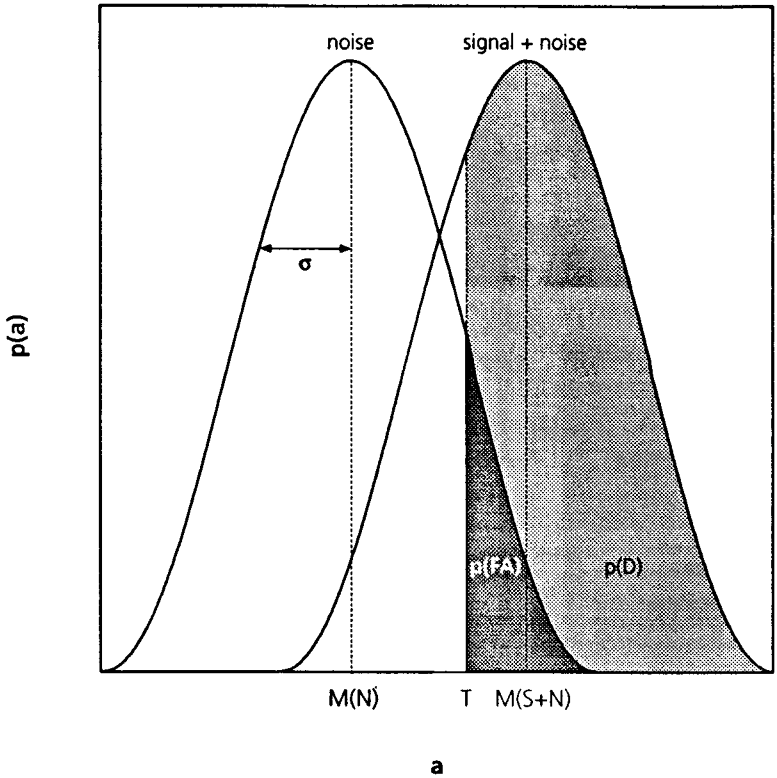

Figure 6: Probability-density distribution of noise and signal plus noise.

diminish the size of the noise fluctuations, the received signal is integrated over a period of time. When a target submarine signal is present, the received signal changes, but its nature remains probabilistic.

Figure 6 shows curves of probability density $p(a)$ plotted against amplitude a for noise alone and signal plus noise. $p(a)$ is the probability that the amplitude of the envelope of the signal receiver output lies within a small unit interval of amplitude centered at a. The mean noise amplitude is $M(N)$ and the mean signal-plus-noise amplitude is $M(S + N)$.

In further analysis, we assume that both noise and signal are Gaussian with equal variance σ^2. Frequently, a ratio d, called the detection index, is introduced in terms of these quantities:

$$d = \frac{[M(S+N) - M(N)]^2}{\sigma^2}$$

This is equivalent to the signal-plus-noise ratio of the envelope of the receiver

Table 1: Detection index values.[40]

p(FA)	p(D)		
	0.6	0.8	0.9
10^{-4}	16	21	25
10^{-5}	21	26	31

output. In a typical situation, the probability density functions of background noise and submarine signal plus background noise overlap. Thus, the sonar operator must set some threshold T in order to make a decision of whether or not a submarine target is present. The area under the curve of signal plus noise to the right of T is the probability that an amplitude in excess of T is due to signal plus noise and is equal to the detection probability $p(D)$; that under the noise curve to the right of T is, similarly, the false alarm probability $p(FA)$. In order to achieve high quality detection, it is important to maximize the probability of detection and minimize the probability of false alarm. Doing either or both will cause an increase in the detection index. Typical values for the detection index are presented in table 1.

For purposes of this paper it is convenient to introduce a quantity called the detection threshold DT, which is defined as the ratio, in decibel units, of the signal power in the receiver bandwidth S required for detection at some preassigned level of correctness of the detection decision to the noise power in a one-Hz band N_0.

$$DT = 10\log_{10}\left(\frac{S}{N_0}\right)$$

For a simplicity we can assume that the statistical properties of the ambient noise and the signal level are time independent and signal is completely unknown. Then, detection threshold is determined by the detection index, receiver filter bandwidth W and integration time t, and can be found from the following formula:[41]

$$DT = 5\log_{10}\left(\frac{dW}{t}\right)$$

The minimum receiver filter bandwidth W is chosen to correspond to the width of the tonal in the target submarine spectrum, since diminishing W below this width leads to a loss of signal energy. The minimum filter band-

Table 2: Detection threshold estimates.

Integration time	filter bandwidth	
seconds	*Hz*	
	1.0	*0.1*
100	−3.5	−8.5
1,000	−8.5	−13.5

width may be limited by the broadening of the tonals in the source level spectrum that occur due to Doppler shifts at reflections from the surface and due to fluctuations of sound channel properties as the submarine-generated sound spreads to the receiver. Experimental measurements[42] in shallow waters have shown that the typical frequency broadening is about 0.1 to 1 Hz at distances of several dozens of kilometers. For deep and Arctic water, the frequency broadening may be less, but it is unlikely to be less than 0.1 Hz.

The upper limit on the integration time is determined by a number of factors. First, the submarine that is to be detected will generally be changing its location with respect to the sonar. Thus the conditions of signal detection also will change. Second, the ocean is not a stationary medium: the properties of the sound channel, the ocean noise level, and ocean noise correlation characteristics can be considered as stationary only during a limited period of time. Third, an increase in the integration time leads to an increase of input information for signal processing, and faster computers with larger memories therefore are required (increasing at least proportional to the square of the integration time). Fourth, even in the best situation, with adaptive algorithms applied in the signal processing to take changes into account, and no limitations due to computer capabilities, the integration time is restricted by the need for timely decision making, especially when the detection range is small.

In table 2, the detection threshold is shown for integration times of 100 and 1,000 seconds. The detection index is assumed to be $d = 20$. This roughly corresponds to $p(D) = 0.76$ and $p(FA) = 10^{-4}$. It is easy to see that increasing the detection threshold by five dB requires increasing the integration time 10 times (to almost three hours!).

In the estimates of detection ranges that we make below, we assume that the minimum detection threshold that can be achieved is −14 dB. This is an optimistic estimate, since such a detection threshold value is probably achieved only in very rare situations.

It is essential to note that significant signal processing gains cannot be achieved by simultaneously increasing the integration time and the array gain. Maximum array gains are likely to be achieved at relatively short integration times of few seconds or even less.[43] Therefore, the maximum values of $(AG - DT)$ for a submarine sonar system in the best circumstances probably do not exceed 15 to 20 dB for a frequency of 30 Hz, and 20 to 25 dB for 300 Hz.

Additional Losses

The estimates above are applicable to the case in which the optimal strategy of submarine detection is applied in known environmental conditions. In real situations, without an *a priori* knowledge of the environment, there is an additional loss in the sonar "budget." In addition, some of the optimal sonar characteristics are mutually exclusive and a trade-off must be sought to optimize the sonar's performance and minimize the losses. In the following analysis, we assume that the sum of all the additional losses due to these factors is five dB. This assumption is very optimistic, and the real losses may substantially exceed this.[44]

ESTIMATES OF DETECTION RANGE AGAINST SUBMARINES

Our estimated detection ranges against submarines under different environmental conditions are shown on figures 7 to 10 in the form of nomographs. The target submarine source level (*SL*) scale is shown on the left side of the figures. To the right of the source level axis, arrows corresponding to the terms on the right side of the passive sonar equation are drawn going either up or down in correspondence to the signs of the terms in the passive sonar equation. A column for the additional loss—the loss due to the lack of *a priori* knowledge about the environmental and target submarine characteristics—is also included. The magnitudes of arrows represent the values of these terms in best circumstances for detection, namely the lowest possible values of ambient noise level, detection threshold, and additional loss and the highest possible array gain. By summing these arrows, figures 7 through 10 allow the maximum transmission loss (*TL*) for which a submarine with a given source level can be detected to be easily determined. The magnitude of this transmission loss, together with the local environmental conditions, will then determine the maximum detection range. On the left side of the transmission loss scale, upper and lower limits of this maximum detection range—depending on

Table 3: Estimation of a detection range against a submarine for a towed array in a deep ocean case (*TL* = *SL* – *NL* + *AG* – *DT* – additional losses). Environmental conditions are assumed to be the best.

TL	SL	NL	AG	DT	Addit. losses	Distance
dB	*dB*	*dB*	*dB*	*dB*	*db*	*km*
			30 Hz			
106	140	55	12	–14	5	> 1,000
86	120	55	12	–14	5	180–210
66	100	55	12	–14	5	1–2
			300 Hz			
109	130	50	20	–14	5	> 500
89	110	50	20	–14	5	55–65
69	90	50	20	–14	5	1–2

the conditions for sound propagation in the water—are indicated. We will now consider the detection range for several specific combinations of sonar sensors and environmental conditions.

Deep Waters

Typically, the conditions for detecting a submarine in a deep ocean are better at lower frequencies. Only in the case where both the source and the receiver are located in the upper mixed layer will the transmission loss increase as the frequency is decreased (because of the leakage of sound energy out of the mixed layer).

Figure 7 and table 3 assess the detection range that could be obtained by a submarine using a towed array in a deep ocean. First, the noise level, array gain, detection threshold and additional losses, with their corresponding signs (plus or minus), are summed. Under the best conditions— a low wind noise level of 55 dB (at 30 Hz), a large array gain of 12 dB (at 30 Hz), a low detection threshold (–14 dB, achieved using a 1,000 second integration time) and low losses, these add to (*NL* – *AG* + *DT* – *additional losses*) = (55 – 12 + [–14] + 5)

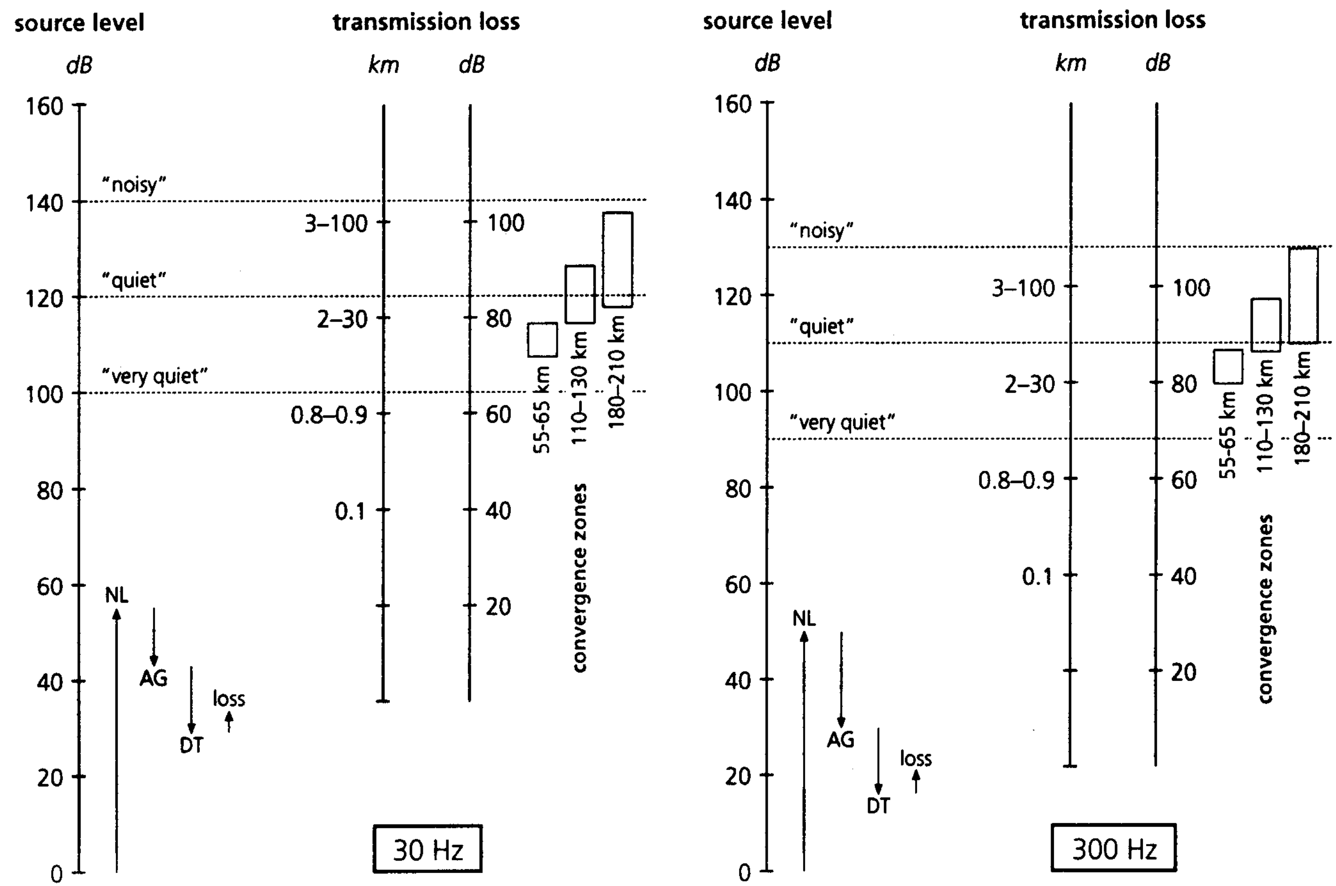

Figure 7: Estimation of a detection range against a submarine for a towed array in a deep ocean case.

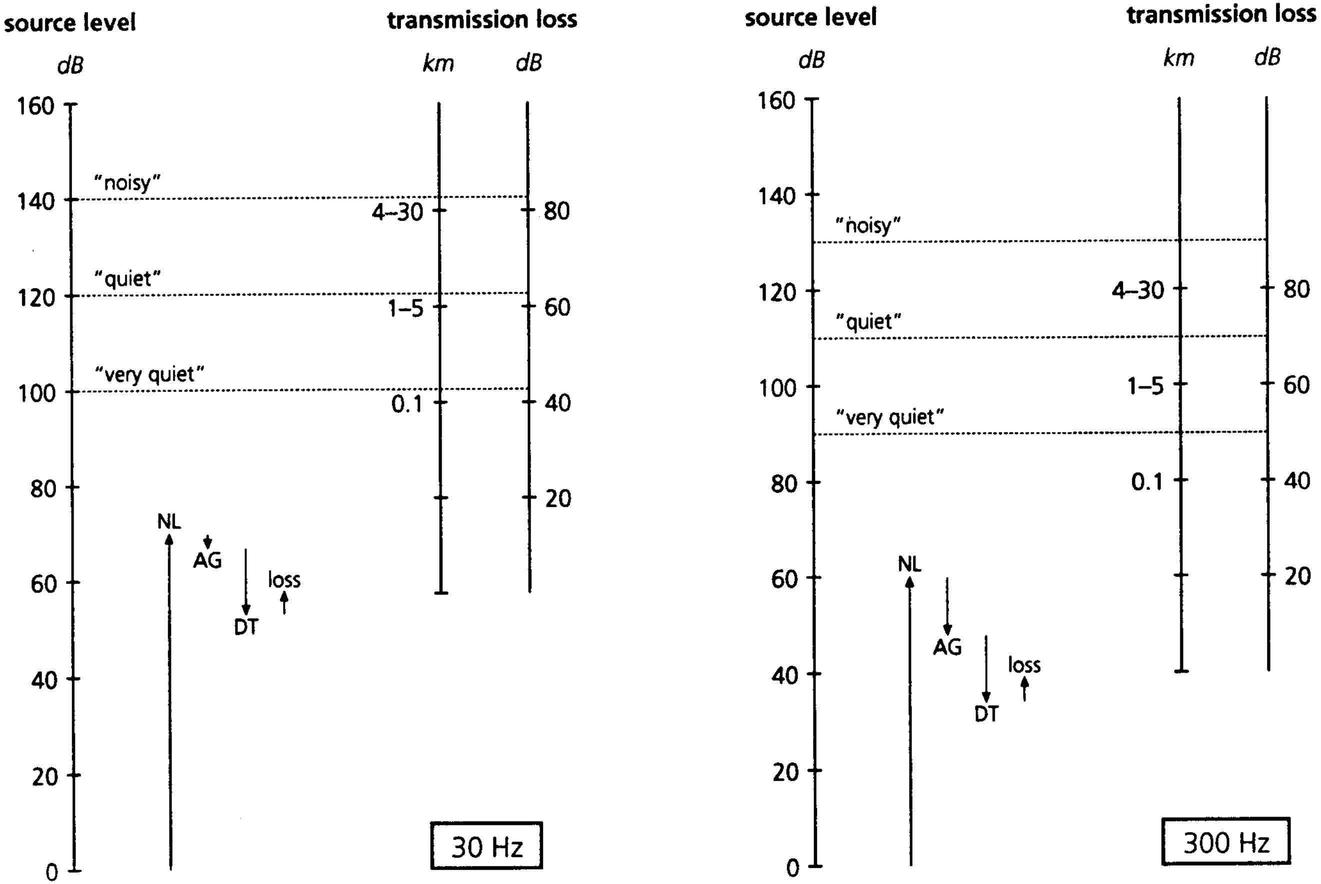

Figure 8: Estimation of a detection range against a submarine for a fixed sonar in a shallow water case.

Table 4: Estimation of a detection range against a submarine for a fixed sonar in a shallow water case (*TL* = *SL* – *NL* + *AG* – *DT* – additional losses). Environmental conditions are assumed to be the best.

TL	SL	NL	AG	DT	Addit. losses	Distance
dB	*dB*	*dB*	*dB*	*dB*	*db*	*km*
			30 Hz			
82	140	70	3	–14	5	5–40
62	120	70	3	–14	5	2–8
42	100	70	3	–14	5	0.1–0.3
			300 Hz			
92	130	60	12	–14	5	< 100
72	110	60	12	–14	5	< 10
52	90	60	12	–14	5	0.3–0.5

dB = 34 dB. Thus, for a "very quiet" target submarine (*SL* = 100 dB at a frequency of 30 Hz) this procedure would leave 66 dB for transmission loss. As shown on the figure 7, this corresponds to a detection range of one to two kilometers. However, as it discussed in the section on Criterion for Distinguishing a Signal in a Noise Background on page 97, it is practically impossible to achieve an array gain of 12 dB for integration times as long as 1,000 seconds. A more realistic value for the sum of the array gain and detection threshold is (*AG* – *DT*) = 15 to 20 dB (for 30 Hz). This would leave only 55 to 60 dB available, which causes the detection range to drop to several hundred meters. If we then take into account that at the low wind noise levels assumed here, the so far neglected shipping noise is dominant, it is clear that the detection of "very quiet" submarines will be very a low probability event.

The prospects for detecting a "quiet" (*SL* = 120 dB at 30 Hz) submarine are much better. In the best situation (low noise level, high array gain, low detection threshold, mixed layer), the detection range can reach 30 to 40 kilometers. Taking into consideration the restrictions on the maximum of value of (*AG* – *DT*) discussed above, we obtain a more realistic value of 10 to 20 kilometers in a mixed layer. However, for a target and a receiver below the mixed layer, the detection range diminishes to one to three kilometers.

On the right parts of the graphs in figure 7, the detection situation is shown for each of the first three convergence zones.[45] As can be seen, "quiet" submarines may also be detected in the first few convergence zones. However, for realistic assumptions, "quiet" submarines would be detectable beyond the first convergence zone (at 55 to 65 kilometers) only under extraordinarily favorable conditions.

"Noisy" submarines can be easily detected in deep oceans at long ranges. In the best detection situation, the detection range against a "noisy" submarine may exceed thousands of kilometers due to the existence of deep sound channels and convergence zones. Under more realistic conditions, a detection range against a "noisy" submarine of several hundred kilometers is possible.

Shallow Waters

The use of a towed array by a submarine is unlikely to be possible in a shallow sea, since the length of such an array will be many times the water depth. In such a situation, it is likely to be difficult to control an array's orientation in the water without severely constraining the motion of submarine. In addition, towed arrays are very expensive equipment, and the chances of damaging them in a shallow environment seem relatively high. However, both the fixed sonar case and the towed array cases are considered here.

The optimum frequency for submarine detection is typically higher in shallow waters than in deep waters, because of higher TL, higher NL, and lower $(AG - DT)$ at lower frequencies.

Detection using a fixed sonar in shallow waters is considered in figure 8 and table 4. Under the best conditions for detection—weak surface winds (wind noise of 60 dB at 300 Hz), maximum array gain of a fixed sonar (13 dB at 300 Hz), and an integration time of 1,000 seconds—the detection range that can be achieved against "very quiet" submarines does not exceed 400 to 500 meters, without even taking into consideration that maximum array gains and minimum detection thresholds can not be achieved at the same time. It is therefore possible to conclude that "very quiet" submarines are essentially undetectable by a bow sonar in shallow waters under any conditions.

The most optimistic prediction for the detection range against "quiet" submarines is 10 kilometers. Even in the best conditions in shallow waters, it is very difficult to achieve a detection threshold of −14 dB. The realistic integration time rarely exceeds even 10 seconds in shallow waters, which gives a detection threshold of −4 dB. It is therefore likely that, even in the best circumstances, a fixed sonar will be capable of detecting "quiet" submarines at

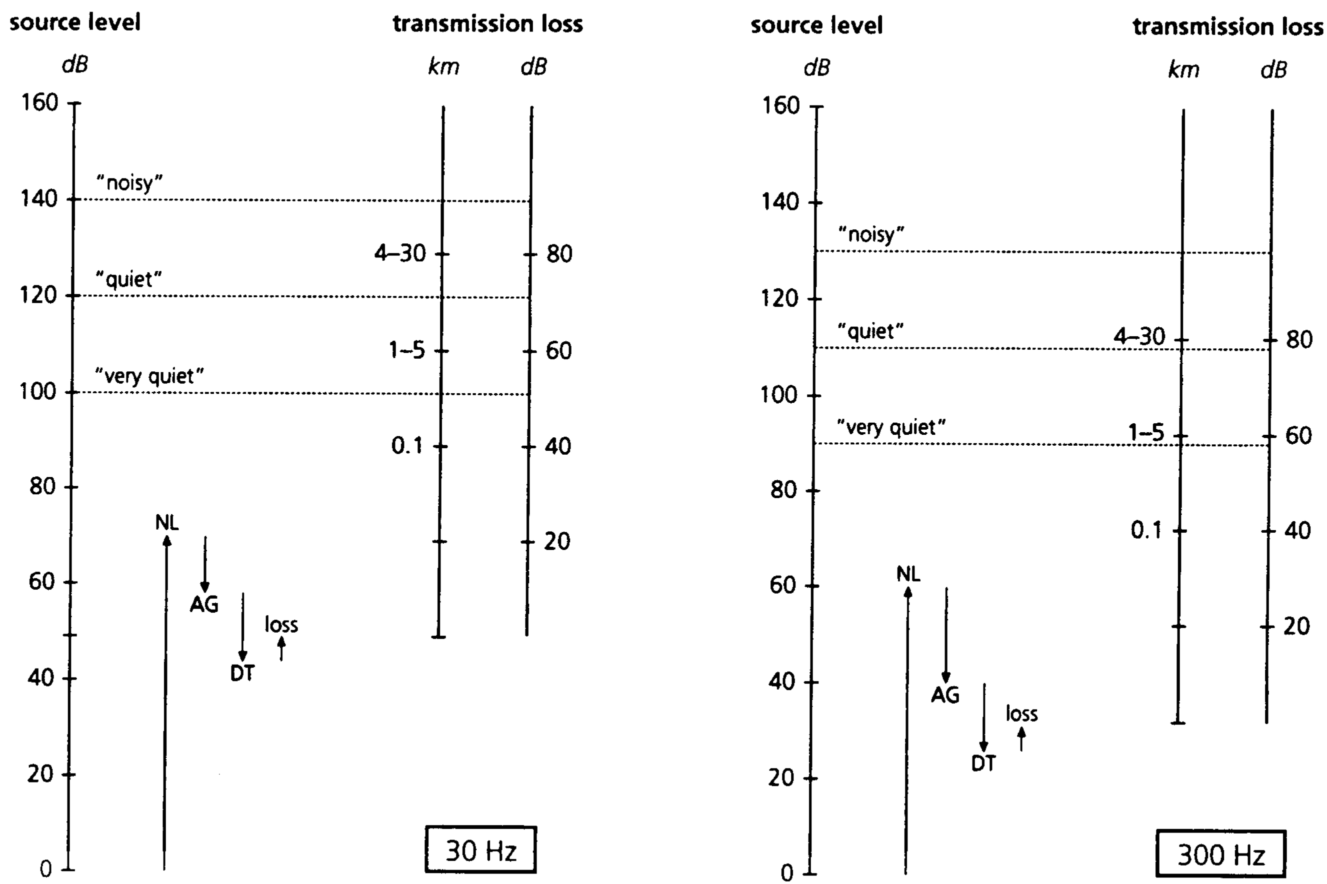

Figure 9: Estimation of a detection range against a submarine for a towed array in a shallow water case.

Table 5: Estimation of a detection range against a submarine for a towed array in a shallow water case (*TL* = *SL* – *NL* + *AG* – *DT* – additional losses). Environmental conditions are assumed to be the best.

TL	SL	NL	AG	DT	Addit. losses	Distance
dB	*dB*	*dB*	*dB*	*dB*	*db*	*km*
			30 Hz			
91	140	70	12	-14	5	< 100
71	120	70	12	-14	5	3–10
51	100	70	12	-14	5	0.3–0.5
			300 Hz			
99	130	60	20	-14	5	< 100
79	110	60	20	-14	5	3–30
59	90	60	20	-14	5	1–5

distances of no more than one to three kilometers. Such a detection range is very short for reliable covert trailing of a submarine for a long period of time. For this reason, it is possible to consider a "quiet" submarine to be invulnerable to the fixed sonar. In poor environmental conditions, the detection range would be even less, and a "quiet" submarine would be undetectable in such conditions.

"Noisy" submarines may be detected at distances of several dozens of kilometers under the best conditions with realistic integration time and array gain values. The detection range diminishes to several kilometers in poorer conditions (for example, a wind speed of more than 10 m s^{-1}).

At first glance, a towed array would appear to substantially improve shallow water detection capabilities at frequencies below 200 to 300 Hz by providing an increase in of almost 10 dB. The resulting detection situation is illustrated in figure 9 and table 5. However, while in the best conditions, the detection range against "very quiet" submarines appears to be higher than for a fixed sonar, in actuality it is unlikely to exceed one kilometer, since an array gain of 20 dB is not achievable at a distances of less than 10 to 20 kilometers in shallow waters.[36]

A "quiet" submarine may be detected at a distance of about 30 kilometers in the best case. However, for more realistic values of the array gain minus detection threshold ($AG - DT$ = 20 to 25 at 300 Hz), the detection range will be less than 5 to 10 kilometers.[46] As the weather conditions get worse, the detection range may drop to essentially zero. For example, at wind speeds of 10 m s^{-1}, the detection range is about 300 meters.

The detection range against "noisy" submarines varies widely. Even under the best conditions, it does not exceed 50 to 100 kilometers, and more realistic estimates of the detection range give a value of several dozens of kilometers. In poorer conditions—when the wind is strong, but the array gain is still large, and the detection threshold is low—the detection range may drop to several hundreds of meters.

Thus, the use of a towed array quantitatively improves the detection capability against submarines in shallow waters and in some circumstances can provide a significant qualitative improvement. "Noisy" submarines will be vulnerable under almost any weather conditions except when there are very strong surface winds (NL = 90 dB). In the best environmental conditions, it is also possible to detect a "quiet" submarine.

Arctic Waters

In the Arctic, the detection range against a submarine decreases more rapidly with increasing frequency than it does in waters free of ice because of losses of energy at reflections from bottom surface of the Arctic ice.

For Central Arctic waters, the detection range may be as large as 40 kilometers during extremely quiet periods of time (NL = 40 dB) even for "very quiet" submarines. Assuming a higher noise level of 60 dB, which is more typical of Arctic waters, and a combined array gain and detection threshold of 15 to 20 dB (taking into account the decrease in the correlation length due to multipaths), we obtain a detection range of less than one kilometer (see figure 10 and table 6). Because of the relatively high level of ambient noise in marginal ice zones, "very quiet" submarines are undetectable there.

In favorable conditions (very low noise level, high array gain and low detection threshold), a "quiet" submarine can be detected at a distance of 40 kilometers. In marginal ice zones, the detection range drops to one kilometer.

"Noisy" submarines are much easier to detect. In favorable conditions, at low frequencies and a noise level of 60 dB, the detection range may approach 100 kilometers. Even in marginal ice zones, a detection range of a couple of kilometers may be obtained during periods of relative quiet. However, during periods of high ridging activity, the detection range is unlikely to exceed half a

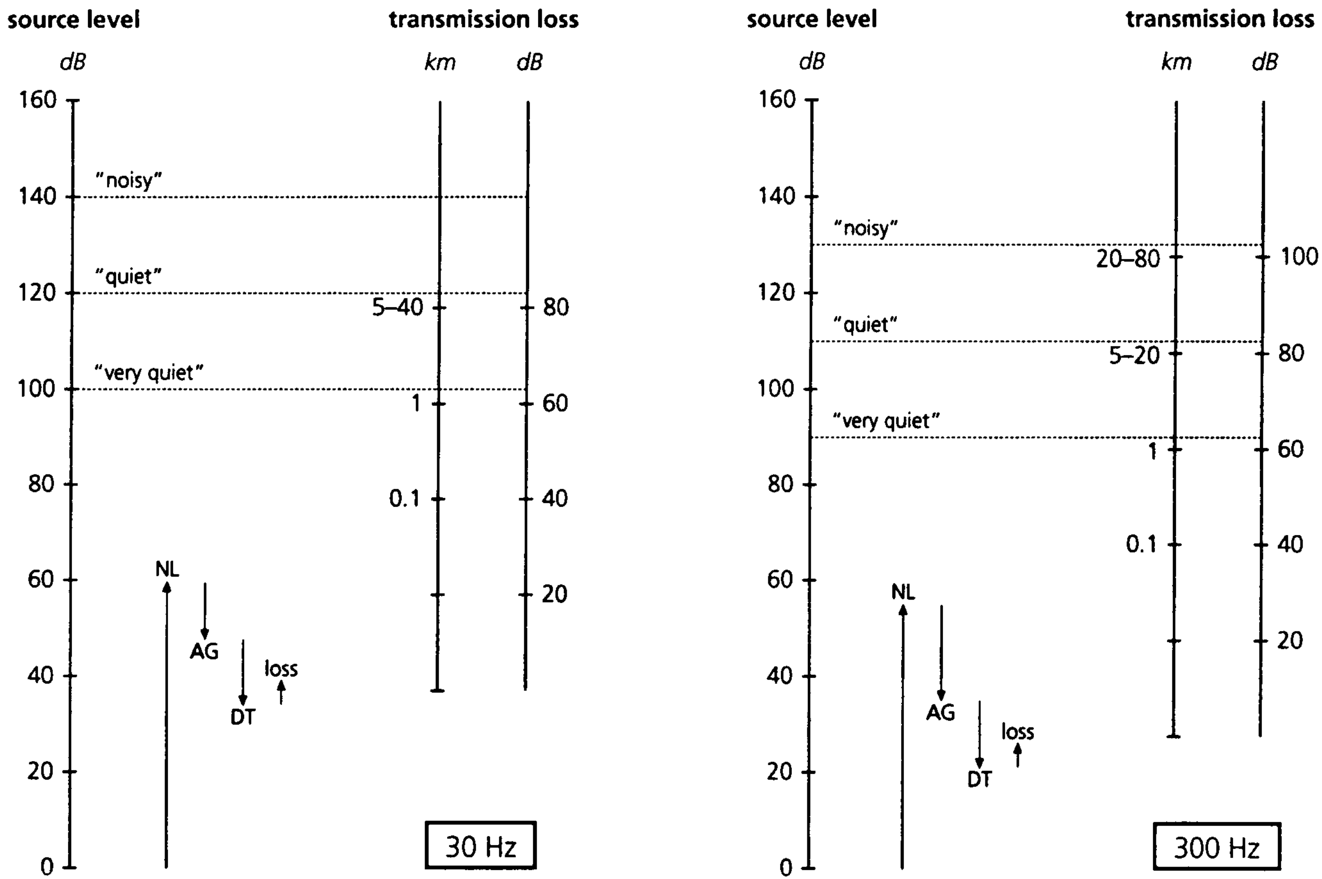

Figure 10: Estimation of a detection range against a submarine a towed array in an Arctic case.

Table 6: Estimation of a detection range against a submarine for a towed array in an Arctic ocean case (*TL = SL – NL + AG – DT* – additional losses). Environmental conditions are assumed to be the best.

TL	SL	NL	AG	DT	Addit. losses	Distance
dB	*dB*	*dB*	*dB*	*dB*	*db*	*km*
			30 Hz			
101	140	60	12	–14	5	< 100
81	120	60	12	–14	5	5–40
61	100	60	12	–14	5	1
			300 Hz			
104	130	55	20	–14	5	20–80
84	110	55	20	–14	5	5–20
64	90	55	20	–14	5	1–3

kilometer.

It appears likely that during quiet periods of time, submarines may be detectable at large distances in the Arctic, but it will be very difficult to trail them for extended periods of time because noise levels can increase sharply during relatively short time intervals with a corresponding decrease in the detection range. It can also be concluded that the marginal ice zones, where ambient noise levels are relatively high, provide a relatively safe shelter for submarines.

CONCLUSION

Our estimates of the detection range against submarines in different environments enable us to draw a number of conclusions which have important implications for the future of Russian undersea strategic forces.

In typical conditions, the detection range against a given submarine in shallow waters or in the MIZ zones of the Arctic is much less than in deep waters. For this reason, the commissioning of modern Russian SSBNs, which are capable of launching a retaliatory strike from locations near their home bases, has substantially increased the survivability of the Russian undersea strategic forces against a preemptive or preventive attack of an adversary.

The detection range estimates made here clearly show the importance of submarine silencing. In particular, as can be seen from figures 2, 3 and 7 to 10, decreasing the submarine source level by a factor of 10 will also reduce the detection range against that submarine almost 10 times. The need to keep the source level at low levels as SSBNs gets older and to replace old missile submarines by new, quieter ones should be also emphasized if Russia continues to rely on such submarines or increases its dependence on them.

A submarine will be undetectable in shallow waters and in the Arctic MIZ unless its source level exceeds the source level for the "very quiet" submarine model. In these areas, the detection range against even a "quiet" submarine is less than several kilometers even in the best case. These estimates are made assuming the best conditions for detection and they are based only on fundamental limits of passive acoustics. Given limitations of a man-made nature and the uncertainties in the knowledge of the ocean properties at a given place and time, the detection ranges can be expected to be lower than the ones obtained above. Thus, the source level of a "quiet" submarine might be considered as a limit below which the appropriate SSBN is invulnerable in shallow seas and MIZ of the Arctic.

The actual level of noise produced by current submarines is, of course, highly classified (and is not known to the author). However, there are indications that U.S. submarines have already reached the "very quiet" level, and it is likely that the newer Russian submarines have done so as well or will do so in the not too distant future. If so, the results presented here strongly indicate that if Russian SSBNs are operated with sufficient care and attention to tactics, and the primary threat to submarines remains acoustic detection, then they will be able to provide a survivable basing mode for a future much smaller Russian nuclear arsenal.

The increasing quietness of submarines broaches another important issue, namely, the safety of submarine operations. As follows from our analysis, in shallow waters, submarines are not able to detect reliably a modern quiet submarine of an adversary at a range that would be enough to avoid an accidental collision.[47] This could lead to accidents involving nuclear submarines and weapons that could result in dangerous political situations. Moreover, such collisions hold the potential to create environmental disasters of possibly significant scale.[48] A possible solution to prevent such accidents would be the working out of specific agreements between the U.S., Russia and other concerned countries to restrict operations of their submarines close to territorial waters and especially in the patrolling areas of SSBNs.

APPENDIX 1: ILLUSTRATIVE U.S. AND C.I.S. STRATEGIC FORCES

Data on the constitution of and numbers of weapons in the nuclear arsenals (at the end of 1992) are taken from Robert S. Norris and William M. Arkin, "U.S. Strategic Nuclear Forces, End of 1992," *Bulletin of the Atomic Scientists,* January/February 1993, p. 57; and Robert S. Norris and William M. Arkin, "Russian (C.I.S.) Strategic Nuclear Forces, End of 1992," *Bulletin of the Atomic Scientists,* March 1993, p. 49. The illustrative after START I levels are from H. Feiveson and F. von Hippel, "Dismantling the Doomsday Machine," *Technology Review,* May/June 1992, pp. 61–69. The data on the time of commissioning of SSBNs and on nuclear missile ranges are from Tom Stefanick, *Strategic Antisubmarine Warfare and Naval Strategy* (Lexington Books, 1987) pp. 156–157.

Table A-1: The U.S. strategic forces.

	end of 1992	after START-I	after START-2
ICBMs			
Minuteman III	500 · 3[a]	500 · 1.8	500 · 1
MX	50 · 10	50 · 10	0
	2,000	1,400	500
SLBMs			
Trident I	320 · 8	192 · 8	0
Trident II	120 · 8	240 · 8	432 · 4[b]
	3,520	3,456	1,728
Bombers			
B52-ALCMs	95 · 16	80 · 20	93 · 10.2[c]
B-2, B-2	95 · 16	84 · 16	20 · 16
	2,900	2,944	750–1,250
Total warheads	**8,420**	**7,800**	**3,000–3,500**

a. Numbers of missiles or bombers times the numbers of warheads carried by each. Warhead loadings are averages and thus may not be integers.

b. Most probably, no Trident II submarine will have a full compliment of warheads (R.S. Norris and W.P. Arkin, 1993, op. cit.) and each launcher will carry 4 warheads to be within START II limits.

c. Post-Start II bomber figures are from Dunbar Lockwood, "Strategic Nuclear Forces Under START II," *Arms Control Today*, December 1992, pp. 10–14, and assume that all U.S. B-1s are converted to conventional missions.

Table A-2: The C.I.S. strategic forces.

	end of 1992	after START-I	after START-2
ICBMs			
SS-18	308 · 10	154 · 10	0
SS-19	225 · 6	0	105 · 1
SS-24	92 · 10	75 · 10	0
SS-25	378 · 1	315 · 1	NA[a]
	5,728	2,605	NA
SLBMs			
SS-N-6, SS-N-8	172 · 1	0	0
SS-N-18	224 · 3	224 · 3	176 · 3
SS-N-20	120 · 10	120 · 8	120 · 6
SS-N-23	112 · 4	112 · 4	112 · 4
	2,492	2,080	1,696
Bombers			
Bear-H-ALCM	75 · 12.8	84 · 12.8	63[b]
Blackjack-ALCM	25 · 12	16 · 12	0
	1,250	1,266	750–1,250
Total warheads	**9,470**	**5,951**	**3,000–3,500**

a. It is possible that 90 SS-25 missiles carrying one warhead will be deployed in converted SS-18 silos and there will be also 400-600 mobile SS-25 missiles. (Dunbar Lockwood, 1992, op.cit.)

b. According to Dunbar Lockwood (Dunbar Lockwood, 1992, op.cit.), after START II, Russia will have 27 Bear-H bombers with six ALCMs each (total 162 warheads) and 36 Bear-H bombers with 16 ALCMs each (576 warheads), assuming that Ukraine will keep the Bear-H and Blackjacks that are now on its territory.
Blackjack bombers are still currently under production and distributed to the Russian Strategic Forces. Presumably, Russia will have a small number of such bombers.

Table A-3: the U.S. submarine strategic forces.

Class	Commission	Launchers/ warheads	Missile range *nautical miles*	Number in 1992	Number after START II
Lafayette	1963–67	16 Trident I/8	4,350	8	0
Ohio[a]	1981–	24 Trident I/8	4,350	8	0
		24 Trident II/8	6,000	5	18
Total submarines				**21**	**18**

a. The Trident II system was deployed on ninth of Ohio class and its successors.

Table A-4: the C.I.S. submarine strategic forces.

Class	Commission	Launchers/ warheads	Missile range *nautical miles*	No. in 1992	No. after START II
Delta I, II	1972–77	12 (16) SS-N-8/1	4,240 (4,950)[a]	13	0
Delta III	1975–82	16 SS-N-18/3	3,530 (4,350)	14	11
Typhoon[b]	1983–	20 SS-N-20/10	4,300	6	6
Delta IV	1985–	16 SS-N-23/3	5,000	7	7
Total submarines				**40**	**24**

a. Numbers, given in parenthesis indicate that there are modifications of the missiles with a differing number and yields of warheads, thus having different missile ranges.
b. Typhoon and Delta IV classes submarine construction was completed in 1990 (Alexander Veledeyev, "START-II Treaty: Naval aspect," *Rossiyskiye Vesti*, 1993, No 15, p.4.)

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NOTES AND REFERENCES

1. Tom Stefanick, *Strategic Antisubmarine Warfare and Naval Strategy* (Lexington Books, 1987) p.72

2. Finally, the influence of historical events, such as the U.S. forcing Soviet submarines to the surface during the 1963 Cuban Missile Crisis, on the thinking of Russian policy makers cannot be neglected. During the crisis, six Soviet diesel submarines were detected and forced to the surface by U.S. ASW forces. Norman Polmar and Jurrien Noot, *Submarines of the Russian and Soviet Navies* (Naval Institute Press, 1991) p. 173.

3. Quiet Submarines a Serious Problem," U.S. Congress, House Armed Services Committee, News Release, 21 March 1989.

4. The Soviet SSBNs of the 1960s and 1970s (Golf, Hotel, Yankee classes) had two major drawbacks: they were noisy and they had short range SLBMs. The last reason was why these submarines had to transit long distances in the Atlantic and Pacific in order to patrol in the open ocean, close to U.S. territory, where the United States and its allies had well developed ASW capabilities. In those days, the Soviet SSBNs appear to have been relatively easy to detect and covertly trail. However, this situation began to change by the late 1970s or early 1980s, when Delta III, Typhoon and Delta IV classes submarines were commissioned. These relatively quiet submarines did not need to make long transits in the open ocean to their patrol areas because they are capable of targeting most of the United States from their home bases near Murmansk and Petropavlovsk-Kamchatsky (Stefanick, *Strategic Antisubmarine Warfare and Naval Strategy*, 1987 p. 33). According to public statements of Russian Navy officials, since the late 1980s, Russian SSBNs have been deployed only in home waters.

5. Viktor Litovkin "Three days aboard the "Typhoon," *Izvestia*, 2–4 March 1992.

6. In spite of the warming of the political climate, American submarines continue their activities close to the Russian SSBN bases. This was demonstrated by the collision of submarines near Murmansk in February 1992 (see, for example, Nikolay Burbyga, Victor Litovkin "Americans Not Only Helping Us, But Spying on Us," *Izvestia*, 21 February 1992, p. 2.; and Eugene Miasnikov "Submarine Collision off Murmansk: A Look from Afar," *Breakthroughs*, Defense and Arms Control Studies Program, M.I.T., winter 1992/93, pp. 19–24) and by another incursion of a foreign submarine into Russian internal territorial waters a month later (A. Pilipchuk "Antisubmariners Were Ready to Use Weapons," *Krasnaya Zvezda*, 28 March 1992, p. 2). Presumably, one of the purposes of these missions is deployment of underwater sensors for gathering intelligence about the acoustic signatures of the Soviet submarines. Desmond Ball

"Nuclear War at Sea," *International Security* **10** (3) winter 1985-86, pp. 3–31.

More recently, on 20 March 1993 a Russian "Delta" class SSBN collided with the USS "Grayling" in the Barents sea (Alexandr Mozgovoi, "20 Meters Separated from a Nuclear Accident," *Rosiyskaya Gazeta,* 1 April 1993, p. 1.)

7. Deployment of such a system seems improbable in the near future (see Stefanick, *Strategic Antisubmarine Warfare and Naval Strategy,* 1987, p. 17; and also Tom Stefanick, "The Nonacoustic Detection of Submarines," *Scientific American* **258** (3), March 1988, pp. 41–47). Nevertheless, according to the press reports, submarines may sometimes under special conditions be observable by satellites (Craig Covault, "Soviet Radar Satellite Shows Potential to Detect Submarines," *Aviation Week & Space Technology,* 8 October 1990, pp. 22–23).

8. Even if the position of an SSBN is known, it can be hard to destroy it, since its position changes continuously. U.S. use of covert ship or air-based short-range weapons for preemptive killing of a Russian SSBN is not practical in the Russian internal seas or the Arctic. This is also true for long-range weapons; in this case, in addition to the problem of finding the submarine, the position of the submarine can change during the weapon's flight time.

9. By the year 2000, the number of Russian SSBNs is expected to diminish from 54 to 24 (see table A1.4). At the same time, the number of U.S. "SSNs will drop from 84 to 60. Barton Gellman "The 'Silent Service' Breaks the Ice," *Washington Post,* 19 April 1992, p. A4.

10. In order to continuously and covertly trail an SSBN, an attack submarine must be able not only to detect the SSBN, but must also be able to determine its bearing and range with a high accuracy during the entire time of trailing. Moreover, the attack submarine must also operate carefully and keep at a distance at which it is undetectable by the SSBN. Thus, the trailing problem is a different and more difficult problem than the detection problem.

11. See, for example, Mark Sakitt, *Submarine Warfare in the Arctic: Option or Illusion?* (Stanford, California: Center for International Security and Arms Control, Stanford University, 1988). In particular, this book considers the problem of how the detection range influences the search time required for finding hostile submarines.

12. We do not consider a submarine's periscope, which is used for surveillance above the water surface and does not help in detecting a submerged target. Moreover, a periscope sticking out of the water could be easily detected by modern surface search radars.

13. In particular, it is possible if the frequencies and relative intensities of acoustic lines in the submarine noise generated spectra are known *a priori.*

14. R.J. Urick, *Principles of Underwater Sound* (McGraw-Hill Book Co., 1983) p. 22.

15. The decibel is a logarithmic unit. If K is a ratio, then that same ratio expressed in dB is equal to 10 $\log_{10}(K)$. For example, if source level exceeds the reference intensity by 100 times, we get $SL = 10 \log (100) = 20$ dB.

16. R.J. Urick, 1983, op. cit., p. 21.

17. Cavitation is a phenomenon which occurs because of the formation of partial vacuums in a flowing liquid as a result of the submarine propeller blades passing through it. The occurrence of cavitation is accompanied by a sharp increase of the radiated sound power.

18. R.J. Urick, 1983, op. cit., p. 332.

19. As a rule, the speed of a submarine on patrol is kept low, because as the submarine's speed increases, the *SL* also increases due to the cavitation and hydrodynamic noise. For example, at speeds of 5 to 8 knots, US and Soviet submarines produce negligibly low levels of noise (Stefanick, 1987, op. cit., p. 9)

20. P.C. Wille, "Ambient Noise: Characteristics of the Noise Field," in H.G. Urban, editor, *Adaptive Methods in Underwater Acoustics* (D. Reidel Publishing Co., 1985) pp. 13–36.

21. Besides using the narrowband processing technique to detect tonals, a sonar operator may also be able to detect the relatively short, but very intense, noises radiated by a maneuvering submarine (such as grinding of the rudder or noises related to a change in the flow regime).

22. Published data for ships and submarines typically show bandwidths of several Hz, although these measurements may been made with equipment with limited frequency resolution. However, even if the actual submarine bandwidths are very narrow, the detected bandwidth at a range of several kilometers would be no less than 0.1 Hz because of frequency broadening during the transmission through the water (this is discussed in more detail subsequently).

23. R.J. Urick, 1983, op. cit., p. 350.

24. The difference between these estimates and the data presented by Stefanick (Stefanick, 1987, op. cit., p. 274) must be emphasized here. The major source of submarine noise in Stefanick's analysis is cavitation, therefore his data on the source level corresponds to the noise integrated over a wide spectral band. In a narrow band, noise caused by cavitation is negligible compared to the machinery noise, at least at low patrolling speeds. For example, a serious problem in submarine construction is damping the sound generated by reduction gears, one of the major sources of noise. According to some informed sources, decreasing the tolerances in the size of the gears from 0.1 to 0.01 millimeters allows a reduction in the submarine source level of a factor of 30 or 40 dB.

25. R.J. Urick, 1983, op. cit., p. 100.

26. Typically the convergence zones are located at intervals of 55 to 65 kilometers. The width of the first zone is roughly several kilometers, the second zone is two times wider than the first, and so on until eventually, at ranges of several hundred kilometers, the zones overlap and become indistinguishable.

27. I. Dyer "The Song of Sea Ice and Other Arctic Ocean Melodies," in I. Dyer and C. Chryssostomidis, editors, *Arctic Policy and Technology* (New York: Hemisphere, 1984) pp. 11–37.

28. T. Acal, "Sea floor effects on shallow water acoustic propagation," in W.A. Kuperman and F.B. Jensen, editors, *Bottom Interacting Ocean Acoustics* (New York: Plenum, 1980, pp. 557–575; F.B. Jensen and W.A. Kuperman, "Optimum Frequency of Propagation in Shallow Water Environments," *Journal of Acoustical Society of America* **73** (3) 1983, pp. 813–819; see also J. Allen "Transmission Loss Variability in Shallow Water," in W.A. Kuperman and F.B. Jensen, editors, *Bottom Interacting Ocean Acoustics* (New York: Plenum, 1980) pp. 485–492.

29. This feature can be used by a target submarine to defeat trailing by another submarine. By increasing its speed, the target submarine forces the hunting submarine

also to accelerate in order to keep trailing. At high speeds, the flow noise becomes very large relative to the signal from the submarine that is being trailed and the detection range against the target submarine decreases. Thus the hunting submarine becomes "deaf" and can no longer continue operating in close proximity to its target.

30. R.J. Urick, *Ambient Noise in the Sea* (Peninsula Publishing, 1986).

31. The noise level in the Arctic is highest near the ice edge, the so called marginal ice zone. The MIZ width is typically several dozens of kilometers.

32. J.K. Lewis, and W.W. Denner, "Arctic Ambient Noise in the Beaufort Sea: Seasonal, Space and Time Scales," *JASA* **82** (3) 1987, pp. 988–997.

33. N. Friedman, *World Naval Weapons System 1991/92* (Naval Institute Press, 1991) p. 611.

34. The newest array, the TB-12X, is 12 times longer than TB-16 and is currently under development. Its sea trials and operational evaluation are scheduled for 1993 (Norman Friedman, 1991, op. cit. p. 633).

35. For example, the sound wavelengths in ocean water at frequencies of 30 and 300 Hz are respectively 15 and 1.5 meters.

36. B. Sholz, "Horizontal Spatial Coherence Measurements with Explosives and CW - Sources in Shallow Water," in G. Tacconi, editor, *Aspects of Signal Processing* (Boston: Dordrecht, 1976) part 1, pp. 95–108.

37. Due to refraction and to reflections from the sea surface and bottom, there may exist several paths (rays) from a source to a receiver. This is a typical situation in the Arctic and in shallow waters.

38. R.J. Urick, 1983, op. cit., p. 231. See also R.J. Urick, *Sound Propagation in the Sea* (Peninsula Publishing, 1982).

39. The signal processing procedure is actually much more complex. The sonar operator can watch signals at several frequencies and keep track of several targets at the same time. However, the principle described here is the fundamental one of sonar narrowband processing.

40. In order to calculate detection index values for a given set of probabilities of detection and false alarms, we assumed that noise is Gaussian and signal level is constant. In this case, the following expressions are valid (R.J. Urick, 1983, op. cit., p. 386)

$$p(D) = \frac{1}{2}\,\mathrm{erfc}\,\frac{1}{\sqrt{2}}\left(\frac{T}{\sigma} - \sqrt{d}\right)$$

$$p(FA) = \frac{1}{2}\,\mathrm{erfc}\left(\frac{1}{\sqrt{2}}\frac{T}{\sigma}\right)$$

where

$$\mathrm{erfc}\,(x) = 1 - \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,dt$$

Values of (T/σ) and $(T/\sigma - d^{0.5})$ were estimated for given probabilities of detection and false alarm by use of tables of numerical data from *Handbook of Mathematical Functions with Formulas, Graphs and Mathematical Tables*, edited by Milton Abramowitz and Irene A. Stegun (New York: Dover Publications, Inc.). After doing so, it is straightforward task to evaluate the detection index.

41. The derivation of this formula can be found in the literature on signal processing. We would refer the reader to R.J. Urick, 1983, op. cit., p. 385.

42. E. Sevaldsen, "Effects of Medium Fluctuations on Underwater Acoustic Transmissions in a Shallow Water Area," in W.A. Kuperman and F.B. Jensen, editors, *Bottom Interacting Ocean Acoustics* (New York: Plenum, 1980) pp. 643–657.

43. R.J. Urick, 1986, op. cit. pp. 3–18

44. See, for example, R.J. Urick, 1983, op. cit., p. 389.

45. In this particular case, a decrease of 15 dB in transmission loss is assumed in the convergence zones.

46. As can be seen, there is a significant difference compared to the deep ocean case. In fact, the detection range against a "quiet" submarine in the "nearest zone" in shallow waters might be a bit larger than in the deep ocean. However, in shallow waters there will be no possibility of detecting a submarine at a range corresponding to that of the first convergence zone in deep waters (55 to 60 kilometers).

47. In this connection, the recent collision of a Russian "Sierra" class submarine and the U.S. "Baton Rouge" that took place in February 1992 in disputed waters off Murmansk should be mentioned (Miasnikov, 1992, op. cit.). Apparently, neither submarine heard the other before the collision. The same thing appears to have happened with the Russian "Delta" class SSBN and the U.S. "Grayling." Fortunately, these accidents did not cause serious damage or severe injuries.

48. It is important to note that disasters in shallow SSBN operating areas like the Arctic and Barents seas can cause much more damage to the environment than accidents in the open ocean, because the potentially dangerous wastes from exploding submarine nuclear reactors and missile propellant can spread throughout a wide area and kill all of the sea life in this area.

OCCASIONAL REPORT:
Center for Arms Control, Energy and Environmental Studies, Moscow Institute of Physics and Technology

The Center for Arms Control, Energy and Environmental Studies, which is affiliated with the Moscow Institute of Physics and Technology (MPTI), was organized in 1990, and initially funded by the International Foundation for the Survival and Development of Humanity, the John Merck Fund, and the Ploughshares Fund. Its purpose is to conduct research and to educate a community of independent and politically sophisticated technical experts who can formulate the technical basis for new policies in a changing international and domestic environment. In particular, the Center aims to provide independent technology and policy assessments for the Russian Parliament and the executive branch of the Russian government by training technology experts for these bodies. The Center also aims to familiarize the Russian public with alternative approaches to national security, environmental and energy problems.

The creation of the Center grew out of contacts between MPTI and non-governmental American organizations engaged in analysis of arms control, environmental and energy policy issues. The principal initial partners with MPTI were the Center for Energy and Environmental Studies (CEES) at Princeton University (arms-control and nonproliferation issues) and the technical group in the Defense and Arms Control Studies Program (DACS) at M.I.T. Although the Center's activities initially focused primarily on arms-control issues, increasing emphasis is now being placed on energy and environmental problems. In the energy and environmental areas, the Center has collaborated with CEES and with the Department of Engineering and Public Policy of Carnegie Mellon University.

The Moscow Institute of Physics and Technology is an ideal place for the study of technically based policy issues. It is an elite technical university, founded in 1946 to produce specialists in high-technology areas for the U.S.S.R.'s national defense industries. Currently, approximately 5,000 undergraduate students and more than 500 post-graduate students are studying at MPTI. Because it features a highly selective admission system, a unique system of teaching, and close ties with most of the research institutes of the Russian Academy of Science and with Russian high-technology industries, MPTI is able to train qualified specialists in diverse areas of science and technology.

ARMS-CONTROL AND NONPROLIFERATION RESEARCH PROGRAM

Studies in several areas are being conducted in conjunction with experts at other institutions, including CEES at Princeton and DACS at M.I.T.

Safeguarding Nuclear Material

Oleg Bukharin (Ph.D. Physics, MPTI, 1992) has been studying problems involving nuclear power and nuclear nonproliferation. His research topics include: nuclear safeguards in the states of the Commonwealth of Independent States (C.I.S.); the plutonium nuclear fuel cycle in Russia; the structure and production capabilities of the uranium nuclear fuel cycle in the states of the C.I.S.; and the U.S.-Russian HEU agreement. (See "The U.S.-Russian HEU Agreement: Internal Safeguards to Prevent Diversion of HEU" and "Weapons to Fuel" in this issue.) Results of this research have been reported at international meetings and presented in research papers and articles.

Dr. Bukharin has spent three extended periods at Princeton. Dr. Bukharin first came to Princeton in August 1990 to study at the Woodrow Wilson School of Public Policy at Princeton University. He also conducted research at CEES on the implications of the Soviet breakup for arms control and international security. Dr. Bukharin returned to MPTI in July 1991. In Moscow, he began studying the problems of nonproliferation and nuclear power.

In October 1992, Dr. Bukharin began an SSRC-MacArthur Foundation Fellowship on Peace and Security in a Changing World. Currently, he divides his time between CEES of Princeton University and MPTI.

Military Space Activities

Maxim Tarasenko (Ph.D. Physics, MPTI, 1988) is currently working as a Center Research Associate on space activities worldwide and the Russian space program. His main areas of interest include: management of the Russian space program (including proliferation and cooperation issues) and a ban on space weapons. In 1991, Dr. Tarasenko spent four months at carrying out research at the Woodrow Wilson School of Public Policy at Princeton University. In 1993, he spent three months in Chicago as a Bulletin of the Atomic Scientists visiting fellow. During his visit, he published an article on the Strategic Defense Initiative's interest in the Russian Topaz space nuclear reactor in the July/August 1993 issue of the *Bulletin*.

Dr. Tarasenko is the author of a book entitled, *Military Aspects of Soviet Cosmonautics* (in Russian), which was partially written during his visit to

CEES in 1991. This was the first Russian book about the Soviet military space program and it was published in September 1992 with financial support from the Center. Additionally, Dr. Tarasenko has participated in a number of Parliamentary activities that will shape the future of Russia's space policy, including the preparation of the new legislative bill entitled "On Space Activity in the Russian Federation."

Strategic Stability—Antisubmarine Warfare and Submarine Detection

Eugene Miasnikov (Ph.D. Physics, MPTI, 1989) has focused his research on assessing detectability of modern submarines. The START I and START II treaties between the United States and Russia substantially enhance the importance of ballistic-missile submarines (SSBNs) in the strategic forces of both countries; thus the survivability of these submarines is a key question for strategic stability.

The first stage of Dr. Miasnikov's research has focused on the question of whether or not it is possible for an attack submarine to detect an SSBN, and the corresponding implications for the survivability of the Russian SSBN force. (See "Can Russian Submarines Survive at Sea?" in this issue.) Dr. Miasnikov started this study, which analyzes the technical capabilities of passive acoustical means of submarine detection, during a visit to M.I.T. in 1991–92. He continued this study at the MPTI Center and during a return visit to M.I.T. Admiral Nikolai Markov and Ambassador Victor Karpov are his key advisers for this project in Moscow.

Miasnikov also published an analysis of a U.S.-Russian submarine collision in *Breakthroughs* (M.I.T. Defense and Arms Control Studies Program, winter 1992/93) which was reprinted in the April 1993 issue of *Submarine Review*.

Dr. Miasnikov's current research interests include continuing work on submarine detection, antisubmarine warfare (ASW) strategy and tactics, technical means for detecting small objects (such as mines) in the ocean, the disposal of nuclear submarines and their reactors, and non-military uses of ASW technologies.

Strategic Stability—Early Warning Systems

Paul Podvig is a Research Associate at the MPTI Center. His research focuses on the impact of modern technology on strategic stability, in particular on the relationship between strategic defenses and arms reductions. He has studied the possibility of incorporating existing early warning radars into a single-site anti-ballistic missile system and the capabilities and operational status of the Russian space-based early warning system. He spent 10 months of 1992 at M.I.T. where he worked on these projects with Theodore Postol and George Lewis. The results of this work were presented at the 1992 Shanghai Summer School on Science and World Affairs, and at seminars at Princeton, M.I.T., and the Moscow Institute of World Economy and International Relations. A paper on this topic is now being prepared for publication in *Science & Global Security.*

Mr. Podvig was the editor of the Russian translation of Cochran, Arkin, Norris and Sands, *Nuclear Weapons Databook: Volume IV, Soviet Nuclear Weapons* (New York: Harper and Row, 1989). This Russian translation was published by the MPTI Center in November 1992, making information on Soviet nuclear weapons available for the first time to the Russian public. He is now working on a similar databook based on Russian data.

Plutonium Disposal

Professor Anatoli S. Diakov is director of the MPTI Center and carries out research in laser physics, nonlinear laser spectroscopy, and elementary processes in gases. His current work at the Center includes work on a weapons-grade fissile material production cutoff. In collaboration with Princeton's CEES, he has been working on the problems of disposing of military and civil plutonium. This analysis presents alternative approaches for dealing with this material, taking into account security, economic and technical concerns.

Professor Diakov has published results from this work in two papers—"Disposition of Separated Plutonium" (with Frans Berkhout, Harold Feiveson, Helen Hunt, Edwin Lyman, Marvin Miller and Frank von Hippel) in *Science & Global Security,* volume 3, numbers 3–4 [1993], and "Eliminating Nuclear Warheads" (with Frank von Hippel, Marvin Miller, Harold Feiveson and Frans Berkhout) in *Scientific American,* August 1993. Some of this research was conducted during his visit to CEES from January to August 1992.

In addition, Professor Diakov was co-organizer of the Moscow Workshop on the Future of Reprocessing and Arrangements for the Storage and Disposition of Already Separated Plutonium in December 1992 at which he presented a paper on the possibility of disposing of Soviet plutonium in high-level waste glass.

Conventional Arms Trade Regulations

Igor L. Urazovsky (MPTI graduate student) is working in the field of regulation and control of conventional arms transfers.

The research includes analysis of regulations regarding arms exports, the relationship between military industries and governments, governmental decision-making processes on arms exports, and methods of arms control in various countries. Urazovsky is also studying the possibility of applying Western arms trade regulations to arms exports from Russia.

The initial stage of research has involved collection and analysis of information about arms export systems in the United States and Russia. He has collected information about the current (1992–1993) arms trade regulations in Russia, and during a visit to CEES in the fall of 1993 he studied the U.S. experience in regulating conventional arms transfers.

He is currently in Russia conducting his research on arms exports in cooperation with the Department of Disarmament Problems (Director, Alexei G. Arbatov) of the Moscow Institute of World Economy and International Relations.

Third-World Ballistic Missile Proliferation

Timur Kadyshev received his Ph.D. in mathematical modeling from MPTI in 1991. He then became a research associate at the Center, working on mathematical and computer modeling of military force balances. In 1992–93, Dr. Kadyshev spent nine months at M.I.T.'s DACS Program, funded by grants from the International Research and Exchanges Board, the Ploughshares Fund, and the Union of Concerned Scientists (UCS). During this visit he worked with Dr. David Wright of UCS and DACS on a project aimed at assessing the North Korean ballistic missile program. (See "An Analysis of the North Korean Nodong Missile" in this issue.)

Upon returning to Russia in August 1993, Dr. Kadyshev became a Senior Researcher at the Center for Program Studies of the Russian Academy of Sciences, although he remains affiliated with the MPTI Center. His current research focuses on arms-control and security issues raised by ballistic missile proliferation.

ENERGY POLICY PROGRAM

Studies in areas of energy efficiency and greenhouse gas emission are being conducted with assistance of experts at the Energy Research Institute of the Russian Academy of Science and the Center for Energy Efficiency, CEES at Princeton University, the Department of Engineering and Public Policy of Carnegie Mellon University and the Washington-based Resources for the Future. One objective of this collaboration is to establish a training program to produce specialists in these area, and an energy and environmental training program has now been started at the MPTI Center. The Center has received a grant from the MacArthur Foundation for its energy and environmental program.

Long-Term Mathematical Modeling of Greenhouse Gas Emissions in Russia

The research interests of Alexander Kolesov (MPTI graduate student) include greenhouse gas emissions, and energy. He is now working on a model capable of estimating the emissions from a variety of human activities and the major direct and indirect consequences of potential policies to reduce emissions. He has also participated in the collection, analysis and presentation of information on the Russian energy industry. He is currently spending several months for research training at the Department of Engineering and Public Policy of Carnegie Mellon University.

Energy Efficiency as a Key Tool for Development of Federal and Regional Energy Policy

Dr. Vladimir Likhachev is studying federal and regional energy efficiency policies in the United States and Western Europe in order to assess their potential for implementation in Russia during the transition to a market economy. This research will be conducted in collaboration with the Resources for the Future, and it is anticipated that Dr. Likhachev will conduct some of this research in the U.S. For the last two years, he has taught the MPTI Center's course on national energy policy.

Combustion of Fossil Fuels in Russia and Greenhouse Gas Emissions

Yuri Borovsky (MPTI graduate student) has research interests in energy management, plant safety, and the interaction of energy and environmental problems. He is now collecting information about energy technologies and Russia's energy industry, with the objective of performing a comprehensive evaluation of innovative energy technologies. The emphasis is on technological measures for minimizing energy-related greenhouse gas emissions.

Energy and Environmental Educational Program

The MPTI Center began a graduate education program in September 1993. This program focuses on: modern technologies for production, conversion and consumption of energy; energy and environmental economic issues; and systems analysis in the energy field. It is intended that incoming graduate students will complete this program in four semesters. Currently, four courses are offered: Fossil-Fuel Energy Systems, Introduction to Economics Issues and Tools, Introduction to System Analysis, and Practices and Tools of System Analysis.

For additional information, contact:

Professor Anatoli Diakov
Director, Center for Arms Control, Energy and Environmental Studies
Moscow Institute of Physics and Technology
141700, Dolgoprudny, Moscow Reg.
Institutskii per., 9
RUSSIA
telephone: (095) 408 63 81
e-mail: mpti@sovam.com