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RESEARCH MEMORANDUM

POLARIS WEAPON SYSTEM (U)

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SUMMARY

This memorandum was written in response to interest within the Air Staff in a factual and unbiased assessment of the Polaris weapon system potential. It is based on past work at RAND in the strategic area and on specific missile systems, as well as on information obtained from the Polaris Special Projects Office and its contractors.

The time period of primary interest is pre-1965, a period for which U.S. strategic systems and force structure may be hypothesized with reasonable certainty. In this context the Polaris weapon system is approached as one of several systems which may improve our over-all deterrent posture and strategic capability. In today's world and for the foreseeable future, deterrence not only is a reasonable philosophy but should be our absolute first priority. For our deterrent capability to be objective it must be designed for the failure of deterrence; i.e., it must function, even if attacked by surprise in a well coordinated and determined manner. It must be inexorable without being inflexible. Further, in the design of strategic forces it must be admitted that deterrence cannot be certain, and there is a finite but incalculable probability of general nuclear war. It is in this environment that RAND has looked at Polaris.

There is much to commend in Polaris as a part of the U.S. strategic forces. Dispersal, concealment, and mobility are combined to give this system a low order of vulnerability. The mobility of Polaris in a medium which favors concealment may rule out the possibility of the enemy knowing in advance the precise geographical coordinates of the force except for the part undergoing overhaul in port or being serviced at a tender.

The removal of strategic targets from the U.S. or populated areas so that targeting this system does not result in collateral or bonus damage is also in favor of Polaris, although no attempt has been made to quantify this asset.

Polaris would be based forward so that under certain contingencies, given reliable command and communications, this system could have the shortest response time from command to weapon impact of any U.S.-delivered weapons, except for our overseas-based IRBM's.* Moreover, in the event of a premeditated enemy attack, Polaris could have a useful wartime life measured in weeks or months, which under present plans no other strategic system would have against a coordinated ICBM and manned bomber attack.

During the period of availability Polaris may also be the answer to adverse political developments which would compromise our basing IRBM's in certain foreign countries.

Conceptually, the Polaris system is interesting as a system with a low order of vulnerability to the expected enemy missile and manned bomber threat, and as a complement to the desired Air Force strategic posture which would include both a counterforce and counter-city strike capability. However, as with all new systems, the solutions to foreseeable technical problems and actual availability dates are to a significant degree uncertain. Presently the first Polaris submarine is scheduled to be operational in October of 1960 with missiles of 1000-n mi range which are designated "A-1." The 1500-n mi missile, designated the "B" model, is scheduled to be operational in mid-1963. The "ready-for-sea date" for the first submarine is April 1960 and for the ninth submarine February 1962, assuming FY-1959

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*The response time of Polaris and our overseas-based IRBM's would be comparable; however, IRBM basing is at present soft, fixed, and vulnerable to surprise attack.

funding. If the sixth through ninth submarines are not funded until FY-1960 they will be delayed about eight months. Deployment dates lag the ready-for-sea dates by six months. The Polaris missile schedule is extremely tight and slippage will undoubtedly occur. However, the urgency of the present situation warrants the effort being made by the Navy toward attaining early availability.

Technical considerations are discussed in Section II. The critical areas at present appear to be, particularly, navigation, fire control, and communications; they are sufficiently critical and important to warrant extreme effort by the Navy. The guidance accuracy of the missile will be no better than the position and azimuth information supplied by the navigation system, and a failure of the fire control computer would put all sixteen missiles on a submarine out of commission.

For the early 1960's the Navy will depend primarily upon three high-power VLF/HF radio stations for transmission from the U.S. These stations are highly vulnerable to modest levels of overpressure. Even if they survived, they would probably suffer from severe blackout in the event that high-altitude megaton shots were used by an enemy for communications disruption or by the U.S. for ICBM defense. Plans should be formulated for the use of any and all applicable communication links, including the SAC links; and various relay schemes should be studied employing ships at sea, many U.S. and overseas stations, and aircraft including SAC alert bombers. The problem of communicating with Polaris submarines is complicated by the fact that the submarine must be alerted or at least have pre-planned listening times in order to put up an antenna to receive. Therefore, seismic equipment on the submarine may be useful as a bomb alarm system.

For later periods the Navy is studying various communication systems such as sonar, underwater cable nets, meteor-burst techniques, satellites, etc.

The early A-1 missile design appears to be less critical from a technical point of view. However, advances in the state-of-the-art are required for the B version, which cannot yet be placed on a reliable timetable. Although none of these problems is insoluble, more time, development, and testing are required for a significantly better estimate of performance and availability.

Under present plans Polaris submarines will operate from overseas tenders for a period of two and a half years and then return to the U.S. for six months, which includes four months in a shipyard and two months in training. While in a State-side shipyard a submarine will undergo recoring of the reactor, depot-type maintenance, and required modifications. While overseas a 90-day cycle is planned with a submarine alongside its tender for 20-30 days undergoing servicing and maintenance, and on station or in transit to and from station for 60-70 days. Two crews per submarine are planned, with each crew taking alternate 90-day duty cycles. The overseas-tender concept appears to offer the most effective and least costly mode of operations.

Based on the above concept and a 30-60-day cycle, which also includes one-third of the nominal tender time being spent in training away from the tender, a Polaris submarine would have an effectiveness ratio of 0.65 if tenders were located in areas from which targets could be reached. That is, 65 per cent of the time submarines would be on station, in transit to or from station areas, or near a tender on training maneuvers. Excluding human factors it appears technically feasible to keep two-thirds of the

Polaris force essentially on station. However, the psychological problems involved in keeping two crews continuously on alternate 90-day duty cycles on the same submarine for long periods are presently unknown.

There appear to be two broad alternatives open to the Soviet Union in countering the Polaris threat by killing the submarines: (1) detecting and tracking submarines in peacetime with the intention of killing them at the time of a coordinated attack on other U.S. retaliatory forces, and (2) locating submarines from patrol aircraft by detecting missiles during launch and in the first part of their flight, followed by a rapid counterattack.

The problem of detecting and tracking any relatively quiet submarine is formidable, even ignoring a final active attack that depends upon detection and tracking. The ability of the nuclear-powered Polaris submarine to be quiet is a critical consideration in vulnerability, and a strong effort should be made in that direction. This is not to say that the Soviet will not be able to take effective action against the Polaris system; but the characteristics of the operating medium, the state of underwater detection technology, and the available tactics favor the evader rather than the tracker if the Polaris submarine is quiet. One scheme for missile detection and anti-submarine attack is based on an airborne system using infrared search and radar ranging on the submarine-launched missile. Multiple air-to-surface missiles are employed against the submarine. A high probability of kill appears feasible within five minutes of an initial detection, and requires about fifty on-station aircraft per million square miles. However, there are also tactics available to counter such a system. The vulnerability of Polaris is discussed in Section V.

Excluding the Arctic Ocean, neglecting water which the Soviet may classify as their own, such as the close-in Barents Sea, Baltic Sea, etc., and considering only western launch areas, the 1000-n mi Polaris could hit 60 per cent of the 135 Soviet cities of 100,000 population and above while operating in an area of 1.7 million square miles. The 1500-mile missile could hit 87 per cent of these cities while operating in an area of 3.6 million square miles.

[redacted] DOE b(3)

For the counter-city mission three levels of damage were considered, ranging from at least 25 per cent to at least 75 per cent structural collapse. Results for the two limiting cases are summarized in the following table.

NUMBER OF WEAPONS REQUIRED ON TARGET FOR A GIVEN DAMAGE LEVEL AGAINST THE 135 LARGEST SOVIET CITIES

DOE b(3)

DOE b(3)

Yield	At Least 25% Structural Collapse		At Least 75% Structural Collapse	
	2 n mi CEP	4 n mi CEP	2 n mi CEP	4 n mi CEP
[redacted]	135	340	480	1200
[redacted]	135	135	150	290
[redacted]	135	135	135	200

[redacted] DOE b(3)

With a 2-n mi CEP eight missiles on target would be required for a 90 per cent assurance level against a 10-psi target. However, against soft military targets whose coordinates are accurately known, Polaris missiles would be quite effective.

[redacted] DOE b(3)

DOE
b(3)

Target damage criteria are discussed in Section V.

System costs for Polaris are discussed in Section IV. For the present program consisting of nine submarines initial investment is estimated at 1256.2 millions and annual operating costs at 152.9 millions. Assuming an effectiveness ratio of .65, i.e., each submarine is able to fire missiles against targets 65 per cent of the time, the cost per missile for initial investment is 13.4 millions, and the cost per missile for annual operating costs is 1.63 millions. The above costs do not include research and development which has been estimated at 1040 millions.

The growth potential of the present Polaris missile system is limited by the geometry of the launching tubes. A significant increase in range beyond 1500 n mi with the present re-entry weight will be realized only by a new two-stage design utilizing a small increase in diameter which is available or utilizing longer launching tubes which are feasible. A significant increase in yield will result only from a significant increase in the yield-to-warhead-weight ratio. A requirement for increased missile range would seem to be primarily a function of submarine vulnerability. Since the submarine is the major part of initial investment, any design changes in the future that result in lower submarine cost can significantly decrease systems cost. There are two outgrowths of the Polaris concept that deserve more study. One is launching missiles from sown canisters, and the other is the use of a submerged mobile barge as a missile base.

Although Polaris appears to be a reasonable and effective ingredient of our strategic posture, particularly in the counter-city deterrent role and against soft, known military targets, it by no means meets all the requirements of a strategic capability. Among other objectives besides deterrence is the limiting of damage the U.S. would receive if deterrence failed, an important element of which is a high-confidence counterforce capability. However, the projection of requirements cannot be precisely made. The future as to the Soviet military posturé, operational capabilities, and intent is extremely uncertain; and the ways that a war might start run the gamut from the premeditated, either well coordinated or poorly coordinated, to one resulting from accidents, mistakes, miscalculations, or sheer irrational expedience.

In the foreseeable future, considering both deterrence and the fact that deterrence is not certain, there exists a requirement for a protected force of manned bombers with multiple weapons, a search capability, and terminal accuracy much superior to that of early generations of ballistic missiles. This requirement is based on the expected Soviet defense, hard targets, and targets whose coordinates are only known in a gross fashion. There also exists the requirement for ICBM's with warheads much larger than the Polaris warhead on the basis of uncertainties and contingency planning. The contingencies visualized are a future ICBM defense requiring penetration aids, increased yield and accuracy against hard known targets, and an S.U. civil defense program. The larger warhead could be devoted to higher yield or higher yield plus penetration aids for both missile and manned-bomber penetration. And finally, there exists the requirement for a sufficient number of protected and dispersed delivery vehicles, not only to insure our capability for the desired damage level against an enemy, but also to make the job of destroying a significant fraction of our strategic force by an enemy infeasibly large.

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I. THE POLARIS WEAPON SYSTEM

The present Polaris approach essentially resulted from the incompatibility of the Jupiter missile with the Navy's ultimate aim for a submarine missile system. During the summer of 1956, at the request of the Chief of Naval Operations, the Committee for Underseas Warfare of the National Academy of Sciences conducted a study program at Woods Hole, Massachusetts, on the problems of countering nuclear submarines, which included a study of the use of ballistic missiles in submarine strategic operations. In October of 1956, the results of this program at Woods Hole (the "NOBSKA report"), including the recommendation for the development of a twenty-to-thirty-thousand-pound, two-stage, solid-propellant, submarine-launched ballistic missile, were presented to Admiral Burke and his staff. In November, plans for a small, solid-propellant missile were reviewed by the Scientific Advisory Committee to the Special Assistant to the Secretary of Defense for Guided Missiles. In December, the Department of Defense approved a plan for shifting the Navy effort from the Jupiter program to the solid-propellant missile system called Polaris. Therefore, it may be stated that the Polaris program got underway at the beginning of 1957.

In November 1957, the target date for achievement of the ultimate tactical missile was advanced from 1965 to 1963, with an operational capability beginning in 1960 with a missile of shorter range.

The Polaris weapon system is based on survivability in the face of a premeditated first attack, thereby creating a degree of objective deterrence. However, reliable command, control, and communication must also survive. For its low degree of vulnerability, Polaris relies on dispersal, mobility, and concealment.

DOE b(1) 1.5(g)

[redacted] Length is 382 ft with a beam of 33 ft. Sixteen missiles are stored in vertical launching tubes around the submarine's center of gravity. The system is designed for a rate of fire of one missile per minute at the surface or at 100-ft keel depth. Ejection is by compressed air.

The Polaris missile is a two-stage solid-propellant ballistic missile, 28.5 ft by 54 in., weighing 28,600 lb. [redacted] Guidance is inertial with a quoted 2-n mi CEP, including the position error of the submarine. The first tactical missile (A-1) is scheduled for 1960 with a nominal 1000-n mi range. The B version is scheduled for early 1963 with a nominal 1500-n mi range.

DOE b(3)

Navigation will be performed by a shipboard inertial navigation system (SINS) which, because of gyro drift, requires periodic position fixes for the desired missile accuracy. SINS supplies information to the fire control computer for proper inputs to the missile, and also supplies the mechanical optical alignment system with an azimuth and a vertical in order to orient the guidance platform.

Availability dates are shown in the following table from the Navy's extended shipbuilding program.

Sub Number	Ready-for-Sea Date
1	4-60
2	7-60
3	10-60
4	1-61
5	4-61
6	7-61

Sub Number	Ready-for-Sea Date
7	10-61
8	1-62
9	2-62
10	4-62
11	5-62
12	7-62
13	8-62
—	—
25	9-63

Deployment dates lag the ready-for-sea dates by six months. Only nine submarines have been authorized by Congress, and the quoted availability dates for submarines 6 through 9 are dependent upon FY-1959 funding. If these four submarines are not funded until FY-1960, an eight-month delay is estimated.

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II. TECHNICAL STATE-OF-THE-ART

A. GENERAL SUMMARY

The present Polaris development program includes two tactical versions of the basic Polaris missile configuration and design, with the Lockheed Missile Systems Division as the prime contractor for the missile less guidance. These are the tactical A-1 and B missiles. The A-1 is intended to provide an operational capability in late 1960 with a sacrifice in missile range. The Polaris B missile with a full range of 1500 n mi is currently programmed for operational use in mid-1963.

This development program further includes three types of test missiles with the same basic configuration and general characteristics as the Polaris B missile. The test missiles are designated the AX, A-1X, and the BX. The AX is a full-scale developmental missile intended to test and develop the propulsive booster components and other missile components in early flight. The A-1X is the test missile for the tactical A-1 missile, and the BX serves as the flight test vehicle for the operational B missile. Although not classified as a test missile, the early tactical A-1 may also be considered as an operational test missile which can provide operational factors that may be included in the B series of missiles, thereby increasing the potentialities of the over-all weapon system.

The guidance system for the Polaris missile is to be a lightweight, all-inertial system weighing approximately 200 lb, composed of an inertial measurement unit, a digital computer, and associated electronics. Its accuracy is to be compatible with an over-all missile system accuracy of two miles. The maintenance concept now being considered is replacement of the complete system in case of malfunction.

The guidance system development is being performed by the MIT Instrumentation Laboratories as prime contractor. The contract for the production of the inertial guidance system, as well as the submarine-based fire control system, has been awarded to General Electric. The SINS system, which is the basic inertial reference and navigation system on board the submarine, is being built by Sperry. However, probably the first three submarines will use a North American Aviation system. At present there are four subcontractors supplying the basic inertial components for the airborne system. They are Litton, Minneapolis-Honeywell, Kearfott, and A. C. Sparkplug. All four companies are building the same MIT-designed gyros and integrating accelerometers.

The nuclear-powered submarine is of conservative design and is somewhat smaller than the Triton which recently has been launched. Production facilities for the Polaris submarine include the Electric Boat Company; Navy Yard, Mare Island; Navy Yard, Portsmouth, N.H.; New York Ship at Newport News, Virginia; and Ingalls Ship at Pasagoulas, Miss. The following brief discussion will cover only major points of the system design.

B. PROPULSION AND PERFORMANCE

The capabilities of the test and tactical missiles will be largely determined by the propulsion system developments. The Aerojet-General Corporation has the responsibility for these developments. The AX test missile incorporates tested propellants giving a sea-level specific impulse of 230 sec in a booster case made from current materials and by current manufacturing techniques. Except for propellants the tactical A-1 and the A-1X missiles require higher performance than is available from the current state-of-the-art for production items as represented by the AX components.

Currently, the development program includes an advanced lightweight case for the second stage of the A-1 missile, with the first-stage case the same as in the AX design. The lightweight case for the second stage of the A-1 missile is the same case required for the later B missile design. The propellants for the A-1 missiles are the same as those for the AX missile and represent current production availability. Higher-performance propellants with a specific impulse of 240-244 sec have been tested, and a limited production of this propellant could serve to increase the performance of the A-1 missile. The use of Polaris B propellants in the A-1 second stage has been suggested in order to offset delays in obtaining the lightweight booster cases without an excessive sacrifice of range. The lightweight case design and the higher-energy propellants are both required in order to meet the Polaris B performance requirements of warhead and range.

Recent tests of the jetevator control system have proved the feasibility of this type of control for rocket boosters, but the tests have also shown that a materials problem may exist if higher-performance propellants are used, i.e., higher exhaust gas temperature. Higher-energy propellants can be used if research on materials accompanies the development of the propellants.

Although this discussion has centered on the development of propulsion components, the design and weight of the guidance components are important parameters in the performance of the Polaris missiles. Performance is presently quoted with the fully operational and lightweight guidance system scheduled for availability compatible with the 1960 operational date for the A-1 missile. Current components of inertial guidance system are considerably heavier than the Polaris components, as estimated. Better estimates for the guidance system cannot be made until complete units are available in early 1959.

Currently the design of the A-1 tactical missile is just pushing the state-of-the-art in materials, fabricating methods, and inspection techniques, while the B design is just beyond current developments. However, advances are required which cannot be placed on a reliable timetable, and they provide a basis for questioning specific Polaris B performance and availability. Because of geometrical design constraints imposed on the Polaris missile by the design of the launching system, alternative solutions for regaining performance in case of unforeseen technical difficulties are somewhat limited. [redacted]

DOE b(3)

Range performance is presently based on nominal characteristics and estimated weights, and there is no reason to question the calculations made by Lockheed for the quoted ranges of the A-1 and B missiles. However, a review of other development programs, as well as component performance, results in conservative estimates which degrade the quoted maximum ranges in order to form an estimate of the operational range. Such an estimate would include the significant variations in rocket performance and weights, and the operational environment, e.g. rain. The actual operational range will have to be determined by flight test.

A set of conservative estimates of operational ranges for the A-1 and B missiles is as follows:

A-1 800-1000 n mi with heavier than programmed guidance unit into account in determining the initial velocity inputs. The basic velocity information is obtained from the SINS system. It is presently planned to launch missiles with essentially no submarine velocity.

The thrust vector is to be controlled by positioning jetevators in the rocket exhaust. The successful development of these jetevators is a major problem area primarily because of the high stiction levels encountered due to the elevated temperature condition. Jetevators have been used in the past in the Snark booster development, but not for the relatively long burning times of the Polaris motors, which are of the order of 60 sec per stage.

It appears that stability at staging may be a serious problem. At staging, the second stage is aerodynamically unstable, and until thrust comes up there is no way of controlling the second stage. Fins or a skirt could increase the stability, but this would add extra weight and drag. Another problem is the possible collision of the first stage with the second stage during the time the first stage thrust is decaying and the second stage thrust is coming up. These problems also exist for the Minuteman second stage in the high dynamic pressure regime.

Guidance is discussed further in Appendix A.

D. NAVIGATION AND FIRE CONTROL SYSTEM

The SINS system and the Fire Control system are by far the most complex parts of the over-all system. The SINS is a shipboard local-gravity inertial system whose purpose is to supply, azimuth, velocity, and position information. This information is sent to the fire control computer so that it can compute and furnish proper initial condition settings, proper values for the airborne computer constants, and the azimuth direction. The SINS system also supplies the alignment system, via an optical system, the direction of north,

A-1	1000–1100 n mi with lightweight guidance and lightweight second stage
B	1400–1500 n mi with lightweight components and the higher-energy propellant.

[redacted]

DOE
b(3)

The Polaris third stage is an integrally designed warhead — [redacted]

DOE
b(3)

C. GUIDANCE

The guidance for the Polaris missile is a velocity-to-be-gained scheme developed originally at MIT for the Thor missile. It is an excellent scheme for an IRBM guidance system. Integrals of thrust and lift accelerations are digital inputs into an airborne digital computer from the integrating accelerometers in the inertial measurement unit. The initial velocity conditions are set in by the submarine-based fire control system. The airborne computer solves a set of guidance equations and regulates thrust cutoff and supplies the proper steering signals.

There are eight preselected targets for the sixteen missiles on board the submarine. For these eight target points and for launch points in the centers of 20-n mi x 20-n mi grids, precomputed inputs to the guidance equations and the azimuth direction are stored on cards. The fire control computer interpolates these values to obtain the proper settings for the exact launch point. In this calculation the velocity of the submarine is taken and the vertical so that the platform can be oriented. The present concept for correcting the drift of the gyros in the SINS system is either by celestial information obtained from star trackers or by position fixes obtained from bottom maps. There is some question as to how often clouds will obscure the stars so that celestial fixes cannot be made. Also, there is some question as to how much of the ocean bottom in the intended areas of operation will be mapped.

One of the problems in using underwater maps is that an active emanating system must be used for an appreciable interval of time. In order to correct SINS for both position and azimuth, more than one fix is required. Possible enemy effort directed toward detection, tracking, and active defense cannot be discounted for the future. Therefore, critical situations can be imagined when the submarine needed a fix and wished to remain quiet. Position and azimuth are so important to the Polaris system that much effort should be expended in this area during the early system development period. An additional capability would result from designing the stellar optical system to also sight on surveyed landmarks and lights.

The fire control system is a very complex one. It must calculate and supply initial conditions, guidance constants, azimuth direction, and velocity corrections for erection of the inertial platform to sixteen missiles under constantly changing conditions. The reliability of such a system seems to be quite a problem, and a failure of the fire control computer would put all sixteen missiles out of commission.

Many of the problems are relieved by the submarine sitting quietly on the bottom with locked gimbals, where possible, particularly in areas or under weather conditions when corrections to SINS might be difficult or impossible to obtain.

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III. CONCEPT OF OPERATIONS

A. OPERATIONAL PLAN

Under present plans Polaris submarines will operate from overseas tenders for a period of two and a half years and then return to the U.S. for six months, which includes four months in a shipyard and two months in training. While in a State-side shipyard a submarine will undergo recoring of the reactor, depot-type maintenance, and required modifications. While overseas a 90-day cycle is planned with a submarine alongside its tender for 13 to 20 days undergoing servicing and maintenance, in training away from the tender for 7 to 10 days, and on station or in transit (to and from) for 60 to 70 days. Two crews per submarine are planned with each crew taking alternate 90-day duty cycles.

The overseas tender concept appears to offer the most effective and least costly mode of operations. It would also appear reasonable to station tenders in areas from which targets could be reached. If the more conservative overseas cycle is assumed, the effectiveness ratio for the force is 0.65. That is, two-thirds of the time, the submarines are overseas away from a tender and, therefore, possibly untargetable. If the tender time could be cut to 13 days, and the time in the U.S. to 3 months, the effectiveness ratio would be increased to 0.80. It appears technically feasible to reach an effectiveness ratio around 0.6 or 0.65; however there may be psychological problems involved in two crews continually taking alternate 90-day duty cycles on the same submarine for two and a half years. For a given support level the cost of the system varies inversely with this ratio. If the support levels are fixed, an increase in effectiveness ratio from 0.5 to 0.7 would result in a 40 per cent decrease in costs or force requirements in order to do the same job.

When the force size is large enough to require several tenders, the tenders can be located so that the submarines would have a target coverage capability in transit to and from their on-station areas. Under this concept the force could have the fastest response time of any protected strategic system proposed to date. The two-week transit time to and from the U.S. out of three years is insignificant, amounting to only 1.4 per cent.

B. LOGISTICS

In a paper distributed by the Chief of Naval Operations, entitled "The Navy of the 1970 Era," 50 missile submarines are allocated to the strategic mission. This force includes about 40 submarines with the final version of the Polaris ballistic missile, and about 10 smaller submarines with later-generation missiles classified as "very precise," which could also be used for tactical purposes.

Taking a force of 50 submarines as an example, and assuming a 30 to 60-day cycle overseas with two submarines per tender and a 6-month shipyard time per three years, with the full 30 days or 6 months spent alongside the tender or in the shipyard, 7 tenders and 9 drydock spaces would be required. If one-third of the nominal shipyard or tender times were spent in training in open waters, then 5 tenders and 6 docks would be required. Further, if a tender serviced 3 submarines instead of 2, only 3 tenders would be required. If multiple drydocks per yard were employed, then points to be supplied are further reduced. The tenders are small shipyards and are, from a maintenance standpoint excluding re-supply, essentially self-sufficient.

From this brief exercise it appears that the logistic requirements for the Polaris system are modest. Five tenders and 3 shipyards and 2 drydocks per yard could support a force of 50 submarines. Two missile depots, one on each coast, might be desirable in order to facilitate the flow of materials. Since we do not have a Navy Logistic Plan, we can hypothesize Hawaii supporting the Pacific force, thus saving 4500 n mi, and two points on the East coast supporting the Atlantic force. One or two tenders for the Pacific and three or four for the Atlantic would be sufficient. For the force used in this example the flow of materials would be from the factories to 2 depots, to 3 yards, to 4 or 5 tenders.

C. EFFECT OF MISSILE RANGE

In order to get an appreciation of the target coverage for the early missiles and also the effect of missile range on target coverage the following nine missile launch points were assumed as being fairly reasonable:

A – off southern coast of Spitzbergen
B – off northern Norwegian coast – vicinity of Tromso
C – off southern Norwegian coast – vicinity of Bergen
D – Tyrrhenian Sea – vicinity of Genoa
E – Northern Aegean Sea – vicinity of Salonika
F – off southern coast of Turkey – vicinity of Antalya
G – Persian Gulf
H – Arabian Sea – vicinity of Karachi
I – off southern coast of Hokkaido, Japan

The ability to hit the 135 cities of at least 100,000 population in the S.U. was considered, using missile ranges of 1000 and 1500 n mi. The only criterion was range; missile performance, reliability, etc. were not taken into consideration. The total population of these 135 cities was estimated to be approximately 43 million in the early 1960's. The following table shows the target coverage for the assumed launching points for a missile of 1000-n mi range.

Launch Point	Number of Cities Within Range	Population (thousands)
A	3	610
B	21	11,653
C	14	10,428
D	14	3,766
E	50	12,124
F	50	12,778
G	10	2,612
H	4	1,008
I	4	930

Approximately 40 per cent of the first ranking cities cannot be hit with a 1000 n mi missile. The total population of the 82 cities included in the above table is 30.0 million.

With a missile of 1500-n mi range the following data apply:

Launch Point	Number of Cities Within Range	Population (thousands)
A	67	16,308
B	86	28,209
C	78	25,424
D	72	23,219
E	89	28,677
F	94	30,346
G	55	13,689
H	14	3,581
I	6	1,225

Approximately 12.5 per cent of the first ranking cities cannot be hit with a 1500-n mi missile. The total population of the 119 cities included in the above table is 38.8 million.

From these tables it is evident that in the initial stages of operations (i.e., few Polaris submarines available) the most advantageous areas for launching missiles to hit cities is the Mediterranean Sea, points E and F, followed by points B and C off the Norwegian coast.

D. COMMAND AND COMMUNICATIONS

The most critical area in the entire Polaris weapon system is the area of command, control, and communication after the event of a Soviet surprise attack. It is important to understand that although the submarines at sea are mobile, their command and control and much of their communications are not. If communications are so disrupted that retaliation is delayed by days and is uncoordinated, then the effects of this retaliation could be well below the expected level, if the enemy had active defense against re-entry bodies, had an ASW capability against the Polaris submarine, and evacuated people from major cities. The characteristics such as mobility, concealment, and dispersal in overseas waters that give the Polaris submarine a low order of vulnerability also make the system very difficult to control, particularly under a coordinated surprise attack on this country and overseas strategic facilities. However, if the Polaris system can be controlled and coordinated even though communications are delayed many hours, the system would retain a significant capability, particularly if the vulnerability, response, and posture of the ZI-based strategic forces were adequately improved. In this case the mixed and diversified strategic forces would augment each other and result in a better capability for both deterrences and counterforce. In fact, the situation can be imagined where Polaris would have a significant value over days or weeks, including a negotiable value for bringing a war to a conclusion.

The system that would be desirable is one that could alert the submarines and transmit orders reliably in a matter of minutes. There are some contingencies where rapid response would be of extreme value. However, such a system is extremely difficult to obtain if the enemy does not cooperate.

For the early 1960's the Navy will depend primarily upon three high-power VLF/HF radio stations for transmission from the U.S. One is located at Annapolis, Maryland, and a second at Jim Creek, Washington; and a third will be located in Maine to be operational in late 1960. VLF and HF antennas are vulnerable to low levels of overpressure of the order of 2 psi. [redacted]

DOE
b(1)
1.5(g)

ecords from ionospheric sounders at dispersed ground location and airborne sounders flown through the surrounding areas indicated that an intense artificial ionosphere was created almost instantaneously at about 35 to 40-mile altitude. This layer was observed to extend to distances of 800 miles or more from the shot area [redacted]

DOE
b(1)
1.5(g)

This ionization decayed after 20 minutes or so sufficiently to allow many Hawaiian circuits to be restored. However, a second and even more intense radio blackout period was observed at Hawaii shortly thereafter. This one lasted for several hours after shot time. Larger weapons or weapons specifically designed to produce absorption and burst at perhaps more optimal altitudes could produce more intense and prolonged effects than those observed for these shots. There are also the possibilities that weapons detonated at about 100 or 200-mile altitude may cause signal interferences extending to higher radio frequencies, or that other types of weapons may eventually prove effective in producing high-intensity background noise in the 1-megacycle to 100-megacycle portion of the spectrum.

The approach that the Navy is presently taking for the early time period before new developments will be available is quite reasonable. This approach considers the use of depth charges which could be delivered by missiles, in order to alert submarines to surface an antenna for receipt of orders, and the use of various relay schemes. The problems involved appear to be those of preplanning and procedures rather than of technical developments. After an attack that the Soviet might launch against the U.S. and overseas facilities, a tremendous amount of communications equipment in the U.S., at sea, and in friendly countries would survive due to sheer numbers. With intelligent preplanning of procedures relative to various contingencies, communications could be quite reliable. The preplanning should include the use of any and all equipment that might have a capability, rather than a few best approaches. Even hardened multiple terminals on the transatlantic cable may be interesting. In such an environment the control of the strategic and defensive forces would be of singular importance.

In order to alert the submarine force, the use of seismic equipment in submarines might be applicable as a bomb alarm system. The only backup for various alert schemes would be preplanned listening times.

For later periods the Navy is interested in such schemes of communicating as sonar, underwater cable nets, meteor-burst techniques, communications satellites, etc. All of these schemes should receive research and development support. Reliable communications are basic to all weapon systems, and especially to mobile systems.

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IV. COSTS

These preliminary cost estimates of the Polaris Weapon System are based on both information obtained from the Navy and RAND estimates of the unknowns. However, they are not to be considered as either precise or final. The Special Projects Office has been quite cooperative in making available information known to them. However, there remain areas of uncertainty. Therefore, the usual admonitions pertaining to cost estimates in general apply.

Cost data obtained from the Navy pertain to nine submarines and one tender, although uncertainty exists as to the number of submarines that will be in the preliminary program. Congress has appropriated funds for six nuclear-powered Polaris submarines in the Fiscal Year 1959 program. This is in addition to the three funded in FY 1958 and currently under construction. Construction of an additional two submarines has been approved, so that five submarines are definitely in the works. However, the additional funds appropriated by Congress for the additional four submarines have not been allocated. It is anticipated that when it next convenes Congress will exert considerable pressure on the Administration to release the funds. The Navy meanwhile is thinking in terms of nine submarines, and it is on this basis that the costs estimates are made.

The plan of operations for the submarines and tender has been outlined. One tender is still contemplated for nine submarines, which Navy personnel feel is adequate. However, there are plans for an additional tender specifically designed to support Polaris submarines. Construction costs for this additional tender are estimated at sixty-one million dollars. Each submarine will have sixteen missiles on board plus an additional sixteen on the tender.

Table 1 on the following page lists the initial investment and annual operating costs by item following the RAND Cost Analysis Department format. These costs are based chiefly on the figures obtained from the Special Projects Office and the implications of these figures.

A discussion of these costs is given in Appendix B.

Table 1

POLARIS WEAPONS SYSTEM – REVISED COSTS, NINE SUBMARINES*

(Amounts in millions of dollars)

Item	Initial Investment	Annual Operating
Installations		
Base Facilities	10.0	–
Training Facilities	0.4	–
Base Maintenance	–	3.4
Equipment		
Submarines	900.0	–
Missile Launching and Control System Equipment	–	43.2
Tender	26.0	–
Tender Equipment	–	0.6
Missiles (160)	171.2	28.9
Missile Containers	8.1	1.6
Base Equipment	7.0	1.3
Training Equipment	5.9	1.1
Stocks		
Initial Stocks and Readiness Reserves	9.4	–
Initial Spares (missiles only)	43.2	–
Initial Spares (shipboard FBM)	9.0	–
Transportation	2.9	0.8
Personnel		
Training	10.1	4.0
Pay and Allowances	–	14.5
Travel	0.4	0.1
Maintenance and Fuel		
Submarines	–	20.3
Tender	–	0.3
Services and Miscellaneous	–	9.6
Command and Major Support Command Administration	–	20.2
TOTAL	1203.6	149.9
If Interim Communications are added:		
Facilities	46.2	2.3
Equipment	6.4	.7
TOTAL	1256.2	152.9
Per Submarine	(139.6)	(17.0)
Per Missile	(8.7)	(1.06)
Research and Development	1040.0	–
TOTAL	2296.2	152.9

*A more detailed analysis of these costs is given in Appendix B.

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V. EFFECTIVENESS

A. VULNERABILITY

The principal characteristic of the Polaris system that distinguishes it from other strategic bombardment systems now planned for the 1960's is its ability to move continuously in a medium which favors concealment. This movement may rule out the possibility of the enemy knowing in advance the precise geographical coordinates for this force, except for the part of it undergoing overhaul in port or being serviced at a tender. It is hoped that the system will be little vulnerable to surprise atomic attacks; and less cautious comments suggest that the system will be invulnerable. However, it would appear that the submarine is not inherently invulnerable. The real question is: what can the Soviet Union do to counter the Polaris threat, and how much effort might it take? It must be assumed that the Soviet Union will work hard at countering this system.

Since the Polaris will come into operation in a period when the Soviet Union is expected to be able to send large numbers of missiles against the U.S. with little or no warning, backed up by manned bombers, the attention focused by the Navy on the problem of surviving enemy attacks in the design of this system is clearly warranted, and it is this aspect of the system that is its chief virtue. However, while peacetime movement and concealment are useful virtues, they are neither necessary nor sufficient in order to be able to strike back. It is erroneous to regard a fixed system as vulnerable and a mobile system as invulnerable. For example, the U.S. has plans for fixed, hard, dispersed bases able to withstand heavy thermonuclear missile attacks; while on the other hand, a few mobile aircraft carriers in a limited area near an enemy represent targets nearly as vulnerable as soft fixed bases to a premeditated surprise attack.

There appear to be two broad alternatives open to the Soviet Union in countering the Polaris threat by killing the submarines: (1) detecting and tracking submarines in peacetime with the intention of killing them at the time of a coordinated attack on other U.S. retaliatory forces,* and (2) locating submarines from patrol aircraft or ships by detecting missiles during launch and in the first part of flight, followed by a rapid counter-attack.

Submarine Detection and Anti-Submarine Attack

This section considers the more typical undersea warfare methods which the Soviet Union might employ in defense against a retaliatory attack by submarine-launched Polaris missiles. Throughout the field of undersea warfare, which is as broad and complex as the field of air warfare, underwater sound devices are the counterparts of radars in air warfare; and they are just as important in determining the characteristics and capabilities of weapon systems. However, underwater sound devices generally work very poorly compared with their radar counterparts. This fact tends to give the intruding submarine a relatively greater advantage than an intruding aircraft.

On the whole the two fields are about even as far as technical development and basic understanding of the physical processes are concerned. Radars

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*There is, of course, the possibility that attempts might be made to kill our submarines in peacetime, especially if this could be done in a way unlikely to give positive evidence of the attack, i.e., if the only evidence we would get is the failure of our submarine to return to base. This might happen if we were to attempt to operate in an area regarded by the Russians as a private preserve. Perhaps more likely would be an attack on submarines in retaliation for some objectionable U.S. move. For example, there have been proposals in DOD that the U.S. sink Soviet submarines that approach too near our coasts. If we were to adopt such a policy, we should expect that some of our Polaris submarines would fail to return to base. In fact, a truly limited war can be imagined which is limited to submarines and only a few submarines.

are far more numerous, more varied, and more commonplace, but these differences do not indicate a corresponding difference in understanding. On the whole pretty fair guesses can be made as to the evolutionary course which radar will take; at least the future is planned on this basis, and that is really the important point for this discussion.

In sonar, at least among those who are not familiar with the subject, there is sometimes an inclination to think that matters are different. This view amounts to a denial of the present understanding of the field; it is an unwillingness to plan for the future on the basis of what is actually known; it is nearly a hope that a miraculous cure will dispel unpleasant reality. It is unwarranted. The main avenues along which sonar improvement can be expected have been clear for years, and development is proceeding down them: higher radiated power, better radiation patterns, lower frequencies, bigger arrays, improved signal processing. As with radar, more data are needed on long-range propagation, especially over-the-horizon effects and long-range clutter. However, one can make fair estimates of the improvements to be expected from a given effort. It is the ocean, not just the engineering skill, which sets the limits and the price on performance.

In both radar and sonar the question is not really whether a major nation has the technical know-how to obtain a certain capability. It is instead whether the nation chooses to pay the price. Just as a sufficiently numerous assortment of radars could be used to track small low-flying aircraft anywhere in the U.S., so too a sufficiently numerous assortment of sonars could track a submarine anywhere in the ocean. The cost of such radar coverage is astronomical; so is the cost of the sonar coverage.

It is not possible to give a concise answer to the question of what range sonars can achieve. It is necessary to break the answer down into at least a few different cases. Besides the nature of the sonar itself, the following variables influence the answer strongly:

- kind of sonar platform
- speed of sonar platform
- depth at which radiator is placed
- water depth to bottom
- depth of target
- temperature structure
- character of the bottom

There are combinations of these variables for which the sonar range is as little as 100 yards, and there are others for which we hope to achieve 100 miles in future equipment. An "average" is essentially meaningless.

Capabilities of U.S. Active Sonar

The estimates presented below of present and anticipated active sonar capabilities are taken entirely from a report prepared during 1956 and published during 1957 by the Committee on Undersea Warfare of the National Research Council.* However, additional comments and information are included which are based, in part, on a series of recent visits to Navy agencies including OpNav, BuShips, USNUSL, NRL, and USNEL.

The active ranges presented are those for 50 per cent probability of detection of a random-aspect submarine at 14 db target strength, and are based on the following set of standard conditions unless otherwise noted.

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*Peterson, S. A., Expected Active and Passive Sonar Detection Capabilities of Current and Future Platform-Equipment Combinations, NRC:CUW: 0241, April, 1957 (Secret).

- Deep water (2500 fathoms), convergence zone paths exist
- Mixed surface-layer depth of 100 ft
- Surface temperature of 50°F
- Sea state 2

This situation represents an approximate average of conditions for the middle North Atlantic over the spring, summer, and fall periods. During the winter the mixed layer depth increases to depths greater than 300 ft because of the higher wind forces and concomitantly higher sea states.

With ASW surface ships at about 15 knots or less, estimated ranges for equipment dependent upon transmission paths near the surface vary from 2 to 12 n mi against a submarine in the layer and from 1 to 3 n mi for a submarine below the layer. The higher value for the submarine below the layer depends upon the surface ship carrying a sonar radiator which can be put below the layer. The higher values for a submarine in the layer show the anticipated benefits of low frequency and high power, but the influence of the layer is evident. It must be emphasized that the 12-n mi estimate, even though by surface paths, is for <u>deep water</u>.

For equipment using the convergence zone, estimates vary from 25 to 60 n mi, dependent upon surface reflection loss. For bottom reflection paths ranges vary from 5 to 15 n mi, dependent upon bottom characteristics.

Surface ships which move about at high speed are virtually useless as compared with slower ships; the curves of self-noise versus speed climb astronomically above about 18 knots, and there is no present reason to foresee much change in this situation. Hence, S.U. surface search forces must obtain search rate by numbers and not by speed.

With airborne equipment using dipped sonar at speeds from 10 to 35 knots, estimated ranges vary from 1.5 to 7 n mi against a submarine in the layer and from 1 to 2 n mi for a submarine below the layer. However, these aircraft move slowly in terms of the distances involved and in terms of the speed with which a submarine can break off sonar contact; hence such craft require basing rather close to the operating area. As things stand today the S.U. does not have such bases near the potential Polaris operating areas except for the Barents Sea. The appearance in the Russian fleet of numerous small aircraft carriers would probably signal the development of such basing capability for the Norwegian Sea. In any event such sonars are intrinsically limited by the weight, size, and power capabilities of the platform and so cannot be expected to show great range improvement in the foreseeable future.

Explosive echo-ranging has not lived up fully to the expectations of a few years ago, and ranges are estimated between 1/2 and 5 n mi. Inasmuch as an explosive source denies the use of some valuable signal processing schemes in the receiver, this is perhaps not surprising.

With a submarine platform, ranges vary from 1 to 10 n mi, dependent upon whether the tracker is noisy or quiet and whether the target is in the layer or below it. However, the submarine can dive in and out of the thermal structure as his target does; if nuclear, it can maneuver and speed up so as to remain on the tail of the target. To do these things the pursuing submarine must use active sonar, and so is vulnerable to attack himself; but at least he cannot so readily be shaken off the trail. Except for the fact that these values pertain to deep water only, these estimates are probably the most conservative of any given in the NRC report.

On the whole the estimates presented are more relevant to the "classic" anti-submarine war in defense of overseas transport than to defense against Polaris. Two factors particularly lead to this comment: the choice of water depth and sonar conditions, and the presentation of 50 per cent probability ranges.

The contemplated use of Polaris undoubtedly involves operation in the North Sea, along the Norwegian Coast, and possibly in the Barents Sea. All these waters are shallower (mostly about 100 fathoms rather than 2500 fathoms), and the temperature structure is probably poorer than that assumed in the NRC report. The NRC estimates for long ranges by reconvergence or by deep-water bottom bounce are inapplicable in shallow water. Even the estimates of ranges by near-surface paths are on the optimistic side in these shallow waters because of temperature structure and bottom reverberation.

Fifty per cent probability detection ranges are useful, but they are perhaps more indicative of the operational problem in a protracted war of attrition than in a sudden-death, all-out strategic nuclear war. The 50 per cent probability ranges should be supplemented by 90 per cent probability ranges, because such high values more nearly characterize the problem faced by the defenders. Because of temperature and bottom conditions it is not uncommon to encounter 50 per cent probability ranges of one or two kiloyards and 90 per cent probability ranges of zero yards. That is, in many shallow water areas the defending forces, especially surface ships and shallow dunked sonars, may never have 90 per cent probability of detection because of temperature structure and bottom conditions.

The NRC report data also tacitly assume that the submarine fails to execute some of the evasive maneuvers which a Polaris nuclear boat could and probably would use. Aside from countermeasures, the boat can turn tail aspect on his pursuer, thereby reducing his echo some four or more db below the value assumed here and knocking the bottom out of 90 per cent ranges for many equipments. Further, the boat can reduce speed to very few knots, thereby nearly eliminating the doppler differential whereby the ASW vessel seeks to sort him out from the reverberation. In shallow seas up to perhaps 200 fathoms the boat can simply lie on the bottom. To discriminate the boat from other objects on the bottom ther becomes very difficult; if the bottom is at all rough and rocky the boat blends in, and only a high-resolution map of the bottom can disclose the boat by its shape. Finally, if the defender is not well equipped with low-frequency passive sonar in the combat area, a nuclear submarine can, if he chooses, simply run away from surface ASW forces. These latter vessels cannot make better than about 15 knots without sacrificing detection range seriously. The nuclear boat can easily afford to go faster if he is reasonably sure he will not be tracked on passive gear.

Capabilities of U.S. Passive Sonar

In recent years the great hope for the ASW problem has been passive sonar: that is, low-frequency listening equipment in deep water to hear the noise radiated by submarines. By using long lines of rather simple receiving units it is possible to obtain considerable directivity even at low frequencies (e.g., 100 cps). The numerous receivers are strung along a multi-conductor cable, so that each output is brought separately to the beach. There phasing networks are used to make steerable beams or groups of fixed beams from a single array of hydrophones. Bearing accuracy of 2 degrees at wavelengths of 50 ft is typical of the performance for existing gear. By triangulation two such arrays can now yield a position fix with typical accuracy of about 4 miles radius; this is good enough for surface active sonar to finish the job with a modest amount of search.

By using low frequency, such shore-based deep listening arrays can achieve detection and tracking at ranges of hundreds of miles because of low attenuation and duct propagation in the deep sound channel. It is important to observe that it is only in deep water that such long ranges can be achieved. In shallower waters bottom absorption and multiple scattering reduce the range drastically.

Much the same techniques which are used in deep-water bottom-mounted arrays can be used in shallow water and in smaller arrays carried aboard ships, notably submarines. In shallow water, as noted above, ranges are perforce less under otherwise similar conditions. Ranges in ship-mounted gear are also less, partly because of interference from own-ship noise, but also because the array is smaller. Much effort is now devoted to quieting the new attack submarines so as to improve their listening ranges; however, it should always be possible for bigger bottom-mounted arrays to give appreciably longer range.

The listening arrays which can yield such long ranges against snorkeling submarines can yield comparably great ranges against noisy nuclear boats (e.g., Nautilus). Furthermore the ranges are quite long against high-speed boats even if they are otherwise fairly quiet. But against <u>slow</u> boats and against slow, quiet nuclear boats the passive detection ranges fall to values comparable to active sonar range or even less.

For the foregoing reason the vulnerability of the Polaris weapon system will be critically dependent upon the ability of the submarine to be quiet. This is probably the most critical factor in the whole problem of Polaris vulnerability, because the S.U. will not find it difficult to track noisy boats. On the other hand they will find it very difficult to detect quiet boats.

For a submarine platform at slow speeds, detection ranges against a snorkeling or cavitating target are estimated to be as much as 90 n mi for certain equipment, while an increase in speed of the platform to about 13 knots decreases the detection range by a factor of 10 and more. If the target is quiet at low speed then detection ranges are low--of the order of 5 n mi or less.

For shore-based deep arrays, detection ranges vary from values of 200 to 1000 n mi against a high-speed noisy nuclear boat such as the Nautilus to (?) to 5 n mi against a quiet battery boat or possibly a quiet nuclear boat at low speed.

Shallow-water arrays are estimated to give detection ranges of 20 to 50 n mi against snorkeling boats and 1 to 10 n mi against quiet boats.

Sonar Countermeasures

Although all sorts of active and passive sonar countermeasures were employed during WW II, it is only rarely that one finds countermeasures brought into a discussion of the potentialities of a sonar weapon system. In this respect the whole field of sonar is less advanced than radar, where a universal consciousness of countermeasures exists. Not that the techniques and devices for sonar countermeasures are lacking; rather the absence of this phase of the problem from sonar system analyses sometimes lends an air of unrealistic optimism to forecasts of capability against a skilled and determined enemy. Polaris submarines could derive much protection from well used countermeasures; they should be incorporated in the weapon system, and they should be accounted for in an estimate of vulnerability.

There are several techniques and devices which can help a submarine avoid detection entirely. Probably the most important of all is simply to be quiet. However, even the quietest boat faces some small chance of being found more or less by accident. One way to diminish this chance markedly is by painting the submarine with a sound-absorbing coating. During WW II the German Navy developed absorbing coatings; there is some controversy over their actual effectiveness and over the absorption mechanism in the material, but there seems little doubt that some absorption was obtained. In this connection it must be emphasized that as little as 3-db echo reduction can have drastic effects on detection probability, especially in shallow water where reverberation limits the detection range severely.

The old NAC and NAE beacons and their various kin are sonar noisemakers which a submarine can eject to jam enemy sonar. They are the counterparts of radar noise and sweep jammers. They work to some degree, and help a submarine to break off sonar contact once his presence in the area is known. To work against the new high-power, low-frequency sonars, bigger and more costly devices would be needed. Such a development is certainly possible; its worth would require careful system analysis. Presumably if such noisemakers have a place in the scheme of things it must be to break off contact by a tailing S.U. boat during peacetime.

A different family of noisemakers could be employed by U.S. boats to jam Soviet fixed sonar installations (such as bottom-mounted or buoy-mounted active or passive systems). Fairly cheap battery-operated noisemakers could be planted close to such arrays. It would probably cost the S.U. more to disable the noisemakers (without damage to their own systems) than it would for us to place them by air drop or by ejection from the torpedo tubes. Such noisemakers, with a useful life of a few weeks, might be laid in times of international tension as part of a low-level alert.

Homing torpedos, both active and passive, are in use. These can, of course, be used as defensive ordnance with considerable effectiveness. A submarine is not helpless against attacking ships, because the submarine can usually detect and track the surface ship long before it is itself detected. However, homing torpedos can also be used against bottom-mounted active sonars. The exchange ratio can be quite attractive, and it should be possible to deter the S.U. from emplacing sizable sonars in international waters.

Dragging or cutting the cables to fixed installations is not very difficult, especially if the location to drag is reasonably well known by virtue of watching the installation go in.

Underwater demolition team (UDT) swimmers can be launched from and recovered by a submarine. If equipped with underwater sleds, such men are quite mobile. In shallow waters they can explore the bottom to find hostile installations. They can cut cables or disable equipment. More subtly, they can move equipment from place to place or rotate it so it gives false bearings. They can cover it with sheets of foam rubber so as to put it out of business. UDT men can also inspect their own submarine to discover limpet bombs; this would seem to be a necessary defensive move, especially in the Mediterranean where limpets might be very attractive to the S.U.

If Polaris submarines plan to lie for appreciable periods in shallow waters off the Norwegian coast, they might help themselves by ejecting from their tubes simple battery-operated echo-repeaters. A bevy of such devices strewn about in shallow waters would give the S.U. forces a collection of false submarine targets to investigate (and perhaps attack).

It should not be unduly difficult to construct a battery-operated device which emits a line spectrum roughly resembling a LOFAR signature of a diesel engine. A series of sharp low-repetition rate pulses is needed. These could be used to deceive or to saturate long-range, low-frequency passive sonar.

Friendly surface shipping can be sailed around in the vicinity of low-frequency passive arrays. These ships can be made to put out sizable amounts of noise (a freighter running light with a bent propeller shaft is especially good at this) and so to render the passive array nearly useless. Of course, anchoring the freighter, doing a fair amount of hull riveting, and then dragging the anchor across the array can be helpful additions to such a scenario.

Surface shipping, even hostile vessels, canbe used to penetrate a barrier. A submarine can run under a surface ship or hang on in his wake with only moderate difficulty, and it is very difficult for search forces to find him there. Unless S.U. destroyers are equipped with exceptionally good sonar, a daring submariner could even tag along under a destroyer returning to port. At night during peacetime a submarine can run on the surface close to merchant shipping with very slight risk of detection. In that position radar is not likely to find him.

At night a submarine can run close to a shore on the surface with small risk of detection, especially if he exercises modest caution to detect unfriendly radar and sonar early enough to dive and lie on the bottom.

In nearly all conditions a submarine is safest at shallow submergence, and he is much safer in shallow coastal waters among islands. This tactic, with quieting, with an echo-reducing coating, and with a few countermeasure devices, should make a nuclear submarine nearly undetectable.

Further discussion of sonar capabilities, sonar propagation paths, and ASW is given in Appendix C.

Missile Detection and Counter-Submarine Attack

If, as seems likely, Polaris submarines will be extremely difficult to locate in peacetime by standard anti-submarine techniques, there remains the possibility that the Russians might attempt to locate submarines by observing the launch and flight of their missiles using patrol aircraft. The capability of this detection method will depend critically upon the speed with which the missile load can be fired, and the Navy hopes that quite short firing periods will be possible. Currently, 1-min intervals between firings are expected, or 15 min in total, and possibly this time can be reduced. However, especially in the early years of operation, system difficulties and malfunctions may seriously slow down this rate of fire. And the longer the time needed for launch, the more opportunity is offered the defense to locate and counterattack before the launch of the entire missile load.

During powered flight, the missiles will probably be easy to detect by infrared techniques from aircraft above clouds at distances out to hundreds of miles. By using combinations of infrared detection and azimuth determination, and radar ranging on the missile, the location of the submarine could probably be determined within 2 n mi or less with high probability on the basis of observing one missile firing. Observation of succeeding missiles would yield still more precise location information. Since the submarine must be very nearly dead in the water while launching, its position will change little between firings. At 5 knots the position would change 0.4 n mi in 5 min.

One possible anti-submarine weapon to use together with a detection system of the type just discussed might be a 3000- to 4000-lb ASM with a 1-MT warhead. Each patrol aircraft could carry at least two. The time of flight to impact at a range of 100 mi would be about 3.5 min with a delivery accuracy of about a mile. At 100 n mi radar ranging could have a accuracy of less than 1000 ft, and 1 n mi in azimuth is 0.6° which is easy to obtain. The equipment aboard the patrol aircraft would not be simple, but such equipment has been designed. It would include a doppler-inertial navigation system and a fire control computer. The area coverage by such a system would be critically limited by ASM performance and the Polaris firing rate. A system designed around a 100-n mi ASM could expect to get an ASM on target within 5 min of detection, and would require 50 patrol aircraft on station per million square miles.

If the operating areas for Polaris were limited, the force required by the Russians to operate an airborne patrol of this type would not be large. It would not have to be a continuous airborne patrol like our over-water DEW operation, but might operate often enough not to be mistaken as a possible signal of attack. However, the back-up ratio would have to be sufficient to operate effectively for at least weeks. An area 1000 by 300 miles in extent in the Norwegian Sea, one of the more attractive areas for our submarines to operate, could be quite well covered by 15 patrol aircraft on station.* However, if the operating area were as large as 5 million square miles, which would be the case with submarines and tenders

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*The Norwegian Sea, which is important for our submarines, is one of the most accessible areas to the Soviet. Also of great importance is the Aegean Sea and the Eastern Mediterranean. Soviet patrol capabilities there are limited now by the need to over-fly a NATO country, but bases in Albania could be built up, and possibly also in the United Arab Republic.

in both the Atlantic and the Pacific, 250 aircraft would be required on station; and with a backup of at least 3 to 1 this would require a force of 1000 aircraft. Such a system would be expensive.

If the Soviets chose to patrol certain areas, there are alternatives open to counter the threat. One is for the submarines to launch close in to shore, especially a steeply shelving shore, e.g., inside a Norwegian fiord or near a precipitous Aegean island. This tactic could make much more difficult the attacker's precise location, especially by radar; while Soviet counter-submarine warheads falling on land would not damage a submerged submarine.

Submarine Physical Vulnerability

[redacted] Better estimates are presently being prepared and will be submitted at a later date.

DOE b(3)

Sub Depth (ft)	Bomb Depth (ft)	Damage Radius (n mi)	Equivalent Hardness in Air (psi)
50	[redacted]	1.6	10
	[redacted]	2.9	4
100	[redacted]	2.5	5
	[redacted]	3.2	4
500	[redacted]	3.6	3
	[redacted]	3.8	3

DOE b(3)

Other possibilities open to the Soviet Union for countering the Polaris system are discussed in Appendix C. However, several points are fairly clear:

1. There are actions that the Soviet Union can take in countering the Polaris threat by attempting to kill submarines, and a serious effort

on the enemy's part to do this should be expected. If the threat of possible Soviet actions is ignored, the capability of the force could be reduced. Especially in the early '60's, when the force is small and operating areas are limited due to missile range, the enemy will have an opportunity to detect and attack the force if he develops the capability ahead of time.

2. There are, however, a wide range of alternatives which appear, at this writing, to hold promise of making extremely difficult the job of countering the Polaris force. Therefore, if sensible tactics are used and if the boats are quiet the Polaris system would not be expected to suffer much attrition before the launch of its missiles.

B. TARGET DAMAGE CRITERIA

The question of what sort of damage capability can be considered a deterrent is unresolved. Intuitively it has always seemed that the expectation or even the mere possibility of massive retaliation must deter a potential aggressor over a larger range of circumstances than would that of some lesser retaliation. However, there has been no definitive analysis of the relation between damage capability and deterrence, and in its absence there is a tendency to gravitate toward some minimal damage capability, since this results in lower system costs.

Estimates, or just pure guesses, for the damage capability necessary to deter vary upward from 25 per cent structural collapse of about one hundred cities and about ten million dead.

Although this lower level of destruction would be calamitous, and the threat of it would inhibit the Russian decisionmakers in some degree, calamities of greater magnitude have already been survived by the Russians. Ten million fatalities would deprive the S.U. of no more than 5 per cent of its total population or 12 per cent of its urban inhabitants. During WW II the German forces at the time of their farthest advance occupied territory which today contains 30 of Russia's 76 largest cities and nearly 40 per cent of its total population. Further, the Soviet population loss resulting from WW II amounted to something like 20 million — 10 per cent of its 1956 population. Evidently even such losses are not disastrous in any final sense, for the Russians were able to continue a major military action, win the war, and subsequently recover. It may be conjectured that a retaliatory force which falls substantially short of being able to threaten damage as great as that from which a recovery has already been made might on some future occasion also fall short of being an adequate deterrent.

At least there is a reasonable doubt that the threat of lower levels of damage is sufficient. The importance of this consideration lies in the increased number of weapons which must be delivered if the desired level of damage is raised. The achievement of 50 per cent fatalities among the inhabitants of large Soviet cities requires about twice as many Polaris-type weapons as would be required if 25 per cent fatalities would suffice. A further doubling takes place if the damage criterion is raised to 75 per cent.

[redacted]

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The above discussion does not consider evacuation, fallout, or fire storms, all of which may be significant.

Possible Effect of a Civil Defense Program on Weapon Requirements

But even now, the full measure of the job that Polaris, or some other delivery system, may face has not been considered. There have been many reports of Soviet progress in implementing a civil defense plan. While those reports are for the most part vague, and while there may be doubt that the measures being taken are of much consequence, present information is none the less consistent with the notion that population shelters resistant to perhaps as much as 50 psi may be generally available in the 1960's. Such hardening, or urban evacuation, or some combination of the two could vastly increase the difficulty of achieving a chosen damage objective.

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It is, of course, not obvious that we should be interested in maintaining our ability to damage population at some preconceived level in the face of measures such as those mentioned. If Soviet leaders elected to protect nothing but urban populations, we might properly be content with the ability to achieve some suitable level of damage to the physical resources represented by their large cities. But it is reasonable to expect that Soviet efforts at civil defense will not neglect non-human resources, and that the difficulty of destroying them will be comparable to that of killing people. In fact, our interest in fatalities arises not out of any conviction that fatalities ought to be a prime objective, but from other sources — among them the belief that a weapon system's calculated performance against population will usually be a fair indicator of its suitability for the disruption mission however defined.*

The Disruption Force and Other National Purposes

The fundamental concern of this discussion has so far been with the deterrence of extreme actions, notably with attacks directly against the United States. However, there is also interest in deterring other undesirable actions and in general with influencing the behavior of other nations. It is particularly in this latter connection that certain asymmetries between the potential combatants are interesting.

To illustrate, suppose that a modest force of low-payload vehicles were procured with the object of achieving a capability to disrupt the Soviet economy by "dusting off" several-score cities; suppose, too, that the S.U. simultaneously procured a much larger force of well-protected high-payload missiles, so that they achieved the capability of obliterating the American economy. It may be conjectured that in this situation American bargaining power would be disastrously impaired. Under no provocation would it be rational to resort to war with the S.U. — the U.S. would be counted on not to initiate war. But the S.U. would feel less constrained, presumably significantly so, and would therefore enjoy all the better of any bargaining. Evidently our damage criteria should not be established without regard for how well it matches that of the S.U. The kind of force that

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*This is not necessarily so. If, for example, the Soviet Union were to harden the industrial sectors of its cities and evacuate its urban populations prior to attack, an optimal attack might be one which aimed at industrial sectors only. In such a case, damage calculations made in terms of population would be misleading to the point of absurdity.

is procured should not be chosen without regard for its effect on our bargaining position.

Neither should a strategic force be procured without regard for the possibility that some of its elements will be used otherwise than as originally intended in the event that deterrence fails. A single strategic vehicle is not customarily relied on to serve us in any time period, and it is quite possible that by the time the weapons need to be used our opinions will have changed as to which weapon system ought to be used against each of the different sets of targets. For this and other reasons, Polaris, like all comparable weapon systems, should be evaluated not merely with respect to deterrence targets, but also with respect to its possible alternative employments: for counterforce targets, retardation targets, pin-down, and in conjunction with other kinds of delivery systems.

In sum, Polaris is an attractive system because it seems to promise a a useful damage capability against soft known military targets and deterrence targets, and combines this capability with a basing principle which offers unique advantages. Those are the first-order considerations.

Compared with its prospective contemporaries, a Polaris missile may prove somewhat deficient over target. Then the more difficult jobs would require several times as many Polaris vehicles as Atlases or other relatively high-payload vehicles. But this disadvantage seems to be compensated for in no small degree by lesser base vulnerability, non-collateral damage, and a mixed strategic force. The advantages of submarine basing may be large enough so that too much concern should not be taken with deficiencies in second-order considerations such as precise target coverages.

Curves for weapon effectiveness are included in Appendix C.

C. NON-COLLATERAL DAMAGE

Until quite recently strategic forces have been located on bases in the U.S. without taking into account either how the vulnerability of these bases to enemy attack might be affected by their location or the extent of civilian casualties that might result from an attack on these bases. Almost all SAC bases are at long-existing airfields, which were built up during a period when they were expected to be used only for training purposes. The fighting would be done overseas.

Now, however, these bases would be the principal targets of a Soviet attack. And if the SAC bases were attacked heavily, the damage to our civilian population, especially from fallout, could be severe. Moreover, since many of the air defenses protecting our cities would have to be penetrated in order for Soviet bombers to reach our bases, the extra cost of delivering a bomb on a city near a SAC base or en route would be small. If it were the case that U.S. cities would in any event be the direct object of attack, then there would be less concern over the collocation of SAC and cities. However, there are many situations in which the Russians would very likely avoid attack on U.S. cities. This would be the case if they desired to destroy U.S. military power but preserve the U.S. economy for exploitation, or if their weapons were limited to what they thought were necessary to destroy our strategic forces.

The Polaris system offers the possibility of separating by a very great distance our retaliatory power from our cities. This is a real advantage of the system. However, separation could be obtained within the limits of the U.S. if our strategic forces were located in the Great Plains region; and this central location is, in fact, planned for our ICBM force.

An attack against these bases would result in very small civilian casualties in heavily populated areas of the country.

D. COMPARISON OF SEA-BASED AND LAND-BASED IRBM'S

This section considers some of the relative merits of sea-based as against land-based missiles of comparable characteristics in overseas locations. More specifically, it attempts to examine the effects of land-basing and sea-basing upon the efficiency and reliability of the weapon system, and some of the possible political consequences of these alternative basing arrangements.

The United States acquired the majority of its overseas base rights under some rather special circumstances. The Korean War was still in progress, the manned bomber was <u>the</u> weapon of strategic warfare, and the Soviet Union had not yet been credited with a significant nuclear capability. These circumstances resulted in a period of several years during which the United States could exercise, and plan on the wartime use of, its overseas base system without significant restrictions by the host countries. Now, however, conditions have changed. If the Anglo-American and French-American negotiations with respect to the IRBM mean anything for the future, they suggest that current and future basing agreements, especially if they pertain to missiles, will involve a much greater degree of direct control exercised by the host country over the weapon system than has been our experience with the manned bomber. It is true, of course, that the United States is required to consult with and obtain the concurrence of host country governments prior to the use of overseas bases for a wartime mission. But this procedure is not nearly so exacting for the manned bomber as it is for a missile which has host country personnel actually manning its launch control consoles. In the latter case, political consultation and agreement will not only have to occur prior to missile launching; actual missile launching without such agreement may prove impossible, except conceivably for the host country.

What these possibilities suggest is that overseas land-based missiles are likely to have built into them significant political delay times in addition to their normal countdown times. Beyond that, it is easy to conceive of circumstances in which their use might be denied to the United States, or, less easily, contingencies in which the host country might fire the weapons without American concurrence. In short, overseas land-basing of missiles might appear to:

a. Lengthen the reaction time of the missile and thereby increase its vulnerability.

b. Introduce a considerable element of uncertainty as to the availability of the missile to the United States.

c. Make possible the launching of the missile without the consent of the United States.

Sea-based missiles, by contrast, would not appear to suffer from these liabilities to the same extent. The system could be kept under full American control; decision times presumably would be shorter; and the United States could determine the circumstances of the weapon's use. Even should the United States desire to have supporting tenders at such places as Scapa Flow, Rota, or Suda Bay available for these systems, its bargaining position with respect to their command and control should be better than in the case of land-based missiles, since the option to move to other locations would always be available in the event of either unacceptable conditions or changed attitudes on the part of a host country. Or perhaps of lesser importance, sea basing of the missile would also provide greater immunity from sabotage and perhaps somewhat increased warhead security.

Overseas land-based missiles run the risk of engendering certain adverse political effects to a greater degree than is likely to be the case with sea-based systems. Land-based systems, if widely dispersed, will need real estate beyond current manned aircraft requirements. If not actually accident-prone, they may nevertheless create a fear of accidents, especially if they should be mobile. They will involve the presence of some American personnel and thus continue the problem of troop-community relations. Because of their presence, these missiles may well increase the fear of the host country that it will become the target of a thermonuclear attack. And because they can be seen, they will serve as constant reminders both of the "balance of terror" and of the host country's role in it. Precisely how these immediate effects would manifest themselves in the internal and external political behavior of the host country is most uncertain. But it is difficult to believe that they would not result in added hostility to the United States and its policies, with the further effect of increasingly stringent conditions concerning the use of the weapons.

Sea-based missiles do not raise real estate problems. Accidents that occur to them are likely to happen at sea, since the submarines will be away from their tenders 80 per cent of the time. They do not add significantly to the problem of troop-community relationships. As targets of enemy attack they do not represent the same hazard to populated areas that land-based missiles do. And because for the most part, they will be out of sight, so they may be out of mind. Far less stigma, fear, and political agitation are likely to be associated with sea-based missiles by friendly or uncommitted nations, as compared with land-based missiles of a similar type.

Although the sea-based missile may seem preferable to the overseas land-based missile in terms of the political constraints and sensitivities that are generally operative abroad, two cautionary points may be worth making. First, there may be overseas areas outside the European theater on which missiles may be based in either a hard or mobile configuration without suffering from the political defects that have been discussed above. Offhand, the prospect does not appear too promising from the standpoint of ensuring both American control and political reliability over extended periods of time, but investigation of the attitudes and receptivity of particular countries might indicate otherwise.

Secondly, to suggest, however tentatively, that sea-based missiles may be preferable to overseas land-based missiles according to the political criteria used here, is definitely not to recommend the surrender by the United States of its overseas base rights. These bases promise to figure very importantly in American military and political strategy for a long time to come.

Appendix A

GUIDANCE

In the velocity-to-be-gained guidance scheme for Polaris, an airborne digital computer solves a set of guidance equations based on an inertial coordinate system where x, y are in the vertical thrust plane at 45 deg to the local gravity vector, and z is normal to the x-y plane.

The integrals of the thrust and lift accelerations are digital inputs into the digital computer from the integrating accelerometers in the inertial measurement unit. The initial velocity conditions are set in by the sub-based fire control system. Thrust is cut off when V_{g_x} (whose direction is approximately along the thrust vector) attains essentially a zero value. For steering, V_{g_y} and V_{g_z} are driven to zero by proper control of the missile's thrust vector.

There are eight preselected targets for the 16 missiles on board the sub. For these eight target points and for launch points in the centers of 20 x 20 n mi grids, precomputed inputs to the guidance equations and the azimuth direction of the x-y plane are stored on cards. The fire control computer interpolates these values to obtain the proper settings for the exact launch point. In this calculation the velocity of the sub is taken into account in determining the initial velocity inputs. The basic velocity information is obtained from the SINS system. It is presently planned to launch missiles with essentially no submarine velocity.

INERTIAL MEASUREMENT UNIT

The major elements of the Polaris inertial measurement unit are a conventional outside-in gimbal system, three single-degree-of-freedom floated pendulous integrating gyros for integrating accelerometers, resolvers, and associated electronics. There will be no shockmounting of the unit. The order of gimballing from inside out is yaw, roll, and pitch with angular freedoms of ± 360 ± 30, and + 30 to − 90 deg, respectively. Resolvers are required between the inner and middle and between the middle and outer gimbals for both platform stabilization and missile control system angular reference. The input axes of the three accelerometers are oriented along the x, y, z, coordinate axes. The gyros are oriented so that the input axis of the pitch gyros is along the z axis. The input axes of the roll and yaw gyros are in the x-y plane but not along the x and y axes. Instead, the yaw axis is along the local gravity vector and the roll axis is normal to it. This orientation does not minimize the effects of drift due to mass unbalance in the yaw gyro. However, drift is not a dominating factor in IRBM accuracy. A constant one-degree-per-hour drift rate results in a one-mile miss at 1500 miles.

ERECTION AND ALIGNMENT

The platform is erected to the local gravity by nulling the sum of the outputs of the x and y accelerometers plus a correction for the velocity of the submarine obtained from the fire control computer. If the scale factors of the x and y accelerometers were the same, this would simplify the operation. One of the specifications on the accelerometers is that their scale factor be within 0.01 per cent of standard. Since at present it is not known how the scale factor of pendulous integrating gyros fluctuates with time, this specification seems difficult to meet. Furthermore, since the accelerometers are being used for erection, their scale factor cannot be easily checked and corrections put into the airborne computer to compensate for any such shifts.

The azimuth reference for alignment is to be supplied by the SINS system made up of three separate SINS units. It is assumed that there is negligible flexing of the submarine structure. Since the mirror on the platform is attached to the outer gimbal and not to the yaw gimbal, back-to-back resolvers are used to drive the platform to the proper azimuth orientation. The electrical and mechanical null alignment of these resolvers must be kept within 20 sec of arc.

PLATFORM STABILIZATION

The stabilization loops have a band pass of approximately 20 cycles per sec. The maximum torque output of the torque motors for the pitch, roll, and yaw gimbals, respectively, are 1.2 ft-lb, 2.4 ft-lb, and 2.4 ft-lb. These values are quite low and require that the uncertainty torques and the mass unbalance of the gimbals be kept quite small. Otherwise, a large portion of the available torque will be used up, and very little torque would be left to isolate the platform from missile motion. Since no production platforms have been assembled, no tests have been made to determine the uncertainty torques and the effects of mass unbalance under high g's. Centrifuge tests of a complete platform must be made in order to determine these effects.

GYROS AND ACCELEROMETERS

The gyros are single-degree-of-freedom, floated integrating gyros made of beryllium. They have been designed by MIT and designated by them as the 25 IRIG. The integrating accelerometers are floated pendulous integrating gyros based on the 25 IRIG and designated by MIT as the 25 PIG. They have a digital output wheel. Both the gyros and accelerometers are being built by the four previously mentioned companies directly from MIT drawings. So far there are no test data available from production units to indicate their performance. To insure a quick reaction time, it is planned to supply the proper amplitude of 60-cycle power to the gyros and accelerometers, so that the spin motors will operate at a low speed and yet produce the same temperature distribution as when the rotors are operating at airborne speed. This concept has not been fully tested to indicate that there will not be a temperature transient when the spin motors are switched to airborne frequency.

THRUST VECTOR CONTROL

The thrust vector is to be controlled by positioning jetevators in the rocket exhaust. The successful development of these jetevators is a major problem area, primarily because of high stiction levels encountered due to the elevated temperature condition. Jetevators have been used in the past, but not for the relatively long burning times of the Polaris motors, which are of the order of 60 sec per stage.

The angular information for the control system is obtained from the resolved gimbal angles of the inertial measurement unit. The angular rate information is obtained from body-mounted rate gyros.

PITCH CHANNEL

Instead of using a pitch angle program to attempt to obtain a zero lift trajectory during the first stage, the appropriate trajectory is programmed by the use of an equation employing velocity information during the first stage for a pitch rate command signal. The values of the constants in the equation determine the shape of this part of the trajectory, which is the same for all ranges. The pitch rate command is an output of the digital computer. This method of producing the approximate zero-lift trajectory is superior on two accounts to programming the pitch rate directly. It reduces the angle attack of the missile in the presence of wind shears and non-standard thrust conditions, and it materially reduces the velocity error at staging due to non-standard thrust conditions and wind.

After staging, the pitch steering is changed to the cross product steering using the velocity-to-be-gained information. This method of steering is excellent, since time variable gains are obtained automatically which properly tighten up the velocity control loop as cutoff is approached. This method of control is similar to the one used on the Thor.

YAW CHANNEL

Since there is no programming to be done in the yaw channel, gross product steering is used in both the first and second stages.

ROLL CHANNEL

Roll control is obtained by merely nulling the appropriate resolved gimbal angle.

STAGING

It appears that stability at staging may be a serious problem. At staging, the second stage is aerodynamically unstable; until thrust comes up there is no way of controlling the second stage. Fins or a skirt could increase the stability, but this would add extra weight and drag. Another problem is the possible collisor of the first stage with the second stage during the time the first stage thrust is decaying and the second-stage thrust is coming up.

POSSIBLE PROBLEM AREAS

1. Reliability and maintainability of the very complex fire control system.

2. Ability to get information for correcting the SINS system so that correct azimuth and position information is available for inputs to airborne guidance system.

3. Jetevator development.

4. Solution to the second-stage stability problem and to the problem of possible collison of the first and second stages at staging, without the addition of too much weight and drag to the missile.

5. Possibly too low maximum torque available for torquing the gimbals. This is dependent upon the uncertainty torque levels and mass unbalance of the gimbals in the production platforms.

6. Difficulty of launching in rough seas.

7. Scale factor shifts in the accelerometers.

8. Problems in production of the guidance system.

Appendix B

COSTS

COST ANALYSIS*

Installations

Base Facilities: One Missile Assembly Facility (MAF) for the initial force of nine submarines and one tender is contemplated. This MAF is planned to be built at the Navy Ammunition Depot at Charleston, South Carolina, by October 1960 and is to have the following capability:

Assembly rate . . .	8 missiles per week
Outloading rate . .	16 missiles per week
Storage capacity. .	90 missiles

Construction costs are estimated at $10 million with an additional $7 million for equipment.

Training Facilities: A crew team training facility will be erected at New London, Connecticut, to provide crew team training for the double crew per submarine program. The breakdown costs are as follows:

Building	$200,000
Equipment and Air Conditioning	153,000
FBM Team Trainer	1,600,000
	$1,953,000

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*See Table 1, page 23.

These are shown in Table 1 as $0.4 million for training facilities and $1.6 million under training equipment.

There is a possibility that another, similar crew team training facility might be constructed at Charleston, depending upon the availability of funds and the magnitude of the program. However, the training capacity at New London represented by these costs and those under training equipment are sufficient to train two crews through the first eleven submarines, or a total of twenty-two crews.

Base Maintenance: The $3.4 million is a Navy figure, and it is not known precisely what is included. Using Cost Analysis Department methods, the maintenance of the incremental facilities should be around half a million dollars per year.

Equipment

Submarines: The Navy gives the cost of nine submarines as $900 million. This corresponds with a previous estimate of $109 million for the first submarine and $100 million for each subsequent submarine. It is felt that, over time, these costs per submarine might be significantly decreased.

The funding summary as presented in FBM Program-Polaris lists expenses by categories for the thirteen submarines which they consider. The average estimated cost for one submarine, obtained by adding together each fiscal year's funds allotted for each category and dividing by thirteen, is:

Item	Millions of Dollars
Ship Construction	$ 78.72
Launch and Handling	6.36
Fire Control.	7.46
Navigation.	8.46
Missile Checkout.	2.49
Test Instrumentation. . . .	.31
Weapon System Trailer . . .	.44
Total . . .	$104.39

Under the category of ship construction are included the following: nuclear powerplant, Bureau of Ships Equipment procurement, basic construction, equipment installation, conventional submarine ordnance and electronics equipment. [redacted]

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Estimates of expected maintenance and replacement of launch and handling, fire control, navigation, missile checkout, test instrumentation, and weapon system trainer components aboard the submarine were not available. Assuming a complexity of equipment comparable to that of equipment used in the missile subsystems, for which replacement at the rate of 20 per cent per year is current Navy thinking, an annual charge of $4.8 million per submarine or $43.2 million for the system was made.

Tender: The tender cost of $26 million applies to the modification of an existing ship. Construction of a new tender at a cost of $61 million is planned if the system grows and if funds are available.

The tender is a floating maintenance and repair facility for both the submarines and missiles, and is equipped with varying classes of machinery and electronic gear. The dollar cost of these items is hidden in the initial investment expenditures for the tender. To be realistic this equipment should be charged ordinary depreciation maintenance and replacement costs. Since the tender does service missiles, it is reasonable to expect that the equipment on board will contain missile checkout and test instrumentation gear. The cost of these items on board the submarine averages out to $2.8 million, and it is assumed that the tender will be similarly equipped. If this is considered to be equivalent to base equipment, annual charges of 18 per cent are usually applied. However, to be consistent, the 20 per cent factor used for submarine equipment was used. It is believed that the tender will also house refresher training equipment, but these costs have been included under the training equipment category.

The Navy source used to obtain annual operating charges lists about $200,000 per year for supplies and equipage. In Navy terminology supplies are consumable items and include electronic and machinery repair parts, soap, swabs, etc. Equipage includes more durable items such as special clothing, life jackets, typewriters, etc. It also includes sheet metal and repair items used by tenders to repair other vessels. This cost has been included under Services and Miscellaneous in order to avoid double counting.

Missiles: The cost obtained for the missiles was $1,339,750 each, including spares. The spares philosophy used was sufficient to replace the complete missile every five years, or 20 per cent. Deducting this amount the price of the missile alone becomes $1.07 million. It is believed that the cost of the missile represents production missiles and excludes those produced for development and testing, the warhead is also excluded.

A breakdown of missile component costs obtained from the Special Projects Office at a later date gives a maximum and minimum for the various components. The maximum represents current experience; the minimum represents what they think they can do with direct contracting and a better learning curve. None of these costs includes any allowance for spares, for checking equipment, or for containers.

The same cost was used for both limites of "Guidance," which is an uncertain item.

Subsystem	Cost (thousands of dollars)	
	Maximum	Minimum
Propulsion (60 per cent of cost in first stage, 40 per cent in second)	$250	$200
Re-Entry Body (less warhead)	32	20.5
Flight Control	43	16
Interstages (i.e. power supplies, wiring, separation devices, etc.)	177	80
Guidance	50	50
	$552	$366.5

Since the missile cost could not be resolved in the time available, the highest cost of $1.07 million was used in the interests of conservatism. The number of missiles for the system for which costs were given was 144, including spares. However, this does not include an amount sufficient for the tender load. Consequently, costs of an additional 16 missiles plus spares have been included in the estimate.

No additional information on the training firings of missile above that of one firing per year has been learned. Official Navy policy appears to be very conservative concerning the use of expensive ordnance for training. In view of this existing policy, three firings per submarine per year were assumed, in expectation that the policy will change as the system matures and is made comparable to other systems. However, this cost category could read $1.07 million per year if the existing training philosophy was rigidly adhered to.

Missile Containers: In order to keep the missile under sufficient environmental control to prevent any damage to the propellant grain during transport, containers are provided. Environmental temperature has been specified at 80°F ± 3°F. These containers are listed at $8,110,000. This amount is held sufficient to purchase enough containers for 144 missiles. Unfortunately, the specific number of containers represented by this figure was not available. A one-to-one ratio of missiles to containers is discounted, as the use of these entails recycling. Applying the spares figure of 20 per cent to the containers as annual replacement, we obtain $1.6 million, which was used to represent annual operating costs.

Base Equipment: The seven million dollars represented here is for the equipment in the Missile Assembly Facility building. Annual operating charges of 18 per cent have been applied against this figure, following CAD procedure in lieu of any figure furnished by the Navy.

Training Equipment: This category includes the following items according to data obtained:

Item	Cost (thousands of Dollars)
Attack Teacher	$2000
Diving Trainer	700
Refresher Training Equipment	500
Maintenance Training Aids	575
Operational Training Equipment	550
FBM Team Trainer	1600
Total	$5925

The FBM Team Trainer will be installed in the crew team training facility. There is some speculation as to whether three Attack Teachers will be bought. At this time the purchase of one is certain. It is not known whether the other two are held in abeyance due to lack of funds or due to uncertainty as to how many are needed to fulfill its mission. The Special Projects

Office claims that the training facilities and equipment delineated above are adequate to train two crews per submarine through the first eleven boats.

Annual operating costs were obtained by applying the 18 per cent factor as in the case of base equipment.

Training equipment for the Polaris system of 144 missiles from the costs available is about $6 million, which is considerably less than the costs under training for Air Force ballistic missile systems such as Atlas or Thor. Considering the factor-of-five difference in personnel and assuming a factor-of-two for complexity, these costs are partially resolved. However, caution is warranted for this category pending further information.

Stocks

Initial Spares and Readiness Reserve: Using a 90-day stock level, following factors used by the Navy for logistic support of Naval vessels and cost figures for nuclear submarines, $9.4 million was the initial investment estimate.

Initial Spares—Missiles: The figure of $43.2 million was obtained as described under Missile Equipment.

Initial Spares—Shipboard FBM System: Nine million dollars is the amount obtained for this item. No further information regarding the spares policy for this category was obtainable. However, this seems low considering the average cost of shipboard components computed above. If we include launch and handling, fire control, navigation, missile checkout, test instrumentation, and the weapon system trainer, the total average cost is $25.7 million per submarine. Nine million dollars is 3.9 per cent of the total cost of $231.3 million for the nine boats, which is a low spares factor.

Hence this figure is conjectural as it is not known exactly what is included.

Spares cost for the naval vessels are usually included in the vessel procurement costs. Hence, it is assumed that the initial spares for submarines and the tender, but not for the missile subsystem, are accounted for in the purchase price.

Transportation

The major item here is the cost of shipping Polaris missiles. Because of dangers involved due to cracking of the solid propellant grain and its requirement for environmental control, it is assumed that the missiles will be flown from the manufacturing facility in California to the Naval stations in the East.

A Lockheed report gives the weight breakdown and estimated costs of flying these missiles using C-133 aircraft. The costs for transporting 160 missiles comes to about $2.6 million. To this is added the costs of transporting ammunition and other supplies.

Annual operating expenses represent costs of flying 20 per cent spares as well as annual supplies replacement.

Personnel

Nuclear training will be taken by 40 enlisted men and three officers per crew or a total of 774 men for the nine-crew complement. Formal nuclear training takes six months plus six months training at the prototype. One-half of each crew goes to the shipyard at which their submarine is being constructed twelve months prior to commissioning. The other half of the crew reports to the shipyard nine months prior to commissioning.

The Navy costs figures for this training is $200 per man per week for 2236 man-weeks, or $8,049,600 for the 774 men. This is equivalent to a total of $10,400 per man. This figure includes all overhead associated with the course. It is notable that the cost of nuclear training for the FBM system is the same as the nuclear training for any other nuclear-powered ship.

<u>FBM Technical Training</u> for the initial system is given as $2,088,000. The breakdown shows 372 man-weeks for formal training plus 150 man-weeks for special weapons training.

The costs as given indicate that 522 men from the eighteen crews will take the course. This implies that of each crew 43 per cent take nuclear training and one half of the remainder (28.5 per cent) take this technical training. Thus it appears that 28.5 per cent of the crews do not take any special training at all.

It is important to realize that costs of submarine school training and specialist training are not included in this estimate, and therefore the amount shown understates total training costs.

<u>Replacement Training</u>: Using personnel numbers obtained previously and arbitrarily augmenting the crew proportionately to account for an additional workload imposed by three more submarines, now nine instead of six, the following estimate was arrived at:

Personnel for nine submarines and one tender

	Officers	Enlisted Men	Total
Squadron	6	6	12
Division	9	6	15
Support.	30	300	330
Submarines	180	1620	1800
Tender	30	852	882
Total	255	2784	3039

The turnover rate received from the Special Projects Office was 20 per cent per year. Charges were made for basic training at $3200 per man. Costs for nuclear and technical training were added under the assumption that the same percentage of the replacements would take these courses as in the regular force. Again, these costs are underestimated by costs of submarine training and other specialist courses.

Pay and Allowances: For submarine personnel, pay and allowances of $10,000 per officer and $5000 per enlisted man were used; for other personnel, $8000 per officer and $3400 per enlisted man were used.

Travel

The estimated obligations for FY 1958 under the account "movements-permanent change of station" as listed in Congressional Hearings for 1958 were used, excluding the travel of midshipmen, aviation cadets, and officer candidates.

Maintenance and Fuel

Submarines: Annual overhaul, restricted availability charges, and the cost of replacing the nuclear core are included in maintenance.* The cost for recoring is from $3 to $3.5 million every 30 months. Again the higher figure was used and prorated on an annual basis. Costs for maintenance and replacement of equipment pertinent to the Polaris are accounted for under the equipment category above.

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*The Navy defines restricted availability as including costs of labor and materials for nonscheduled repairs. Nonscheduled repairs are defined as repairs occurring between regularly scheduled overhauls to accomplish specific items of work such as routine minor repairs, repairs occasioned by collision, grounding, fire damage, etc.

Tender: This charge of $300,000 includes charges for overhaul, fuel, and restricted availability. Supplies and equipage, training ammunition, and medical costs have been included under "Services and Miscellaneous" to avoid double counting. If the items attributable to the tender as annual costs are accumulated under one heading, the total amounts to $1.2 million yearly.*

Services and Miscellaneous

Materials, supplies, and contractual services for administrative work, medical and food services, training ammunition, and miscellaneous POL fall in this group. Miscellaneous POL was computed at $100 per man per year, since it was not possible to distinguish utility services and fuel costs.

Command Administration

In estimating weapon systems costs it is desirable to include the pro-rata share of the intermediate and major commands which support the operational units. Lack of information prevented use of a similar method. Instead, Navy Appropriation Account titles were examined to determine those most applicable to the Polaris system. Items in these accounts relating to major equipment expenditure were excluded in an effort to isolate annual expenses and to prevent inclusion of inapplicable items. The Polaris system's proportional share of these expenditures was then estimated.

Interim Communications

In the Navy document Fleet Ballistic Missile Program Polaris, FY '59-60, estimated funding requirements are given for the program through FY 1960.

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*This was not done in this report, in order to make the various categories as comparable as possible to the usual RAND format.

Admittedly this program is for 13 submarines with growth potential through a total of 25.

Command Communications: Under the broad heading of Logistics and Operational Support, command communications in the amount of $92,414,000 are listed. This is, of course, an optimistic program, but some parts of this amount are necesssry for the mature Polaris system even if only bare essentials are provided. Listed under Communications and Facilities Equipment are:

a. Augmentation of VLF Maine Equipment and Facilities
b. Overseas Radio Receiving Equipment and Facilities
c. Communications Field Test
d. HP/HF Radio Station

Funds requested for the above are $46,176,000 for facilities and $6,450,000 for equipment through FY 1960. These items provide, in the Navy's own language, only an interim communications capability. Hence it appears reasonable to include this amount in the initial investment for the system. The sum of $39,074,000 for the development of new and existing VLF equipment, development of HARE transmitters and receivers, SESCO, Whisper programs, etc., may be included under Research and Development.

The implications are, however, that since the $52.6 million for communications provides only interim capability, expenditures for facilities and equipment will probably be required. Annual charges using factors of 5 per cent of facilities costs and 11 per cent of equipment costs have been made. This cost appears as an addition to the Table 1 rather than as part of the body of the table, because funds for this portion are not yet authorized, and conceivably may never see the light of day. The main parts of the table express the costs of the items which are most certain of expectation and, hopefully, the implications of costs on annual operations.

Research and Development

Available references list R and D expenses for the system as a whole as between one billion and 1.040 billion dollars. The precise content of this category is obscure; however, ideally it should include the various research and development programs pertaining to submarines, communications, navigation and guidance which are directly applicable to the Polaris program. This obviously would include expenditures for the Ocean Survey program, for the Compass Island and Observation Island experimental test ships, etc. Thus, in order to include costs incurred by the system, this category is also shown separately. As elsewhere, the highest estimate has been used in the interests of conservatism.

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Appendix C

UNDERSEA DETECTION AND ASW

This section considers the undersea warfare methods which the Soviet Union might employ in defense against the Polaris system. Throughout the field of undersea warfare, which is as broad and complex as the field of air warfare, underwater sound devices are the counterparts of radars in air warfare. However, underwater sound devices generally work very poorly as compared with their radar counterparts. This fact tends to give an intruding submarine a relatively greater advantage than, say, an intruding aircraft. Hence, the Soviet Union might use other undersea warfare devices such as mines or underwater swimmers to supplement the more conventional ASW forces.

GENERAL STATE OF THE SONAR ART

There is a widespread impression that the field of sonar is not really well developed; that with a "big push" real breakthroughs could be obtained; that heretofore the field has perhaps languished for want of real talent and real money. Certainly more money and more talent would be welcomed and would be useful, but the basic impression is entirely erroneous.

Sonar is at least as highly developed a field as radar. There are few techniques in the radar bag of tricks which have not been at least examined (usually tried out at sea) in sonar. Indeed, just because the sonar problems have been harder than the radar problems at any particular time in history, the sonar scientist has often been driven to try harder and to try fancier tricks. Hence, many of the newer techniques in radar are fairly old in sonar.

On the whole the two fields are about even as far as technical development and basic understanding of the physical processes are concerned. Radars are far more numerous, more varied, and more commonplace, but these differences do not indicate a corresponding difference in understanding. On the whole, pretty fair guesses can be made as to the evolutionary course which radar will take; at least plans for the future are made on this basis, and that is really the important point for this discussion. In sonar, at least among those who are not familiar with the subject, there is sometimes an inclination to think that matters are different. This view amounts to a denial of the present understanding of the field; it is an unwillingness to plan for the future on the basis of what is actually known; it is nearly a hope that a miraculous cure will dispel unpleasant reality. It is unwarranted.

Much is already known about sound in water, and there is no more basis to anticipate a big breakthrough in sonar than in radar. The main avenues along which sonar improvement can be expected have been clear for years and development is proceeding down them: higher radiated power, better radiation patterns, lower frequencies, bigger arrays, and improved signal processing. As with radar, more data are needed on long-range propagation, especially over-the-horizon effects and long-range clutter. However, one can make fair estimates of the improvements to be expected from a given effort. It is the ocean, not just the engineering skill, which sets the limits and the costs on performance.

In both radar and sonar the question is not really whether a major nation has the technical know-how to obtain a certain capability. It is instead whether the nation chooses to pay the price. Just as a sufficiently numerous assortment of radars could be used to track small low-flying aircraft anywhere in the U.S., so too a sufficiently numerous assortment of sonars could track a submarine anywhere in the ocean. The cost of such radar coverage is astronomical; so is the cost of such sonar coverage.

SONAR PROPERTIES OF THE OCEAN

Before considering the performance of specific sonar systems it is useful to outline some of the relevant characteristics of the ocean. In a general way these establish the "ground rules" with which the sonar designer is faced. Inasmuch as sonar almost never works as well as its radar counterpart, it is helpful to note some of the differences which lead to the disparity.

The velocity of sound in sea water is approximately 4800 ft/sec. The velocity is dependent upon both temperature and pressure, so this is only a rule of thumb. Sonar is at a disadvantage with respect to radar because of this slow information rate. The ratio of propagation velocities is about 200,000 whereas the ratio of typical vehicle speeds is generally about 100, so the disadvantage is real and is not compensated by slowing down the clock.

The attenuation of sound in sea water is quite severe except at very low frequencies. At 24 kc, which is a convenient frequency from the standpoint of wavelength (2.4 in.), the attenuation is about 5 db per kiloyard (one way). In radar, the attenuation in the medium is generally trivial even at long ranges, except for the water and oxygen absorption bands. To achieve an echoing range of 40,000 yd, which is modest for radar, a 24-kc sonar would have to overcome 400-db attenuation, which is fantastic. Fortunately for the sonar designer, this attenuation is quite frequency-dependent and is much more moderate at low frequencies; at 10 kc it is about 1 db/kiloyard, and at a few hundred cycles it is of the order of 0.05 db/kiloyard. These lower frequencies involve longer wavelengths and consequently large arrays, and not much work was done in low frequencies until after World War II.

At 24 kc, the "standard" U.S. frequency during World War II, the wavelength of sound in sea water is, as we have seen, about 2.4 in. Hence, such sonar is in many respects comparable to 4900-mc radar. One may compare the dimensions of the radar antenna with those of the sonar transducer directly; even beamwidths of only a few degrees require radiators less than 6 ft in diameter. However, attenuation precludes use of such sonar frequencies at ranges in excess of a very few thousand yards.

To avoid attenuation the designer may go down to, say, 10 kc. Here the attenuation does not make echo-ranging impossible out to ranges of perhaps 20,000 yd, but the wavelength is 5-3/4 in. This is comparable to 2000-mc radar as far as antenna size goes. Sonar radiators 10 or 20 ft across are quite practical, but it is rather difficult to drag a 20-ft diameter object through the water beneath a ship. To get really low attenuation, and hence to make possible ranges of, say, 100 miles, the sonar designer is driven down to frequencies of the order of 1 kc. Here the wavelength is 4.8 ft--comparable to 200-mc radar. Arrays of the order of 100-ft long are needed to achieve beamwidths of a couple of degrees, and such arrays begin to approach the dimensions of ships themselves.

If attenuation alone limited sonar, hugh low-frequency sets would long ago have been built. However, sonar is plagued by clutter--or reverberation, to the sonar man. Only the most sophisticated modern radars are significantly aware of clutter arising from any scatterers except the earth's surface, but sonar is relatively much more limited by reverberation than is radar. Partly this is because even the deep ocean is a rather thin layer of water. It is as if the atmosphere were only about 12,000 ft thick with another solid earth (and trees) up above. Under such conditions one would see radar targets free of clutter only at very short ranges, and that is exactly what happens to sonar. For long-range sonar all targets are "low altitude" targets. Furthermore the ocean is surprisingly inhomogeneous, not only because of marine organisms, but also because of temperature and salinity gradients.

All these lead to reverberation from the body of the water itself, and this tends to become very important in long-range systems. It is as if our 12,000-ft radar atmosphere were thoroughly cluttered with birds of assorted sizes and shapes.

Also the ocean exhibits marked refraction effects which sometimes help and sometimes hinder each party in the ASW problem. On the one hand, downward refraction tends to limit the range at which a sonar near the surface can detect a target (beyond this range the submarine is "below the horizon"). On the other hand, surface ducting can lead to greater than average range. Downbending is connected with reconvergence effects, and it is presently hoped to extend sonar ranges significantly (e.g., to 30 and perhaps 60 or more miles) by echo ranging in reconvergence zones. Refraction conditions also underlie the existence of the deep sound channel whereby SOFAR and LOFAR achieve very long detection ranges in deep water. Variations in refractive paths contribute to rapid fluctuations in the phase and amplitude of signals propagated over appreciable distances. These modulations "smear" the signal spectrum in much the same manner that radar ground clutter is smeared, and this hampers sophisticated signal-processing schemes which rely upon signal integration.

Other sonar characteristics of the ocean of less importance deserve mention. One of these is naturally occurring noise. Whereas the deep ocean basins are fairly quiet except for sound which "leaks" down from the top, this is not at all true of shallower waters such as surround all the continents. In virtually all shallow tropical and temperate waters noise produced by marine life (e.g., cracking shrimp, croakers, groaners, etc.) is a definite impediment to passive sonar which seeks to detect quiet targets. In addition, the noise of surf breaking on a coast or in whitecaps at sea hampers listening. The noise of the wind itself is not negligible. Aboard surface craft the noise of the waves washing against its own hull puts a lower limit on the background self-noise level that such a ship can achieve. In arctic regions where ice occurs, the noise level of the ice moving around against itself or against a shore can be high.

Bottom conditions affect sonar performance, especially on continental shelves. These vary from exposed bare rock to deep soft mud. In the former bottom reverberation is severe, in the latter bottom absorption is severe; there is some kind of sonar operation which will be affected adversely for whichever extreme occurs. This tends to force the sonar designer to design his system (i.e., frequency, pulse length, radiation pattern, etc.) to fit the particular area in which it will be used. However, these bottom conditions vary rather quickly from place to place; and the "optimum" sonar may be one which does not work very well in any one place, in order to comprise among the highly diverse conditions it must meet.

The attenuation of sound in sea water is so great and so frequency-dependent that for practical purposes one can be confident that any sonar system which operates over acoustic path lengths of only a couple of dozen miles must use audible frequencies. Hence, for such systems, the entire operable frequency range above about 50 cps can be monitored by one pair of human ears. This situation is in drastic contrast to the radio and radar frequency ranges, which are so wide that elaborate search receivers are needed. In the microwave region especially, quite secure communication could be achieved by hiding a narrow band signal some place in the many available kilomegacycles. This is virtually impossible in sonar; with a simple hydrophone and amplifier one man can cover the whole band simultaneously and continuously. Furthermore, the human ear is a fairly sophisticated signal processor. When a man turns his attention on a particular signal in a background of interfering signals he is using a tunable filter of adjustable bandwidth which he can narrow down (subconsciously) to less than 50 cps. Consequently "secure" sonar communication systems are to be taken with a grain of salt; the operator might not recognize the signal but he would probably detect it. For the same reason it is a simple matter for a submarine to monitor for hostile sonar; except at short ranges he cannot be significantly threatened by a signal he cannot hear. To cover even the frequencies which could be used against him at very short ranges the submariner need use only a few more ears with fixed-tuned superhet receivers.

Just as radar suffers a peak power limitation because of dielectric breakdown, so sonar is peak-power-limited by cavitation of the ocean. For typical shipboard active systems, cavitation sets an upper limit on the pulse power which can be radiated. This precludes the possibility of raising the power sufficiently to overcome own-ship noise at high speed, and so shipboard sonar is speed-limited. Cavitation also precludes raising the output power by dozens of db in order to work into the refractive shadow zone by scattering.

The very large, high-power systems which are now under development or presently proposed are all quite low-frequency systems. To get useful directivity patterns they require radiators so large that even at a megawatt power level the intensity at the radiating surface would be comparable to existing sonars. At megawatt levels the prime sources of power pose greater problems than does cavitation.

Because of the requirement to use low frequencies in order to achieve long ranges, sonar pulses must be very long in comparison with radar pulses. At the very low frequencies sonar designers are finding it desirable to use pulses of the order of 1 second long and even longer. Consequently 1-megawatt pulse power in sonar is much more of an engineering problem than is 1 megawatt in a radar whose pulses are a microsecond or so long. Such sonar pulses are so long that the pulse length compares to the thermal time constants of the system, and the engineering problems begin to take on some of the aspects of 1 megawatt CW. People are thinking in terms of self-contained nuclear reactor supplies to provide the radiated power in some contemplated systems.

SONAR PROPAGATION PATHS

Until very recently radars operated over a simple radar-line-of-sight transmission path; refraction conditions occasionally produce ducts and holidays, but these are generally looked upon as exceptions to the normal situation. It is only the recent work on over-the-horizon radar that introduces radar transmission paths which are normally other than straightforward. Hence persons familiar with radar are usually not accustomed to the variety of transmission modes which are used in sonar.

In most areas the ocean can be divided vertically into two main regions on the basis of water temperature. Starting at the surface and moving downward one usually encounters first a layer of water whose depth extends, typically to one or two hundred feet (rarely less than 10 or greater than 400), in which the temperature is not particularly predictable and may vary rather erratically. If strong winds have been blowing, this upper layer may be well mixed, with the result that temperature does not vary with depth.

On the other hand if mixing has not been strong, then a fairly steep drop of temperature with depth may occur. Less common, but not rare, are cases of increasing temperature with depth and of inversion layers.

Beneath this surface layer one passes into the deep-water regime. Here the ocean is quite stable, and the pattern of dependence of temperature upon depth is quite uniform from time to time and from place to place. The temperature falls with depth, at first rapidly and then slowly, approaching constant temperature at great depth. The boundary between the two regions is often rather sharp and is called the thermocline.

These patterns of temperature versus depth are of paramount importance in any understanding of sonar performance. The velocity of sound varies with temperature and with pressure, and these (with salinity which is usually less important) determine the refraction conditions in which sonar propagation occurs.

Increasing pressure (depth) causes an increase in the velocity of sound of about 1.8 ft/sec per 100 ft. Decreasing temperature causes a decrease in the velocity of sound in the order of 8 ft/sec per degree F. Consequently, near the surface in the upper layer the velocity of sound can increase with depth, remain constant, decrease with depth, or vary in a more complicated pattern depending upon the interplay of these two effects. Below the thermocline the velocity always fall with depth initially because the temperature term dominates the pressure term. At a greater depth (a few thousand feet) the temperature gradient becomes small and the pressure term begins to control, and below this depth the velocity increases with depth. Hence there is a depth at which the velocity is a minimum. This is the axis of the deep sound channel, which is a fairly permanent duct in the deep ocean.

In the neighborhood of the surface these characteristics usually cause the sound propagation paths to be quite complex. Negative temperature gradients above the thermocline cause downbending and tend to produce a surface "shadow zone." This is the counterpart of the horizon shadow in radar, but the sonar horizon may occur only a couple of kiloyards from the source. Positive temperature gradients or isothermal water above the thermocline lead to upbending and the consequent formation of a surface duct in which shallow targets may be detected at greater-than-average ranges. However, these same conditions tend to produce a shadow zone at the depth of the thermocline, with the result that a target below the thermocline may be poorly detectable.

Generally speaking, sound which passes down through the thermocline enters the upper region of the deep sound channel. Sound waves moving above the axis of the channel are bent downward; those below are bent upward. This duct traps the sounds and their intensity falls off slower than the inverse square law. If the sound waves avoid surface and bottom reflections, which tend to scatter and absorb sound, and if the frequency is low enough to avoid excessive attenuation, then sounds can propagate in the duct for hundreds of miles with modes loss of intensity. This is the basis of SOFAR and LOFAR.

These effects serve to illustrate why it is really not possible to give a concise answer to the question of what range sonars can achieve. It is necessary to break the answer down into at least a few different cases. Besides the nature of the sonar itself, the following variables influence the answer strongly:

- Kind of sonar platform
- Speed of sonar platform
- Depth at which radiator is placed
- Water depth to bottom
- Character of the bottom
- Temperature structure
- Depth of target

There are combinations of these variables for which the sonar range is as little as 100 yd, and there are others for which it is hoped to achieve 100 miles with future equipment. An "average" is essentially meaningless.

The ray paths also help to illustrate the importance of tilting sonar. By tilting the radiator up or down the sonar operator can change greatly the intensity of sound which arrives at different regions. This introduces another factor into detection range calculations which should not be ignored. When one attempts to estimate the range at which the probability of detection is 50 per cent, the answer is dependent upon what the operator is <u>trying to do</u>. In a tilting system, for example, what tilt is he using to search with? Tilt is only one of a group of variables which enter into this question. Others include the azimuth sector width over which search is conducted, the speed of the search platform, and the range scale (prf) which is chosen. An estimate of search rate capability which includes these factors is quite involved, and a broad general treatment of the subject is nearly useless. However, it should be noted that statements of detection range frequently pertain to the characteristics of the sonar set when aimed optimally at the target, and they then do not include the other factors which influence search rate. It should not be assumed too hastily, for example, that a ship advancing across the ocean can search uniformly a circle whose radius is equal to quoted values of sonar detection range.

It is relevant to the Polaris problem to note that refraction conditions are a minor consideration when the sonar angle of tilt is steep. The sound rays are then no longer grazing the temperature layers, and the bending of the rays is trivial (except for precise fire control). Hence upward-looking and downward-looking sonars and fathometers work much more predictably than do search sonars. If a surface ship can get into position more or less directly above a submarine, and if the sonar is free to tilt so as to cover most of the hemisphere below, then the submarine finds it more difficult to escape. However the surface ship is, under these conditions, hard put to keep up with the submarine as it twists, dives, and speeds up; then it is maneuverability and speed which enable the submarine to escape rather than intrinsically poor sonar performance.

A submarine chasing another submarine has the advantage over a surface vessel that it can go up and down through the temperature layers as its target does. Furthermore, the chasing submarine can enjoy the same speed and maneuverability as its target. Hence a nuclear submarine equipped with modern active and passive sonar has a good chance of remaining on the trail of a target indefinitely once he has been vectored in and contact has been established.

Finally, it should be noted that the importance of the temperature structure is appreciated by both submariners and ASW forces and as much by the S.U. as by us. It is standard practice in our Navy, and presumably in the Soviet Navy, for submarines and surface ASW forces to make fairly frequent measurements of the temperature structure of the water (the instrument used is called the bathythermograph, frequently abbreviated to BT).

Hence it may be assumed that both parties in an ASW problem know the temperature structure and attempt to optimize their tactics with respect to it.

The foregoing discussion is a very abbreviated exposition of propagation paths as they affect sonars presently in operational use. However, although it is intrinsic in what has been said so far, the emphasis has not been placed on propagation paths which underlie new developments now under way. These new sonars look very promising and are expected to be in operational use in a few years. To understand them it is necessary to consider more carefully the sound rays which curve down into the deep sound channel. During World War II, and even today, such sound was lost for practical purposes except insofar as it contributes to long-range reverberation.

In sufficiently shallow water or with sufficient downward tilt the sound hits the bottom where some of it is absorbed and some is reflected. The fraction which is absorbed may be quite high, but that which is reflected moves upward and either hits the surface or simply curves back to the bottom. That which hits the surface is not reduced significantly by absorption, but at the same time it is not reflected uniformly, because the surface is not perfectly smooth. The sound goes on bouncing off the bottom and surface, being scattered to some degree in each reflection and being absorbed in the bottom until bottom absorption, scattering, geometric divergence, and attenuation consume it. For existing operational sonars whose frequencies are generally above 10 kc and whose pulse powers are typically on the order of 10 kw, the absorption, attenuation, and scattering reduce the useful signal level so rapidly that sonar ranges in shallow water are very poor. Not only does the signal disappear into noise, but it also must compete with severe reverberation.

It is clear that the processes of absorption and attenuation can be combatted by increases in radiated power. Furthermore these processes and the severity of scattering from a rough surface can be combatted by lower frequencies. Hence development has been heading toward high-power, low-frequency sonars to operate by bottom bounce. Such sonars seek to detect targets via these reflecting paths. As an example, the LORAD program at USNEL (which is only one of several of interest for bottom bounce) is presently radiating 30 kw between 1 and 2 kc. A staggered program of multiple-frequency pulsing is used to overcome the limited data rate of sonar, and correlation techniques are used in the receiver. The next development step will go to 200 kw, and future plans envisage 1 megawatt.

At best, bottom-bounce systems must find their targets embedded in severe reverberation. The radar man can conceive the typical shallow-water problem to involve using 300-mc radar to find a 5 or 10-knot target in an atmosphere only 1000 ft high with earth (trees, etc.) top and bottom. Present developments are using sine wave, fm, and noise pulses with digital computer correlation in the receiver to dig the target out of the clutter. However, it is apparent that the ability to find the target at all is dependent in large part upon the frequency difference between the doppler from the target and the equivalent doppler spread of the reverberation. Consequently, the detection range, especially in shallow water, will probably always depend fairly critically upon target radial velocity. This is one of many instances in which slow speed helps the submarine avoid detection.

There is no basic difference between the use of bottom bounce in shallow waters (continental shelves) and deep waters (ocean basins) except that in the former the number of reflections is greater, with consequently greater losses and shorter useful ranges. However, in deep waters the use of bottom bounce leads up to and resembles the other main area of present development, which is reconvergence-zone echo ranging. When sound curves down from the surface in deep water it finally passes the axis of the deep sound channel and there starts to curve back up. At a range in the order of 30 miles it comes back up to the surface layer and most of it probably actually hits the surface. There is a sort of focusing effect which tends to bunch the rays back together again at this range; so the sound is said to "reconverge" in a zone at this range. After surface reflection the sound heads back down again, passes into the duct, is bent up again, forms a second reconvergence zone, reflects again, and so on.

Until scattering, divergence, and attenuation reduce the signal below useful levels, there is a tendency for several successive reconvergence zones to exist. For sources near the surface these are equally spaced about 25 to 30 miles apart, and each zone has an annular width of about 10 per cent of its range. Various scattering processes occur both at the surface and in the volume, so the geometric regularity of ray diagrams tends to be destroyed. The first reconvergence zone usually shows up as a region in which the acoustic intensity is markedly higher than on either side. However, scattering fills in the intervening regions, and later zones become successively less pronounced, blending into a fairly uniform distribution after about three zones.

In reconvergence-zone echo ranging the number of reflections is not great, and signal level falls off primarily because of geometric spreading and attenuation. With sufficient pulse power these can be overcome, and so high-power systems are under development. The LORAD program is primarily aimed at reconvergence, with bottom bounce in a secondary role.

Reconvergence-zone ranging, like bottom bounce, must combat reverberation. When an annular region perhaps three miles across is returning echos from 30 miles away, even a deep submarine is immersed in surface reverberation. To discriminate the target against the reverberation background, reliance is placed on relative Doppler discrimination. It remains to be seen just how reliably a target may be detected at various radial speeds in the different zones.

Two other characteristics of reconvergence-zone ranging need to be mentioned. One is that such ranging is dependent for its operation upon the refocusing from the deep sound channel. This is not always as strong as one might wish, and its characteristics are not the same in the Atlantic as in the Pacific. There are those who expect it to be quite successful in the Pacific but not as good in the Atlantic. Lastly, it should be noted that reconvergence systems will probably give solid coverage out to a few kiloyards (perhaps as much as 10 or 20 kiloyards in favorable circumstances, but sometimes much less); then there will be a holiday in the coverage out to perhaps 25 to 30 miles, at which point fairly reliable detection under favorable circumstances may occur over a span about 3 miles wide. Beyond this will be another 25-mile holiday where detection probability is very poor, and at about 50 or 60 miles a band perhaps 6 miles wide where the probability will be better but probably not really good. When such systems become operational, they will present some interesting problems to the operational people in the development of doctrines for optimum use of this peculiar pattern of detection probability. It may turn out, if the detection probability in the first zone is high enough in enough sonar conditions, that a screening line of reconvergence-zone sonars in deep water could be spaced about 35 to 40 miles apart. Estimates beyond this range are, for the present, pure speculation.

CAPABILITIES OF U.S. ACTIVE SONAR

The estimates presented below of present and anticipated active sonar capabilities are taken entirely from a report prepared during 1956 and published during 1957 by the Committee on Undersea Warfare of the National Research Council.* However, additional comments and information are included which are based, in part, on a series of recent visits to Navy agencies, including OpNav, BuShips, USNUSL, NRL, and USNEL.

The active ranges presented in Table 2 are those for 50 per cent probability of detection of a random-aspect submarine at 14-db target strength, and are based on the following set of standard conditions unless otherwise noted.

- o Deep water (2500 fathoms), convergence zone paths exist.
- o Mixed surface layer depth of 100 ft.
- o Surface temperature, 50°F.
- o Sea state 2.

This situation represents an approximate average of conditions for the middle North Atlantic over the spring, summer, and fall periods. During the winter the mixed layer depth increases to depths greater than 300 ft due to the higher wind forces and concomitantly higher sea states.

Platform A: Convoy Escort Surface Ship (~15 Knots)

See Table 2.

Platform B: Hunter-Killer Surface Ships (20-30 Knots)

This platform will have somewhat poorer performance than that shown for the first four convoy escort equipments. It is doubtful whether either

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*Peterson, S. A., Expected Active and Passive Sonar Detection Capabilities of Current and Future Platform-Equipment Combinations, NRC:CUW:0241; April 1957 (Secret).

Table 2

PLATFORM A: CONVOY ESCORT SURFACE SHIP (~15 KNOTS)

Transmission Path	Equipment	Average Range for 50% Probability of Detection (Kiloyards)		Status
		Submarine in Layer	Submarine Below Layer	
Near Surface	SQS-4 8-14 kc	4.5	1.5	In production, one year to fleet use.
	SQS-4 8-14 kc, tri-beam	8	3	One prototype, four years to fleet use.
	SQS-4 8-14 kc, tri-beam, hull and 250-ft towed transducer.	8	7	In development, 7 years to fleet use.
	SQS-23 5 kc	12	3.5	In development, 7 years to fleet use.
	2-4 kc sonar	25	4	Research stage, 10 years to fleet use.
Convergence Zone	2-4 kc sonar	Zone 57-63	Zone 57-63	Research stage, 10 years to fleet use.
		(114-131, depends upon surface reflection loss)		
Bottom Reflection Path	2-4 kc sonar	Zone 10-30 (depends upon bottom characteristics)		Research stage, 10 years to fleet use.

convergence zone paths or bottom reflection paths can be utilized by equipments on this platform because of its high background noise. In order to overcome the background interference a very large equipment (appoximately 16 x 10 ft) would be required, which would introduce a large amount of drag and consequently decrease endurance drastically. A well-shielded, deep variable-depth sonar should give some improvement. However, the basic limitation of sonar operated at high speeds appears to be flow noise, which has not been appreciably reduced to date.

Platform C: Picket Surface Ship (Slow)

This platform should be capable of carrying a very large equipment, which could be towed if necessary to reduce the effects of high sea states. First and second convergence zones should be reached and possibly the third. Bottom reflection paths should provide ranges from about 10 kiloyards out to 40 or 50 kiloyards, depending upon the smoothness of the bottom. When surface ducts 250 ft deep or more exist (mid-Atlantic, winter), ranges as great as 100 kiloyards may be obtained on targets in the duct.

Platform D: Coastal Patrol Craft

The SQS-9 (12, 14, 16, and 18-kc searchlight, 100-ft variable-depth sonar) is available for this type of craft. Ranges of about two kiloyards should be achieved against both deep and shallow targets with a layer depth of about 100 ft.

Platform E: Airship, Helicopter, Seaplane or Hydrofoil Craft

See Table 3.

Platform F: Explosive Echo-Ranging from Fixed-Wing Aircraft and Other Platforms

See Table 4.

Platform G: Submarine

See Table 5.

Table 3

PLATFORM E: AIRSHIP, HELICOPTER, SEAPLANE OR HYDROFOIL CRAFT

Equipment	Average Speed of Advance of the Platform (Knots)	Average Range for 50% Probability of Detection (Kiloyards)		Status
		Submarine in Layer	Submarine Below Layer	
AQS-2 25-kc airship towed variable depth sonar	24	2.9	1.8	Under evaluation.
AQS-4 20-kc, helicopter 70-ft dipped	11	1.9	1.3	In fleet.
NRL LOMASS-3 2-kc, scanning (Airship dipped; in layer)	35	15	3.5 (7)	Under development, laboratory prototype by December 1957.
NRL LOMASS-3 2-kc, sacnning (helicopter dipped; in layer)	35	12	3.2 (6)	Under development, laboratory prototype by December 1957.

Table 4

PLATFORM F: EXPLOSIVE ECHO-RANGING FROM FIXED WING AIRCRAFT AND OTHER PLATFORMS (VARIABLE WATER CONDITIONS MIXED LAYER 0-150 FT THICK)

Transmission Path	System	Average Detection Range* (Kiloyards) Submarine in Layer	Average Detection Range* (Kiloyards) Submarine Below Layer	Status
Near Surface	"Interim"	1 5.5 10.5	2	Available in less than one year.
	Vertical directivity in receiver (to reduce bottom reverberation).	1 10.5 10.5	3	May be available 3-5 years.
	Two hydrophones (omnidirectional) at 60 and 300 ft.	1.5 5.5 10.5	3.5 5.5 7.5	May be available 3 years.
	Two vertically directional hydrophones, one shallow, one deep.	2 10.5 15.5	3	May be available 3-5 years.
Total depth (all near surface conditions)	Very deep source and receiver (~12,000 ft)	30 50	30 50	May be available 7-10 years.

*When more than one range is given, first number is for >50 per cent probability of detection, second for >50 per cent probability under some conditions, <50 per cent under others, and third for some improvement expected but degree uncertain.

Table 5

PLATFORM G: SUBMARINE

Transmission Path	Equipment	Platform Operating Condition	Average Range for 50% Probability of Detection (Kiloyards)		Status
			Target in Layer	Target Below Layer	
Near Surface	BQS-3 Single ping	Submarine quiet in layer.	10		In fleet.
	HTC 200	Below layer.		7.5	
	SQS-4 8-14 kc	Transiting: (noisy), shallow.	6	2.5	A few in fleet.
	SQS-4 8-14 kc	Transiting: (noisy), deep.	3.5	5	A few in fleet.
	5 kc	Quiet, shallow.	21	4.5	Part of integrated sonar proposed for 585 nuclear submarine. Research stage, 10 years to fleet use.
	5 kc	Transiting: (noisy), shallow.	16	3.5	"
Convergence Zone	5 kc	Quiet.	Zone 56.5-63	Zone 56.5-63	"
Bottom Reflection	5 kc	Quiet.	Zone 20-50	Zone 20-50	"

Table 6

PLATFORM J: DEEP VEHICLE (REMOTE PLATFORM)*

Platform Depth (fathoms)	Average Range for 50% Probability of Detection (Kiloyards)			Area Covered (sq mi)	Status
	Target Above Layer	Target Below Layer	Target at 1000 ft		
500	10	10	16	80	NRL--Tests scheduled January 1957. Feasibility depends upon surface reverberation, data urgently needed.
[redacted]	15	15	20.5	175	NRL--Funds requisitioned for 1958. Feasibility depends upon surface reverberation, data urgently needed.
[redacted]	24.5	24.5	30	450	
[redacted]	33.5	33.5	39.5	1000	

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*The table applies to an upward looking sonar, omnidirectional in the horizontal plane, which may be located at the depths shown. The ranges stated are the horizontal radii to the outside of the annular search patterns of this equipment when an isothermal mixed layer 200-ft deep exists. No ranges are given for the inner radii of the annular search patterns because of the lack of data concerning surface reverberation.

Platform H: Bottom-Mounted (Shore)

Very-long-range, active, deep-ocean surveillance systems are under consideration. Too little is known about many of the basic parameters, however, to permit any significant predictions at this time. It appears that ranges of 50 to 100 miles may be achieved by large, fixed active systems in shallow coastal water during periods of the year when the water is fairly well mixed.

Platform I: Fixed Buoys

Such platforms in deep water can afford sonar performance ranging from a few kiloyards to very long ranges depending upon their size, power, and depth. Communication to the monitor can be provided by cable, radio, or sonar links. Certain applications of such devices appear quite attractive and are being investigated.

Fixed surface-looking buoys arranged in barriers may be the only practical method of providing coverage of some shallow coastal regions during periods when propagation losses are very high.

Platform J: Deep Vehicle (Remote Platform)

See Table 6.

The following are a variety of comments on individual entries in the tabular data presented above.

In Table 2 the improvement in range between rows 2 and 3 for targets below the layer illustrates the influence of a surface layer. In row 2 the sonar is mounted on the hull of a surface ship and so is above the layer. In row 3 the surface ship carries a sonar radiator which can be put below the layer. Such variable-depth sonar (VDS) (towed sonar) has been tested but is rare in the operational forces. Future modification will install this feature in the operational forces. In this same table, rows 3, 4, and 5 show the anticipated benefits of low frequency and high power, but the influence of the layer is evident. It must be emphasized again that the 25-kiloyard estimate, even though by surface paths, is for deep water.

Platform A, presented in Table 2, is described as "Convoy Escort Surface Ship (~15 knots)." The "Convoy Escort" part of this description is really not significant; the table applies to surface ASW ships at 15 knots, independent of their mission.

Platform B is deserving of note. This may be looked upon as Platform A simply speeded up. The remarks made by the NCR report are well taken. Surface ships which move about at high speed are virtually useless when compared with slower ships; the curves of self-noise versus speed climb astronomically above about 18 knots, and at present there is no reason to foresee much change in this situation. Hence, S.U. surface search forces must obtain search rate by numbers and not by speed.

Platform C probably deserves a place in a balanced mixture of ASW forces. However, in coastal waters it does not pose too serious a threat to a submarine, because the submarine can avoid the picket, and because even a picket ship does not enjoy a very good range in shallow water.

Platform D may be looked upon as an inexpensive version of Platform A. Inasmuch as the S.U. will presumably be hunting Polaris-carrying submarines in coastal waters, it may be expected that such craft will be numerous in their fleet. The building time for such craft is much less than for full-fledged ocean-going destroyers, so it is not at all impossible for the S.U. to acquire large numbers of these in a few years. Hence large numbers of such "PC boats" might turn out to be the most potent threat faced by the submarines. Once a PC boat makes a contact he can call in his big brothers to maintain the contact and to make the kill.

Platform E (Table 3) is a handy adjunct in a mixed ASW force because it can move rapidly into an area of suspected contact and there help to establish the contact. However, even these aircraft move slowly in terms of the distances involved and in terms of the speed with which a submarine can break off sonar contact. Hence, such craft require basing rather close to the operating area. As things stand today the S.U. does not have such bases near the potential Polaris operating areas, except for the Barents Sea. The appearance in the Russian fleet of numerous small aircraft carriers would probably signal the development of such a basing capability for the Norwegian Sea. In any event such sonars are intrinsically limited by the weight, size, and power capabilities of the platform and so cannot be expected to show great range improvement in the foreseeable future.

Platform F (Table 4) has not, we understand, lived up fully to the expectations of a few years ago. Inasmuch as an explosive source denies the use of some valuable signal processing schemes in the receiver, this is perhaps not surprising. In any event, where three ranges are listed for each set, the first number is probably a better one to contemplate than the second or third.

Platform G (Table 5) is the potent one on its own merits. As mentioned previously, the submarine can dive in and out of the thermal structure as his target does; if nuclear, it can maneuver and speed up so as to remain on the tail of the target. To do these things the pursuing submarine must use active sonar, and so is vulnerable to attack himself; but at least he cannot so readily be shaken off the trail. Except for the fact that these values pertain to deep water only, the various estimates in Table 5 are probably the most nearly conservative of any given in the NRC report.

Under Platform H the word "may" should be presented in boldface, red type. No evidence has been found to support the 50 to 100-mile estimate given here; it appears to be pure speculation based upon a 300-cps-to-2-kc research program which has so far not yielded such results.

In many respects Platform I does not involve sonar problems, as such; it is an alternative platform. However, it may be noted that buoys are particularly vulnerable to several countermeasures. Furthermore they often require a friendly shore, which the S.U. does not have in most of the areas of interest. Outside the 3-mile limit it is quite possible that various nations might sweep the buoys up either "accidentally" or as hazards to navigation.

The remarks in the last column under Platform J (Table 6) hold the key to this question. This matter of the competition of surface reverberation with the echo, and the extent to which doppler discrimination can improve the echo/reverberation ratio, was discussed above. Unfortunately the NRC report fails to append this remark to several other line items where it is also warranted. In any case, this platform is of limited interest in the Polaris context because of water depth.

On the whole the estimates presented are more relevant to the "classic" anti-submarine war in defense of overseas transport than to defense against Polaris. Two factors particularly lead to this comment: the choice of water depth and sonar conditions, and the presentation of 50 per cent probability ranges.

The contemplated use of Polaris undoubtedly involves operation in the North Sea, along the Norwegian Coast, and possibly in the Barents Sea. All these waters are shallower (mostly about 100 fathoms rather than 2500 fathoms), and the temperature structure is probably poorer than that assumed in the NRC report. Those instances in which the NRC report estimates long ranges by reconvergence or by deep-water bottom bounce are inapplicable in the shallow water. Even the estimates of ranges by near-surface paths are on the optimistic side in these shallow waters because of temperature structure and bottom reverberation. The main body of the Norwegian Sea is about 1500 fathoms deep, and the deep-water conditions assumed in the NRC report will be met to some degree. However, in this area the deep sound channel may be poor because of the effects of ocean currents, and reconvergence may be poor. Furthermore the temperature structure above the thermocline will probably be poor much of the time. In the Mediterranean extensive areas of deep water are found, but poor temperature conditions may be expected because of strong surface heating and rather poor mixing. Even in the Mediterranean a Polaris-carrying submarine is likely to spend most of its time in shallow coastal waters and among islands. In such cases the remarks above concerning the shallow northern areas apply here as well.

Estimates of 50 per cent detection probability range are useful in all circumstances; however, they are perhaps more indicative of the operational problem in a protracted war of attrition than they are in a sudden-death all-out strategic nuclear war. For the latter, 50 per cent probability ranges should be supplemented by 90 per cent probability ranges, because such high values more nearly characterize the problem faced by the defenders. Because of temperature and bottom conditions it is not uncommon to encounter 50 per cent probability ranges of one or two kiloyards and 90 per cent probability ranges of zero yards. That is, in many shallow water areas the defending forces, especially surface ships and shallow dunked sonars, may never have 90 per cent probability of detection because of temperature structure and bottom conditions. Such an area is that off Halifax, and conditions off the Norwegian coast might well be similar.

The NRC report data also tacitly assume that the submarine fails to execute some of the evasive maneuvers which a Polaris-carrying nuclear boat could (and probably would) use. Aside from countermeasures, which are discussed below, the boat can turn tail aspect on his pursuer, thereby reducing his echo some 4 or more db below those assumed here, and thereby knocking the bottom out of 90 per cent ranges for many equipments. Further, the boat can reduce speed to very few knots, thereby nearly eliminating the doppler differential whereby the ASW vessel seeks to sort him out from the reverberation. In the shallow seas (up to perhaps 200 fathoms) the boat can simply lie on the bottom. To discriminate the boat from other objects on the bottom then becomes very difficult; if the bottom is at all rough and rocky the boat blends in, and only a high-resolution map of the bottom can disclose the boat by its shape. Finally, if the defender is not well-equipped with low-frequency passive sonar in the combat area, a nuclear submarine can, if he chooses, simply run away from surface ASW forces. These latter cannot make better than about 15 knots (and preferably much less) without sacrificing detection range seriously. The nuclear boat can easily afford to go faster if he is reasonably sure he will not be tracked on passive gear.

The only existing active ASW sonar development program which is not reasonably well covered in the NRC estimates is the Colossus I program at USNUSL. This is a bottom-mounted, upward-looking chain of active sonars for use as a barrier line in shallow water. Such sonars are essentially inverted fathometers, and they enjoy the same relative freedom from refractive effects; hence their operation is quite reliable from a sonar viewpoint. They are reverberation-limited: a submarine can be detected reliably only at ranges shorter than the range to the surface. A range gate is used to exclude the surface return, and this serves to establish the minimum spacing between radiators in the string. The gap in coverage midway between two radiators and near the surface must not be big enough to permit a submarine to sneak through. The USNUSL program has determined that in 250 fathoms the maximum permissible spacing between units is 200 yards (in shallower water it would be correspondingly less). The Colossus I program has used frequencies in the interval from 16 to 26 kc with 3 watts radiated (which gives 34 db signal/noise ratio in state 6 sea noise). They believe they can put up to 500 such units (25 miles) on one two-conductor cable. Automatic data processing would be provided at the transducer. It is USNUSL's rough guess that at 20 units per mile the cost would be $75,000 per mile plus installation costs plus shore station costs plus operating costs. They note that water currents might make trouble in laying the equipment; pack ice on the shore would also make trouble.

If a suitable friendly shore were available, then systems such as Colossus I would be quite feasible and reliable though costly. If permitted to operate as planned, they would probably be nearly perfect if means were provided to sort out shallow submarines from surface vessels. The submariner's response to such a system would involve countermeasures. Apart from acoustic countermeasures, one effective countermeasure would be to drag the equipment up with hooks as soon as it is laid. Perhaps the subtlest trick would be to drape acoustic covers over a few of the units so that they appeared to work but never gave any echos. Since the units are active, it would be easy to find them, and such covers could be put in place by UDT men. Between these two extremes lies a whole spectrum of countermeasures, some of which are discussed below.

PASSIVE SONAR

In recent years the great hope for the ASW problem has been passive sonar, that is, low-frequency listening equipment in deep water to hear the noise radiated by submarines. By using long lines of rather simple receiving units it is possible to obtain considerable directivity even at low frequencies (e.g., 100 cps). The numerous receivers are strung along a multiconductor cable so that each output is brought separately to the beach. There phasing networks are used to make steerable beams or groups of fixed beams from a single array of hydrophones. Bearing accuracy of 2 deg at wavelengths of 50 ft is typical performance for existing gear. By triangulation two such arrays can now yield a position fix with typical accuracy of about four miles radius; this is good enough for surface active sonar to finish the job with a modest amount of search.

By using low frequency, such shore-based deep listening arrays can achieve detection and tracking at ranges of hundreds of miles because of low attenuation and duct propagation in the deep sound channel. It is important to observe that it is only in deep water that such long ranges can be achieved. In shallower waters bottom absorption and multiple scattering reduce the range drastically.

Much the same techniques which are used in deep-water bottom-mounted arrays can be used in shallow water and in smaller arrays carried aboard ships, notably submarines. In shallow water, as noted above, ranges are perforce less under otherwise similar conditions. Ranges of ship-mounted gear are also less, partly because of interference from own-ship noise, but also because the array is smaller. Much effort is now devoted to quieting the new attack submarines so as to improve their listening ranges; however, it should always be possible for bigger bottom-mounted arrays to give appreciably longer range.

In addition to the ship-mounted medium-size passive arrays, there are also available for use small expendable air-droppable passive sonobouys. These listen for submarine noises and send the signal to aircraft by radio. Such bouys are much too expensive for continuous large-area surveillance, but they assist a hunter-killer group in establishing initial contact and in re-establishing a lost contact.

U.S. fleet-type submarines can travel only about 150 miles on batteries (this at low speeds; at high speed the distance is much less). Such submarines must operate their diesels at points in the ocean not more than 150 miles apart. Consequently, in an area under passive sonar surveillance such a submarine stands a poor chance of transiting the area undetected. Actually even this statement must be moderated, because such a boat can reduce the likelihood of detection quite a bit by running slowly on his diesels and/or by going on the surface.

The listening arrays which can yield such long ranges against snorkeling submarines can yield comparably great ranges against noisy nuclear boats (e.g., Nautilus). Furthermore the ranges are quite long against high-speed boats even if they are otherwise fairly quiet. But against slow boats and against slow, quiet nuclear boats the passive detection ranges fall to values comparable to active sonar range or even less.

For the foregoing reason the vulnerability of the Polaris weapon system will be critically dependent upon the ability of the submarine to be quiet. This is probably the most critical factor in the whole problem of Polaris vulnerability, because the S.U. will not find it difficult to track noisy boats. On the other hand they will find it very difficult to detect quiet boats.

CAPABILITIES OF U.S. PASSIVE SONAR

The material presented below is taken from the same National Research Council report that was used as a source of information on active systems. The comments made there concerning assumptions, etc. apply here as well.

Platform A: Submarine (Slow and Medium Speed)

See Table 7.

Platform B: Shore-Based, Aircraft Sonobuoy and Submarine-Mounted

See Table 8.

Platform C: Picket-Ship, Very-Low-Frequency Systems

It will be desirable at times to maintain surveillance of ocean areas from surface picket ships rather than from shore based installations or from aircraft. Several very-low-frequency passive systems have been suggested for this use and are briefly described in the following paragraphs.

Bottom-Mounted Arrays

Experience in conducting acoustic survey operations has shown that a ship can stream to an eight- or ten-mile length of cable terminated in hydrophones on the bottom for considerable lengths of time and under fairly severe weather conditions. Both broad-band and narrow-band analyzing equipment presently available for shore based use or under development for airborne or submarine use could be adapted for use on picket ships. Such systems with about eight hydrophones in deep water might be expected to give a reliable range of the order of 100 miles on a snorkeling or cavitating submarine. To reduce the possibility of attack by a very quiet submarine, small explosive charges can be thrown periodically to check for echos both with the bottomed hydrophones and with an overside hydrophone.

Table 7

PLATFORM A: SUBMARINE (SLOW AND MEDIUM SPEED)

Equipment	Type of Target	Platform Operating Condition	Maximum Recorder Detection Range (Kiloyards)	Aural Classification Range (Kiloyards)	Status
BQR-3A (5-ft line hydrophone in dome, trainable)	Snorkeling (U.S.) or cavitating (any type propulsion)	Patrol Quiet	X	18	About 30 in fleet. Primarily a fire control sonar with bearing accuracy ~0.1° in ATF. If fitted with a bearing recorder, detection performance would be almost equal to BQR-2B.
		13 kn	X	4	
	Quiet	Patrol Quiet	X	2.5	
BQR-2b and Bearing Recorder 1-4 kc Recorder; 0.3-15 kc aural (approximately 6-ft diameter circular array of 48 3-ft-high lines)	Snorkeling (U.S.) or cavitating (any type propulsion)	Patrol Quiet	110	18	First production equipment now installed. Production equipments for most of the fleet contracted for (~60).
		13 kn	13	4	
	Quiet (shallow)	Patrol Quiet	10	2.5	
BQR-4a and Bearing Recorder (10 x 20-ft conformal array of 8-ft-high lines); 0.6-4.8 kc recorder; .15-4.8 kc aural	Snorkeling (U.S.) or cavitating (any type propulsion)	Patrol Quiet	160	30	Approximately 8 in fleet. A few will have bearing recorders, others will get them.
		13 kn	20	9	
	Quiet (shallow)	Patrol Quiet	17	9	

(Continued)

Table 7 (Cont'd.)

Equipment	Type of Target	Platform Operating Condition	Maximum Recorder Detection Range (Kiloyards)	Aural Classification Range (Kiloyards)	Status
HTC 200 (~5 x 7-ft searchlight trainable)	Snorkeling (U.S.) or cavitating (any type propulsion)	Patrol Quiet	X	18-30	One prototype just evaluated. Future uncertain. Also provides single ping echo ranging and directional communication.
		13 kn	X	4	
	Quiet (Shallow)	Patrol Quiet	X	2.5	
36 ft x 24 ft conformal array of spots (one row high); 0.5-2 kc recorder; 0.15-5 kc aural	Snorkeling (U.S. or cavitating (any type propulsion	Patrol Quiet	180	50*	Part of integrated sonar proposed by USL for 585 nuclear boat (1958 building program.
		13 kn	11	~3	
	Quiet (Shallow)	Patrol Quiet	12	4*	
8-ft diameter Cylinder 4-ft high; 1-2 kc recorder; 0.3-10 kc aural	Snorkeling (U.S.) or cavitating (any type propulsion)	Patrol Quiet	170	48	Part of integrated sonar above, primarily designed for active detection at 5 kc intermediate and short range passive tracking and fire control (cannot use LOFAR).
		13 kn			
	Quiet (Shallow)	Patrol Quiet	16	9	

(Continued)

Table 7 (Cont'd.)

Equipment	Type of Target	Platform Operating Condition	Maximum Recorder Detection Range (Kiloyards)	Aural Classification Range (Kiloyards)	Status
PUFFS; three equally spaced 6-ft lines on 250-ft base line; 0.2-8 kc	Snorkeling (U.S.) or cavitating (any type propulsion)	Patrol Quiet	10-15 (for range determination, accuracy about 2 per cent or range)		Passive ranging system. Breadboard model has had limited sea tests by NOL.

NOTES:
1. Localization by passive equipments about ± 2°.
2. BQR-2b--Automatic target following will provide bearing accuracy of ± 0.25° on noisy target at 12 kiloyards on patrol quiet platform.
3. BQR-7 BTL described in LOFAR sheet.

*It is proposed to use a LOFAR analyzer with this equipment which may permit classification at recorder detection range when platform is at patrol quiet.

Table 8

PLATFORM B: SHORE-BASED, AIRCRAFT SONOBUOY AND SUBMARINE-MOUNTED (VERY LOW FREQUENCY PASSIVE SYSTEMS)

Platform	Water Depth (fathoms)	Type of Target	Type of Analysis	Detection Range (miles)	Localization	Classification	Status
Shore-based, deep arrays	>1000	Snorkeling (U.S.)	Narrow band (LOFAR)	100-400[1]	$\sigma = 2^\circ$[2]	Good but not 100 per cent[6]	Operational[8]
Shore-based, deep arrays	>1000	Low speed, Snorkel (British)	Narrow band (LOFAR)	75-300	$\sigma = 2^\circ$[2]	Good but not 100 per cent[6]	Operational[8]
Shore-based, deep arrays	>1000	High speed, snorkel or battery (British)	Narrow band (LOFAR)	75-400[3]	$\sigma = 2^\circ$[2]	Good but not 100 per cent[6]	Operational[8]
Shore-based, deep arrays	>1000	High speed, nuclear (NAUTILUS)	Narrow band (LOFAR)	200-1000	$\sigma = 2^\circ$[2]	Good but not 100 per cent[6]	Operational
Shore-based, deep arrays	>1000	Low speed, nuclear	Narrow band (LOFAR)	10-100	$\sigma = 2^\circ$[2]	Good but not 100 per cent[6]	Operational[8]
		Quiet battery		?-5		Good but not 100 per cent[6]	Operational[8]

(Continued)

Table 8 (Cont'd.)

Platform	Water Depth (fathoms)	Type of Target	Type of Analysis	Detection Range (miles)	Localization	Classification	Status
Shore-based, shallow water, short arrays	<100	Snorkel (U.S.)	Narrow band + broad band	20-50	5° (Estimated)	Good but not 100 per cent[6]	Available 1958
	<100	Quiet battery	Narrow band + broad band	1-10	5° (Estimated)	Good but not 100 per cent[6]	Available 1958
Shore-based, very deep water arrays	>2500	Note 4	Narrow band + broad band			Good but not 100 per cent[6]	Under study
Shore-based, medium depth arrays	100-1000	Note 5	Narrow band + broad band			Good but not 100 per cent[6]	Available 1958
Aircraft sonobuoy	>1000	Snorkel	Narrow band + broad band	30-100	10°	Good	Production 1958
Aircraft sonobuoy	>1000	Cavitating	Narrow band + broad band	20-40	10°	Requires surface observation + listening	Production 1958
Aircraft sonobuoy	>1000	Quiet	Narrow band + broad band[7]	1/2-2 (Estimated)		Good	Production 1958

(Continued)

Table 8 (Cont'd.)

Platform	Water Depth (fathoms)	Type of Target	Type of Analysis	Detection Range (miles)	Localization	Classification	Status
Aircraft sonobuoy	<100	Snorkel	Narrow band + broad band[7]	10-40	10°	Good	Production 1958
Aircraft sonobuoy	<100	Cavitating	Narrow band + broad band[7]	10-30	10°	Requires surface observation + listening	Production 1958
Aircraft sonobuoy	<100	Quiet	Narrow band + broad band[7]	1-5	10°	Good	Production 1958
Submarine (quiet condition)	[redacted]	Snorkel	Narrow band + broad band	30-100	2°	Good	BQR-7 Experimental Model.
Submarine (quiet condition)	[redacted]	Cavitating	Narrow band + broad band + demodulation	10-50	2°	Fair	BQR-7 Experimental Model.

NOTES:
1. A nominal figure of 200 miles is generally used. There is a small seasonal variation and also a difference between areas of the ocean.
2. At 200 miles from each of two or more stations it is approximately a circle of 4-mile radius.
3. By changes in propeller and fin design the blade and shaft lines can probably be greatly reduced, thereby cutting the high speed snorkel range to 75 to 200 miles and the high-speed battery to a much lower figure.

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Table 8 (Cont'd.)

NOTES (Cont'd.):

4. Better ranges than deep arrays for quiet targets but poorer ranges on noisy targets.
5. Ranges intermediate between those of deep water and shallow water arrays.
6. The addition of an ideal broadband bearing analyzer to the narrow band analyzer should yield an improvement in classification.
7. Can be combined with explosive echo ranging to improve detection probability, localization, and classification.
8. A prototype broad band space correlation system (SIGMA) for use with existing SOSUS arrays has been evaluated at Eleuthera. (See USL Report No. 308.) Range on cavitating submarines, 100-200 miles.

COMMENTS:

Saturation. Saturation by random shipping may well be a problem in peacetime. In wartime, with controlled shipping, saturation by targets may not be a problem if sonobuoy equipped aircraft are available to examine in succession all targets in a given beam.

Future Possibilities. Range increases are questionable as improvements in detection capabilities may be balanced by quieting of future submarines.

Jamming. Jamming by the enemy may be feasible.

Decoys. Decoys may be feasible and would contribute to the saturation problem.

Interfering targets will cause more trouble to 2-hydrophone CODAR than to SIGMA, but a system combining the best properties of both should be possible.

Floating Array

As an extension of the sonobuoy principle, a small amount of work has been done with floating arrays. In one proposal, hydroplanes are mounted on the spokes of an umbrella-like structure about 50 ft in diameter which in turn is suspended from a buoy. Either a cable link or a radio link to the ship can be provided. The analyzing equipment would be similar to that used for the bottom-mounted array. This system would also be expected to have a range of about 100 miles on a snorkeling or cavitating submarine; the bearing accuracy would probably be less than that of the bottom array. It could also be used with small explosive charges for echos. This system has the disadvantage of drifting unless an anchor can be devised; it has the advantage of permitting the picket ship mobility for evasion or attack if a radio link is used.

Ship Sonobuoys

Either short-life or long-life sonobuoys can be used, singly or in pairs. The characteristics and analyzing equipment would be essentially the same as the aircraft equipment, but simpler than the floating array. Handling would also be simpler, but the expected range on snorkeling or cavitating submarines would be only about 50 miles. Again, explosives could be used to help detect nearby quiet submarines. The sonobuoy system requires little special-handling equipment on the ship, and therefore can be quickly installed on any vessel capable of maintaining station.

Conclusions

These data are as complete as they could be made within the limited period of preparation. Predictions of performance in other propagation situations would be very desirable, and should include deep mixed layers, shallow depressed channels, intermediate depth water (~1000 fathoms), and shallow water (~100 fathoms). It would also be worth while to establish a mutually acceptable set of representative propagation conditions to serve as a basis for comparison of various sonar platform-equipment combinations.

Fewer comments are needed at this point than were appended to the NRC data concerning active systems. This is partly because the data speak for themselves; if all data relevant to snorkeling submarines and high-speed submarines are ignored, then one can pretty well infer the situation as it would pertain to a slow, quiet nuclear boat. Alternatively one can see in these tables the detection and tracking ranges which the S.U. might achieve by passive sonar against noisy boats. Row 5 of Table 8 is singled out for further comment. The range of 10 to 100 miles listed for shore-based deep arrays against low-speed nuclear boats is at least highly misleading, if not just plain wrong. Perhaps this estimate is applicable to the Nautilus, which is an exceedingly noisy boat. It should not be construed from this that such ranges will be obtained against quiet, low-speed boats. A far better estimate for that case is shown in the following row of Table 8: against quiet battery boats, "?" to 5 miles. Between these two limits, it might turn out that "?" is a better estimate than "5".

The comments appended in the NRC report to Table 8 are well taken and deserving of more attention. This is the subject of the following paragraphs.

SONAR COUNTERMEASURES

Although all sorts of active and passive sonar countermeasures were employed during World War II, it is only rarely that one finds countermeasures brought into a discussion of the potentialities of a sonar weapon system. In this respect the whole field of sonar is less advanced than radar, where a universal consciousness of countermeasures exists. Not that the techniques and devices for sonar countermeasures are lacking; rather the absence of this phase of the problem from sonar system analyses sometimes lends an air of unrealistic optimism to forecasts of capability against a skilled and determined enemy. Polaris submarines could derive much protection from well-used countermeasures; they should be incorporated in the weapon system, and they should be accounted for in an estimate of vulnerability.

There are several techniques and devices which can help a submarine avoid detection entirely. Probably the most important of all is simply to be quiet, and this has been discussed above. However, the quietest boat faces some chance, albeit small, of being found more or less by accident. One way to diminish this chance markedly is by painting the submarine with a sound-absorbing coating. During World War II the German Navy developed absorbing coatings; there is some controversy over their actual effectiveness and over the absorption mechanism in the material, but there seems to be little doubt that some absorption was obtained. In this connection it must be emphasized that as little as 3-db echo reduction can have drastic effects on detection probability, especially in shallow water where reverberation limits the detection range severely.

After the war the U.S. Navy supported a development program at M.I.T. to carry on from the German start. By the late 1940's the M.I.T. program had produced a coating which, in the laboratory, yielded about 10-db or more echo reduction over the temperature and pressure ranges of interest to a submarine. That coating was more effective against the sonar frequencies then in use (e.g., 24 kc) and would undoubtedly have given poorer absorption at lower frequencies. The M.I.T. laboratory tests were sufficiently promising to lead to a full-scale trial at sea, and the U.S.S. <u>Cubera</u> was coated (Project Mystic). Numerous mishaps occurred during the trial program. The necessary clean metal surface was not obtained, with the result that large patches of the coating failed to adhere and washed off shortly after the Cubera put to sea. Furthermore the material laid down on the Cubera was demonstrably not that prescribed, presumably because the workmen were not sufficiently skilled and trained. The net result was little or no echo reduction in the trial. This event, perhaps coupled with a basic question as to the extent to which U.S. submarines, as their mission was then conceived, would benefit from echo reduction, led to a widespread loss of interest in the program.

It would appear that the value of such a coating to a Polaris boat would be so great as to justify a very sizable program aimed at producing a practical coating. The goal need not be very large absorption, although this is certainly desirable; the goal should include useful absorption at low frequencies (e.g., down to 1 or 2 kc). Above all the goal should be practicability; there is no reason to suppose that a low-frequency coating need to be so thick as to be impractical, and there is no reason to suppose that a coating cannot be bounded tightly to the hull by routine careful work in a Navy yard. It should be noted that the USSR did not suffer the disappointment of Project Mystic and so may not be deterred from developing such coatings for Russian boats.

The old NAC and NAE beacons and their various kin are sonar noisemakers which a submarine can eject to jam enemy sonar. They are the counterparts of radar noise and sweep jammers. They work to some degree, and help a submarine to break off sonar contact once his presence in the area is certainly known. To work against the new high-power, low-frequency sonars, bigger and more costly devices would be needed. Such a development is certainly possible; its worth would require careful system analysis.

Presumably if such noisemakers have a place in the scheme of things it must be to break off contact by a tailing S.U. boat during peacetime. If nuclear-warhead ASW weapons were employed, such ejected noisemakers would be of small help because of the large lethal radius.

A different family of noisemakers could be employed by U.S. boats to jam Soviet fixed sonar installations (such as bottom-mounted or buoy-mounted active or passive systems). Fairly cheap battery-operated noisemakers could be planted close to such arrays. It would probably not cost the S.U. more to disable the noisemakers (without damage to their own systems) than it would for us to place them by air drop or by ejection from torpedo tubes. Such noisemakers, with a useful life of a few weeks, might be laid in times of international tension as part of a low-level alert.

Homing torpedoes, both active and passive, are in use. These can, of course, be used as defensive ordnance with considerable effectiveness. A submarine is not helpless against attacking ships, because the submarine can usually detect and track the surface ship long before it is itself detected. However, homing torpedoes can also be used against bottom-mounted active sonars. The exchange ratio can be quite attractive, and it should be possible to deter the S.U. from emplacing sizable sonars in international waters.

Dragging or cutting the cables to fixed installations has been mentioned previously. This is really not very difficult, especially if the location to drag is reasonably well known by virtue of watching the installation go in.

U.D.T. swimmers can be launched from and recovered by a submarine. If equipped with underwater sleds such men are quite mobile. In shallow waters they can explore the bottom to find hostile installations. They can cut cables or disable equipment. More subtly, they can move equipment from place to place or rotate it so that it gives false bearings. They can cover it with sheets of foam rubber and so put it out of business. U.D.T. men can also inspect their own submarine to discover limpet bombs; this would seem to be a necessary defensive move, especially in the Mediterranean where limpets might otherwise be very attractive to the S.U.

If Polaris submarines plan to lie for appreciable periods in shallow waters off the Norwegian coast, they might help themselves by ejecting from their tubes simple battery-operated echo-repeaters. A bevy of such devices strewn about in shallow waters would give the S.U. forces a collection of false submarine targets to investigate (and perhaps attack).

It should not be unduly difficult to construct a battery-operated device which emits a line spectrum roughly resembling the LOFAR signature of a diesel engine. A series of sharp, low-repetition-rate pulses is needed. These could be used to deceive or to saturate long-range, low-frequency passive sonar.

Friendly surface shipping can be sailed around in the vicinity of low-frequency passive arrays. These ships can be made to put out sizable amounts of noise (a freighter running light with a bent propeller shaft is especially good at this) and so to render the passive array nearly useless. Of course, anchoring the freighter, doing a fair amount of hull riveting, and then dragging the anchor across the array can be helpful additions to such a scenario.

Surface shipping, even hostile vessels, can be used to penetrate a barrier. A submarine can run under a surface ship or hang on in his wake with only moderate difficulty, and it is very difficult for search forces to find him there. Unless S.U. destroyers are equipped with exceptionally good sonar, a daring submariner could even tag along under a destroyer returning to port. At night during peacetime a submarine can run on the surface close to merchant shipping with very slight risk of detection. In that position radar is not likely to find him.

At night a submarine can run close to a shore on the surface with small risk of detection, especially if he exercises modest caution to detect unfriendly radar and sonar early enough to dive and lie on the bottom.

In nearly all conditions a submarine is safest at shallow submergence, and he is much safer in shallow coastal waters among islands. This tactic, with quieting, with an echo-reducing coating, and with a few countermeasure devices, should make a nuclear submarine nearly undetectable.

ALTERNATIVES TO SONAR

Inasmuch as sonar works as poorly as it does, one may well inquire why it is the predominant anti-submarine detection method. The answer is simply that all the alternatives are even less versatile and useful. Though sonar ranges are short, all other techniques offer even shorter range and most have additional limitations. Nevertheless there are alternatives, and these must be anticipated in the defense of a Polaris-carrying submarine.

MAD (Magnetic Airborne Detector or Magnetic Anomaly Detector) gear carried in low-flying aircraft can detect a submarine by the disturbance which the submarine's steel hull makes in the earth's magnetic field. In the long run the submarine could counter this device by degaussing or by the use of non-magnetic steels, but these measures are not now contemplated in the Polaris program. The detection range of MAD is only about 1500 ft (maximum) and so the gear is chiefly useful in closing a narrow channel or in localizing a contact established by other means.

Magnetic loops--that is, cable loops on the bottom--can also be used to detect the presence of the magnetic disturbance caused by the submarine. Such loops are of quite limited applicability because of the need for a friendly shore, because they only work in fairly shallow water in areas of small natural magnetic disturbance, and because it is impractical to use them in areas where water currents are strong.

There is at present a development program (Project Clinker) which uses airborne passive infrared gear to detect a trace on the surface caused by the passage of a submerged submarine. There is not much doubt that the trace is weakened by deep submergence and by slow speed. It is not yet clear how soon after passage the trace appears, nor is it yet clear that identification of the trace can be sufficiently reliable. At best the surface tends to be cluttered by windrows and by traces from surface ships. On the other hand it may turn out that a nuclear boat leaves an especially strong or characteristic wake because of the large amounts of heat vented outboard. It is not now appropriate to go beyond the foregoing remarks because an evaluation program for Clinker is under way, and the results have not yet been reported to us.

The submarine will be especially vulnerable to covert attack when in and when leaving port. At those times it would be fairly easy for covert U.D.T. men (disguised as sportsmen, for example) to attach devices to the hull of the boat. This would involve a certain amount of risk, but it should not be assumed to be an unacceptable risk, especially if it is known that the submarines fail to inspect themselves at sea. Various harbor defense devices to protect against free swimmers exist, but it would be foolish to suppose they cannot be penetrated. The devices could be limpet bombs, mentioned previously, but they might also be noisemakers or lights or dye-markers which would facilitate detection when set off by a time clock. Self-inspection at sea would seem to be the surest defense against such devices, and is just one more mission for a team of U.D.T. men aboard the submarine.

MINES

Unlike all other major naval powers in recent years, Russia has a naval tradition and history of mine warfare. Mine warfare is regarded as one of the main branches of the Russian naval service, and career officers serve their stint in the field as a matter of course. Russia is known to have a large stockpile of thoroughly modern mines and has used them in the recent past. It must be assumed that Russian planners will at least consider the use of mines in defense against Polaris.

Naval mines can be grouped in two main types: moored mines and ground mines. Moored mines are buoyant and are held at a preset depth by an anchor; a lock can be used to hold them down until it is desired for them to float up to position. Ground mines lie on (or in) the bottom; they need not be buoyant and so can carry a heavier charge (2000 lbs is typical, as compared with 600 lbs for moored mines). All mines could carry nuclear charges.

Modern mines are highly developed; when laid gently and with care they are reliable. They can be laid by submarine, by surface vessel, and by air (either with or without a parachute). Moored mines, once they let up to depth, are relatively easy to locate by high-resolution sonar (although search rates tend to be low), and they can be swept by conventional minesweeping techniques which cut the anchor cables. Ground mines are exceedingly hard to locate; for all practical purposes this remains an unsolved problem despite a great deal of development effort. Furthermore, no satisfactory sweeping methods are available for use against a sophisticated ground mine.

Mines in present stockpiles can be routinely outfitted with any mixture of the following gadgets:

- delayed rise to depth (moored mines, preset at time of laying)
- delayed arming (usually up to 1 year, preset at time of laying)
- ship counter, which simply counts down one digit from a preset number every time the mine would otherwise have gone off
- magnetic signature
- acoustic signature
- pressure signature

Among those developed but not usually used are optical sensors, vibration pickups, and cosmic ray background sensors; no doubt still others exist.

Not all of these gadgets would be useful specifically against Polaris. For example, the ship counter is suited to a protracted war of attrition and is used to make a ground mine hard to sweep. Ship counters could be used in anti-Polaris mines, but very possibly would not be. On the other hand, delayed arming would probably be very attractive.

It is possible to lay down a defensive mine field in territorial waters, announce its presence, and defend it. To transit such a mine field would be essentially impossible if the defender used some sonar pickups to detect stealthy activity. At the present time there are no areas where such a defensive mine field would much hamper Polaris operations. However, if the political situation around the Mediterranean were to change, this might no longer be true.

An extensive mine field such as this could be used to exclude all ships, friend and foe alike. (To leave open lanes for the passage of friendly ships invites the submarine to sneak through by following.) However, it is possible to assemble mines which are specifically directed against submarines; not only moored mines set below surface shipping, but also mines which are set for specific submarine signatures are undoubtedly possible. One conceivable combination, which exploits the *quietness* of the submarine, would be to require a magnetic signature, a weak pressure signature, and the absence of an acoustic signature. Even more specificity would be obtained by requiring the signature of the *nuclear* submarine. And the Russians might even be able to concoct a device which recognizes *American nuclear* submarines.

It is one thing to lay down an extensive mine field in territorial waters; it is quite another to mine international waters. In most areas the Russians would stand small chance of doing it without detection, and probably other nations would resist with force. Exceptions might be made for the Barents Sea, where the Russians are strong and our surveillance is haphazard. The Black Sea is a lot more risky, but not necessarily critically so.

Sporadic sneak mining in open waters (or even covert mining in NATO territorial waters) is much harder to detect. It is not beyond all reason that such methods might be used to attrite our submarine force in peacetime. An occasional loss at sea, even if known to be by mine, would cause all sorts of diplomatic furor but would be difficult to pin down. An exploded mine is fairly anonymous, particularly in waters which were mined during World War II. It would be exhausting and fruitless to sweep extensive areas against sporadic mining; the only real hope would be to catch them in the act, and this is unlikely.

Remotely operated mines are quite feasible, not only by cable to the beach or to a friendly boat, but also by acoustic or low-frequency radio control. It may seem a drastic approach, but it is not beyond technical possibility for the Russians to lay numerous controlled nuclear mines in potential Polaris operating areas, these to be detonated simultaneously with an attack on the U.S. How effective any plausible level of such mining would be is most uncertain, but it must be borne in mind that the Polaris weapon system may be sensitive to modest levels of shock.

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Appendix D

WEAPON EFFECTIVENESS

Figure 1 shows the number of weapons required for the destruction of point targets as a function of hardness, yield, and CEP.

Figures 2 through 7 show the number of weapons required for various average levels of structural collapse and fatalities against a target system made up of the 135 Soviet cities with populations of at least 100,000. These curves were generated from information available in RAND Research Memorandum RM-1671,* which is a detailed analysis of the structure of eight Soviet cities and their vulnerability to a wide variety of attacks. Fatalities were associated with structural collapse of buildings. The buildings were assumed to be drag-sensitive, which reduces the overpressure requirement for larger-yield weapons. The effects of radioactive fallout or fire storm were not considered, nor were civilian defense shelters, although the population was protected by those measures available to an unhardened city. There was no evacuation of the population. The attack consisted of using weapons of the same size on the entire target system. For those targets requiring more than one weapon, multiple aim points and multiple weapons up to 13 were considered. The force size represents the number of weapons that must be detonated on target. No allowance has been made for the effects of enemy attrition or disruption; nor have launch and inflight reliabilities been accounted for.

In generating these graphs a particular weapon yield was chosen first. The number of these weapons required for each of RM-1671's eight exemplar

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* Hanunian, N. A., Urban Blast Damage, Weapon Yields, and Delivery Accuracy (U), RM-1671, July 15, 1957 (Secret-Restricted Data)

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Table 9

SUMMARY OF WEAPON-EFFECTIVENESS FACTORS

	Exemplar Cities									
	Stalingrad	Molotov	Komsomolsk	Saratov	Tashkent	Ufa-Chernikovsk	Gorkiy	Groznyy	Others*	Total
Number of Similar Cities	3	3	6	8	11	12	13	35	44	135
Population of Similar Cities (thousands of Persons)										
Total	4,578	1,066	1,320	4,131	3,717	4,079	11,627	6,891	5,596	43,005
Largest	3,176	538	330	731	778	901	4,839	350	211	
Smallest	525	147	113	240	101	109	188	102	102	
Radius of Similar Cities (miles)										
Largest	4.5	4.0	2.9	4.3	3.0	4.5	5.9	4.7	2.7	
Smallest	3.2	1.7	1.4	1.6	1.5	1.0	1.8	0.9	0.8	

*"Others" are to be lumped together with either Tashkent or Groznyy, whichever has the smaller number of weapons required.

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270

cities was then determined for the desired damage level. Due to having discrete weapons, the average damage level was often larger than the desired damage level. This is particularly true for the case of a large weapon against a small city, in which one weapon does considerably more damage than desired.

The number of weapons for each exemplar city was then multiplied by the number of cities similar to the exemplar. The sum of these products represents the force size required for the conditions chosen. The accompanying Table 9 summarizes the various factors pertinent to this method.