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PROJECT HARTWELL

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

A REPORT ON SECURITY OF OVERSEAS TRANSPORT

VOLUME I
of 2 volumes

Contract No. N5 ori 07846

21 September 1950

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A REPORT

ON

SECURITY OF OVERSEAS TRANSPORT

21 September 1950

VOLUME 1

(of 2 volumes)

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PROJECT HARTWELL

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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PREFACE

Project Hartwell was initiated by the Navy as a short-term intensive assault on the technical barriers that now limit the effectiveness of anti-submarine and anti-mine warfare. The group's function was to explore the potentialities inherent in old and new methods, suggest future long-range programs, and formulate recommendations that could be used by the Navy to guide research and development.

From the outset, it was apparent that the group could not restrict its attention to anti-submarine and anti-mine warfare, but must cover the broader problem of overseas transportation. This immediately led to consideration of areas not directly under Navy cognizance. However, study of such diverse matters as internal transportation to all possible ports, port facilities, packaging, and design of merchant ships was imperative if all the factors affecting overseas transportation were to be recognized. Since the Navy is responsible for harbor defense and protection of overseas transport, and since design of ports and ships is critical to these problems, such matters also must be studied by the Navy.

Because of the nature of the Project, the Hartwell Report does not profess to be exhaustive. Rather, it attempts:

1. To study the problems that confront the Navy in the performance of its responsibility to protect overseas transport and its own task forces;

2. To appraise the efficacy of present planning and equipment to solve these problems;

3. To suggest and recommend means by which gaps may be filled and deficiencies remedied.

The present study was carried out by a group of thirty-three scientists during a three-month period ending 31 August 1950. Since many Project members had other commitments during this time, the effort devoted to the study represents the equivalent of twenty full-time scientists, plus aides. The Project membership is described briefly in Appendix L. The sources of information available to the group are listed in Appendix K.

PREFACE (cont d.)

Since 1 January 1950, two other groups have reported similar studies, but with slightly different terms of reference: the "Low" Report and the Project MAID Report contain their findings. The Hartwell group, while in substantial agreement with the findings of both reports, differs in certain specific conclusions and certain suggested means of implementation. Some phases of this same subject are currently under study by the Operations Evaluation Group and by the Weapons Systems Evaluation Group.

The Specific Conclusions and Recommendations of the report proper are based on the material included in the various Appendices. The General Conclusions and Recommendations, on the other hand, are not based on appendix material but stem from personal observation and belief of the Hartwell personnel. The content of these conclusions and recommendations was discussed exhaustively by the project membership and only a few changes were made as a result of the terminal meeting (see Appendix K) The final draft represents almost unanimous concurrence, a noteworthy circumstance in view of the controversial issues involved and the diversity of the staff.

The Appendix material does not, in most cases, embody the same degree of discussion and concurrence. The Project membership was divided into small working groups, each to study a particular phase of overseas transportation. Thus, the Appendices represent the thinking and approval of sub-groups, rather than of the entire staff. However, as noted above, the major conclusions and recommendations stemming from these Appendices received over-all endorsement.

The shortness of the working period made necessary certain editorial expedients One of these has resulted in non-alphabetical order for the appendices, and another is the use of marginal lining in the appendices This method of drawing the readers' attention to certain paragraphs is employed to indicate those ideas that the Hartwell group considers important. It in no way indicates what is old or what is new. In fact, no distinction is made anywhere in the report between old ideas and new ones. The group believes that the matter of emphasis is overwhelmingly more important than allocation of credit.

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PROJECT HARTWELL

SUMMARY REPORT

I. BASIC ASSUMPTIONS

STRATEGIC SITUATION

1. The adversary is the U.S.S.R. The U.S. will be joined by the North Atlantic Pact Nations.

2. The interests of the U.S. and its allies will be threatened in Europe, the Americas, North Africa, the Middle East, Japan, Southeast Asia, and India. (The group's thinking has been concentrated largely on the North Atlantic Ocean and its environs, but many of the considerations are equally applicable to other areas.)

3. The U.S.S.R. will have as a primary objective the interruption of intercontinental supply of men, materiel, and civilian supplies between the U.S. and its allies.

4. Overseas transport will be by ships primarily, with aircraft playing only a secondary role.

5. The U.S. and its allies will maintain air superiority over the sea lanes and harbors in practically all the ocean areas, and will deny operation of U.S.S.R. surface craft in practically all the ocean areas. (The group has not considered how this will be accomplished.)

6. It will be imperative for the U.S. and allies to keep open the sea lanes to harbors in its areas of interest, to ensure operation of port facilities, and to protect shipping against submarines and mines. (The major effort of the Hartwell group has been devoted to the problem of achieving this objective.)

TIME SCALE

Most of the Hartwell recommendations, if accepted and carried out with efficiency and dispatch, can begin to be in service in two years' time. This is in no sense a guess or a judgment as to when hostilities will commence, but simply an arbitrary date for which this group can estimate U.S.S.R. capabilities and by which date many U.S. countermeasures can be provided.

The Hartwell recommendations are still valid if the date of conflict is delayed or if there is no all-out war but only a series of "Korean incidents". On the other hand, it is obvious that little of the Hartwell program can be immediately effective in the event of all-out war in the

I. BASIC ASSUMPTIONS (cont.)

next few months; even so, these recommendations, if put into effect, during the course of that war would materially increase the nation's military capabilities.

U.S.S.R. CAPABILITIES

1. The U.S.S.R. is entirely capable of any particular major technological effort; but it cannot simultaneously carry out diverse large-scale projects with equally high priority. Because the importance of overseas transport to the Atlantic Pact nations is self-evident, it is axiomatic that the U.S.S.R. will concentrate on measures designed to disrupt and jeopardize shipping, particularly since such an effort in submarine and mine warfare would not make great inroads on its over-all economy. Therefore, it is to be assumed that the U.S.S.R. will manufacture and use mines, submarines, and submarine weapons, despite any intelligence that may seem to indicate the contrary.

2. By September, 1952, the U.S.S.R. can have a fleet of several hundred modern submarines equivalent in performance to the German Type XXI or the Guppy-snorkel. At a minimum, the U.S.S.R. will have 200 to 300 submarines, snorkel-equipped but otherwise comparable to current U.S.S.R. types. The Soviet construction capacity will be 100 such submarines per year.

3. The U.S.S.R. will have adequate stockpiles and production of long-range pattern-running and acoustic-homing torpedoes.

4. The U.S.S.R. will have available stockpiles and production of influence mines sufficient to mount a major mining effort. The present Soviet aircraft fleet is adequate to sow these mines in European waters; the present Soviet submarine fleet is capable of a small-scale mining effort in both European and U. S. waters.

5. The U.S.S.R. has atomic weapons. The U.S.S.R. may use atomic weapons against surface ships and against port installations.

6. The minimum effort that the U.S.S.R. can be expected to make against U.S. and allied shipping is serious.

II. SPECIFIC CONCLUSIONS AND RECOMMENDATIONS

ATOMIC WEAPONS

Tactical Air-Burst Weapons

1. Additional atomic weapons for tactical use can and should be developed; in particular, it is most important to develop light atomic weapons of small diameter, which can be delivered by small, fast, carrier-based aircraft. Such planes can approach

II. SPECIFIC CONCLUSIONS AND RECOMMENDATIONS (cont.)

ATOMIC WEAPONS

Tactical Air-Burst Weapons

their targets at low altitudes and deliver the missiles by means of a simple rocket from a range that ensures precision of delivery and reasonable safety of pilot and aircraft. Such weapons should prove useful against a great variety of military targets – for example, against ships, against shore installations, and against inland targets.

Effective anti-submarine warfare requires above all the knocking out of enemy port installations. For use against port installations, both air-burst and underwater explosions should be considered.

ASW Weapons

The use of underwater atomic weapons against submarines provides a means of obtaining a sure kill when identification is positive. Such an atomic explosive has, inherently, a large radius of action, sufficient to sink a submarine at least one mile distant from the point of detonation. Some of these weapons can and should be provided immediately.

Deep-Water Test

For more accurate evaluation of an atomic ASW weapon, the Navy should proceed with plans for a deep-water test explosion, with the bomb at a depth probably between 1000 and 2000 feet, and with submarines and submarine test bodies at various depths and horizontal distances from the explosion. The effect of a deep explosion upon surface vessels (here the threat is principally against us) can be determined in the same test. As part of the program, model tests and theoretical work should be pursued.

Military Planning

2. Too few Naval officers are adequately informed about the potentialities of atomic weapons, and the responsibility of planning for the use of atomic weapons is restricted to an even smaller group. Similarly, too little consideration is being given to defense against the use of atomic weapons by the U.S.S.R.

Unless the use of atomic weapons is an integral part of the military thinking of all ranks, the U.S. will enter any future war under a serious handicap.

U.S. Stockpile

3. The U.S. rate of production of fissionable materials should be increased immediately. The U.S. stockpile is already such that atomic weapons could be used tactically in large numbers. However, since the ASW weapon is only one of many conceivable important tactical applications, a larger stock of atomic explosives is highly desirable. An increased rate of production is technically feasible and economically reasonable.

II. SPECIFIC CONCLUSIONS AND RECOMMENDATIONS (cont.)

ATOMIC WEAPONS

U.S. Stockpile

For certain purposes, the cost of using atomic weapons is less than the cost of using any other explosive. Also, the cost of using an atomic weapon is reasonable when compared with the cost of finding, identifying and killing a submarine, or of finding, identifying and not killing a submarine.

U.S.S.R. Stockpile

4. Accurate information on the U.S.S.R. rate of production and stock of fissionable material would provide clues to possible Soviet strategic and tactical uses of atomic weapons. It is imperative to secure such information in order to gauge the magnitude of the problems of defending ports, sea task forces, and convoys (as well as for important non-naval objectives). Therefore, an extraordinary effort, utilizing the most ingenious and critical minds, should be made to obtain such knowledge.

OTHER WEAPONS AND WEAPONS SYSTEMS

Helicopters

5. The helicopter, as a vehicle invulnerable to torpedo attack, with a high search rate against submarines, the ability to operate with task forces, convoys, and fast independents, and to destroy submarines once contact is made, seems the most promising single weapon system for anti-submarine warfare. The development of a suitable all-weather vehicle, an improved sonar, and a weapon should be accelerated. Secure communications and station-keeping navigation should also be considered.

Airborne Hunter/Killer Tactics

6. The search problem and the attack problem are different. A "single package" system in which one plane carries radar, localizing and identifying equipment and weapons, although it may have its tactical uses, represents a costly technical and tactical compromise. Parallel development of team tactics, utilizing one plane equipped with the best possible search radar that can be built, accompanied by planes equipped especially for investigation and attack, is strongly urged. The principal factor influencing the efficiency of search is radar performance. Every effort should be made to improve it, and nothing should be allowed to compromise radar performance in the search plane.

The attack plane should be equipped principally for identification, fire control, and weapon-carrying ability. In this connection, improvement of MAD, development of sonobuoys, wake detectors, and effective killing weapons are necessities. A nuclear-explosive anti-submarine weapon should be considered. Effective liaison

II. SPECIFIC CONCLUSIONS AND RECOMMENDATIONS (cont.)

OTHER WEAPONS AND WEAPONS SYSTEMS

Airborne Hunter/Killer Tactics

between the attack and search units should be accomplished by a radar relay with video insertion. With this arrangement, the attack plane can be vectored without giving the submarine prior knowledge of the attack. In order to prevent neutralization of U.S. search radar by submarine countermeasure receivers, radar flooding is essential.

SSK

7. An anti-submarine submarine has certain unique advantages in the field of ASW, which make its development of great importance. It is capable of: (1) long-range listening; (2) all-weather operation, and (3) maintaining patrols in waters that are dominated by enemy aircraft. Results of recent experiments show that the use of large, low-frequency listening arrays may yield detection range of 100 miles or more on snorkeling submarines. Increased basic knowledge of the propagation of low-frequency sound in the sea is needed, and research in this field should be initiated immediately. Also, methods of communication and navigation, as well as SSK tactics, need investigation. There seem to be no technical obstacles to the development of anti-submarine submarines. Project Hartwell has not evaluated their tactical use.

MV Weapon System

8. A new concept of a weapon system for use with fast merchant vessels should be exploited. This system should incorporate a large low-frequency torpedo-detection array and a helicopter system. The anti-aircraft defense is not considered in detail in this report.

Small Craft

9. For certain operations, small patrol craft are desirable. The existing SC-PC type patrol vessel is relatively ineffective because of poor sea-keeping qualities and inadequate search equipment and armament. These defects should be eliminated and a new prototype vessel constructed and evaluated. The new vessel should incorporate maximum ahead-thrown armament and dunked or towed sonar, be economical to build and operate (wooden hull and standard engine design), and have centralized control of sonar data, fire control, and command to keep crew requirements at a minimum.

Torpedoes

10. An anti-submarine torpedo for use by surface craft or aircraft must not enter the water until it is close to the submarine, because long underwater approaches, to within the guidance range, result in a tremendous penalty in terms of increased torpedo size and long time-of-flight. With close entry, a guided torpedo should use low speed during search and fast closing speed after lock-on. The lock-on

II. SPECIFIC CONCLUSIONS AND RECOMMENDATIONS (cont.)

OTHER WEAPONS AND WEAPONS SYSTEMS

Torpedoes

running range should be consistent with the range of the sensing equipment. Torpedoes for use from surface ships should be airborne, probably rocket-fired, to the point of entry. Only in this way can the range be made sufficiently large to permit attack from surface ships out of range of submarine counter-attack. With intelligence supplied by helicopters or other long-range detection techniques, the air-water torpedo, properly developed, can restore the supremacy of the surface team.

Barrier Patrol

11. The protection of the Eastern Seaboard against enemy submarine action and long-range enemy aircraft can be strengthened through an AEW-ASW barrier patrol along the Nova Scotia-Bermuda-Puerto Rico line, a distance of 1500 miles. A barrier 90 per cent effective against both submarines and aircraft would cost in the neighborhood of $350,000,000 per year; $100,000,000 would provide a barrier 50 per cent effective. Such a barrier results in reduced costs in other operations by: (1) reducing coastal convoy escort requirements; (2) reducing coastal and harbor defense requirements; and (3) eliminating the requirements for IFF on the Eastern Seaboard.

SHIPPING AND PORTS

New Fast Ships

12. New fast merchant ships with sea speeds greater than 19 knots are imperative to meet the requirements of a global war and should be built now at a target production rate of 150 ships per year. The present merchant fleet of slow ships cannot support this type of war (as evidenced by the Korean experience). There are insufficient fast ships in the total allied merchant fleet to meet war requirements. Seventy per cent of the present available fleet of merchant vessels is slow and obsolete and suited only to restricted ocean routes. The new fast merchant ships should be flexible, all-purpose types, capable of fast turn-around through installation of fast cargo-handling gear and good cargo-stowage characteristics. They should be equipped with anti-submarine weapon systems including torpedo-detection arrays and helicopters. These vessels, so equipped, are considerably less vulnerable than slow ships to air and submarine attack and are the only type that can economically support a long supply line in wartime.

Port Dispersal

13. Action should be taken to place all suitable minor U.S. ports in a state of readiness to handle war shipping in case any major U.S. port is made unusable through enemy action. Dredging and terminal

II. SPECIFIC CONCLUSIONS AND RECOMMENDATIONS (cont.)

SHIPPING AND PORTS

Port Dispersal

rehabilitation should be begun, and interior transportation should be revised to permit diversion of export traffic through any combination of major and minor ports, both here and abroad.

Ship Turn-Around

14. Modern mechanical materials-handling equipment and industrially engineered work methods, with fast ships, can reduce turn-around time by a factor of two. Such equipment already exists and should be introduced in U.S. ports and integrated with efficient terminal operations. Modern cargo stowers and fast level-luffing cranes operating from mobile land mounts and self-propelled barges should be constructed. Joint military control over packaging of export freight should be instituted. Mobile military-port operating units should be activated, equipped, and trained. Longshore labor problems should not be allowed to interfere with reduction of ship turn-around.

DETECTION AND IDENTIFICATION

Sonar Development

15. Present sonar suffers from restrictions imposed by the compromises of multipurpose design and by failure to exploit all the possibilities of the medium. There is need for high-performance, specialized, single-purpose equipments; in particular: (1) low-frequency directional listening arrays; (2) echo ranging and listening from helicopters and special surface craft; (3) improved echo ranging for fire control; (4) echo ranging and listening from buoys, anchored or dropped from aircraft, and (5) listening gear for warning against torpedoes.

Research on Sound in the Sea

16. Sonar performance can be very greatly improved and underwater sound, in general, can be made much more useful to the Navy than it is now. However, in order to achieve these objectives within a reasonable time, the present scale of effort devoted to research and development in the sonar field must be very greatly extended. In fact, the present effort is trivial in comparison with the effort needed to secure our overseas transport. In particular, a major program of basic research on the behavior of sound in the sea should be initiated promptly in order to guide the exploitation of low-frequency sound for long-range detection, identification, tracking, communications and weapon guidance. More fundamental knowledge is especially needed about: (1) sound transmission phenomena, such as time and space coherence, diffraction effects, scattering, and the effects of thermal structure, including

II. SPECIFIC CONCLUSIONS AND RECOMMENDATIONS (cont.)

DETECTION AND IDENTIFICATION

Research on Sound in the Sea

geographic variations; (2) sound spectra of submarines, surface vessels, and torpedoes, and (3) applicability of correlation techniques and improved methods of data presentation.

New Methods

17. Several new methods for detecting submarines have shown enough promise in brief trials to justify further investigation. These include infrared wake detection, sonic detection of bubbles in the wake, and trail detection by ions or condensation nuclei. Underwater electrical potentials, and bubbles in the wake, look promising for short-range identification. Wake detection by pH measurement should be investigated. Longer-range MAD, using paramagnetic resonance, looks very promising on paper (See Conclusion 29).

DF

18. The current development of an interim direction-finding network should be continued, but with changes that will permit some interception of flash signals. This system can be in operation by 1952 and will always serve to intercept normal transmission and slowed-down transmission which might defeat a network designed for detection of flash. For the interception of flash transmission, main reliance should be placed on the development of an inverse SS Loran network capable of giving absolute fixes with average errors of ten miles or less, and fixes relative to one of our nearby vessels with three-mile errors. Such a system can be built primarily from existing equipment but requires development of a few devices for storage and data presentation. An experimental program should be initiated immediately.

Airborne Radar

19. Although the advance in radar techniques, represented by the APS-20 and subsequent developments, has nearly compensated for the initial advantage that the development of the snorkel gave to the submarine, radar performance is still marginal and snorkels will become harder to see in the future. For the future, the airborne radar program can and must be extended to include: a larger number of big-dish (8 × 3 ft.) search radars; development of much larger antennas, including sideways-looking antennas; increased support for research on sea-clutter, propagation, presentation, integration and correlation techniques; research and development on rapid-scan radar for attack, and plane-to-plane communication for hunter-killer teams. For snorkel search, it is more important to increase maximum detection range, now limited by power, antenna size and operator factor, than to reduce minimum range.

II. SPECIFIC CONCLUSIONS AND RECOMMENDATIONS (cont.)

DETECTION AND IDENTIFICATION

Presentation of Data

20. The methods now used to present radar and sonar information to the operator are inefficient. Great improvement in over-all performance can be obtained by making the presentation effective. The following ways of tailoring the output of the gear to the sensory capabilities of the operators should be investigated: (1) storing information and delivering it to the operator at a rate that is optimal for him; (2) repeating the presentation (from storage) of questionable signals; (3) building temporal integration into the gear, and (4) interleaving the outputs of slow-scanning devices to provide a more nearly continuous flow of data. The conditions under which the operators (especially sonar operators) work should be improved.

Radar Flooding

21. U.S.S.R. submarines can be, and almost certainly will be, equipped with simple radar listening receivers of the direct-detection type which will maintain a wide-band omnidirectional watch for radar pulses. Such a receiver can hear a search radar long before the radar can find the snorkeling submarine. Hence a submarine that submerges whenever the listener indicates the presence of a search radar will be safe from detection. The best counter-countermeasure is to insure that enemy submarines always hear radar signals (or simulated radar signals) in areas where we wish to use search radars. This can be achieved over an area of one million square miles by flying one hundred planes equipped with low-power radars or radar simulations, or by fifteen planes carrying high-power radars at high altitude. With about the same effort, spread more thinly, we could make an enemy submarine anywhere in the North Atlantic hear signals so frequently that it might decide to ignore them. Once this effect is achieved, our search radar is back in business. A significant part of the flooding job can be done by commercial or military transport aircraft on other missions, if they carry radar or radar simulators. The flooding technique is vital to the successful use of radar against submarines; it needs planning and a modest amount of development.

HARBOR DEFENSE

22. The defense of harbors requires an integrated system to counter aircraft dropping bombs and laying mines, submarines laying mines or attacking shipping in the harbor approaches, and sneak

II. SPECIFIC CONCLUSIONS AND RECOMMENDATIONS (cont.)

HARBOR DEFENSE

craft attempting to penetrate the inner harbor. A vital element of this system is an accurate method of traffic control of all shipping in the harbor area to make the harbor more efficient in bad weather and to steer friendly shipping away from defensive mine fields and enemy-laid mines. A radar system designed for traffic control could also be used for recording mine splashes. Mine sweeping, mine location and destruction, anchored sonars for detection of underwater craft, torpedo nets, and patrol craft must be developed and procured. It is urgent that we immediately survey all our primary and secondary harbors, plus those overseas harbors for which we will have responsibility, in order to establish a defense system appropriate to the harbors in question. Such surveys must include a study of the harbor bottoms in order to make possible mine location and disposal. A harbor-defense manual should be written and circulated.

MINES AND MINE COUNTERMEASURES

23. Countermeasures against mines should be studied vigorously and on a new basis. Unless successful countermeasures are achieved, the threat of mine warfare to our shipping will be so great that it would be difficult to exaggerate it. Mine measures and mine countermeasures should be the responsibility of a single group within the Navy. This group should have at its disposal laboratories, test stations, modification centers, and the closest liaison with military policy-making authorities. The development of equipment for mine location is urgent. Mine countermeasures should be integrated with other methods of harbor defense. Offensive mine warfare should be prosecuted primarily in terms of attacks against submarines. Close cooperation with the British and other Atlantic Pact nations is vital.

COMMUNICATIONS

Submarine Communications, Loran

24. Two-way communications between submarines and shore stations, surface vessels, aircraft, and other submarines can be greatly improved in quality and extent, while maintaining security. A thorough study of the use of the entire electromagnetic spectrum including underwater propagation at low frequencies, and the low-frequency underwater-sound region, plus correlation and presentation techniques, should be instituted. Such work may make possible IFF systems between submarines and other types of vessels

II. SPECIFIC CONCLUSIONS AND RECOMMENDATIONS (cont.)

COMMUNICATIONS

Submarine Communications, Loran

or stations. Secure Loran and private communications in general will be made feasible by the exploitation of new electronic techniques including correlation. Such an extension of submarine communications is a necessity if SSK techniques are to be used.

Secure Communications

25. Components for radio frequencies in the neighborhood of 50,000 Mc/sec should be developed for use in secure short-range communications and radar, in station keeping, and in short-range navigation. Hidden-transmission methods should be investigated.

Traffic Information Center

26. The present Atlantic Command Headquarters center for handling information is adequate for shipping control and for anti-submarine warfare based on the present naval doctrine which leaves considerable initiative to local and task force commanders. Should serious enemy air attacks develop along the Eastern U.S. Seaboard, or should broad use be made of AEW-type equipment, much more rapid and accurate methods of data handling will be required. Adoption of the Nova Scotia-Bermuda-Puerto Rico Barrier would make such a system mandatory.

OCEANOGRAPHIC PROBLEMS

27. The Navy should increase the amount of work being done on the physics and chemistry of the oceans. In particular, information is needed on: (1) the currents and bottom sediments in harbors and their approaches (for mine warfare); (2) on bottom topography and ocean currents in other areas (for submarine navigation); (3) on the oceanographic factors affecting the routing of convoys (particularly in coastal regions); (4) on the physics of surface waves and their effects on radar sea return and sonar reverberations; (5) on surf conditions, and (6) on the propagation of low-frequency underwater sounds and the causes of ambient noise.

ADVANCED-TYPE POWER PLANTS

28. Submarines: Significant improvement in submerged speed and range is possible. Present submarine diesel engines can be quickly converted to closed-cycle submerged operation with stored oxidant. Such a conversion might give a guppy-type submarine a 340-mile submerged range at 18 knots or a 3000-mile submerged range at 6 knots. This performance could be exceeded if new thermal power plants were installed in present or new submarines. The fuel cell is the only battery development that potentially surpasses the thermal power plant; further work is needed to delineate its characteristics. The submerged range of

II. SPECIFIC CONCLUSIONS AND RECOMMENDATIONS

ADVANCED TYPE POWER PLANTS

a successful nuclear-powered submarine will greatly exceed that of a chemically fueled submarine, unless either the sea water itself or the oxygen dissolved in the sea water can be efficiently used as an oxidant in the latter type. It appears possible to achieve significantly quieter submerged operation by the elimination of propeller cavitation and by the use of acoustic isolation in the design and installation of the power plant.

Torpedoes: New power plants now under development are distinctly superior to those used in World War II torpedoes. The engineering know-how needed to build a power plant for a small (approximately 500-pound), 30-knot speed, and 4000-yard range anti-submarine acoustic-homing torpedo is available now. Further research and development could increase the speed and range of all torpedoes. Virtually wakeless thermal power plants provide greater speed and range than electrical systems. Elimination of the noise due to propeller cavitation will make both thermal and electric power plants suitable for 40-knot acoustic torpedoes.

NEW-TYPE MAD

29. In the final stages of anti-submarine attack, it is so important to be able to locate a submerged submarine, and to identify it as such, that a vigorous effort to improve magnetic detection methods should be made. Present MAD, already highly developed, cannot be much improved, but magnetic detection utilizing paramagnetic resonance looks promising enough to warrant further investigation.

III. GENERAL CONCLUSIONS AND RECOMMENDATIONS

Note: The following general conclusions and recommendations are not elaborated or documented by appendix material.

FLEXIBILITY

1. Flexibility is one of the most important doctrines in our preparation for war. Since the enemy can choose the scale and locale of future war, it is imperative that our plans, weapons, and equipment be extremely flexible. It is as important to "stockpile flexibility" as to stockpile weapons, materials, and personnel.

SYSTEMS CONCEPT

2. The present bureau organization of the Navy includes no bureau concerned with the engineering of systems of which such items as ships or airplanes are components. The emphasis is on components, perfection of which does not assure excellence of

III. GENERAL CONCLUSIONS AND RECOMMENDATIONS (cont.)

SYSTEMS CONCEPT

systems. It is important that the concept of systems engineering be construed and cultivated broadly within, and especially between, the Material Bureaus of the Navy.

MEASURE AND COUNTER-MEASURE

3. The separation of measure development from countermeasure development, whether by secrecy barriers or by organizational structure, is detrimental. The two developments should interact. They should be administered by the same director.

HYDROFOILS

4. The present Navy program for hydrofoil research and development seems excellent.

ATTRITION

5. It is not enough to evade enemy attacks upon our ships. We must subject the enemy's weapons of attack to attrition.

MILITARY INTELLIGENCE

6. Since all our operations are vastly affected by intelligence or lack of intelligence concerning plans and capabilities of the enemy, we must make every effort to improve our intelligence about U.S.S.R. resources, production, and weapons development. It is obvious that if we have poor intelligence the scale of our effort must be greater, since we must then provide countermeasures for all possible weapons instead of all probable weapons. It is urgent that the scope of the intelligence effort be expanded, and that top-flight personnel be enlisted for all phases of the intelligence problem, that is, for the gathering, evaluation and dissemination of information about the resources and course of action of the U.S.S.R.

SELECTION AND TRAINING

7. The selection and training of operating personnel can make or break any weapon system.

TRUE SUBMERSIBLES

8. The U.S.S.R. may have true submersibles with high underwater speeds and low influence fields sometime in the forseeable future. Such submarines will be more difficult to counter than present Soviet types or the Type XXI, but countermeasures that are effective against the latter types will be useful against true submersibles.

STOCKPILES

9. Stockpiles of critical items should be built up now in the United Kingdom and in North Africa.

ELECTRONICS RELIABILITY

10. The desirability of electronics reliability need not be emphasized, since acceptance of the principle is fast becoming a matter of naval doctrine. However, in practice, this principle is often sacrificed for saving of space or weight, for multipurpose design, or for design to meet all possible future requirements. Simplification of design and intelligent analysis of military specifications

III. GENERAL CONCLUSIONS AND RECOMMENDATIONS (cont.)

ELECTRONICS RELIABILITY

can do much to make such compromises unnecessary. Steps should be taken (1) to increase vacuum tube life by improvements in the design of the tubes themselves and of the circuits in which they are used; (2) to simplify maintenance; and (3) to indoctrinate development personnel in the principle of electronics reliability.

IV. SUGGESTED IMPLEMENTATION

Work is under way, with varying degrees of boldness, on many of the recommendations listed above. It is the conviction of the Hartwell Project that certain items, old and new, deserve special emphasis and immediate action. These items fall into three categories. The first category includes items that require construction or production work with some engineering guidance. The second category includes items not yet ready for production engineering, and calls for immediate expansion of development activities. The third category requires reorientation of our present planning and administrative methods.

A. The following items require immediate construction with a minimum of engineering development.

1. Radar-flooding equipment.
2. Airborne radars with large sideways-scanning antennas.
3. New fast ships.
4. Modern port equipment in existing major ports and in minor ports.
5. Short-range rockets for delivering atomic explosives.
6. Harbor-defense radar.

B. The following items require extensive development work, and should be given immediate emphasis and extended support.

1. Deep underwater atomic tests with associated model tests and calculations.
2. Low-frequency sound gear.
3. Helicopters with dunked sonar and ASW weapons.
4. Mine-countermeasure systems, including improved, and simplified underwater object locators.
5. Secure communications and Loran systems.
6. Development in the 5-millimeter band.
7. A network for flash DF.
8. Paramagnetic resonance MAD.

IV. SUGGESTED IMPLEMENTATION (cont.)

C. The following items require changes in over-all planning.

1. Establishment of a mine and mine-countermeasure facility.

2. Exhaustive revision and improvement of the present underwater-sound program.

APPENDIX A

ATOMIC WEAPONS

I. GENERAL SUMMARY

A. Postwar Thinking

After the close of the war in 1945, the thinking of our civilian and military planners regarding nuclear weapons was influenced strongly by both fact and myth, among which the following ideas were predominant.

Myth: The atomic bomb was the "Absolute Weapon"; one bomb would "wipe out" Manhattan; a few bombs would make the earth uninhabitable.

Myth: Because it was the "Absolute Weapon", another war was unthinkable -- international control would surely be adopted.

Fact: There were then very few bombs; these, therefore, were enormously expensive.

By reason of this last fact, and because of its "absolute" nature, the atomic bomb would surely be reserved solely for strategic uses.

Fact: (?) The U.S.S.R. did not have the bomb. They would require 5 to 20 years to reproduce our achievement, not because of lack of scientific talent, but because of industrial ineptness.

Myth: Secrecy is synonymous with security; the tightest sort of secrecy implies the tightest security.

B. The Present Situation

The actual situation is now vastly different from both the mythical and the factual situations in 1945. The tactical and production picture has changed markedly in the intervening five years, and there is now grim realism in the international picture. Some relevant facts of 1950 are these.

1. The atomic bomb, i.e., fission bomb, is not an "absolute" weapon, but it is a tremendous asset in our arsenal.

2. International control is today as "unthinkable" as was war in the "atomic age" five years ago.

3. Instead of a few bombs, we undoubtedly have a stockpile of

several hundred atomic bombs today.

4. These bombs are variously estimated as costing between one and five million dollars each.

5. We know there is more than one type of bomb and that there is considerable flexibility in their possible design and use.

6. We are informed through AEC reports that production improvements and weapon improvements have added substantially to our strength.

7. We know that U.S.S.R. has atomic bombs, and that they have been intimately informed of our technical "secrets" (Fuchs). We do not know their stockpile or their production rate. It may even be greater than ours.

8. It appears that our production rate of atomic weapons has not been limited by any fundamental natural bottlenecks, but has been determined largely in the light of the past international situation. Without doubt a larger production rate than our past one is possible, either for ourselves or for the U.S.S.R.

C. Secrecy Versus Security

The realization of the relevant facts about atomic energy has been extremely restricted by the policy in this field that "secrecy is security". Also, as a consequence, the conclusions that should be drawn from the facts of atomic energy in 1950 have not been made or even considered to a sufficient degree.

The policy of "secrecy is security" was written into the Atomic Energy Act of 1946. This policy meant that the changing picture of production, of improvement, of assessment of the bomb as a weapon was available to only a few, and was denied, in effect, to those officers in the N.M.E. who are charged with the solution of difficult tactical problems for which we currently have no satisfactory weapons.

During the last year or two, some progress has been made in disseminating sifted information regarding atomic weapons to responsible officers and civilians in our armed services; but it is still apparent

that a full understanding and evaluation of these weapons is almost completely lacking outside the gr[illegible] that have the direct responsibility for atomic energy. Thus, when we find no planning for "operational requirements" or tactical uses of nuclear weapons -- offensively or defensively -- in the over-all submarine problem it is understandable; but it is also very dangerous.

The absence of the necessary general knowledge about atomic explosives in the armed services creates a most dangerous situation, for atomic weapons are a reality not only in our hands, but in those of our enemies, and a widespread and thorough understanding of their potentialities and probable uses is essential to any kind of military planning.

Our further development of the design and use of nuclear weapons will not progress at a satisfactory rate so long as the field remains a mystery to all but a small group. Under these circumstances, we are likely not to develop the best weapons and applications, and we may be unprepared for what the enemy has in store for us. It is typical that little or no consideration has been given to the use of these weapons against our ships or against submarines, and little thought has been given to their tactical employment in any field.

D. Dangerous Misconceptions

As a result of the earlier "myths" and the continuing secrecy, there are today a number of misconceptions about nuclear weapons, many of which are shared by even those who have had some degree of indoctrination. It is still quite commonly believed that:

1. Atomic bombs will probably never be used in large numbers. (By large numbers in this connection we mean a thousand or more.) False
2. They are necessarily 5 to 6 feet in diameter. False
3. They necessarily weigh several tons. False
4. Safety to plane and pilot requires that they be delivered only by large bombers and from high altitudes, 30,000 to 40,000 feet. False
5. They are useful only against large cities. False

6. The U.S.S.R. cannot produce them in significant numbers in the near future. False

7. They are extremely expensive. False

8. Secrecy still spells security in the atomic energy field. False

These ideas are simply not true, and their acceptance can have the gravest consequence. The adoption of these misconceptions by our military experts constitutes another of the relevant facts of the atomic energy picture of 1950.

Not only is very little consideration being given to weapons, but what is done is often wrong. For example, it is commonly accepted that atomic weapons would not be used against ships or submarines. This is typical of the false conclusions arising from incorrect and insufficient data.

E. Conclusions

GENERAL

Several broad conclusions are inherent in the facts of atomic energy in 1950.

1. Sufficient nuclear explosives can be made available for tactical uses.

2. Planning and development of tactical atomic weapons for the Navy should have high priority.

3. The tactical uses of the atomic weapons must be considered from two points of view: (1) how we may use such weapons; (2) how such weapons may be used against us and how we can counter the threat.

4. The secrecy policy as applied under the Atomic Energy Act of 1946 is endangering national security by enforcing an inadequately low level of work on the development of atomic weapons for tactical uses. Several changes must be made in this policy if an adequate level of thought, research, and development on tactical atomic weapons is to be achieved.

SPECIFIC

Stemming from the broad conclusions above and the documentation presented in Section II, specific conclusions and recommendations

may be drawn.

1. In the hands of the U.S.S.R., atomic weapons can be extremely dangerous against our shipping: the effect on a carrier task force or on a convoy may be disastrous; harbors and ports are similarly vulnerable.

2. In our hands, atomic weapons can probably provide an effective anti-submarine weapon; they can also be effective against enemy port installations and submarine bases. In particular, among other possible atomic weapons (guided missiles, bombs, artillery) a short-range fin-stabilized rocket carrying an atomic explosive should be designed to be fired from low-flying, carrier-based aircraft.

3. Further testing of atomic weapons against ships and submarines is needed; in particular, at least one deep underwater nuclear explosion should be made.

4. The production of atomic weapons should be materially increased in order to obtain an adequate number for the many possible tactical uses. The Hartwell Group believes that our goal should be about 10,000 atomic weapons.

5. The number of officers and civilian experts, serving the National Military Establishment, who are sufficiently informed about the facts of atomic weapons, must be increased. Specific encouragement should then be given to consideration of tactical uses of nuclear weapons by the research, development, and operations groups of the Navy.

6. As a catalyst in promoting a program of developing and countering nuclear weapons, a lecture series embodying the best present information on tactical uses of nuclear weapons should be prepared and delivered to cleared Navy personnel. Some preliminary ideas on this subject, in both the offensive and defensive aspects, are discussed in Section II of this Appendix.

7. It is essential that an extraordinary effort be made to

obtain accurate information on the U.S.S.R. production of atomic weapons. This intelligence effort should utilize the most critical and imaginative scientists and engineers.

II. ATOMIC EXPLOSIVES AS TACTICAL WEAPONS

A. Cost and Availability of Atomic Explosives

1. Dollars and Man-Hours

The cost of atomic bombs, estimated as between one and five million dollars each, is very small in terms of the destructiveness or of the range of effect. In certain circumstances, in dollar or man-hour terms, atomic bombs are the cheapest available explosive for a given amount of damage or radius of action. The limitations on the use of atomic bombs for possible tactical and strategic purposes arise from competing uses for the limited supply; and, as mentioned in Section I above, it is believed that this supply, which is already large enough to make tactical use attractive, can be substantially increased. The present stockpile may be several hundred nuclear weapons; several thousand nuclear weapons would certainly permit substantial tactical and strategic uses. For example, a reasonable fraction of such an augmented supply might make naval nuclear weapons decisive in anti-submarine warfare, as well as allowing for the possibility of useful amounts of mobile nuclear power.*

2. Size, Weight, Material, and Weapon Type

Atomic weapons differ from ordinary weapons in their functional dependence upon the size and shape of the weapon. Early models of atomic bombs were designed with a great excess of conventional explosives and other equipment to insure maximum efficiency, reliability and safety. Under the circumstances, this was the only

*A nuclear power plant for ship propulsion requires the equivalent in nuclear fuel of several nuclear weapons. It should also be noted, as indicated below, that not all nuclear weapons require the same investment in fissionable material.

reasonable approach to the design, but it resulted in a weapon so large and so heavy that it could be delivered only by our largest bombers and -- for reasons of safety -- only from altitudes of 30,000 feet or more.

Today, the situation is radically different. Although the size and weight of atomic weapons are largely determined by the auxiliary equipment and design, a wide range of sizes and a fairly wide range of fissionable-material content is now possible. In addition, a spectrum of nuclear weapons can be envisaged in terms of the amounts of uranium and plutonium included. It is because of these new possibilities that we believe that the tactical rather than strategic uses of fission weapons will be of the utmost importance in a future war.

3. Material and Explosive Yield vs. Size and Weight

a. Unit Weapon

For tactical uses, there are many obvious advantages to reducing the size and weight of atomic explosives. For the moment, we shall attempt to outline the cost of varying the size and weight of atomic weapons, in order that expenses may be balanced against the advantages that accrue. For this purpose, it is necessary to define a standard unit -- what we may call a unit weapon. For the unit weapon, we choose an atomic bomb yielding the nominal amount of energy equivalent to 20,000 tons of TNT, and using the minimum amount of fissionable material that is presently feasible for this purpose.

b. Explosive Yield as Function of Size

In reducing the size and weight of fission weapons, compared to the unit weapon, there are two directions in which we can proceed. We can reduce the size and weight while taking a loss in explosive yield -- that is, while reducing the equivalent number of tons of

TNT involved in the explosion. Or, we can maintain the TNT equivalent while compensating for the reduction in size and weight by increasing the amount of fissionable material incorporated in the weapon.

It appears that, in order to avoid changing much standard equipment, it would be desirable to obtain a fission weapon with a maximum diameter of 21 inches. We shall now compare such a weapon, weighing approximately 1700 pounds, with a unit weapon. It is believed that, by accepting the additional cost in terms of lost explosive efficiency, it would be necessary to sacrifice approximately a factor of four in explosive energy, reducing the TNT equivalence to approximately five kilotons, or perhaps somewhat less. In analyzing this choice, it is necessary to realize that the effective range* of an atomic weapon varies very closely as the one-third power of the total energy release. Consequently, the loss factor of four in energy release corresponds only to a factor of 1.6 in the range. If the range is originally 1.6 miles, the new range, after accepting the cost of going to 21-inch diameter, is now 1.0 miles.

In the above example, the range selected is not entirely accidental. A much closer discussion of the range of effectiveness of atomic weapons against various targets will be given in Section B. However, the order of magnitude used in the example is correct. It can be seen, therefore, that for many purposes it may be highly preferable to accept such a loss in range in exchange for the possibility of using tactical atomic weapons that are more effective from the point of view of availability, flexibility, and accuracy of delivery than are large air-dropped atomic bombs. Although, in the long run, it may be desirable to design special weapons, it seems possible to introduce atomic weapons into the naval fleet most rapidly by maintaining the present rocket and bomb sizes for air delivery and by fitting atomic weapons into the necessary configurations. The

* "Range" is the radius of action for a certain effect.

development program, both for the optimal weapons and for those that can be used more immediately with existing equipment, should be undertaken at once.

c. Material Investment as a Function of Size

The other method of reducing the size and weight of an atomic weapon, keeping constant its explosive yield rather than its atomic fuel content, results in the employment of approximately four times as much fissionable material in order to shrink the weapon to the 21-inch diameter. Although this factor may be somewhat changed, even in the near future, the order of magnitude appears to be correct at the present time.

4. Summary

Undoubtedly, further development of small weapons will change these estimates. Even present developments and immediate possibilities could be given a far more extensive and incisive treatment. Detailed design of tactical weapons may very well mediate between the two lines of approach described; however, a manual of weapon design would be out of place here. The crude ideas will suffice and the cost estimate should not change substantially. We may conclude that, for many purposes, the intrinsic cost need not be increased, because we can easily afford to accept the reduction of one-third in the range of effectiveness in order to obtain flexible weapons. For other purposes, it may be necessary to pay for three weapons, measured on our unit basis. Such a cost does not seem to be exorbitant, for, when tactical uses are considered at all, we should be, as we perhaps already are, in the position of being able to use bombs rather more freely than has been believed to be the case in the past.

In summary and as a general theorem, we can state that, other things being equal: the smaller and lighter a bomb, the greater will be the scope and frequency of application against military targets. It is, therefore, of great practical importance that we aim for the smallest and lightest design practicable in the present state of the art.

It is not possible to give definite lower limits to the size and weight of a bomb, for these will decrease with the increase of technical knowledge and skill, and will depend, too, on the specific purpose as well as on the choices between uranium and plutonium, each of which has definite advantages and disadvantages.

However, it is already clear that the cost of reducing size and weight of atomic weapons in order to make them practical for tactical uses is one that we can afford to bear.* Indeed, tactical atomic weapons are weapons that we cannot afford to ignore.

Atomic weapons are cheap in comparison with the damage that a submarine can do. A sure kill may save a large part of a convoy or a carrier task force, or leave in operation a port that might otherwise be knocked out.

B. The Effects of Nuclear Weapons

1. Introduction

The effects of nuclear weapons constitute far too broad a subject for full discussion here. A great deal of information has been collected and is available in several reports. [1,2,3] A brief discussion of the effects of nuclear weapons is presented below. It includes a listing of some of the effects anticipated

* It should be noted that the cost of an atomic anti-submarine weapon is not excessive in view of the cost of getting an opportunity. A contact and identification, "... in the average will probably cost at least $4,000,000...In this light how can anyone question the importance of providing the best possible Sunday Punch". J. A. Lee VX-1 and Aerial ASW, June 16, 1950.

[1] Effects of Atomic Weapons (EAW), Government Printing Office, June 1950.

[2] Technical Inspection Report, BuShips Group, Final Report on Test Able and Test Baker.

[3] Effects Produced by the Explosion of Shallow Charges in Deep Water with Particular Reference to the Atom Bomb, Report No. N.C.R.E./R. 147, by J. H. Powell and W. D. Hart, March 1950. Much of the material on model tests, used as a basis for the figures given, derives from this report and has been checked against both the Bikini tests and EAW.

and some specific estimates (based on various sources) of the range of effectiveness of nuclear weapons against submarines, against surface ships, and against ports. Certain information is also included because of its relevance to the problem of planning and evaluating a deep underwater atomic explosion. Finally, certain questions will be raised about which we as yet possess inadequate information. Because less material is available elsewhere about them, underwater explosions are emphasized here.

2. Summary of Air-Burst Information

The information relevant to air bursts of atomic weapons is particularly extensive and has been well presented in certain references (see EAW, Sec. 5.78-5.82). In the following table, ranges are given for the various effects that are expected.

Table II-1

Expected Effect	Range (in 1000 Yards)
Sinking and heavy damage	0.8 to 1.0
Moderate damage	1.5
Immobilization	?*
Median lethal dose to unprotected personnel (400 roentgen)	1.4
Skin burns	See EAW, 6.53-6.62**
Douglas fir burns	1.8
Douglas fir chars	2.2
Gabardine burns	2.0
Rubber (synthetic) burns	2.2

* The range at which normal surface vessels are expected to be immobilized is probably somewhat greater than the moderate-damage range quoted in the table. This inference is drawn from the fact that in the Bikini Baker test, for which a more thorough evaluation was made, the immobilization range is considerably greater than the moderate damage range.

** Skin burns involve such a complicated group of factors that a single range for all circumstances would be misleading.

These figures apply, of course, to vessels on the surface of the water. Because very little energy enters the water, the effect of air burst against submerged submarines is expected to be entirely negligible. Although we shall discuss the underwater nuclear explosion far more thoroughly, present information seems to indicate that the air burst may be the more effective against surface ships.

3. Anticipated Effects from Underwater Nuclear Explosions

Three effects may be distinguished in discussing underwater nuclear explosions:

(a) Shock;

(b) Base surge;

(c) Wave effects.

Most of the available information concerns the shock effect, which appears to be the most important. Much less is known about the base-surge effect, which is far harder to evaluate. There is also information from the Bikini Baker test about the wave effect in shallow water, which so far does not appear to be significant as a weapon.

The underwater burst can be discussed in terms either of its effectiveness against surface ships or its effectiveness against submarines. More information is available about underwater bursts against surface ships. However, a certain amount is known about submarines, and it is rather encouraging from the standpoint of using nuclear weapons in undersea warfare.

Both underwater and air bursts will be effective against ports.

4. Underwater Nuclear Explosions Against Surface Vessels

a. Eventual-Sinking Range

The effectiveness of atomic weapons against surface vessels is much better known than the effectiveness against submarines. Using the nominal atomic bomb of 20 kilotons equivalent TNT, the range is probably about 750 yards when the burst is produced at the optimum

depth under the water. This range is defined as the range within which all normal surface ships will be sunk -- not immediately, but eventually. Using this criterion, it appears that the optimum depth at which an explosion should be produced is approximately 1300 feet below the surface of the water. However, the effect is not particularly sensitive to the charge depth between about 600 and 1800 feet. (see Fig.II-1).

According to the results of the Bikini Baker test (as summarized, for example, in EAW, p. 176 ff) the eventual-sinking range at Bikini was about 600 yards from surface zero for a nominal atomic bomb, and the range for all types of vessels was very much the same. The range of 750 yards quoted above is the result of applying scaling factors to model experiments involving a model Bikini and a model deep-water test. The agreement between the results of model testing and the Bikini Baker tests lends credence to the 750-yard range (see Fig.II-2). Other estimates have been made, for example, in EAW: the "heavy damage range" has been estimated to be about 1000 yards for a deep underwater burst. Therefore, 750 yards may be somewhat conservative, although the definition of heavy damage is so lax that the 1000-yard range could hardly be used. From the Bikini results, it may be directly inferred that some ships will be sunk out to approximately 900 yards in a shallow underwater burst. This implies that some ships would also be sunk beyond 750 yards by a deep burst.

b. Other Ranges

Other ranges may be defined. The range for immediate sinking, for example, is somewhat less, approximately 600 to 650 yards if the bomb is at optimum depth. Again, ranges for lighter damage could be defined. Reference to experiments using models at approximately 1/50 scale on a linear basis leads us to the conclusion that other ranges are somewhat more sensitive to the charge depth (see Fig. II-1 and II-2). For example, light damage is substantially increased by placing the explosion at greater depth. On the other hand, the immediate-sinking radius decreases (in certain cases) when the charge depth is increased.

The light damage that occurs beyond the eventual-sinking radius may have great importance. For example, heavy damage to boilers at the Bikini Baker Test extended to approximately 750 yards, and moderate damage to the same kind of equipment extended as far as 900 yards. It was believed that the radius at which ships would be immobilized by the shallow underwater blast would be approximately 1000 yards. An estimate has been given in EAW that the immobilization radius for deep underwater explosion may be 1500 yards. In any case, the immobilization radius should be considerably greater than the 750 yards quoted as the sinking radius (see Fig.II-2).

c. Effect of Ocean Bottom

Setting off a charge on or near the bottom of the ocean enhances the damage and increases the range compared to an explosion at the same charge depth but with no bottom. By using the bottom effect, an increase of approximately 50 to 60 per cent over the largest range in infinitely deep water may be obtainable. From this consideration, it is clear that surface vessels are not saved from deep underwater-burst effects by sailing in the comparatively shallow waters that some of our convoy routes are likely to travel.

d. Summary of Shock Damage

Another way of summarizing the data on surface-ship damage would be to say that a deep underwater burst may have effective ranges against surface ships 25 to 50 per cent greater than at the Bikini Baker test. The worst conditions from the point of view of ships, when the bottom is found at exactly the right depth, are likely to lead to ranges of effectiveness for atomic weapons against surface vessels of approximately twice those found at Bikini.

All the above estimates are made while maintaining the explosive yield at the nominal value of 20 kilotons of TNT. As has been mentioned previously, if the explosive yield is changed, the range should be scaled as the 1/3 power of the explosive yield: a factor of 1/4 in explosive yield leads to a range approximately 2/3 the initial one.

e. Further Possibilities

As pointed out above, light damage leading to immobilization extends considerably beyond the eventual-sinking range. Also, the damage produced beyond the eventual-sinking range can be increased by increasing the charge depth. The charge depth at which the immobilization range is maximized is undoubtedly greater than 1500 feet.

It may prove tactically most effective in many cases to optimize the immobilization radius rather than the eventual-sinking radius. Immobilized ships may be disposed of with other weapons or possibly successive atomic explosions. The number of ships that can be thus disposed of is probably far greater than the number that can be sunk as the result of the primary atomic blast.

Also, reference to Figure II-2 indicates that the damage produced beyond the eventual-sinking radius by appropriately deep charges is only slightly less than that needed to cause eventual sinking, whereas it extends much farther. It may therefore be possible to lengthen the eventual-sinking range considerably by a simultaneous increase both in the charge depth and the explosive yield. Nevertheless, it appears that the important thing is to maximize the immobilization range due to the primary underwater burst.

The entire problem of evaluating the effect of atomic explosions upon ships beyond the eventual-sinking range probably requires further study. Operational difficulties encounted on ships beyond this range may make them "sitting ducks".

f. Base-Surge Effects

Up to this point, the discussion has considered only the shock-wave effects from an underwater explosion. There are other effects of underwater atomic weapons which are considerably harder to evaluate. Of these, the most impressive is probably the base-

surge effect (see, for example, EAW. p. 41 ff, and p. 143 ff; also p. 276 ff).

It is now clear that the base surge, a cloud of spray highly contaminated with radioactivity which sweeps out after the underwater burst, was not a specialized phenomenon seen only at Bikini but can be expected to occur in many types of underwater explosions. The depth at which the charge should be placed in order to produce the maximum base surge differs from that required to produce the maximum shock effect against surface ships. Although the charge depth for maximum base surge is not so great, an atomic explosion at approximately 500-foot depth would probably be reasonably effective for both purposes. As the charge depth increases, however, the base surge becomes a less important factor and finally disappears, probably at a depth of approximately 1000 feet. At optimum, the base surge can be expected to be approximately 25 per cent larger than that produced at Bikini.

g. Debatable Value of Base Surge

The radioactive effects of the base surge are of debatable value. Only the crudest ideas on this subject can be presented here.

Possible serious effects of the radioactivity on stationary targets are discussed in Section 6. An indication of their magnitude may be gotten from the example of the U.S.S. Crittenden which, in the Bikini Baker test was located approximately 1700 yards from surface zero. A small leak was present in the seal of the after-ventilation system. Through this leak, sufficient radioactively contaminated aerosol is believed to have entered to "kill all personnel in the after engine room".* On the other hand, many statements are available to the effect that the amount of radioactive contamination left by the base surge was too slight to have constituted an adequate weapon.

In addition to the problem of evaluating the radioactivity

* NDRL Report No. 551

as a weapon against stationary targets, the evaluation of the base surge against ships involves the question of their mobility. Because the base surge takes several minutes to form and to sweep out to reasonable distances from surface zero, proposals have been made for vessels to outrun the base surge in the event of an underwater burst. This may be possible for ships outside the immobilization range, but ships within this range will be overtaken and engulfed.

In the light of conflicting opinion as to the value of base surge, a critical investigation of this field seems desirable, particularly an investigation of the breathing and ingestion problems raised.

h. Wave Effects

The possible wave effects observed at Bikini were disappointing from the standpoint of weapon use. Whether or not they will inevitably be unimportant seems a little harder to answer. However, unless new information indicating their significance arises, it seems necessary to discount them and to concentrate primarily on the shock and secondarily on the base-surge effects. It should be pointed out, however, that at least one ship, the U.S.S. Saratoga, suffered substantially from wave damage (see EAW, P. 178 Sec. 5.118).

5. Underwater Nuclear Bursts Against Submarines

a. General

With respect to the effects of underwater bursts on submarines, the information available is much less extensive. The conditions of the Bikini test were unfavorable for causing submarine damage; therefore, most of the conclusions about submarines must be drawn on the basis of small-scale tests, extrapolated by use of the same type of scaling laws that prove successful in interpreting surface damage. Unfortunately, the submarine problem suffers from the addition of a new dimension -- the depth of the submarine. As a result, model experiments have provided less-adequate data, and the

interpretation of these data is less clean-cut. For surface ships, model data can be calibrated against the Bikini test; for submarines, such a calibration is less meaningful.

Nevertheless, use of underwater nuclear explosions against submarines seems hopeful; it appears possible to sink submarines at considerable distances from deep underwater bursts. If the submarine is at an appropriate depth, it is probable that the horizontal range of sinking will be two miles.

Even less is known about the effects of an underwater explosion upon submerged submarines that are beyond the sinking range of an underwater burst. To what distances submarines will be immobilized is completely unknown; similarly, in what region they will be forced to surface is only a matter of speculation. Doubtless the ranges for these effects are very large.

b. Effect of the Depth of Submarine

When the submarine is acting as a surface vessel, it is at least as hard to sink as other surface vessels and possibly, as indicated by model tests, somewhat harder. As the depth of the submarine increases beyond 100 feet, the ease of sinking becomes far greater. The sinking range probably increases approximately linearly at first, reaching about a mile when the submarine is at the depth of a hundred feet and possibly extending, as mentioned above, to two miles when the submarine is 200 feet or more beneath the surface (see Fig. II-3).

c. Effect of Charge Depth

The effect of charge depth on submarine damage is quite marked. For submarines submerged 200 feet at 1000 yards from the explosion, an explosion 100 feet deep may be sufficient to cause sinking. However, for submarines at greater distances the charge depth must be increased; for submarines at 1500 yards it is probable that the charge depth must be nearly 400 feet in order to cause sinking damage. It is by increasing charge depth to the

order of 1000 feet that it appears possible to cause submarine sinking at a mile and a half or two miles. Optimum charge depth is probably greater than 1000 feet (see Fig. II-4).

From this discussion, it is clear why the conditions at Bikini led to a submarine sinking radius of approximately 900 yards. It is also clear that a true deep burst will lead to a great increase in sinking range. To check the factor of 4 or more that may be gained in the range, further testing is highly desirable.

d. Effect of Ocean Bottom

Just as for surface ships, the presence of the ocean bottom at charge depth seems to increase the damage done by an underwater burst against submarines. Unfortunately, because of the approximate nature of the experiments, this effect has not been so well evaluated for submarines as it has for surface vessels. A crude comparison between bottom effect at optimum depth and largest range at infinite depth leads to the belief that the bottom effect for submarines is about the same as for surface vessels.

e. An Interesting Possibility

At a charge depth of approximately 3500 feet, it appears that eventual sinking of normal surface vessels has been eliminated, even at surface zero. The charge at this depth is clearly far too deep for effective use against surface vessels. On the other hand, a charge at this depth may still be enormously effective against submarines. This implies that deep explosions (if correctly planned) may be used against submarines, even in the presence of surface vessels of our own fleet. It may be possible to sink a submarine in a radius of over a mile while leaving surface vessels at a radius of half a mile unaffected.

6. Use of Atomic Explosions Against Ports

The defense of ports against atomic weapons constitutes one of the most serious problems in a future war. Although no extensive attempt is made here to evaluate them, the consequences of both shallow underwater and air burst atomic explosions in our ports

should be anticipated. The employment of atomic weapons against Soviet harbors, port facilities and submarine bases should also be considered.

The use of an air burst against port facilities can be evaluated by reference to the extensive material in EAW on air burst damage to cities in general. A certain amount of information can be derived from Table II-1 in Section 2.

A shallow underwater atomic bomb burst for use against harbor facilities can be evaluated by reference to Bikini data in EAW (p. 178). It has been estimated that the air shock effects of such a burst taking place within something like one-half mile from shore "would cause serious damage to harbor facilities and to warehouses and other structures near the water. Appreciable damage would, of course, occur some distance away." Wave effects should be more serious in the case of ports than they are against ships. A mile from surface zero at Bikini, the maximum wave height from trough to crest was about 20 feet, and even at 2 miles the wave height had a maximum of about 10 feet. Such waves could do serious damage.

The base-surge effects are clearly not escapable in the case of port facilities. The radioactive contamination and the dose from the base surge as it passes over the neighboring regions are well summarized in EAW (8.84 to 8.100). Lethal doses of radiation may be received several miles from the point of detonation, and contamination may be serious over more than a mile (see EAW, Figs. 118.91b and -118.91c). However, it should be remembered that the radiation dose rate dies off quite rapidly, and that decontamination and burying of radioactivity are possible.

7. Need for Further Testing

The information used in estimating the effects of an atomic underwater blast on submarines comes almost exclusively from model experiments which are scaled up according to laws that agree with

the necessary scaling between model Bikinis and the full-scale Baker test. It would be reassuring, however, to have a full-scale test performed with sufficient submarine test bodies and submarines for calibration.

Some of the criticisms that can be leveled against the model tests are: (1) the use of model tests involves a double-scaling problem in which not only the pressure and energies that lead to damage are scaled but also the damage itself must be scaled; (2) the type of model used in previous submarine tests is certainly only a crude representation of an actual submarine; (3) the ranges so far tested correspond to about one mile at full scale. The conclusion that submarines can be sunk at two miles by a deep burst is an extrapolation from present data.

Although the present data warrant the belief that submarines are vulnerable to atomic weapons (at least in the region of one mile), it is extremely important to check the conclusions drawn above. Further model testing can help in getting an accurate evaluation of the underwater burst as an undersea weapon. It is desirable to compare the model data with data from a full-scale underwater test.

The information from the Bikini Baker test is consistent with the picture presented here for submarine damage. However, the conditions at Bikini were unsuitable for testing submarine damage. The water was too shallow for adequate anti-submarine use of underwater explosions. The charge depth was less than 100 feet, whereas anti-submarine weapon depths should be more than 1000 feet. Consequently, our only full-scale test of underwater atomic weapons does not bear cogently upon the use of atomic explosives as anti-submarine weapons, and the estimates of submarine-sinking range made above require further full-scale testing.

The most significant effect to seek in a deep underwater test is the submarine killing. Such a test should not be designed to test simultaneously the base-surge effect and submarine killing. For base-

surge effect, the charge depth should be approximately 500 feet, while present evidence indicates that submarine sinking increases as the charge depth increases beyond 1000 feet. A true submarine weapon test should be made with a charge at 1500 or possibly 2000 feet.

Such a deep test is useful also for evaluating the effects of deep underwater blasts against surface ships. In particular, the increase of surface-ship immobilization range with increase of charge depth can be checked concurrently with the submarine-killing effect. For maximum immobilization range against surface ships, the charge depth should be at least 1500 feet and possibly more.

Regardless of the final decision for charge depth, it will undoubtedly be necessary to distribute submarine models at various depths in order to get adequate insight into the submarine-killing problem. These models should be calibrated by providing a small number of submarines for the test.

At least one deep test is necessary; more may prove desirable. Although the base surge may be a valuable weapon against ports, it has been once tested at Bikini and should not be allowed to divert the aim of a true deep test for submarine killing and surface-ship immobilization.

8. Summary

Information about the air burst as a weapon against surface ships is collected in Section 2 (see Table II-1). Underwater explosions against surface ships are discussed in Section 4, while their employment against submarines is discussed in Section 5. The information on underwater explosions is briefly summarized in Table II-2 below.

Damage to ports is briefly treated in Section 6. In Section 7, the need for a true underwater test is discussed, and some considerations relevant to its planning are given.

Table II-2		
EFFECTS OF DEEP UNDERWATER BURST		
Expected Effect	Range (in 1000 Yards) Surface Ships	Submarines
Sinking	0.75	2 to 4
Moderate damage	0.9	?
Immobilization	1.4	??
Base-surge radioactive contamination	*	
Wave effect	Small?	
*See Section 4-g		

Certain conclusions should be emphasized:

1. Present data indicate that air bursts are somewhat more effective than underwater bursts against surface ships.
2. Very-deep underwater explosions may present great advantages both against surface ships (increasing immobilization range), and against submarines (increasing sinking range).
3. Submarines seem to be more vulnerable to atomic weapons than do surface ships.
4. In very shallow water (less than 500 feet, perhaps) the effectiveness of underwater explosions is decreased because of insufficient charge depth.
5. The effect of the ocean bottom is to increase the damage. This increase, at maximum, results in approximately 60 per cent increase in the ranges quoted for deep-water explosions.
6. The damage to a ship from an underwater atomic explosion is either so great where the range is small, or so thoroughly spread over the vessel at large range, that damage control becomes extraordinarily difficult, if not impossible.

7. Against ports, both air bursts and underwater explosions will be effective.

8. Further testing of underwater explosions is needed, especially a deep-burst test, largely oriented to increase the accuracy of evaluation of atomic weapons against submarines.

C. Tactical Uses of Atomic Weapons

1. Opportunities for Atomic Weapons

Atomic explosives can be used against both land and water targets by both the U.S. and the U.S.S.R.

a. Land Use

Many tactical uses of atomic weapons in land warfare can be considered.* Possibly, beachheads can be cleared with atomic weapons; and if correct altitudes are chosen for air bursts, landings may be facilitated.

b. Naval Use

1. Ports and Pens: - In considering the effect of atomic weapons on the general problem of maintaining our shipping, several opportunities for atomic weapons should be pointed out. Atomic explosives are needed as weapons against enemy ports, to prevent submarines from being repaired and outfitted and from leaving their bases. We must also anticipate possible Soviet use of atomic explosives against our ships and ports.

2. ASW Use: - In addition to their use against port installations, harbors, and submarine pens, atomic weapons are valuable for use against submarines. In certain circumstances, for example, if a submarine is identified near a carrier task force, a sure kill should probably be the first objective. In such a case, atomic weapons might be employed at once. An underwater atomic explosion will certainly have a large guaranteed range of killing submarines at any reasonable depth (a submarine that remains on the surface, is, of course, vulnerable to conventional attack).

* See for example, Appendix B of Project MAID Report.

3. Other ASW Use: - In other cases, the immediacy of submarine killing may not have the same importance. Nevertheless, atomic weapons present real advantages in ASW use. These advantages stem from the great range of killing around the point of detonation.

In certain circumstances, a submarine contact will be obtained with sure identification -- for example, when the submarine has been seen on the surface or when it has fired torpedoes. If the submarine has not been definitely sunk by the immediate use of conventional weapons, it becomes necessary to maintain contact with the submarine until killing has been achieved. To maintain contact within the range of a mile and a half or so necessary for obtaining a kill with atomic bombs is far simpler than to maintain contact to within the small range of conventional weapons.

On the problem of maintaining contact, reference is made to Appendix D. One crude system may be useful as an illustration. Listening sonobuoys could be carried by search planes, thrown from surface vessels, or shot out to great distances in extremely simple rockets. Such sonobuoys would cost a few hundred dollars each and would be capable of locating a submarine within about one mile. A large supply of them could be distributed over the ocean surface, and they would provide sufficiently accurate ranging for a submarine moving at reasonable speed. A submarine that attempts to avoid detection by moving at extremely slow speeds in order to decrease the noise output will stay within atomic-bomb range for some time. In either case, therefore, atomic weapons can be brought up by carrier-based aircraft for the purpose of securing a certain kill.

c. Use Against Surface Shipping

Atomic weapons can be used against surface vessels. The U.S.S.R. may find it advantageous to employ them to disrupt our shipping; they may eventually be able to equip airplanes for atomic bomb delivery, not only against harbors, but also against our task forces and convoys. They might also find it advantageous to equip some submarines with atomic weapons to be used either against our sea forces or our port installations. In this case, the importance of knocking out such a submarine is all too obvious.

Soviet use of atomic weapons against convoys, for example, would force upon us extravagantly large ship spacing. The area covered by a convoy consisting of a large number of vessels with large spacing would become extreme, and the cost of providing adequate protection would rise correspondingly. Resorting to smaller numbers of ships per convoy provides only a partial answer, for the number of convoys then increases, and the cost of protection runs high while the number of targets on the ocean increases. On the other hand, abandoning the convoy system entirely puts us back in the position in which we found ourselves at the beginning of the last war, and similar disastrous consequences may be expected from submarine warfare. A solution to this difficulty appears to lie in the new fast ship program (see Appendix B and C) and in extremely efficient anti-submarine warfare. Again, the value attached to eliminating enemy submarines is incalculable.

Although the U.S.S.R. would probably have more motivation for using atomic weapons against surface shipping, some opportunities may be presented to the U.S. also.

2. Variety of Nuclear Weapons

To exploit our opportunities for using atomic weapons, not only are a large production rate and stockpile requisite, but more than one type of atomic weapon is needed. Air-burst weapons are needed against surface ships and land targets. Underwater explosives provide an anti-submarine weapon and, when used at extreme depths, may prove even more effective than air bursts against surface ships. Both air bursts and shallow underwater explosions must be considered for use against harbors and port installations.

Extremely tough missiles are required to penetrate resistant structures such as submarine pens; such a weapon already exists. For water entry, far less structural strength is requisite; this problem is susceptible to many solutions. Air-burst weapons present an even milder structural problem.

a. Airbursts

The appropriate weapon for air burst is different from an underwater atomic bomb dropped from an airplane. For air burst, the weapon should utilize a short-range, accurate rocket to carry the atomic explosive.

In order to avoid early detection, interception and anti-aircraft fire, and in order to achieve high accuracy, low-flying aircraft should be employed in delivering atomic weapons. It is likely that, for most tactical uses against military targets, an aircraft a few hundred feet above the surface will be most effective.

Delivering an atomic airburst from low-flying aircraft can be achieved most simply and reliably by using an atomic bomb as the explosive in a short-range fin-stabilized rocket fired from a low-flying airplane. A rocket range of four to five miles will insure reasonable safety from anti-aircraft fire as well as from the explosion itself. A radar sight, in conjunction with a simple time fuse or airlog, will insure accuracy of delivery. With such a mechanism, the probable error should not exceed 100 yards in deflection and 200 yards in range.

For firing from the ground or from a ship, the same weapon could be used, but the dispersions may be large unless pre-set controls or some type of guiding is employed. A spin-stabilized rocket should be considered for this application.

In addition to preparing rocket atomic weapons for our use, we should anticipate the Soviet use of rocket delivery to create air burst against either ships or ports.

b. Underwater Explosives

Against ships or submarines, an atomic bomb might be equipped with a simple depth fuse. With the fuse set for a depth of 1000 feet or more, an airplane flying 400 miles an hour would be more than a mile away from the explosion even if the sinking rate is 100 feet/second. This distance is more than adequate to insure the

safety of pilot and plane because the effect of such an explosion is largely confined to the water.

For use in shallow water -- for example, against ports -- such a bomb equipped with a time-delay fuse set for 20 to 30 seconds' delay can be delivered safely from low altitude.

Such bombs constitute the most obvious type of weapon for underwater anti-shipping applications. It is possible, however, that the U.S.S.R. may consider using atomic torpedoes; atomic torpedoes could be developed, although only airborne torpedoes appear to possess advantages for our use.

3. Value of Intelligence; Gathering and Evaluating Information

In any consideration of possible uses of atomic weapons by the U.S.S.R., the greatest value attaches to accurate and comprehensive intelligence. It is essential that we know the Soviet sources and supply of fissionable material and weapons, their technical developments, and their intentions. The Soviet utilization, for example, must be linked to supply; if we are to avoid dissipating our energies in futile attempts to counter every conceivable use of atomic weapons, we must have intelligence that will indicate the priority of probable use. Our port defenses, convoy spacings, and shipping losses, are only a few examples of the problems that are greatly influenced by the state of Soviet atomic technology. We must obtain the most accurate possible knowledge of U.S.S.R. weapons progress.

In order to gather and evaluate the necessary information, imaginative technical and scientific personnel must be employed in all intelligence activities. A smooth flow of information through the people gathering information, those evaluating it centrally, and those engaged in parallel technical development in our own laboratories must be devised and implemented. The results to be obtained are of utmost significance. Some of the most inventive and critical technical people must have access to the entire field

of intelligence activities and problems, must be free to devise intelligence systems, and must be given intellectual responsibility for getting the best over-all job done.

4. Final Remarks

Since the conclusions of this Appendix are presented in summaries of the various sections and in the General Summary (Section I), it is unnecessary to reiterate them here. Briefly, the important role of fission weapons will be in tactical rather than in strategic fields. Such a change in emphasis has a great military advantage to us, and the possibility of U.S.S.R. tactical use is one for which we must be prepared.

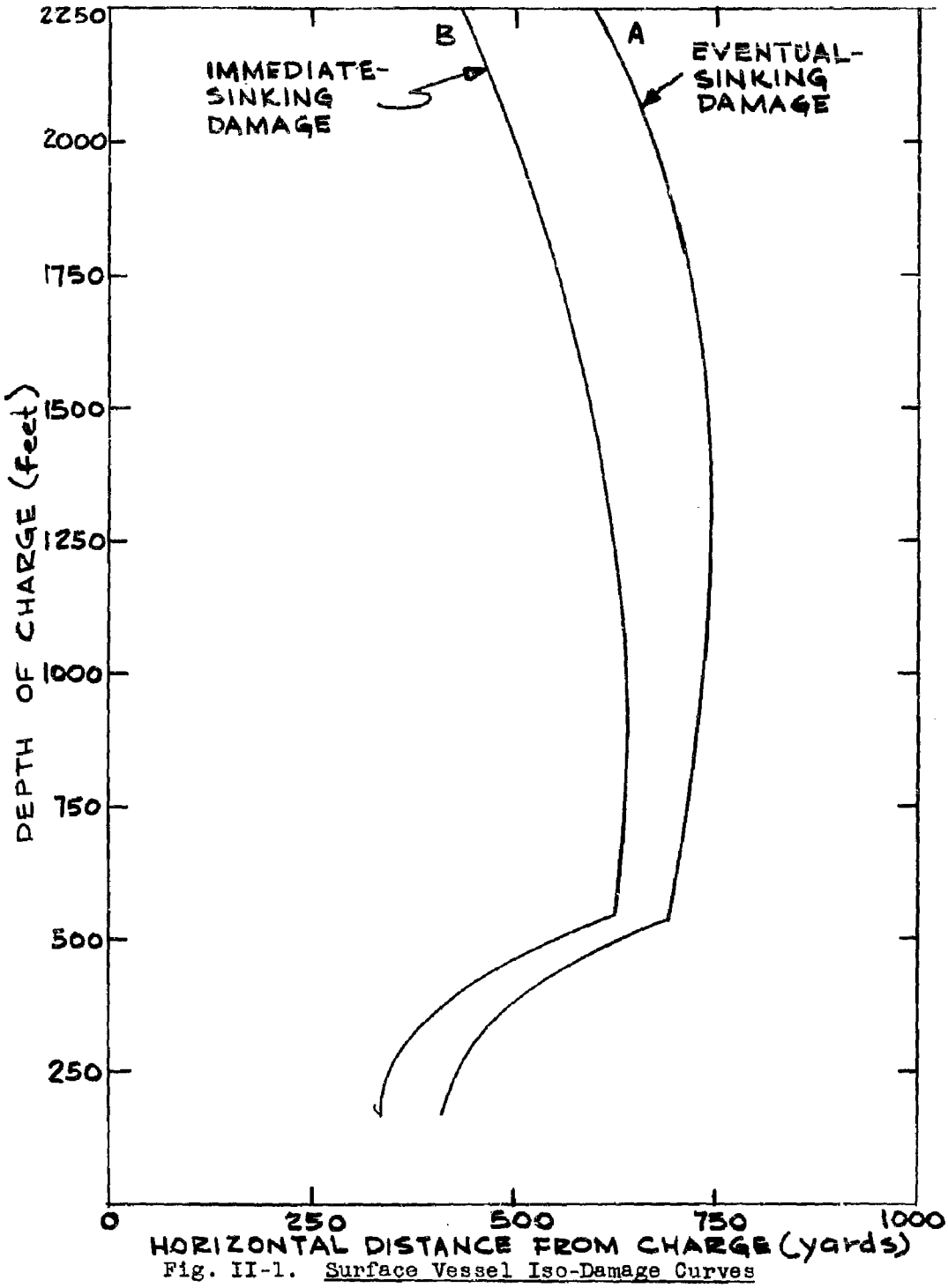

Fig. II-1. Surface Vessel Iso-Damage Curves

The iso-damage curves corresponding to immediate sinking and eventual sinking are plotted. The optimal charge depth increases as the damage requirement decreases, passing from about 700 feet for optimal immediate sinking to 1300 feet for eventual sinking. The optimum depth for immobilization is clearly considerably greater than 1300 feet.

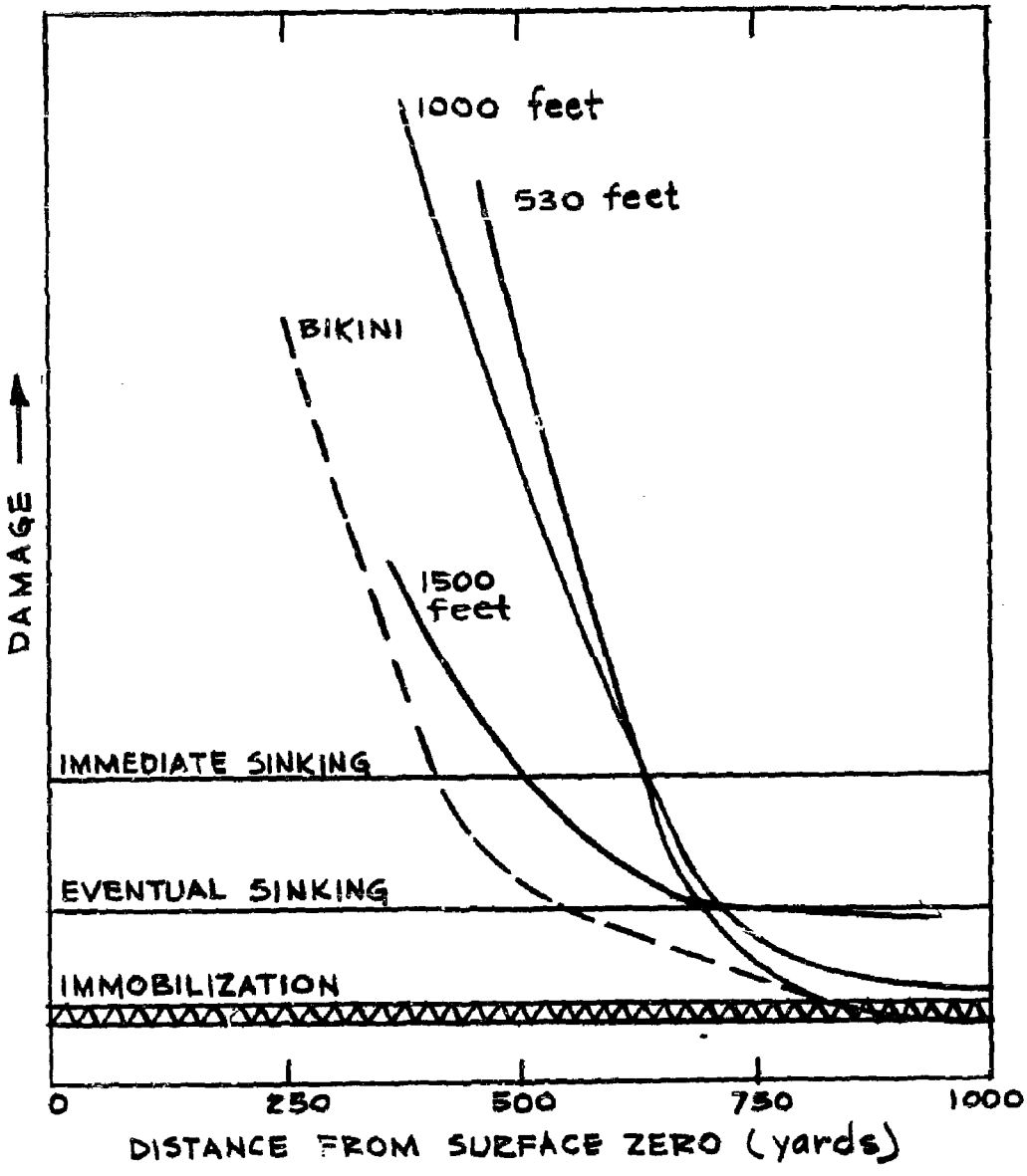

Fig. II-2. Damage to Surface Vessels

The damage to surface vessels has been measured in terms of the depression caused in the panels of the hulls of models. A Bikini curve is included to show the calibration, and other curves are labelled with the charge depths for a deep-water burst.

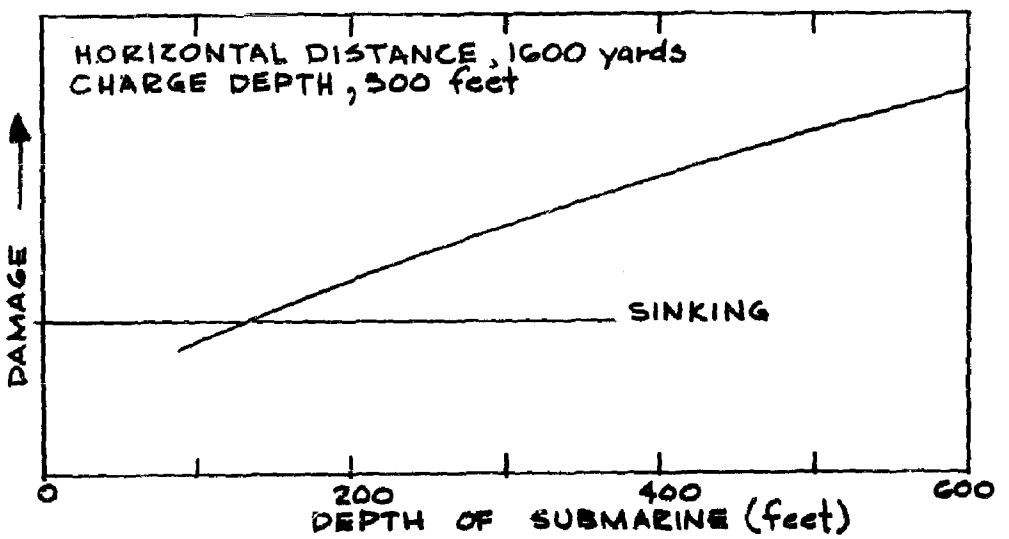

Fig. II-3. Effect of Submarine Depth

The damage has been quantitatively measured in terms of the amount of crushing of the hull of the submarine. The sinking line has been approximately checked against the Bikini-Baker test. It may, in fact, be rather too high on the damage scale. It corresponds, roughly, to 2 feet of crushing of the hull.

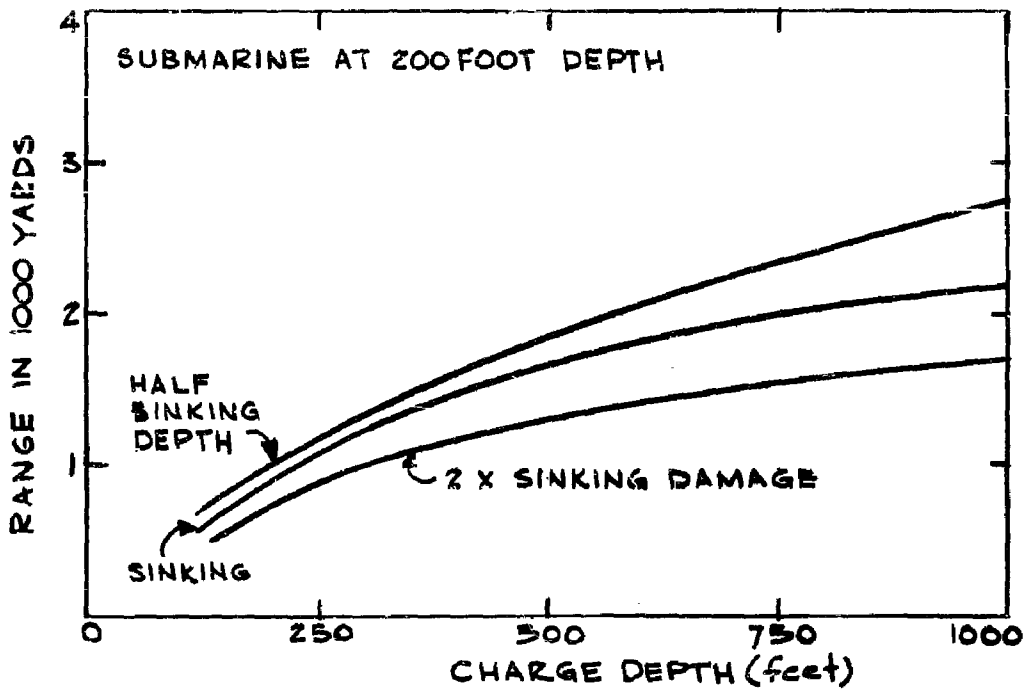

Fig. II-4. Range of Submarine Sinking Versus Charge Depth

The curve labelled sinking in this figure has been crudely calibrated against the sinking produced by the Bikini-Baker test. This test is not particularly incisive in evaluating the required damage. It indicates that the damage may be somewhat less than has been assumed here. The damage assumed here corresponds approximately to a two-foot crushing of the submarine hull. Because of the uncertainty in the amount of damage required for sinking, curves at one-half the assumed sinking damage and twice the assumed sinking damage are included -- that is, at approximately one foot hull crushing and 4-foot hull crushing.

The curves here apply against a submarine submerged 200 feet; as the submarine depth increases, the curves would move up. For example, for a submarine submerged 600 feet, the sinking curve probably reaches 2 miles at a 1000-foot charge depth.

Although these curves may not continue to rise so steeply as the charge depth is further increased, it is expected that they can be extrapolated to greater charge depth. They indicate that charge depths of over 1000 feet should be used against submarines.

APPENDIX B

WEAPONS AND WEAPONS SYSTEMS

I. INTRODUCTION

In case of war, a primary objective of the U.S.S.R. will be the interruption of supply lines to our allies. Since Western Europe promises to be a major theatre of operations, the North Atlantic area will be fruitful hunting grounds for Soviet submarines. If we are to win this "Second Battle of the Atlantic," an over-all defense must be put into operation immediately upon the outbreak of hostilities. Such a defense should be based on the following principles:

(1) It must be a diversified "defense-in-depth". It should be arranged so that the raiders will have to run a gamut of hazards to reach station and carry out their mission. Further, it must not depend on any single tactic.

Submarines cause us the least trouble when they are destroyed while at their bases. These bases should be attack-bombed as strategic targets of first importance. Where feasible, mine fields and barrier patrols should be placed across submarine transit routes. Our merchant ships, convoys, and task forces must be capable of effective defense and counteraction against submarines. Our coastal and harbor defenses must be good enough to discourage and prevent enemy action against these vital areas.

One possible "defense-in-depth" is shown in Fig. I-1. Our shipping lanes and traffic density for World War II, possible submarine transit routes, World War II sinkings by area, and loran daytime coverage areas are indicated. That part of the defense system consisting of SSK, MAD and aircraft patrols, and mine fields is shown in relation to the strategic situation. The details of any such system may be controversial, but its

final purpose must be to make the submarine attrition rate unacceptable to the enemy.

(2) Integrated control of attack units and shipping should be exercised by a Traffic Information Center. This center uses the information available to deploy our forces and route shipping in the most advantageous way. In this respect, the importance of adequate and accurate intelligence information cannot be overestimated. The availability of such data may, to a large extent, determine our success in countering threats to shipping. It is equally important that information flow freely, but with security, from individual elements to the TIC and vice versa. Good communications are vital.

(3) The defense must not depend on withholding of tactical or weapons design information from the enemy. It is inevitable that, over a period of time, they will know our tactics and have information about our weapons. Our defense must remain effective under these conditions.

(4) There is no single cure-all.

(5) The defense must be directed toward the killing of submarines. A wholly passive defense cannot be effective in the long run because build-up of the enemy forces eventually neutralizes the system. Further, passive defense permits submarines to range freely over the ocean, carrying out attacks of opportunity on shipping, harbors, or coastal cities. Submarines must be sought out and killed.

The number of merchant vessels sunk will always be roughly proportional to the number of submarines available to the enemy. Obviously this number must be kept to a minimum. This can be done by reducing the enemy potential to build submarines and to kill as many as possible of the submarines already completed. If x represents the number of submarines available to an enemy, the rate of change of the number

available to him will be given by Eq. (I-1),

$$\frac{dx}{dt} = K - \ell x, \qquad \text{(I-1)}$$

where K is the enemy's building rate and the loss rate ℓx is a statement of the assumption that the number of submarines sunk will be proportional to the number of submarines available. This is, of course, an oversimplification, but it at least results in an equation that can be integrated and interpreted. The integral of Eq. (I-1) is

$$x = \frac{K}{\ell} + (x_0 - \frac{K}{\ell})\epsilon^{-\ell t}, \qquad \text{(I-2)}$$

which is illustrated in Fig. I-2. The intercept of the curve x_0 is the number of submarines the enemy had in the beginning. The solid line represents the total number of submarines available to the enemy when there are no sinkings and a constant building rate prevails. The dashed line is the equilibrium number of submarines available for a given value of the rate of production and the rate of loss. For example, using the unit of time as a month, a loss rate of 10 per cent submarines per month and a building rate of ten submarines per month, one obtains the equilibrium number of submarines at 100. It is obvious, therefore, that the number of submarines available is critically dependent on the sinking rate and that any consideration of shipping must provide for methods of destroying enemy submarines.

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Having established these principles, we shall now examine some possible elements for shipping defense.

II. THE ANTI-SUBMARINE SUBMARINE

The anti-submarine submarine has certain unique advantages in the field of ASW which make its development of great importance. It is capable of: (a) long-range listening; (b) all-weather operation; and (c) patrolling in waters subject to enemy air operations. These assets make it the only means of maintaining effective barrier patrols outside enemy harbors or across certain enemy submarine transit routes.

The anti-submarine submarine gathers its information principally by listening. Results of recent deep-water experiments have shown that the use of large, low-frequency (0-500 cps) arrays may yield detection ranges as great as 100 miles on snorkeling submarines. It appears that such an array will furnish information accurate enough for closing and attack. Increased basic knowledge concerning propagation of low-frequency sound in the sea and performance of large hydrophone arrays is necessary. Research in this field should be initiated at once.

Effective weapons are necessary to successfully conclude an attack once the target has been brought into range. The Mk. 14 or 18 torpedoes fired in spread appear adequate, although not ideal for the purpose because of their high noise (see Appendix B, Section VII). The Mk. 35 is better and could be improved still further by providing it with a reliable influence fuse. A short-range underwater rocket or high-speed torpedo with reduced warhead is desirable for short-range attacks.

Navigation, station keeping, and communications (between submarines) are matters of great importance to an anti-submarine submarine operation. The possibilities for navigation are manifold: in some tactical situations loran or star-fixes may be obtained by the usual methods; it may be possible to develop a high-frequency (for security) bottom scanner to aid in navigation using bottom topography when exposure must be kept to a minimum; preplanted

sonar transponder station keeping beacons could be used, and so forth. Limited areas of the ocean floor can be charted at reasonable cost (by submarine reconnaissance if necessary) and usually present sufficient "landmarks" to be reliable.

Limited communication (and IFF) between submarines can be developed using underwater sound or the underwater electric potential system. A microwave (6 mm) radar relay can also be useful. The cross-purposes of communications and security make it doubtful that any completely satisfactory system can be devised; however, a workable compromise can be achieved by utilizing the above-mentioned components.

Project Hartwell has not made an operational evaluation of the anti-submarine submarines; a study (both experimental and theoretical) should be undertaken by the Navy for this purpose. If tactics prove feasible, as we feel they are, effort should be put into two vehicles: (1) the converted fleet-type, and (2) an entirely new prototype. The conversion should include (a) streamlining, (b) small changes of machinery to allow silent hovering, and (c) installation of a hydrophone array for improved listening; but otherwise the conversion should be kept as simple as possible. The new design should feature minimum size, simplicity of operation, and automatic control to reduce crew requirements. It is desirable that this vessel displace no more than 500 tons and carry a crew no larger than 25.

The anti-submarine submarine is potentially an important ASW vessel; it should receive full evaluation and be exploited to the limit of its tactical and technical capabilities.

III. HELICOPTERS

The availability to the U.S.S.R. of the long-range torpedo has seriously increased the vulnerability of our convoys, escort ships, and independent ships of all types. The range of these torpedoes exceeds the range of present sonar aboard escort ships.

For countering this threat, the helicopter with dunked sonar is the most promising weapon. It is invulnerable to torpedo attack, has a high-search rate, has the ability to operate with M/V convoys or naval task forces, and can destroy submarines once contacted. Further, large scale operations with this weapon are economically feasible in terms of personnel and total effort. However, the helicopters now in existence or under development do not appear to incorporate all the requirements needed. In particular, all-weather instrumentation and greater lift are necessary. More effort should be put into this program (it could be augmented considerably by convincing the large aircraft companies and the NACA that this development is of major importance). The helicopter would carry an improved dunked sonar for detection. All frequencies up to and including supersonic should be considered in designing the equipment. Commercial and university agencies should be utilized to augment work now being carried on in Navy laboratories. The importance of the helicopter and its sonar warrants duplication of effort in order to obtain the best possible equipment.

Tests should be initiated immediately with existing equipment, and continued as new equipment becomes available, to determine the average range to which a helicopter can approach a maneuvering submarine. Only by determining this range can the weapon requirement be defined precisely. The Mk. 24, a 12-knot passive homing torpedo, even if influenced-fused, appears to be marginal because of high underwater speed capability of modern

submarines. Improved homing weapons of higher speed, including active homing, may be able to satisfy the requirements. (Cf. Appendix F). In any case, a "Sunday-Punch" weapon is equally as important as the helicopter and its sonar.

Navigation and communication between the helicopter and its mother ship are necessary. Provided equipment weight can be kept reasonable, methods now available for airborne navigation and VHF voice links appear satisfactory, except from a security standpoint. The short range required for helicopter operations makes possible the use of the 6 to 8-mm band for secure navigation and communication. This band should be exploited to produce a light-weight, single-package unit for both functions.

IV. AIRBORNE RADAR SYSTEMS

Provided radar-flooding techniques are used, airborne radar continues to be the best means for detecting submarines. Hence, every effort must be made to develop the most effective combination of radar search and techniques of attack and kill. There are two broad approaches: single-package airplanes, and teams of specialized search and attack units.

A. The Single-Package Airplane

The single-package tactical airplane is required for two purposes: carrier operations in open sea, and land-based operations over coastal waters that are cluttered with reflecting objects. The single-package plane must be equipped with adequate equipment for detecting, localizing, and recognizing submarines, and with armament for destroying them. These requirements make it particularly useful in waters containing flotsam, fishing craft, islands, and other reflecting objects -- in short, wherever there are many radar targets that must be investigated individually. Clearly, a weapons system of this type will have limited performance because, as a single-package device, it will necessarily be a compromise. A further limitation, resulting from the multipurpose design, is that a plane investigating a target is not available for continuing systematic search. Nevertheless, this plane will fulfill important functions.

The Navy is planning to use the XS2F as the single-package vehicle. It seems adequate for the task. BuAer's development of radar sets AN/APS-44 and -49 promises to provide suitable radar equipment. This program should receive continued support. Improved MAD, sonobuoys, and wake detectors are needed for the fire-control phase of the operation. Present plans call for the use of the Mk. 41 torpedo as a killing weapon; although capable of satisfactory operation, this is so large that only

one may be carried at a time by the XS2F. It is important that the single-package plane not be a "one-shot" device. There is a clear need for a small torpedo to alleviate this situation (see Section VII).

B. Search-and-Attack Team

The fundamental advantage of the team of specialized units is freedom from the limitations imposed by compromise. The inherent difficulty of detecting snorkels makes it imperative to capitalize upon that advantage by using the best radar obtainable. The long-range radar required for effective search of large areas will need as large an antenna and as much power as it can carry. The plane that carries the radar should not carry anything else but detection and evaluation devices: one torpedo would displace six operators, and it will take many operators rotating through short shifts to extract from the radar the information it can, in principle, supply. Furthermore, there will be many hours of search for each sighting, and it would be inefficient to carry, throughout the search, the heavy armament that is required for the kill alone.

For these reasons, there is need for a team of specialized search and attack planes. The search plane should be highly differentiated for detecting, localizing, plotting and relaying of information. The attack planes should be highly differentiated for recognition, fire control, and attack. Tactics require both very fast attack planes to reach the submarine as soon after detection as possible, and long-endurance attack planes to continue the attack as long as it takes to make the kill. In the final stages of a long attack, the aircraft would be joined by surface craft, helicopters, hunter-killer groups, and anything else that could be brought to bear.

The search plane must be big enough to carry a large antenna

and to provide comfortable working space for the operators. Long range is desirable, but speed favors efficiency of search. The Constellation appears to be the most suitable existing plane. A plane designed for the purpose would permit greater specialization and, therefore, greater economy.

Existing planes and planes under test appear to be suitable for both the fast and the long-endurance attack functions.

The principal factor influencing the efficiency of search is radar performance. Every effort should be made to improve it. Improvement is imperative because snorkels will shrink in radar cross section, and the problem of detection will become more difficult. Promising developments include larger antennas, more power in shorter pulses, correlational and integrational techniques, and the use of a number of operators in parallel, with frequent rotations.

The search plane must have plotting facilities. Careful plotting will probably be the best answer to the problem of false targets. There must be an efficient means of relaying the presentations from the search plane to the attack planes. Video insertion will be very helpful.

The attack planes must have equipment for precise localization, for recognition, and for fire control. This would include radar, sonobuoys, wake-detection devices, and MAD.

These planes would carry enough explosive, either conventional or nuclear, to assure a kill. Light, homing torpedoes for anti-submarine work would also be especially useful here.

V. SMALL BOATS FOR COASTAL ESCORT, SEARCH, AND ATTACK

During the course of military operations, it is often necessary to protect harbors, inlets, or a section of coastline against enemy submarine attack. Small surface patrol craft are well suited to this function, but the existing SC PC type is relatively ineffective because of poor search equipment and inadequate armament. These vessels may be improved by incorporating a towed or dunked sonar and increasing armament. Landing craft may be converted to effective patrol ships by installing large numbers of rockets, such as mouse traps, and suitable sonar.

However, a new vessel with anti-submarine patrol as its sole purpose should be designed. Maximum ahead-thrown armament and towed or dunked sonar should be incorporated. This new prototype should consider economy of manufacture and operation. Cruising radius and speed may be sacrificed for simplicity (cruising speed of 12 to 15 knots and operating radius of 500 to 1000 miles is sufficient). Wooden construction and standard engine design seem suitable. Centralized control of sonar data, fire control, and command will enable crew requirements to be kept at a minimum. Radar and loran may be used for search and navigation, short-range VHF for communication. It is important to have suitable vessels available.

VI. WEAPON SYSTEM FOR MERCHANT SHIPS

The convoy system, as practiced in World War II, is essentially an exchange of time for security of transport. Although convoys were slow in delivering material, they did so in comparative safety. Today, the menace of attack by fission weapons, long-range pattern-running torpedoes, and new-type submarines makes large concentrations of slow ships undesirable from a defense standpoint. Experience in World War II has shown that fast ships, sailing either in convoys or as independents, are relatively safe from submarine attack. The fast MV is an essential element in countering the atomic bomb and submarine menaces to shipping. However, if the advantages of these ships are to be exploited to the fullest, measures to increase attack and evasion capabilities are necessary. An effective weapon system can be developed and should be considered an integral part of any ship-construction program.

Shipping in general is subject to two types of enemy attack: by submarine, and by aircraft. When ships are sailing as independents or in small convoys, it is necessary that they carry at least a part of their own protection, leaving escort vessels, if any, free to cope with the enemy directly. For instance, escort carriers should not be required to load their decks with helicopters to the exclusion of air-interceptor and anti-submarine planes.

In order to counter the two modes of enemy attack, the following measures should be instituted.

(1) Merchant ships should be designed so that they may carry one or more helicopters. So equipped, a ship may supply part of its own protective screen, if in convoy. If sailing as an independent, the helicopter can be used to clear a path ahead of the ship and to give warning of submarines before they come within torpedo range. The helicopter desirably should carry a killing weapon so that it may attack a submarine when detected.

(2) A fast ship can take effective evasive action even after a torpedo has been launched in its direction. Such a ship needs a torpedo listening device so that, when fired upon, it will have time to turn tail-to, thus materially reducing the probability of a hit. Further, it may tow a torpedo countermeasure (akin to Project General) over the fantail, further reducing the probability of a hit.

(3) High-altitude bombing by aircraft using guided bombs is a serious threat. Provision for installation of countermeasures and ship-to-air guided missiles to combat such attacks should be a part of the armament of all merchant ships.

(4) Low-level airborne attacks, especially those using torpedoes, continue to be a serious menace. Conventional AA guns will not be satisfactory against planes carrying long-range homing or pattern-running torpedoes. A ship-to-air homing missile with an effective range in excess of 20,000 yards and operable down to sea level is needed. Conventional guns will, nevertheless, be required to deter simple attacks, such as the use by the enemy of rockets, skip bombs, dive bombs, kamikaze tactics and conventional torpedoes. The Hartwell group did not attempt to evaluate the arming of conventional merchant vessels used in convoys. The preceding remarks apply only to fast independents and to such of the faster ships as can contribute to the over-all AA effectiveness. There is at present no substitute for complete air superiority.

A ship or group of ships with such a weapon system will be a formidable opponent for enemy submarines or aircraft. A great deal has been said and written about the advantages and disadvantages of fast merchant vessels and on the relative merits of independents vs. convoyed ships. These two questions are not mutually dependent. Whether a ship should sail independently or in convoy will generally depend on the immediate circumstances facing the sailing. However, certain general conclusions can be drawn as to the relative merits

of fast ships compared to slow ones, whether they sail in convoy or as independents. These arguments are presented here in logical form.

The probability of sinking a ship is generally expressed as a product of three terms:

Probability of Sinking = (Probability of Detection)

x (Probability of Closure) x (Lethality of Weapon),

or

$$P_s = P_D \times C \times L. \qquad \text{(VI-1)}$$

The first term in Eq. (VI-1) is the probability of detection of a vessel or a group of vessels considered as one unit. The question arises as to how this depends on the speed of a merchant vessel or a convoy in going between two points, such as New York and Liverpool. Let us assume for the present that the detection range of such a ship or convoy does not depend on its speed. We can then recognize two extreme conditions: (a) that the detecting vehicle (submarine) is at rest, and (b) that the detecting vehicle (aeroplane) is moving much more rapidly than the ship. Between these will lie the most realistic case of the detecting vehicle (submarine) moving at about the same speed as the ship. In situation (a), the probability of detection depends only on the length of path traveled by the ship between a point of departure and a point of destination. If this distance is ℓ and the detection range of the submarine is d, then the number of square miles swept out by the merchant vessel is ℓd. If there are x independent submarines per square mile in the ocean, the number of contacts is $x\ell d$. It is obvious that the velocity of the ship does not enter this expression, and hence no advantage would be derived from a fast ship as compared to a slow ship. In case (b), the number of square miles swept out in the process of search is proportional to the speed of the aeroplane V and to the time available to the aeroplane for finding the merchant vessel. The time available is obviously equal to the length of path ℓ

divided by the speed of the merchant vessel $\underline{v}$. If the detection range in this case is D, then the probability of detection will be proportional to $D\,\ell V/v$. In other words, against air detection it is highly important to reduce the time at sea to a minimum by increasing the speed of a merchant vessel as far as possible. Finally, in the case of the moving submarine the situation is nearer to case (a) than to case (b). The OEG Report 51 (Eq. (3), page 94), gives an expression for $\underline{Q}$, the sweep rate in square miles per hour as a function of the ship's speed $\underline{v}$ and the submarine's speed $\underline{u}$*, with $\underline{R}$ being the effective detection range.

$$Q = \frac{4R}{\pi}(u+v)\int_0^{\pi/2}\sqrt{1 - \sin^2\delta\,\sin^2\psi}\;d\psi, \qquad \text{(VI-2)}$$

where

$$\sin\delta = \frac{2\sqrt{uv}}{u+v}\,.$$

If we write $u = aV$, so that $\underline{a}$ is the ratio of speed of submarine to merchant vessel, we can reduce the above elliptic integral to

$$Q = \frac{4R}{\pi}\,v(1+a)\int_0^{\pi/2}\sqrt{1 - \sin^2\left(\frac{2\sqrt{a}}{1+a}\right)\sin^2\psi}\;d\psi = 2bRv. \qquad \text{(VI-3)}$$

The probability of detection is then given by the expression

$$P_c \propto \frac{\ell}{v} \times 2bRv = 2b\ell R \qquad \text{(VI-4)}$$

where the only term depending on velocity is $\underline{b}$ the relative probability of detection. A plot of b as a function of the relative velocity of submarine and merchant vessel is given in Fig. VI-1. It is obvious from this figure that the probability of detection is not a strong function of velocity of the merchant ship. For a given speed of the submarine -- say, 10 knots -- the faster the ship, the

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*In this section, $\underline{u}$ is the effective patrol speed of a submarine, not its maximum submerged speed. Hold-down tactics should be assumed throughout.

smaller is a, the smaller is b. Table VI-1 indicates the relative gains in going from a 10-knot merchant ship to a 20-knot merchant ship. It is shown that the decrease in detection by doubling the speed in this case is only about 15 per cent.

Table VI-1

Relative Probability of Detection of Merchant Ships by a 10-Knot Submarine

Speed of MV v(knots)	Relative Speed a	Relative Probability of Detection b
10	1	1.27
13.3	3/4	1.15
20	1/2	1.06

It may be concluded, therefore: if the detection range does not depend on the speed of ship or convoy, then, at least against detection by submarines whose speed is equal to or less than that of the merchant vessel, the probability of detection is reasonably insensitive to the ship's speed.

So far as the probability of detection by submarines is concerned (P_D in Eq. VI-1), the relative merits of fast and slow ships depend on the detection range as a function of speed. These factors can be discussed only qualitatively since, in each case, specific details are more important than general principles. There are three detection methods available to the submarines: optics, sonar, and radar. So far as optics is concerned, there is no advantage or disadvantage as a function of ship speed. Optical detection depends more on the production of smoke and on superstructure design than on any other features. There is no reason to suppose that a fast ship should be any worse than a slow one. Radar detection is very critically dependent upon the height of a ship

except under conditions of strong radar trapping. Anything that can be done to reduce superstructure, and particularly reflecting surfaces at the tops of superstructures, will reduce the radar range on a ship from a submarine. These considerations apply equally to fast and slow ships. Sonar detection depends on the noise produced by the propeller of the ship and by engine noise coupled by the ship's structure to the water. Here, again, if proper design features are considered, new fast ships should not be so noisy as present slow ships.

The second term, C, of Eq. (VI-1) covers the probability of closure after a ship has been detected. It is sometimes assumed that the range of the weapon is greater than the detection range. Such considerations are, however, unrealistic. During the last war, detection range averaged approximately 7 miles, and torpedo ranges averaged under 2 miles. In the future, it should be expected that radar, optical, and sonar ranges by enemy submarines on our ships should be of the order of 30 to 40 miles. It is unlikely that fast enemy torpedoes will have ranges in excess of 30,000 yards (15 miles). There will, therefore, in general, be a problem of closure. Since this problem becomes all the more difficult when a submarine's speed is reduced, it is absolutely mandatory that submarine hold-down tactics be used. Under the present condition, this reduces the speed of the submarine to about 10 to 12 knots. The OEG reports and studies have shown that the ability to approach a ship is a strong function of the ratio of the speed of the ship to the speed of the submarine (OEG Report No. 51, page 95). The knee of the curve reproduced in Fig. VI-2 occurs at the point where the ratio of the speeds is equal to one. Hence, if the submerged speed of the submarine is approximately 10 knots, the probability of closing can be reduced to approximately one-fifth in going from, say, 8 knots to 16 knots. <u>The conclusion is that the speed of merchant vessels should always be higher than the speed of</u>

enemy submerged submarines. While no absolute figures can be given on enemy submarine capabilities, an increase in submerged speed requires larger engines and probably an increase in self-noise. The first consideration reduces the submarine's ability to stay on station, and the second increases the probability of his being detected by our escort equipment. In short, while the factor of 5 cannot always be realized if the enemy continues to raise the submerged speed of submarines, the improvement in the safety of our ships always increases with increased speed. This is particularly true if our ships are equipped with listening devices capable of picking up a fast-moving submerged submarine at ranges in excess of torpedo range. It is not impossible to contemplate that a 20-knot merchant ship, equipped with listening devices, could always escape from an 18-knot submarine.

The third term, L, in Eq. (VI-1) is the probability of killing after the submarine is in firing position. At this point, the fast merchant vessel has an extraordinarily better chance than the slow ship. It is not unlikely that a listening device that will pick up a torpedo at its extreme range can always be made. For the sake of concreteness, let us assume that the enemy has a 30,000-yard torpedo capable of a speed of 30 knots. If such a torpedo is detected by a 20-knot merchant vessel, the merchant vessel may turn tail-on to the torpedo, resulting in a relative speed between torpedo and ship of only 10 knots. Since the torpedo has an ultimate range in the water of 30,000 yards, corresponding to a running time of approximately one-half hour, it can close, relative to the ship, only to 10,000 yards. Hence, the effective range of the 30,000-yard torpedo has been reduced to 10,000 yards. The submarine had to approach within 10,000 yards of the ship to fire with the accuracy required of 30,000 yards. Obviously, the listening range of the equipment on the merchant vessel had to be only 10,000 yards under these conditions. If the ship had a speed of 10 knots instead of 20 knots, the submarine could have fired at 20,000 yards and the

listening device on the ship would have required a range of 20,000 yards. The faster the ship, the more difficult is the approach problem for the submarine, as well as the fire control problem, and the lesser is the requirement on the quality of the listening device on the merchant ship.

In the following it is assumed that merchant vessels or convoys of merchant vessels are equipped with listening devices that enable them to pick up a torpedo as soon as it is fired, with sufficient accuracy to permit turning of the ship or convoy in a direction opposite to the on-coming torpedo. For illustrative purposes it is also assumed that submarines can carry torpedoes whose performance is limited to the equivalent performance of a 30,000-yard torpedo at 30 knots. Better torpedoes would affect the numbers obtained in the following but not the argument or the general nature of the conclusions. It is the purpose of this calculation to obtain the maximum range at which a submarine can fire and still reach the target under optimum conditions, but subject to the above assumptions. It is a consequence of this calculation that an expression is obtained for the maximum torpedo detection range required by the merchant ship as a function of ship speed.

The resistance in water to a torpedo is very closely proportional to the square of the torpedo speed s. Hence, if the torpedo initially contains a certain amount of energy available as fuel, and the efficiency of conversion of this fuel to motive power remains constant, the range in the water of the torpedo will be, roughly, inversely proportional to the square of the torpedo speed. The range at any speed of the torpedo will therefore be given by the expression

$$R = R_o \left(\frac{30}{s}\right)^2; \quad R_o = 30{,}000 \text{ yards.} \qquad \text{(VI-5)}$$

If we assume, as indicated above, that the ship turns away from the torpedo as soon as fired, the overtaking velocity of the torpedo is given by $(s-v)$ where v is the speed of the ship. Since

the running time of the torpedo is the same, whether in the coordinates of the water or in the coordinates of the merchant vessel, the firing range r is given in terms of the range in water by the expression

$$r = \frac{R(s-v)}{s} = \frac{R_o 900(s-v)}{s^3} = 900R_o \left(\frac{1}{s^2} - \frac{v}{s^3}\right). \qquad \text{(VI-6)}$$

If this is differentiated with respect to torpedo speed, keeping the ship speed constant, we obtain an expression for the ratio of torpedo velocity to merchant-vessel velocity, which gives the maximum, and hence the optimum, firing range:

$$\frac{dr}{ds} = 0 = 900R_o \frac{d}{ds}\left(\frac{1}{s^2} - \frac{v}{s^3}\right) \text{ or } s = \frac{3}{2}v. \qquad \text{(VI-7)}$$

Substituting this expression for the firing range, we get an expression for the optimum opening range of firing a torpedo set at the best possible speed:

$$r = \frac{400R_o}{3v^2}. \qquad \text{(VI-8)}$$

These results are shown plotted in Fig. VI-3. It will be seen that the opening range against a 10-knot merchant vessel can be as high as 40,000 yards, whereas against the 20-knot merchant vessel this drops to 10,000 yards and for 30-knot vessel to 3,300 yards. It may also be concluded from this diagram that the listening range for detecting a torpedo falls off very rapidly as the speed of the merchant vessel is increased. In fact, the same curve may be used to establish the maximum performance requirement. If the torpedo is fired with any speed other than the optimum, the range requirement on the listening gear is reduced.

It is concluded that there is a very high premium to be attached to fast merchant vessels, since they force the submarine to close to within acceptable sonar range and to expose itself to counter attack. It is concluded, further, that pattern-running torpedoes, if limited to the performance in the assumption above, become

increasingly less effective as the speed of the merchant vessel is increased, thus essentially reducing the time available within the convoy to negligible amounts.

The probability of killing will depend very largely on the type of torpedo to be used. A conventional type torpedo requires the estimate or measurement of the cross-component of speed of target. The errors of this determination are directly proportional to the speed of the target. In addition, the time of flight will depend on the distance to be traveled which, in turn, is dependent on the escape velocity of the merchant ship. The probability of hitting, therefore, will be a strong function of the speed of the merchant vessel, the details of which, however, will depend on the specific method of tracking employed by the submarine. The pattern-running torpedo also suffers markedly as the speed of the merchant vessel increases. Let us assume that a pattern can be established such that, once within a convoy, the torpedo will move within the convoy. The effectiveness then of a pattern-running torpedo is proportional to the time a torpedo spends in a convoy after reaching it. Of course, the faster the convoy, the more difficult is the programming of the pattern to realize the above assumption. Let us again assume a pattern-running torpedo with a total run of 30,000 yards and a speed of 30 knots. In addition, let us assume that the submarine closed to within 10,000 yards of the convoy. Under these conditions, the pattern-running torpedo would barely reach the convoy if the convoy could turn tail-on and hence would be useless. Against the 10-knot convoy, the overtaking speed would have been 20 knots and one-third of the total running time would have been available for running within a convoy. Clearly, then, the speed of the convoy markedly reduces the effectiveness of pattern-running torpedoes unless the pattern-running torpedoes are fired from within the convoy itself, a condition which must be prevented. The effectiveness of pattern-running torpedoes arises from their long path in a convoy.

A fast convoy forces the use of fast torpedoes, but the range of a torpedo having a given initial power source and constant efficiency is approximately inversely proportional to the square of the speed of the torpedo.* This establishes, in effect, a limit to the usefulness of pattern-running torpedoes; that is, assuming a detection range, it is possible to compute the speed of a convoy that will just eliminate the advantage of a pattern-running torpedo over a directly aimed torpedo.

Many other advantages accrue to fast merchant vessels, advantages which are not related to the "probability of sinking". One major advantage is the reduction on the requirement of the number of escorts. Much has been said about the necessity for decreasing the turn-around time in ports and of improving the cargo-handling facilities. All these are to the good; but quite irrespective of whether the turn-around time can be reduced, the number of escorts required is proportional only to the fraction of the total turn-around time spent at sea. Obviously, therefore, increasing the speed of a convoy from 10 knots to 20 knots reduces by one-half the number of escort ships required for the same degree of effective protection per ship. Conversely, for a given number of escort ships, doubling the convoy speed doubles the number of effective escorts. If the operational data available from the last war can be used as a guide, this would imply that the number of sinkings would be reduced by a factor of two through this step alone.

The danger of a ship to air attack is also a function of the ship's speed. Any quantitative discussion is impossible without a detailed statement of the method of attack. Against kamikaze planes,

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*Increasing the speed of the assumed torpedo reduces the range to about 15,000 yards. Against a 20-knot ship, the extreme opening range then becomes 7,500 yards. The maximum opening range occurs when the speed of the torpedo is 1.5 times the speed of the MV.

the speed of the ship probably does not enter. However, against dive-bombing, high-flying bombing, and against low-flying torpedo planes carrying conventional torpedoes, the maneuverability associated with high speed is a strong factor. Finally, a doubling of the speed, assuming that it can be accomplished by a halving of the loading time, reduces by half the total number of ships. Apart from considering the economics of the cost per ton freight delivered, it is apparent that the total quantity of armament to arm all our fast merchant ships will be cut in half. The same argument holds as for the number of escort vessels.

In addition to their logistic superiority, fast ships are much less vulnerable to enemy attack. To meet the supply requirements for a global war, it is imperative that new fast merchant vessels be built now.

VII. TORPEDOES

A. Enemy Capabilities

Modern developments in homing and pattern-running torpedoes give the submarine rather formidable offensive weapons against surface vessels, including anti-submarine vessels. The possibilities in this direction were by no means fully exploited in World War II. The Germans employed passive acoustic torpedoes with some early success, but these were relatively easily countered by towed noisemakers or "foxers". Our submarines employed a passive torpedo of rather slow speed against Japanese escorts, with considerable success. Active homing torpedoes, such as the American Mk. 37, now under development, are considerably more dangerous. They will attack quiet targets, and many circuit tricks are available for making them insensitive to various types of decoys. Even passive homing systems can be modified to be much less sensitive to towed noisemakers than is the case at present.

A torpedo that homes on the transmitted pings of a searching or attacking A/S vessel can be extremely dangerous. This is especially true if the ships employ omnidirectional transmitting systems, as in QHB scanning sonar. Control information is then available to the torpedo on every ping -- usually at intervals of 5 seconds or less. This information can be used in the torpedo control system to establish a collision course, so that the infrequency of the information would not seriously affect the accuracy. If the torpedo were detected in time, the sonar transmissions could be stopped, but the torpedo would still pass under the ship so long as it maintained its course. The great threat of such a weapon lies in the fact that the torpedo and the submarine can detect the ship's sonar at much greater ranges than they can themselves

be detected, probably out to 10,000 yards.

A wake-following torpedo is a particular hazard to surface vessels because it is very difficult to counter. If fired from astern, it is also difficult to detect because of interference from the ship's own propellers.

A wire-guided torpedo with a reporting link reporting sonar information back to the submarine may also be dangerous. Such a weapon might be an effective embodiment of a scheme to track on the ship's pinging sonar.

B. Torpedo Countermeasures

The very multiplicity of possibilities makes the countermeasure problem especially difficult. Against active torpedoes of the echo-ranging type, the use of light shallow-draft vessels may be quite effective, since echo-target strengths depend strongly on draft. If the weapon uses an influence explosive of the magnetic type in order to increase its effectiveness (especially necessary for a weapon that homes on sonar pings), a non-magnetic vessel would be invulnerable. However, acoustic proximity devices could be developed which would be effective even against shallow-draft wooden vessels.

If the approach of the torpedo can be detected in time, the effective countermeasure would be to turn-tail and run as fast as possible in the hope of staying ahead of the torpedo until its run is expended. The effectiveness of this tactic could be enhanced by dropping a short-lived influence mine astern the vessel which would detonate and destroy the torpedo as it passed -- probably actuated by the torpedo's noise. This would be effective against almost all types of torpedoes, homing included, but would certainly confuse ASW teamwork.

Under certain conditions, enemy submarines using ping-homing torpedoes may force surface vessels to discontinue use of their

sonar. This situation can be partly overcome through the use of towed or dunked sonar; but a real answer requires more imaginative solutions -- such as helicopter dunked sonar and new torpedoes.

Enemy capabilities against convoys and task forces have been discussed elsewhere. Pattern-running and wake-following torpedoes are special threats. The "sleeping beauty", a floating mine which becomes a pattern-running torpedo as the convoy or task force approaches, is especially dangerous; among other things, its use hardly exposes the enemy submarine.

The threat of these weapons lies in the fact that they can be fired or launched from ranges beyond the detection range of present surface-vessel sonar screens.

C. Weapons Requirements

The primary requirement of any weapons system, whether for surface ships or aircraft, is that a minimum time should elapse between the detection of the submarine and the arrival of the weapon at the submarine. This is necessary, first because of the difficulty of both surface ships and helicopters to hold and close a contact once made, and secondly because it allows the submarine a minimum time for evasive action and jamming.

Airborne homing anti-submarine torpedoes, launched either from aircraft or helicopters, should be as small as possible. The size and design features should be determined by the following considerations: (1) the explosive charge should be large enough but not too large (about 50 to 75 pounds); (2) an influence fuse should be provided; (3) the lock-on range should be consistent with the maximum sensing range; (4) the speed during the closing run should be optimum for the fastest expected speed of the target; (5) the search phase should require a minimum of time consistent with the capabilities of the sensing device; (6) the fuel-power plant combination should be the smallest for the particular speed range

required; (7) low self-noise should be considered; (8) collision course (constant-bearing) control should be used; (9) provision for extra fuel for re-attack should be omitted; (10) alternate methods of homing (active and passive) should be available. These requirements are on the whole obvious, but intelligent compromise may often be required.

In the next few years, enemy submarines (with underwater escape speeds as high as 20 knots) may be anticipated. Hence, for this period, a torpedo with a 30-knot speed is about optimum (see Appendix B, Section VI). Under these conditions, the running lock-on range should be three times the sensing range. With present sonar technology, an active sonar with a range of approximately 1,300 yards may be expected in equipment of usable size. Hence, a running range of 4,000 yards is needed. It is estimated that present type thermal engines weighing about 100 pounds are capable of this performance. Reverberations require the use of narrow sonar beams which, combined with the small size of the vehicle, results in the use of high frequencies. The narrow beam imposes a limit on the search scan. A search schedule similar to that of the torpedo Mk. 41 seems necessary. However, the same angular scan rate of 10° per second can be provided at a much reduced speed with a considerable saving in fuel. The external design of the vehicle, the engine design and mounting, and the propeller design should all contribute to minimizing the self-noise. A torpedo of the type here described should weigh under 500 pounds.

Future airborne anti-submarine homing torpedoes can be made to meet the requirements imposed by any forseeable future enemy submarine, provided research on self-noise of newer propulsion systems is carried along vigorously.

Anti-submarine torpedoes for use from surface ships are generally waterborne throughout their run. This results in large

torpedoes (1,500 pounds) characterized by long times of travel. Any extension in range is likely to aggravate both short-comings. However, the times of travel are the most serious. Even at speeds in the neighborhood of 40 knots, times of travel at extreme ranges of a half-hour can be expected. The most promising approach to this problem is through use of the air medium. As an example, one can consider the use of a torpedo essentially similar to the aircraft torpedo described above. If its weight can be kept below 500 pounds, such a torpedo can be launched by rockets from a surface vessel and with aerodynamic lift reach a range in excess of 20,000 yards. Considering the homing range of the torpedo, an angular accuracy of 1 to 2° will suffice. An elementary short-lived gyro-control system may be required. It is possible but not necessary to make these amphibious torpedoes complicated.

Amphibious homing torpedoes with long range (20,000 to 30,000 yards) and rapid flight (300 knots) will provide the surface ship with a weapon of great flexibility. For example, a surface ship can bolster a helicopter in contact with a submarine with an arsenal full of torpedoes. Range control may be from ship, from helicopter, or by programming. Parachute arrest or rocket brakes may be employed to reduce range ballistic errors. Dubious contacts can be exploited by escorts without leaving position. Fundamentally, the amphibious torpedo gives the surface ship a weapon greater in range than that possible to the attacking submarine.

D. Torpedo Weapon for SSK

SSK submarine tactics are strongly dependent on detection equipment. It is now sufficiently clear that the SSK presents nearly an ideal deep-water platform which will make long-range low-frequency listening with large arrays the principal detection method. Ranges in excess of 35 miles against an enemy snorkeling submarine should be realized. The tactic of the SSK should then be

to close on the enemy submarine on a course and speed program that gives minimum danger of counterdetection. The SSK will, therefore, first close at a higher speed and arrive at a minimum speed with the enemy submarine directly on the beam. The SSK can, under these conditions, approach with impunity to almost the active sonar range of the enemy submarine -- say 4,000 yards. At this point, a spread of conventional gyro-controlled torpedoes similar to the Mk. 18 (4,000-yard range, 29-knot speed) seems adequate, if quiet. However, the Mk. 18 torpedo is far noisier and larger than is required. A development leading to a smaller, quiet torpedo with a smaller warhead and longer range is desirable. This is consistent with the concept that the SSK should be a rather small (500-ton) vessel.

Since it is possible for an SSK to detect a submerged submarine, homing torpedoes must also be available. The torpedo Mk. 35 is tactically adequate except for its excessive noise. Its chief drawbacks are high cost and lack of collision-type course control. Both defects can be overcome.

If enemy submarines have adequate torpedo listening equipment, their best evasion tactic is running away. The torpedo speed must be from 1.5 to 2 times the maximum speed of the enemy submarine and have a range in water about 3 times the enemy active sonar range. For this use, a passive homing as well as an active sonar torpedo should be available.

E. General Comments on Torpedo Program

Except for minor engineering details, homing devices have remained essentially as they were at the end of World War II. All passive acoustic torpedoes use much the same transducer patterns and the same basic electronic functions as were used in the mine Mk. 24 in the war. Even the frequency remains standardized. The two major active systems, the Mk. 37 and Mk. 35, incorporate only minor improvements in the homing devices. Some progress has been

made with wire-guidance methods, although the tactical use of such systems has not been studied. Very little work has been done in the field of wake following and that at very low priority. Potential dividends in both possible homing ranges and invulnerability to decoys make this a very attractive field, in spite of difficulties. The following of a wake in three dimensions, while more difficult than in two, is by no means impossible. Thus, a wake follower is a potential anti-submarine weapon. The Mk. 35 homing system has some wake-following features, but the echo thresholds must be set so high that the sensitivity to submarine wakes, except possibly very close to the surface, is of no practical importance. Detection schemes employing the change of acoustic impedance of water due to the presence of bubbles seem to offer the greatest promise, but schemes employing UHF reverberation to detect persistent turbulence may be worth exploring.

In the anti-submarine field, non-guided torpedoes--i.e., torpedoes that run a pre-set course such as a gyro- or fixed-pattern run, do not appear to be of great importance except for an SSK weapon against snorkeling submarines. Even in the case of atomic warheads, the long time of flight probably makes waterborne delivery ineffective compared to the flying-fish types of delivery.

An unguided torpedo is always working on antiquated information -- i.e., the fire control data available at the instant of launching--whereas a homing or tracking weapon keeps itself up to date as it goes along. The major weakness of homing weapons is their liability to jamming and decoying, and it is for this reason that a multiplicity of systems is desirable, as is minimum transit time to the target.

The trend towards increased cost and complexity in torpedoes is one to be viewed with alarm. This trend is not objectionable in itself, but cost usually reflects man-hours in production. The

torpedo is an expandable device, and its effectiveness depends not only on the quality of its performance but also on its ability to be produced in quantity at short notice; both factors are of equal importance. Each addition to the torpedo system must be scrutinized with the question, does it pay its own way in terms of the ultimate function? The torpedo is unfortunately a gadgeteer's paradise. Unlike the automobile, it is not produced for a competitive market, and hence cost is not a major consideration in the designer's mind. On the other hand, it is a precision device that invites pet ideas and gadgets. A weapon that cannot be brought to a satisfactory production rate is not very valuable, no matter how remarkable its performance.

The present complexity in torpedoes reflects a tendency in the whole program to think in terms of hardware rather than systems. The designers at the working level are insufficiently interested in and concerned with the ultimate function of the device -- in tactics. Engineers must understand and think in terms of the end uses of the device. The potential for this type of thinking is available in a number of laboratories, but it tends to be discouraged both by the Bureau of Ordnance and by the laboratory managements. The Bureau could encourage this type of thinking by fostering analytical projects on weapons systems within the working laboratories, supplying such information as they need. However, this encouragement will be of no value unless the people engaged in the studies feel that use is being made of their work, and that their findings are reflected in Bureau decisions. A feasibility study of the amphibious-torpedo weapons system might well form the basis of one such project. Such a study should be broad enough to cover all aspects of the system including the detection performance of the helicopter.

The ultimate limitation in homing-torpedo performance arises

from self-noise. For example, the maximum speed of the Mk. 35 torpedo is at present fixed at 27 knots by its self-noise. Yet despite many millions of dollars spent in the development of hardware for homing torpedoes, relatively little effort has gone into the study of the factors that affect self-noise, and into methods for reducing it. Design decisions involving large expenditures are made on the basis of hunches and surmises with little scientific backing. In wartime, with shot-gun tactics at a premium, this is necessary. But for 5 years it has been known that self-noise is important, and yet there is still little fundamental scientific data on which to design a low-noise propulsion system. It appears that our most advanced weapon, the Mk. 35 torpedo, is supersonically one of the noisiest torpedoes for its speed ever built! Thousands of man-hours have gone into unsuccessful tests just because of the lack of basic knowledge. How much better if some of this effort had been diverted to finding out why torpedoes are noisy, before all the hardware was designed! Self-noise reduction should be a major factor in design rather than an afterthought to be given attention after the system has been designed and built on the basis of other considerations. There are still no data on the noise output of unconventional propulsion systems, such as pump jets and ducted propellers. The whole problem of noise is of sufficient importance to warrant a major fraction of the research effort of a single laboratory such as the Ordnance Research Laboratory at Pennsylvania State College.

VIII. SEARCH-KILL SYSTEM FOR THE AGGRESSIVE DEFENSE OF THE EASTERN SEABOARD AND COASTAL WATERS

It is essential that the Eastern Seaboard of the United States be protected against enemy attacks. These attacks may take various forms, among them: (1) direct attack by aircraft from the sea; (2) missiles launched from submarines lying off the coast; (3) attack of coastal shipping by submarines. The availability of atomic weapons in the hands of the enemy emphasizes the importance of preventing such attacks. Our defenses must extend in depth out from the coastline. A particularly attractive defense line runs from Nova Scotia to Bermuda to Puerto Rico -- a distance of 1500 miles. It is proposed that a 500-mile-wide strip centering around this line be established for airborne radar patrol. This patrol is to serve both AEW and ASW functions. To the west of this patrol zone would lie an enemy-free zone, some 500 miles wide, running along our Eastern Seaboard. By closing-in the relatively short distance between Puerto Rico and continental South America (via the Lesser Antilles) with small surface patrol craft and land radar stations, the enemy-free zone would be extended to include the Caribbean, the approaches to the Panama Canal, and the entire Gulf of Mexico area.

The following highly desirable features would result:

1. The necessity for convoy and escort in the zone would be obviated;
2. Measures necessary for coastal patrol and harbor defense would be greatly reduced;
3. Information on shipping would be provided;
4. An early-warning system against both high-flying and low-flying aircraft and missiles would result, thus closing the gap of the present CONAC radar net.

5. The identification task of CONAC would be eased, since all authorized air traffic would be directed to cross the coastline at the invulnerable but convenient Maine and Florida entry points; any aircraft endeavoring to cross the coastline at any location would be immediately intercepted.

The patrol zone would be manned by aircraft, probably Constellations, equipped with the best available anti-snorkel radar, as well as an early-warning aircraft radar. These planes would have a search function only and carry no weapons. Once a submarine is located, weapon-carrying planes from bases not more than one hour distant would be directed for the attack. The attack would be pressed to completion with all available equipment. Because of radar-flooding techniques, the submarine would not be aware of its detection, and this, coupled with its slow speed, will prevent its escape during the time the attack plane is en route. The attack-and-kill team would be joined by surface ships if available.

The effectiveness of the system may be calculated in the following manner. Data from OEG Study 343 indicate that the longest submerged run of which modern Soviet submarines are capable is about 360 miles. Such a run completely exhausts the submarine's batteries and requires at least four hours' snorkeling time for recharging. Hence, a conservative width for the search line is about 500 miles. Other parameters are:

w = speed of searching aircraft = 180 knots;

W = sweep width of radar against snorkels (for the APS-44 or -49, this is estimated to average about 35 miles);

L = length of search path;

N = number of planes patroling in a single search strip of width W; there are 500/W strips in the complete area;

n = number of periods that the submarine snorkels; this factor must be taken into account because, by breaking up its total snorkeling time into several periods each of length 4/n hours, the submarine can materially reduce the probability of detection.

Consider the submarine during one snorkeling period. The probability of its falling under surveillance at some time is the ratio of the area surveyed during the period to the area within which the search is conducted. The area searched within any strip may be written,

$$N(wW\ 4/n + K),$$

where K is some function of the <u>instantaneous</u> search area. Then the required probability is:

$$X = \frac{N\ (wW\ 4/n\ + K)}{W\ L}$$

Then the probability of the submarine's not falling under surveillance in any of the n periods is

$$P_o \quad (1 - X)^n$$

Thus the probability of the submarine's being under surveillance at least once during his passage through the search area is:

$$P_S \quad 1 - (1 - X)^n.$$

Figure VIII-1 shows a plot of P_S as a function of n, where K $(\pi/4)\ W^2$; that is, the area of a circle of diameter W, and L has been taken as 1500 miles (the airline distance from Nova Scotia to Puerto Rico). It may be seen that the detection probability does not vary appreciably with the number of snorkeling periods except where n is small. In any case, we can be conservative by considering the <u>minimum</u> probability for each N as determining the effectiveness of the barrier. Figure VIII-2 shows these probabilities as a function of the total number of planes flying patrol (N 500/W) at any time. Assuming that a total of 6 planes is

required for each plane flying, the total number necessary to maintain the patrol may be computed; these values are also indicated in Fig. VIII-2.

A similar calculation may be carried out to determine the search effectiveness against aircraft. Figure VIII-3 shows patroling planes in one strip with their instantaneous search area against enemy planes indicated. If we consider relative motion of a plane trying to cross the search line at a speed u and the search plane (speed w), the enemy will effectively be crossing the line at an angle θ where $\theta = \tan^{-1}(w/u)$. The probability of his being detected in a single strip is then

$$y = \frac{NW_A/\cos\theta}{L} = \frac{NW_A}{Lu}\sqrt{u^2 + w^2} ,$$

and, as before (if strips are independent), the probability of detection is

$$P_{D_A} = 1 - (1 - y)^{500/W} .$$

To consider the most unfavorable case from our point of view, set w = o and compute P_{D_A} as a function of N. The sweep width W_A can be conservatively estimated as 100 miles and L, as before, is 1500 miles. Figure VIII-2 shows P_{D_A} as a function of the number of patroling aircraft. This calculation is based on the assumption of independent search strips -- independent in the sense that search schedules in the strips are not interrelated. The detection probability against aircraft can be increased by scheduling flights in adjacent strips. However, such a scheme, if discovered by the enemy, would allow his aircraft or submarines to cross the search line undetected.

In any search operation of this type, the false-contact problem becomes an important factor. It is entirely possible that the

incidence of false contacts will be so large as to render the entire operation unfeasible. This is considered highly unlikely, however, for the proposed search line lies well away from the coast and coastal shipping lanes, so that the presence of small boats and floating trash is at a minimum. In addition, targets may be evaluated by efficient plotting in each plane before counteraction is taken.

A good navigational scheme is essential to this operation. In particular, once a contact is made, accurate location data are needed so that the attack phase may be carried out. The present loran system is adequate for this purpose over much of the patrol area; however, extension of the system to those parts near the West Indies, not now serviced, is needed.

The approximate cost of the operation as a whole may be estimated on the basis of figures obtained from OEG Study No. 327. The capital cost per year of a Constellation-type airplane equipped with the necessary radar is estimated at $250,000 (5-year life). Four hundred planes require a total capital cost per year of $100,000,000. Operational cost of such aircraft runs about $500 per flight hour, including servicing and maintenance as well as ground facilities. Total operational cost for one year would be $240,000,000. The initial cost of ground installations to service and provide storage area is estimated to be about $20,000,000; this would cover the cost of construction of three airports, located in Nova Scotia, Bermuda, and Puerto Rico. Reasonable coverage could be obtained for a smaller expenditure. Such a cost is not out of proportion to the over-all ASW, harbor, and coastal protection effort. It is entirely possible that the savings attained in these latter efforts would more than make up the required expenditure.

It is concluded that the search-killer patrol offers a very

attractive scheme for the combined fields of domestic harbor defense, coastal convoying, early warning against aircraft, and aggressive ASW.

Recommendation for immediate action: a trial patrol should be flown. A trial would evaluate some of the unknown factors, such as the frequency of false targets and the effect of operator reliability. The results of such evaluation may be used to give a better idea of the operational effectiveness of this scheme.

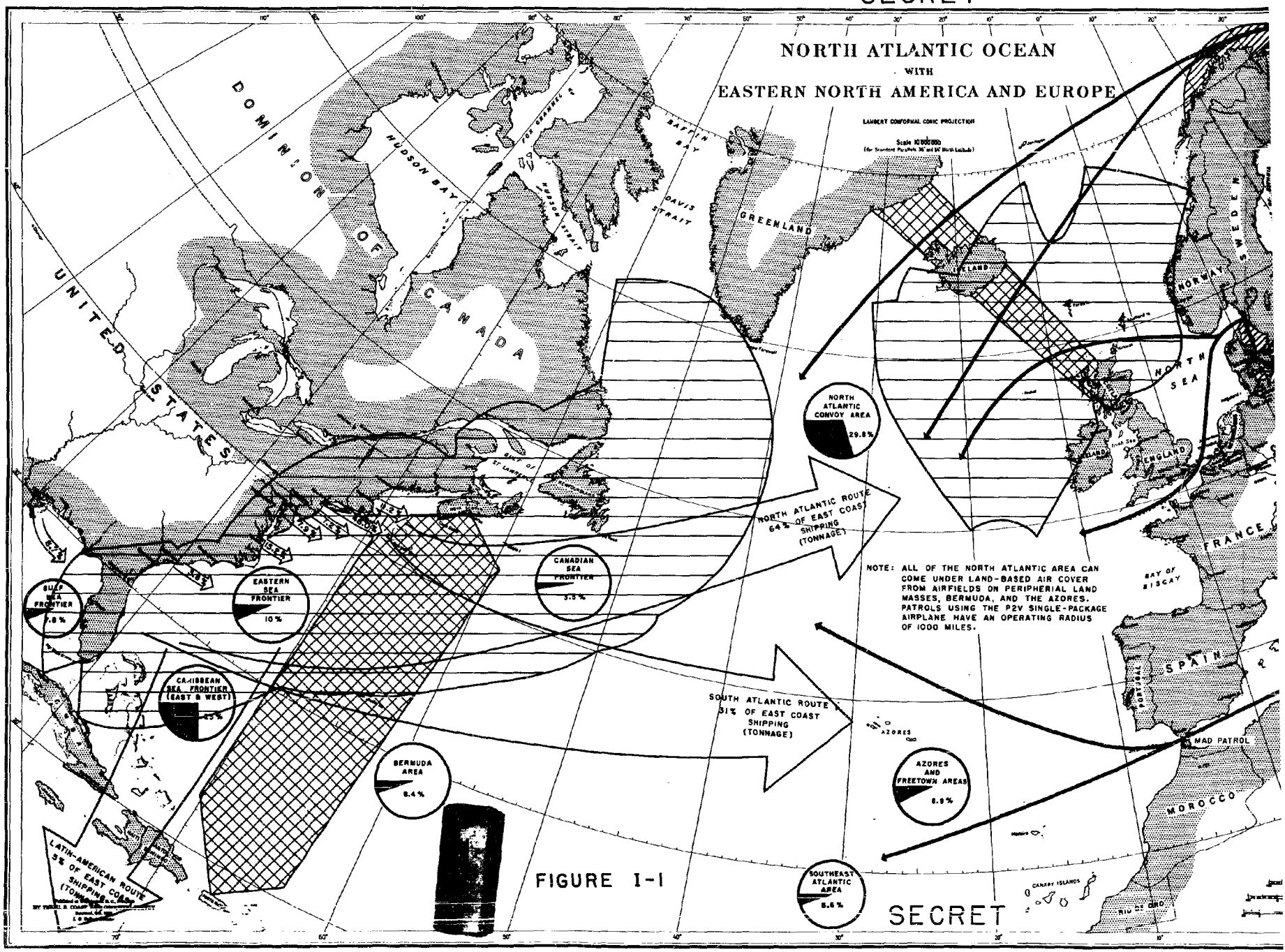
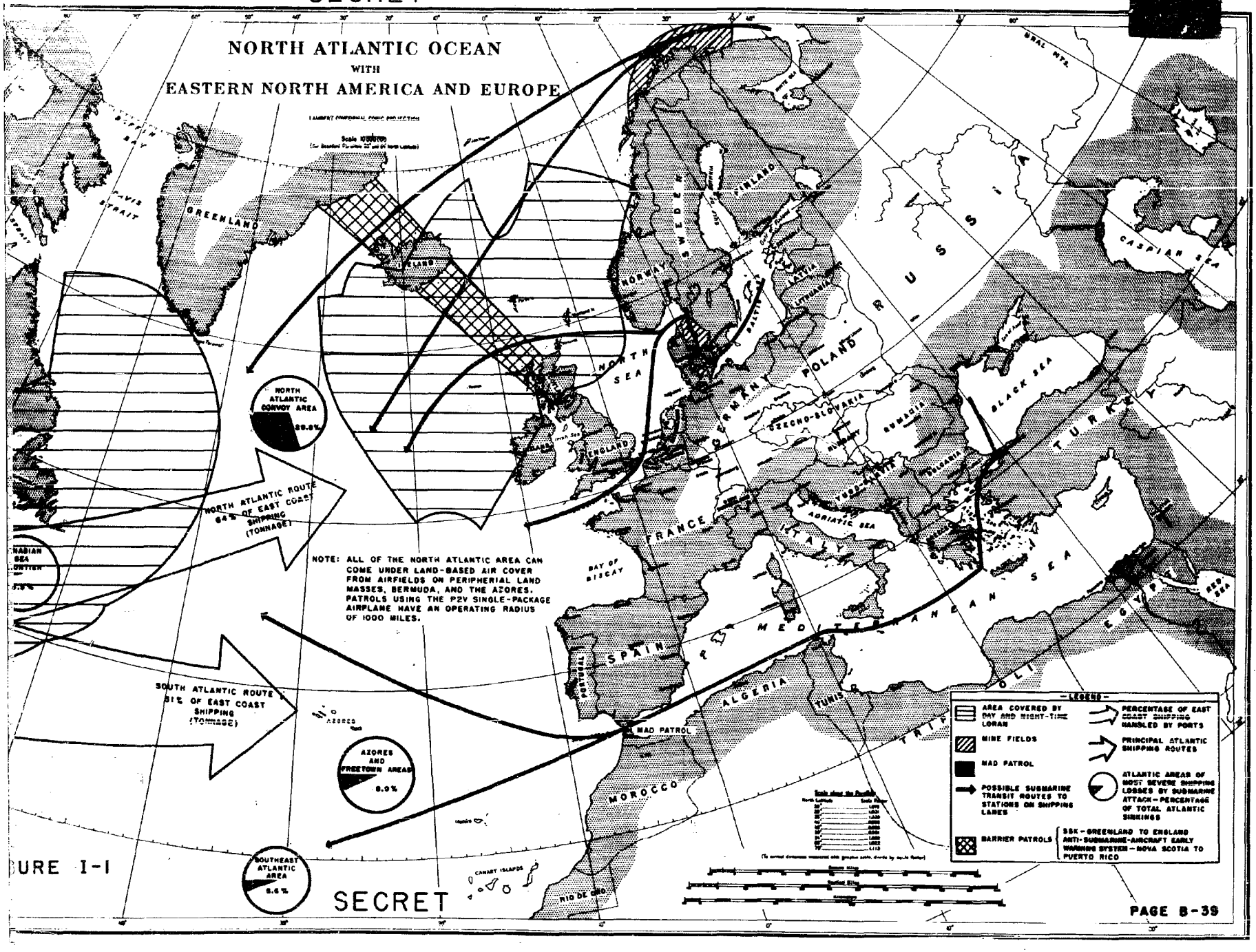

NORTH ATLANTIC OCEAN
WITH
EASTERN NORTH AMERICA AND EUROPE
LAMBERT CONFORMAL CONIC PROJECTION
DOMINION OF CANADA
UNITED STATES
HUDSON BAY
FOX CHANNEL
HUDSON STRAIT
BAFFIN BAY
DAVIS STRAIT
GREENLAND
ICELAND
NORWAY
SWEDEN
NORTH SEA
ENGLAND
FRANCE
BAY OF BISCAY
SPAIN
PORTUGAL
MOROCCO
AZORES
CANARY ISLANDS
MAD PATROL
NORTH ATLANTIC CONVOY AREA 29.8%
NORTH ATLANTIC ROUTE 64% OF EAST COAST SHIPPING (TONNAGE)
SOUTH ATLANTIC ROUTE 31% OF EAST COAST SHIPPING (TONNAGE)
LATIN-AMERICAN ROUTE 5% OF EAST COAST SHIPPING (TONNAGE)
GULF SEA FRONTIER 7.8%
EASTERN SEA FRONTIER 10%
CANADIAN SEA FRONTIER 3.5%
CARIBBEAN SEA FRONTIER (EAST & WEST) 25%
BERMUDA AREA 8.4%
AZORES AND FREETOWN AREAS 8.9%
SOUTHEAST ATLANTIC AREA 5.6%
NOTE: ALL OF THE NORTH ATLANTIC AREA CAN COME UNDER LAND-BASED AIR COVER FROM AIRFIELDS ON PERIPHERIAL LAND MASSES, BERMUDA, AND THE AZORES. PATROLS USING THE P2V SINGLE-PACKAGE AIRPLANE HAVE AN OPERATING RADIUS OF 1000 MILES.

FIGURE I-1


NORTH ATLANTIC OCEAN
WITH
EASTERN NORTH AMERICA AND EUROPE
LAMBERT CONFORMAL CONIC PROJECTION
Scale 1:8,000,000
(For Standard Parallels 33° and 45° North Latitude)
BAFFIN BAY
DAVIS STRAIT
GREENLAND
ICELAND
NORWAY
SWEDEN
FINLAND
GULF OF BOTHNIA
GULF OF FINLAND
ESTONIA
LATVIA
LITHUANIA
BALTIC SEA
RUSSIA
POLAND
GERMANY
NORTH SEA
ENGLAND
Irish Sea
CZECHO-SLOVAKIA
HUNGARY
RUMANIA
BULGARIA
YUGOSLAVIA
ADRIATIC SEA
ITALY
FRANCE
BAY OF BISCAY
SPAIN
PORTUGAL
MEDITERRANEAN SEA
ALGERIA
TUNISIA
TRIPOLI
MOROCCO
EGYPT
RED SEA
BLACK SEA
CASPIAN SEA
TURKEY
ARAL SEA
AZORES
CANARY ISLANDS
RIO DE ORO
NORTH ATLANTIC CONVOY AREA
89.8%
NORTH ATLANTIC ROUTE
64% OF EAST COAST SHIPPING (TONNAGE)
SOUTH ATLANTIC ROUTE
31% OF EAST COAST SHIPPING (TONNAGE)
AZORES AND FREETOWN AREAS
8.0%
SOUTHEAST ATLANTIC AREA
5.6%
NOTE: ALL OF THE NORTH ATLANTIC AREA CAN COME UNDER LAND-BASED AIR COVER FROM AIRFIELDS ON PERIPHERIAL LAND MASSES, BERMUDA, AND THE AZORES. PATROLS USING THE P2V SINGLE-PACKAGE AIRPLANE HAVE AN OPERATING RADIUS OF 1000 MILES.
MAD PATROL
Scale along the Parallel
North Latitude
Scale Miles
(To correct distances measured with graduated scale, divide by scale factor)
Nautical Miles
Statute Miles
Kilometers
-LEGEND-
AREA COVERED BY DAY AND NIGHT-TIME LORAN
MINE FIELDS
MAD PATROL
POSSIBLE SUBMARINE TRANSIT ROUTES TO STATIONS ON SHIPPING LANES
BARRIER PATROLS
PERCENTAGE OF EAST COAST SHIPPING HANDLED BY PORTS
PRINCIPAL ATLANTIC SHIPPING ROUTES
ATLANTIC AREAS OF MOST SEVERE SHIPPING LOSSES BY SUBMARINE ATTACK—PERCENTAGE OF TOTAL ATLANTIC SINKINGS
SSK—GREENLAND TO ENGLAND ANTI-SUBMARINE-AIRCRAFT EARLY WARNING SYSTEM—NOVA SCOTIA TO PUERTO RICO

URE I-1

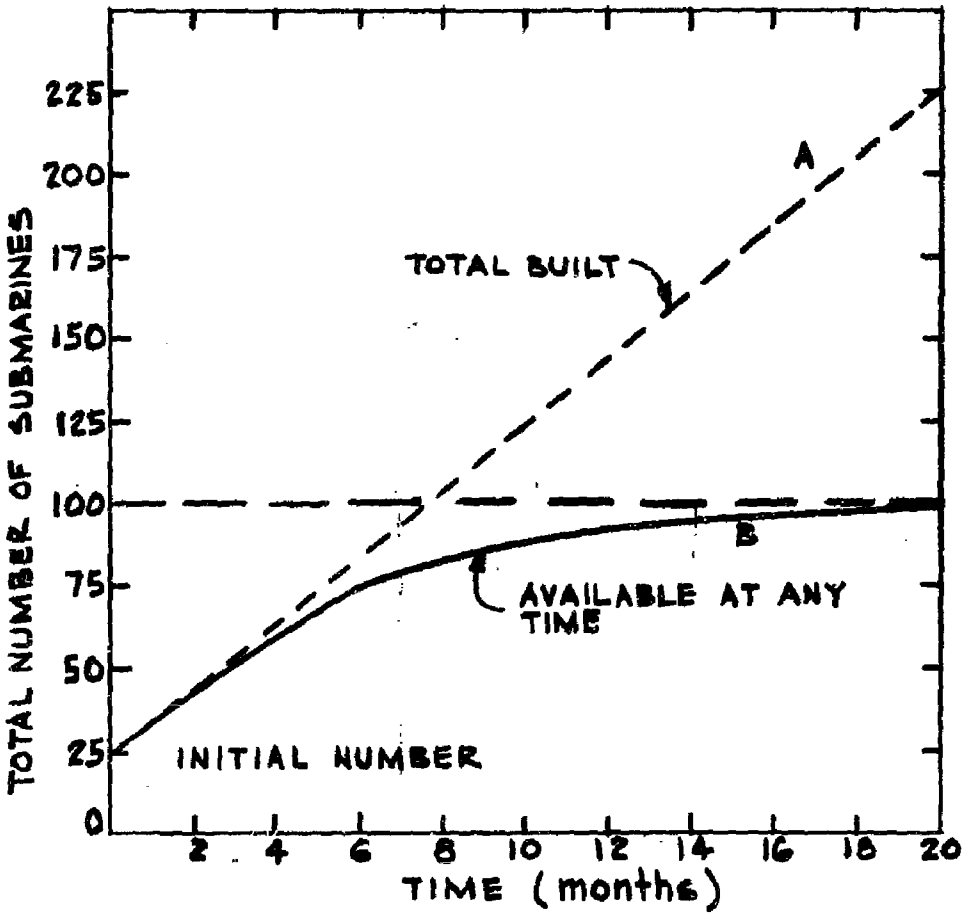


Fig. I-2 Typical Curve of Available Number of Submarines With:

A. No Killing, Building Rate 10/Month
B. Killing Rate 10/Month

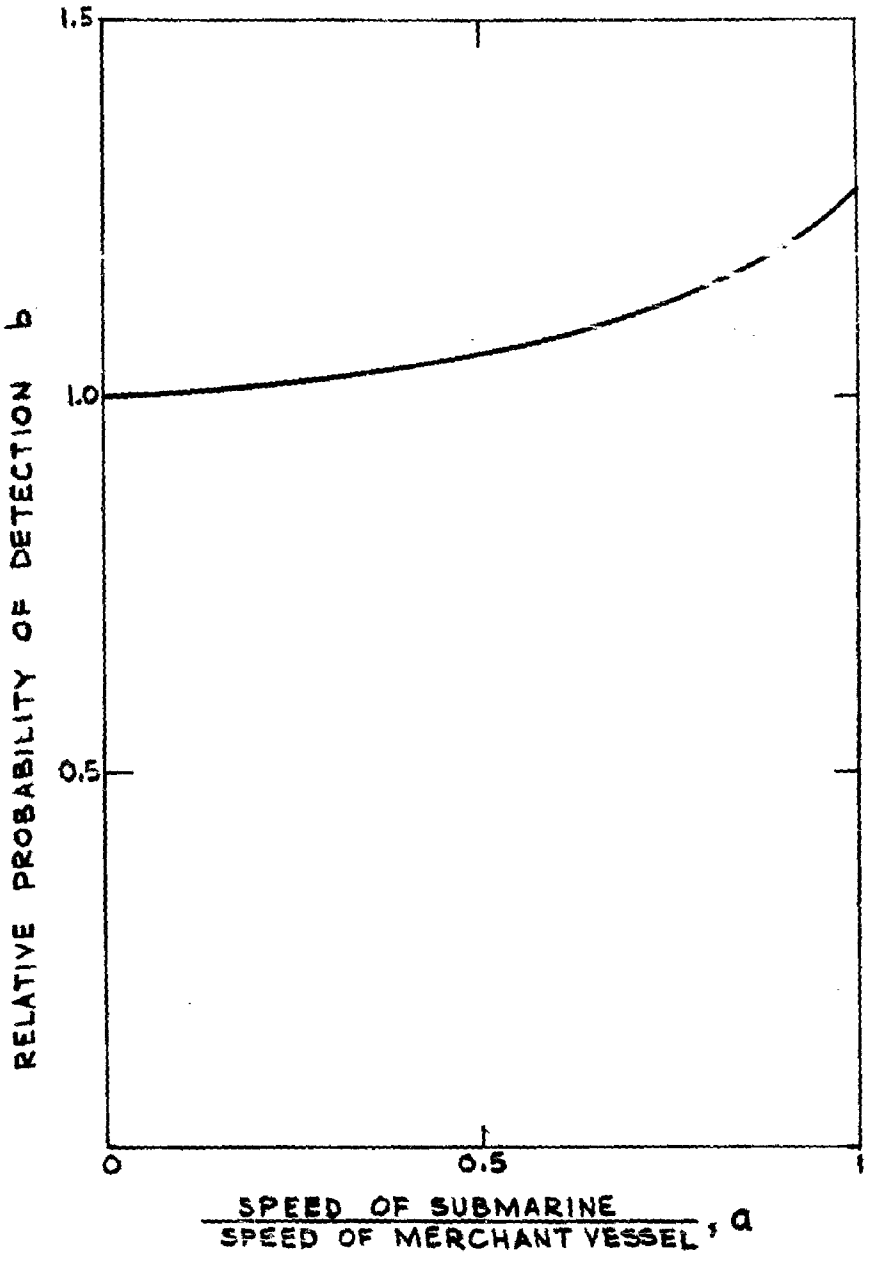


Fig. VI-1 Effect of Relative Speed on the Probability of Detection

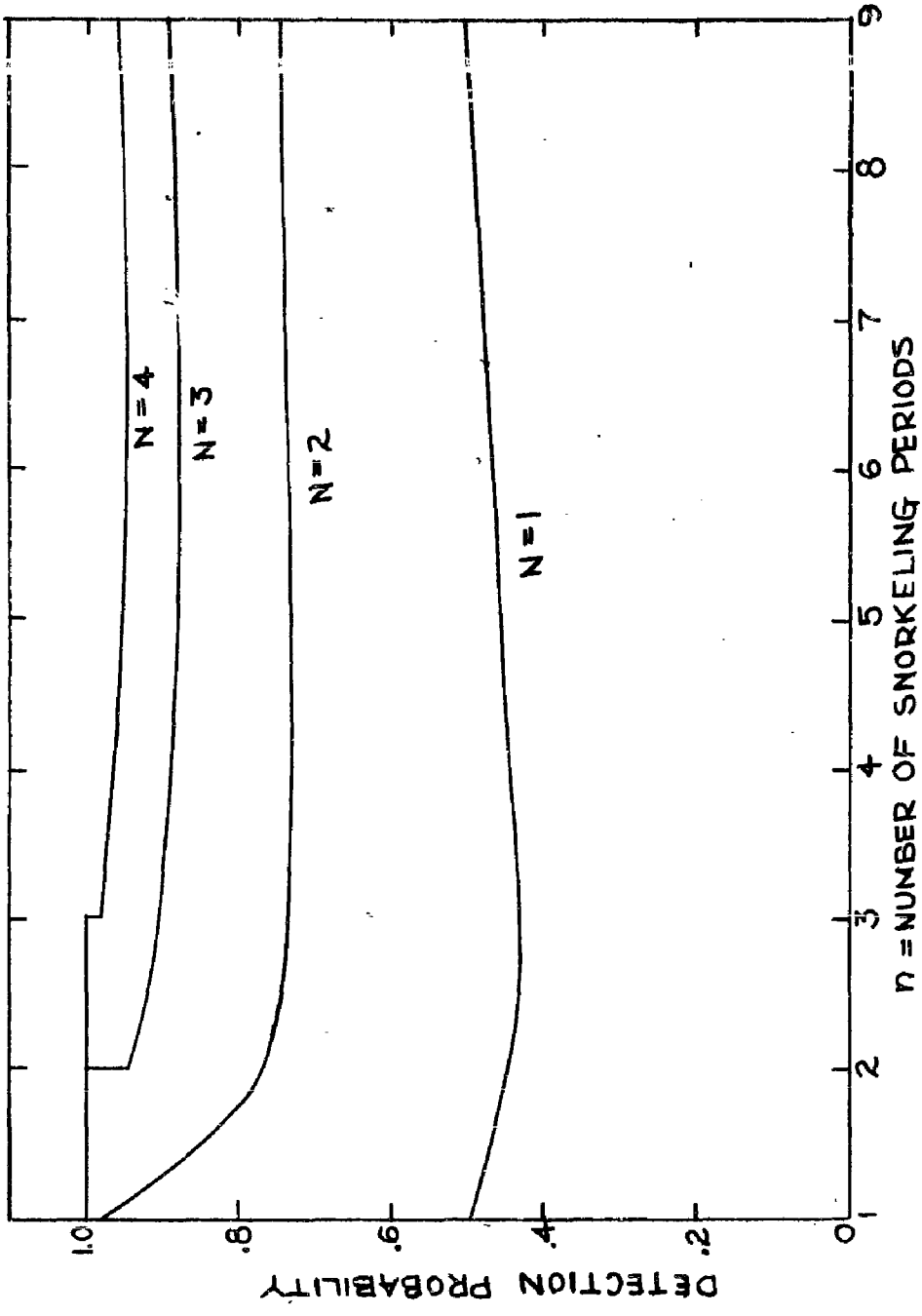


Fig. VIII-1 Probability of Detection as a Function of Number of Snorkeling Periods. (N = number of search planes in each strip)

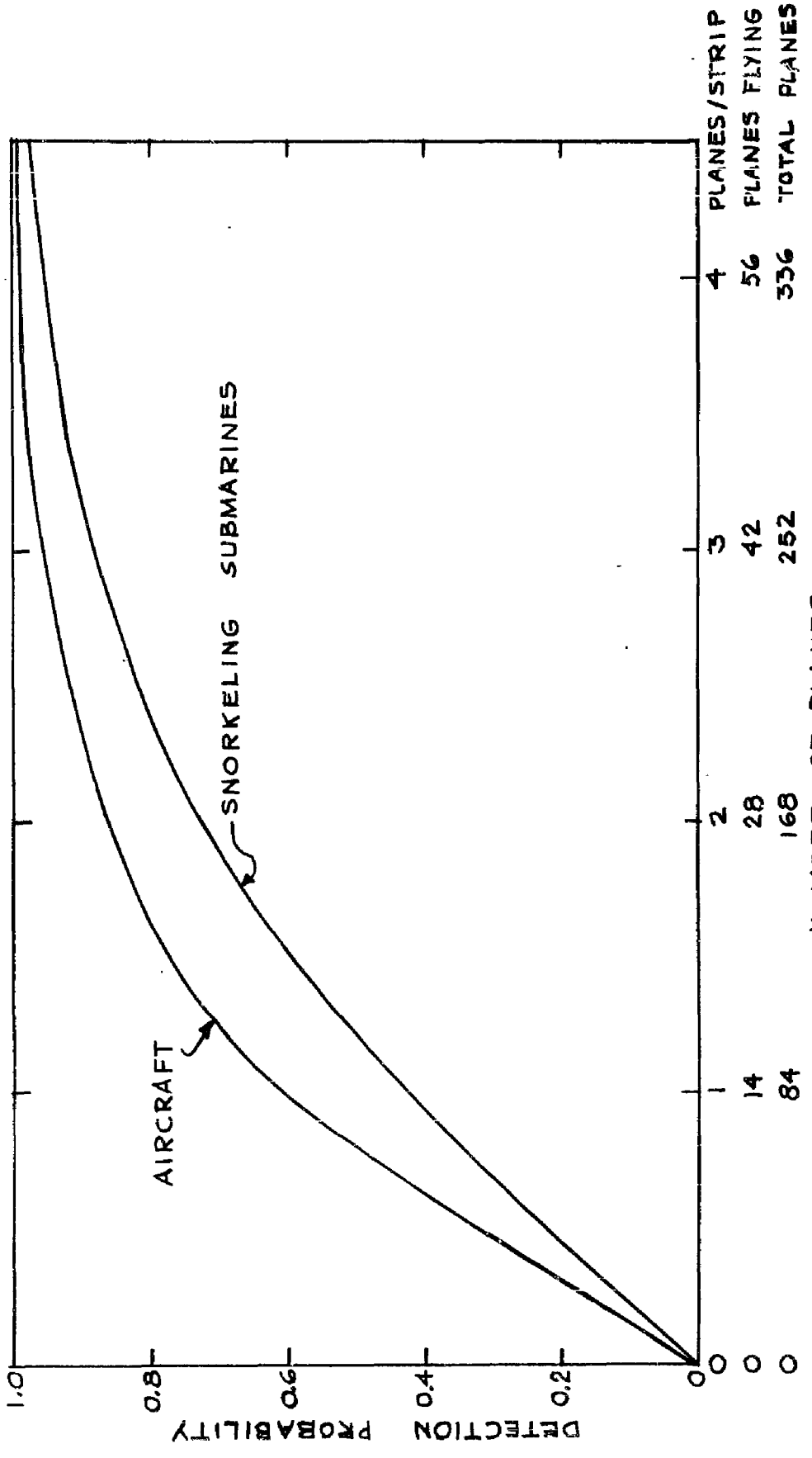


Fig. VIII-2 Effectiveness of Nova Scotia-Bermuda-Puerto Rico Patrol as a Function of Effort

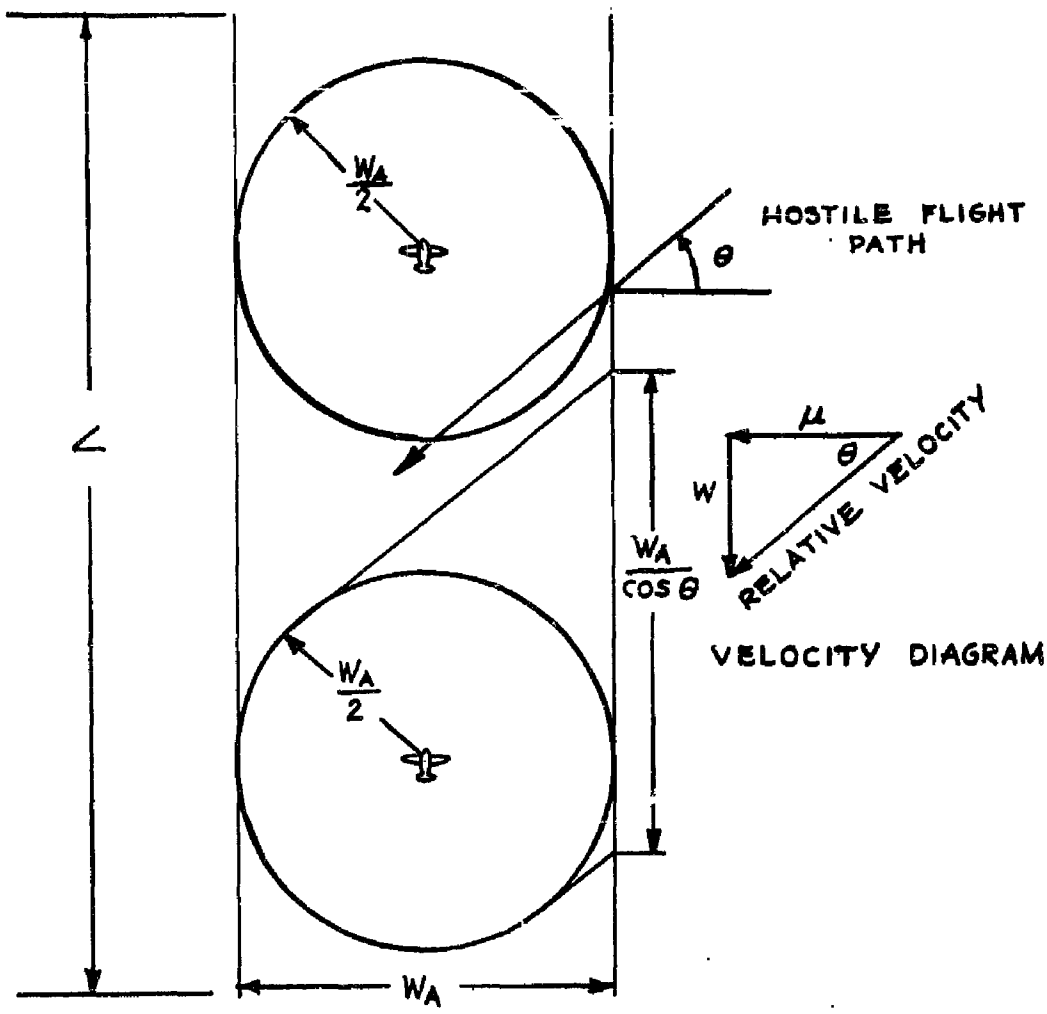


Fig. VIII-3 Relative Motion of Search Planes and Hostile Craft Crossing Search Line

APPENDIX G

COMMUNICATION

A. Submarine Communication

The communication facilities now available to the fleet seriously limit the operational tactics of the SSK submarine. The existing equipments do not have adequate range or reliability for surfaced or submerged operation, and they do not provide the privacy or freedom from detection that is extremely important in this type operation. In this Appendix, several methods of communication are examined, their present status evaluated, and an estimate made of the potentiality of each of these for the submarine service.

This problem logically divides into three distinct parts, shore-to-ship, ship-to-shore, and inter-fleet communication (where the inter-fleet communication may be between two or more submarines, or can be between a submarine and ships of a fleet or supporting aircraft). The discussions of private communication and slow-speed data transmission at the end of this Appendix apply to the three categories.

1. Shore-to-Submarine Communication

The long-wave radio now employed provides a satisfactory means of transmitting from shore bases to submarines at sea. In the absence of airborne relay stations, the long-wave transmitters provide the most reliable transmission method now available. Unfortunately, because of the large transmitting antennas required for satisfactory operation, long-wave transmission cannot be employed for submarine-to-base communication, and short-wave or relay transmission must be employed.

The existing long-wave facilities can transmit to a surfaced submarine anywhere in the world, and normally have sufficient signal strength to permit operation slightly below

the surface of the ocean. If hunter-killer submarines are to be employed across transit routes close to the enemy homeland, it will be important to relay intelligence to the submarines without the necessity of exposure. It is possible to increase the operational depth of the present low-frequency receivers by the following means.

(a) Use slower transmission rates and narrow-band receivers: -- If this is done, it might be necessary to provide recording equipment that would enable the operator to play back the code message at higher speeds. Such devices have been developed at the Bell Telephone Laboratories. An alternate scheme would be to provide slow-speed teletype service which could be operated over a narrow intelligence band.

(b) Use larger antennas: -- As shown in Annex (A) of this Appendix, the signal received by the loop on the submarine is proportional to the cross-sectional area of the loop. If necessary, large single-wire, high-Q loops or trailing wires could be employed, increasing the received signal by as much as 10 to 20 db.

(c) Improved receiver input circuits: -- Above the surface of the water, the reception of long-wave transmission is limited by local static and, therefore, the important factor governing reception is the relative strengths of the desired signal and the static. However, if the receiving antenna is in the water, both the static and the signal are attenuated; as the depth of the submarine is increased, signals become weaker and finally are masked by the noise originating in the receiver. Recently, substantial improvements have been made in receiver

input circuits and, if modern circuits were employed in the long-wave receivers, considerably better sensitivity could be achieved.

(d) Direction finding: -- The loop antenna can be used for direction finding. Many submarines actually do use low-frequency transmissions for this purpose. If the loop were made to rotate, it could be used more effectively for this purpose. Also, the location of a small number of additional, strategically located, shore stations would greatly increase the precision of such fixes.

2. Submarine-to-Shore Communication

Because it is not possible to put an efficient low-frequency transmitting antenna on a submarine, these frequencies cannot generally be used for transmission from a submarine to a shore base. Instead, it is necessary to rely on short-wave ionospherically propagated radio waves. The equipment for this purpose appears to be fairly reliable, and the ionospheric predictions provided to the fleet appear to be adequate most of the time. If it were necessary to improve the reliability of the short-wave communication, this could be done by using shorter time predictions or employing back-scatter methods to determine proper frequencies for specific transmissions. This information could be supplied to the submarine on the conventional low-frequency Fox schedule.

3. Submarine-to-Submarine Communication

a. Surface Operation

For moderate range (50-mile) inter-fleet communication on the surface, high-frequency transmission (greater than 30 Mc) can be made reliable. The use of longer waves is not recommended for such transmissions, because they would require greater power and are subject to ionospheric transmission which

could propagate the transmission over large distances. If too short a wavelength is used, the signals will attenuate too rapidly, and unsatisfactory performance will result. The present submarine fleet employs a 100-Mc communication system for inter-fleet operation, and reports unreliable performance. An examination of Fig. G-1 shows that satisfactory transmission can be achieved over a 50-mile range with moderate powers at 30 Mc, but that powers considerably greater than it is feasible to use would be necessary for adequate performance at this range at 100 Mc. The 100-Mc equipment is airborne equipment that was designed to take advantage of the long line of sight provided by a plane flying at high altitudes.

b. Underwater Operation

At the present time, two methods exist for communication between a submerged submarine and the surface fleet. Low-frequency electromagnetic waves and modulated acoustic waves have been employed for short ranges.

(1) Electromagnetic Communication

Recent experiments have aroused considerable interest in the possibility of using radio-frequency electromagnetic transmission for communication through the water. Certain confusion has been caused by experiments that indicate that transmission was not affected by placing the transmitting radiator or receiving electrodes at considerable depths under water. An analysis of this (presented in Annex A) indicates that this is not so, and shows how the confusion could well have arisen. The analysis, described in detail in the above Annex, indicates that reliable audio-frequency transmission between submarines whose antennas are relatively close to the surface of the water (of the order of 50 feet) can be obtained up to a range of approximately

20,000 yards if large loop antennas are employed. The design of antennas for this application would be a considerable chore, since, for effective transmission, they must be large, perferably having dimensions the size of the submarine. To carry such equipment without affecting submarine operation is difficult. The same antenna could probably be used as part of the long-wave listening system discussed in Section 1.

If it were desired to operate the SSK fleet at greater depth and still maintain communication, it would be possible to do so if one employed low intelligence rates and went to very-low carrier frequencies, i.e., of the order of 10 cycles per second. Ranges of the order of 20,000 yards at depths of 200 feet might conceivably be obtained. There is insufficient information regarding atmospheric noise at these frequencies to make a reliable calculation regarding the performance of such a unit. It is also difficult to evaluate the vulnerability of this system to enemy detection.

(2) Acoustic Communication

A good sonic telephone is now available to the fleet. The unit, employing single sideband transmission, has a reliable range of approximately 10,000 yards. For SSK team operations, considerably greater range is needed. Also, under certain conditions it will be important to communicate with greater privacy than is permitted by this system. The possibility of using narrow-band low-level signals and noise-carrier systems at low frequencies offers some promise of achieving longer-range hidden communication. Whether or not one of these systems can be made to work depends upon how seriously multipath phenomena mutilate the

transmitted signal. Experiments are necessary to evaluate the practicality of single-sideband code transmission, frequency modulation employing good limiters, noise transmission, etc.

The same experiments that will clarify the low-frequency listening requirements for sonar will provide information necessary for design of this system (see Appendix D, Section I).

B. Narrow-Band Transmission Methods

To use very-low-frequency electromagnetic or acoustic carrier frequencies (10 to 100 cycles/sec), it is necessary to have available a slow-speed data transmission system -- that is, one requiring the transmission of only a few bits of information per second. It would be possible to send code at a slow rate, but experience has shown that, if the code speeds are reduced sufficiently, it becomes extremely difficult to send and receive. This problem can be met by employing an automatic device that allows code to be recorded by the operator at high speeds and transmitted at low speed, and then to be recorded at low speed and replayed rapidly at the receiving point. Magnetic-tape recorders having the properties needed for such a system have been developed by Dr. Potter's group at BTL.

An alternate way of handling this problem would be to use a multiple-tone slow-speed teletypewriter for the data transmission system. Such slow-speed systems are also desirable for the hidden communication systems that will be discussed in a later section.

C. Hidden Communication

In many ASW operations, such as the employment of hunter-killer aircraft teams, fleet station keeping, helicopter listening, and wolf-pack SSK tactics, the ability to communicate is so important that a certain amount of communication will be necessary even if it jeopardizes the operation. For this reason, it is

very important to achieve the ability to use electromagnetic waves with freedom from detection. Two alternate solutions to this problem appear possible: (1) the use of radio wave that attenuate very rapidly and thus limit the propagation; and (2) the use of transmission methods that make the radiated signals difficult or impossible to detect without elaborate equipment or a knowledge of a special code employed in transmission.

1. Oxygen-Absorption-Band Communications and Radar

Electromagnetic radiation in the vicinity of the 6-mm wavelength region is attenuated very rapidly by an oxygen absorption line. This absorption effect can be utilized to limit the transmission of signals to ranges in the order of a few miles. The exact amount of attenuation and, consequently, the system range can be controlled by the proper choice of frequency. The components for this equipment -- receiving and transmitting tubes, crystals, antennas etc. -- do not exist. We recommend that emphasis be given to this program and that groups familiar with the problem (e.g., BTL) be engaged to carry this program forward.

2. Hidden Transmission Methods

Several schemes for hiding radio carriers have been suggested. Two of them will be discussed in detail and a third will be suggested.

a. Narrow-Band Low-Power Carrier

If low-intelligence-rate signals (1 to 10 cycles per second) are transmitted, it is possible to use narrow-band filter techniques or cross-correlation detectors to make equivalently narrow-band receivers. Such systems could be employed with either acoustic or electromagnetic carriers. When such extremely narrow bands are employed, exceedingly small carrier powers are usable if necessary. For example, if an information band of 10 cps is employed in a system using a carrier frequency of 100 Mc, a transmitter power of less than one milliwatt would extend the range of the system

to 50 miles, while a 10-kc-wide receiver would have to come in to about a third that distance to get a detectable signal from the same source. A similar result could be achieved with an acoustic underwater transmitter; however, because of the narrow effective bandwidth of the ear as a filter, lower data rates would be required to hide messages. This disadvantage could be overcome by using several carrier frequencies simultaneously and employing a lower data rate on each of the individual carriers.

b. Noise Transmission

A random-noise voltage or a noise-modulated transmitter with its carrier suppressed can be used to convey intelligence. If a wide band of noise is employed, the energy density of the transmitter can be reduced to an arbitrarily small value. In this way, it is possible to reduce the power at some arbitrary point from the transmitter to a value less than the background noise so that it would be difficult for a search receiver to recognize the transmission. If, at the same time, the actual modulation or intelligence bandwidth were kept small, it would be possible to achieve a usable post-detector signal-to-noise ratio. At points in space beyond this, it would be possible to carry on satisfactory communication, but it would not be possible, or at least not easy, for the signal to be recognized and DF'd on.

Three different systems should be considered. The first two use random-noise transmission and correlation detectors, and the third employs random-spaced pulses and a coincidence pulse detector. The three systems have many characteristics in common.

As an example, a noise-modulated system employing autocorrelation detection will be described. The output from a noise generator (see Fig. G-2) is fed into a delay line having several taps. Modulation is accomplished by successively

selecting the outputs from these various taps. If a direct voltage from the noise generator is transmitted simultaneously, either mixed with the output of the delay line or transmitted on a separate frequency, a signal can be detected by processing with an autocorrelator. If the noise-source output and the delayed noise are mixed and then fed into an autocorrelator consisting of a delay line having delays equal to those in the transmitter, and the products of the output and input signals taken and integrated, one channel will have a signal output. This channel will correspond to the circuit that has been closed in the transmitter. If the reference noise is transmitted on a separate channel, products are formed between the delay-line output and the output of the separate channel; the result, however, will be the same. There is a good reason for employing a separate channel. If the signals are mixed for single-channel transmission, the delay line will behave like a comb filter. This characteristic would be detectable on a panoramic receiver. However, it would be extremely difficult for anyone to apply the correlation techniques necessary to detect the signal if the reference noise is transmitted on a separate channel. As an example of the system parameters for such an equipment, one case will be computed. If a circle is drawn at some arbitrary radius (say, 20 miles) around the transmitter and it is arbitrarily assumed that at this point signal emission should add only 10 per cent to the noise in the background and if this system is to handle a 3-kc intelligence band and have a 30-db S/N ratio at that point, a 3-Mc noise band would be required. This is easily handled on a UHF or microwave circuit. With a 10-cycle intelligence bandwidth, such as might be employed for slow-speed teletypewriter system, a noise bandwidth of 30 kc would be needed.

It has been suggested* that, instead of transmitting the reference noise signal, it could be recorded and then reproduced synchronously at the transmitter and receiver. Such a system would have marked advantages over the simpler ones just described. It would have not only the features of a hidden-transmission system but also those of an excellent cryptography system. Since nothing but noise is radiated, with no inherent reference signal, it would be impossible to detect and receive messages carried by the modulation. In addition, such a system would be considerably more economical of bandwidth than the previous one; however, the problem of the mobile, synchronized noise source would be extremely difficult in the case of wide-band intelligence. It might be resolvable for narrow-band systems.

c. The third system suggested, by Dr. J. R. Pierce of BTL, uses random pulse pairs to carry the intelligence signal which is detected by a coincidence circuit. By making the pulses short, it would be possible to spread the energies of this system over a wide band and thus obtain some measure of privacy. It would also be possible to use such a system with synchronized pulse sources to obtain the cryptography feature inherent in the system proposed above.

Each of these systems has attractive features beyond those described. If a number of such transmitters were operated on the same channel, the effect of the additional transmitters on the first would be to add a small increment of noise to the output, so that one could have a system of common-channel operation very much like a time-division multiplex system. This would have enormous advantage in fleet operations, since many transmitters could be operated on a

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*Adams and DeRose of Federal Telecommunications Laboratories

single frequency. Each unit could have its own distinct correlation time or times, and selection between stations would be made by switching from one group of delay times to another. This would eliminate the problems of frequency selection that now cause such serious confusion in fleet operations. Theoretically, it would be possible to do this with a time-division system; however, in synchronized time-division systems, the problem of obtaining accurate synchronization between a large group of mobile equipments is extremely difficult and, in fact, has not been successfully solved.

D. Traffic Information Center

As we envisage it, a Traffic Information Center for the North Atlantic knows the locations and courses of all U. S. and allied naval vessels, merchant ships, and aircraft. It receives information about enemy submarines and aircraft, as well as our own, from Nova Scotia-Bermuda-Puerto Rico patrol. It hears immediately about all sightings of and sinkings of or by enemy vehicles. It has intelligence concerning departures of enemy submarines from their pens. It knows the course of every naval engagement as the engagement develops. It digests and evaluates this information, using modern, high-speed methods, and provides the means for exercising moment-to-moment control over the activities of our forces on, under, and above the Atlantic Ocean.

Such a Traffic Information Center does not now exist. The question is, should it not exist?

The participation of aircraft and nuclear explosives in sea warfare have the effects of (1) speeding up operations, and (2) reducing the degree to which spatially separated operations are functionally isolated. As a result, events taking place in various parts of the Atlantic are interrelated tactically as well as strategically. Under these circumstances, control must be cen-

tralized to be effective.

Centralization of control will require highly developed communications and ultramodern processing of information.

The communications requirements will include: (1) an increased number of channels, (2) a reduction of delay in transmission, (3) greater security from interception and DF-ing (but not necessarily cryptographic secrecy), (4) a reduction of self-interference, (5) greater resistance to jamming, and (6) greater reliability. These requirements are sine qua non for coordinated high-speed warfare. To meet them appears to be within the limits of technological feasibility (cf. Appendices D and G), but present military and naval communication is below the level that can be achieved. The over-all problem of Service communication is in need of intensive study by a group of the best minds that can be brought to bear upon it.

The processing of information on the grand scale and at the high speed that will be required of the information center is a new problem. Techniques for routing and for storing information have been developed for more specialized purposes (e.g., fire control, control of interceptor aircraft), and these techniques will be useful in the Traffic Information Center. However, it will take study and experience to determine optimal methods for filtering the incoming information, comparing data from various sources with each other and with data from storage, and deciding upon optimal courses of action. In our opinion, the Traffic Information Center will have to evolve. The evolution can be guided, but trial and error will play important roles. It is important, therefore, to set up a center now, to give it work to do, and to let it (1) start borrowing what it can from what has been learned about CIC's, AIC's, radar nets, etc., and (2) begin to work out new problems that arise.

In summary: a Traffic Information Center will very probably be of extreme value in the not-far-distant future. Because the

center will be complex and will pose new problems, it will not suffice to try to set it up when the need becomes pressing. Therefore, the Navy should start now with a pilot plant.

Recommendations:

(1) That the Navy construct a modern, high-speed information center for use in connection with the proposed Nova Scotia-Bermuda-Puerto Rico patrol. This will serve as a pilot plant.

(2) That a group consisting of naval officers and civilian experts in communication and information study the problem of the interrelation of actions in sea warfare. This study will determine the magnitude of the advantage that would result from contralization of control. It will also determine requirements for communications and for processing of information.

(3) That a group of civilian experts in communication study the over-all problem of military and naval communications. (The Traffic Information Center is but one of many considerations that support this recommendation.)

(4) That research and development in the processing of information, especially with reference to problems of sea warfare, be accelerated. (The pilot center of Recommendation (1) will contribute to the formulation of these problems.)

(5) That the Operations Rooms at the Headquarters of the Atlantic Command and of the Sea Frontiers be improved and expanded to enable them to operate more rapidly on larger amounts of more detailed and up-to-date information.

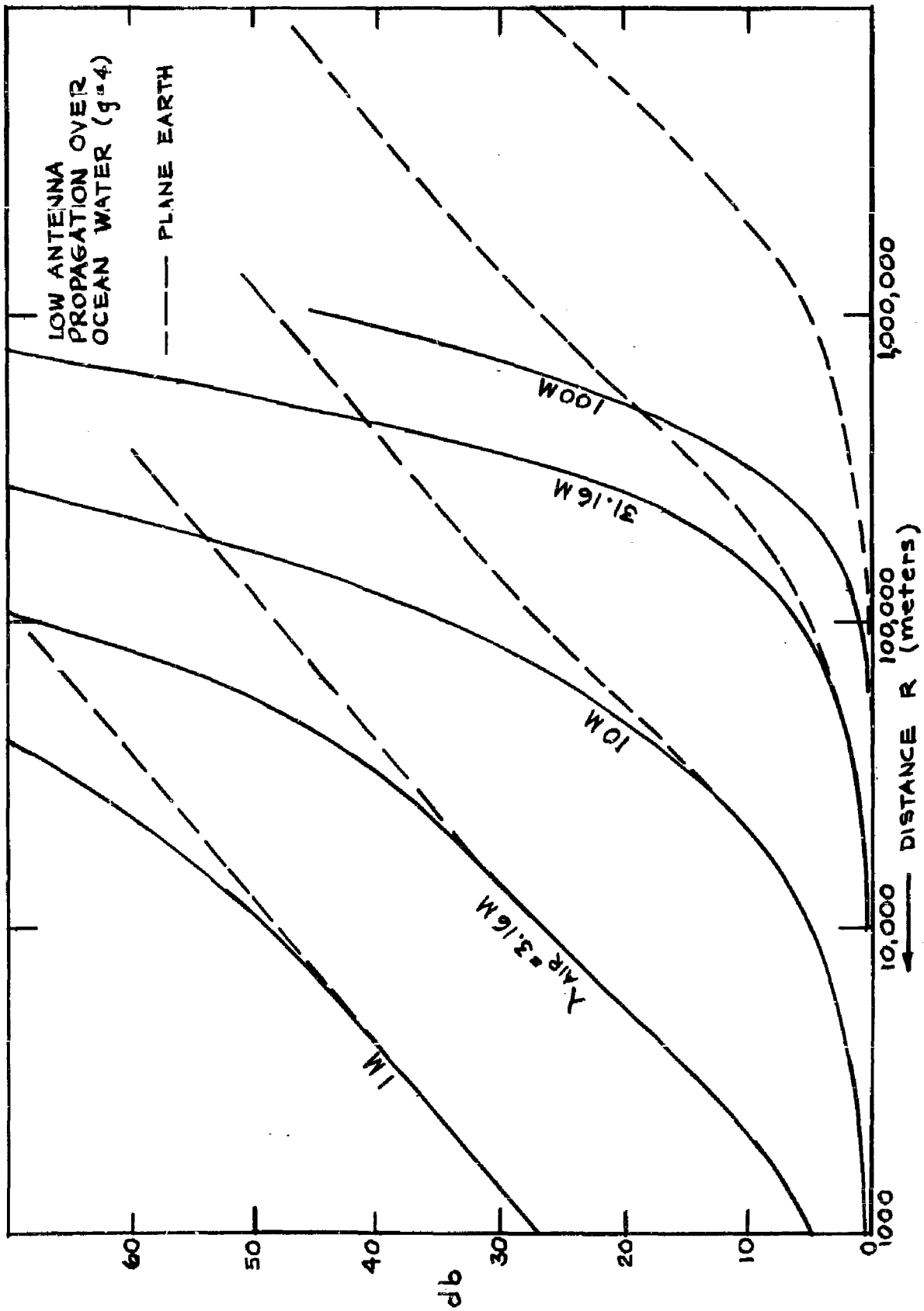

Fig. G-1. Source: Burrow and Gray; Earth's Curvature and Ground Wave Propagation, IRE Jan. 1941, p. 16

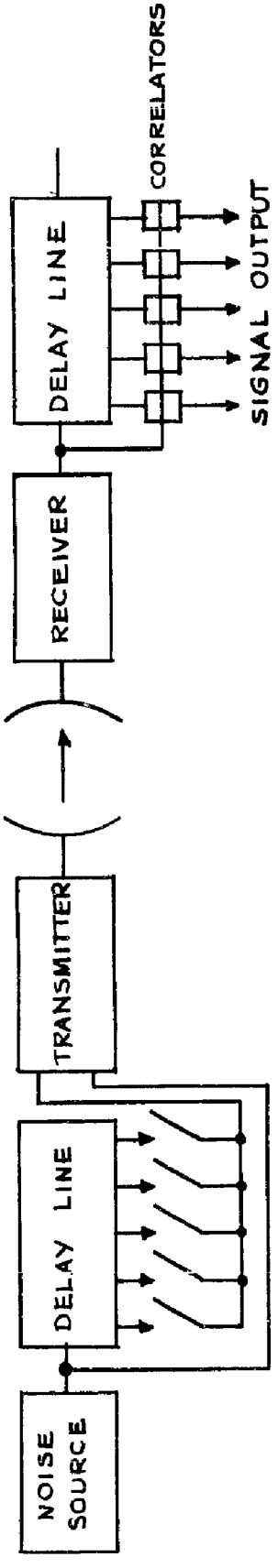

Fig. G-2. Simplified Schematic of Noise-Modulated Communication System

APPENDIX G

ANNEX A

Under Water Electric Potentials

Recent tests made at Scripps Oceanographic Institute and the Navy laboratory at New London have indicated that low-frequency electromagnetic waves could be used for signaling between submarines or between a submarine and surface craft. The most interesting aspects of the reported experiments were that the attenuation of the signals through the sea water appeared to be considerably less than Maxwell would have predicted and that the signals received at a distant point appeared to be independent of the depths to which the transmitting antenna was lowered. This is an anomaly, not predicted by Maxwell; we believe that we understand the mode of transmission, and the reason that the signal appears to be independent of transmitter depth.

In both reported experiments (Scripps and New London), ranges of the order of 5000 yards are indicated. In both cases, low-frequency signals 100 to 20,000 cycles/sec are established in the water by establishing a potential between a pair of electrodes as shown in Fig. G-(A)-1. The signal is received by a second pair of electrodes and amplified. If one assumes that the propagation is through the water from the transmitter to the receiver, Friis has computed a loss of approximately 800 db for a transmission path of 1000 meters and reasonable antenna dimensions at each end. This indicates some other mode of propagation. What we believe is happening is indicated by Fig. G-(A)-2.

The antenna in the water sets up an electric wave which establishes a vertical component of the electric field in the space above the water. For the moment, we will assume that the field in the water is established right at the boundary. If this were not the case, it would be attenuated as it propagates toward the boundary. In any event, the vertical component of the field above

the water will propagate with considerably less attenuation than the field in the water. Associated with the vertical field in the air is a small horizontal component of the field in the water. This field induces the potential which is amplified at the receiver. Friis has derived an expression for the field received via such a transmission path, using like horizontal transmitting and receiving antennas as shown in Fig. G-(A)-3. This gives a receiving power

$$p_2 = p_1 \frac{s^4 \, b^2}{16 \, r^6} \qquad (1)$$

(conductivity, etc. are included in the constant)

where s = antenna length,

b = radius of terminating sphere,

r = distance between antennas.

Using the same system parameters employed before, i.e.,

s = 2 meters,

b = 0.1 meter,

r = 1000 meters,

the signal attenuation is 200 db. This is still substantial; however, a proper juggling of the parameters would reduce this figure somewhat.

Equation (1) is in substantial agreement with the experimental data previously noted.

The mechanism outlined above neglects attenuation through the sea water which should increase exponentially as the antennas are lowered. This is contrary to the experience of both reporting groups. The lack of dependence upon depth could be due to the following unsuspected effect (Fig. G-(A)-4). The generator, cables and electrodes form a loop system as shown. If the electrodes are close to the surface (Fig. G-(A)-4-A) the loop formed is small; as the electrodes are lowered into the water, the loop area increases. Both the groups referred to above have reported

that the signals increase at first as the electrodes are lowered into the water and that, after they are immersed a few feet, nothing further happens. This would be expected if the mechanism proposed above actually exists. The electromagnetic field in the water drops off very rapidly with depth; hence, as the electrodes are lowered, they soon reach a point where the fields become vanishingly small. Increasing the effective loop area to include regions in the water where there are no magnetic fields will not increase the effectiveness of the loop. Thus, extending the electrodes indefinitely will not alter the situation markedly. Lowering the electrodes is, in effect, only changing the position of the ground terminals in the system.

A detailed examination of this and other low-frequency propagation situations is presented in the following paragraphs which give the results of a theoretical study of electromagnetic wave propagation in or above sea water at very long waves or low frequencies.*

Sheets A and B give the free-space transmission loss between two dipoles and two loops, respectively. The equations for the mismatch loss, A(5) and B(3), illustrate the inefficiency of small antennas, and the sheets are presented to orient the reader with respect to such factors.

Sheet C gives the transmission loss, Eqs. (3) and (4), between two dipoles in sea water. The mismatch losses between the transmitting dipole and its generator and between the receiving dipole and its receiver are not included in Eqs. (3) and (4) since these losses may be neglected for the impedance values encountered. The example shows that communication is not practical

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*The reader is referred to S. A. Schelkunoff's "Electromagnetic Waves" (pp. 81-85, 131 and 163) for the fundamental propagation and field equations.

because of the exponential attenuation loss. The d-c case, Eqs. (5) and (6), is of no practical value.

Sheet D, Eq. (9), gives the transmission loss between two dipoles slightly below the surface of sea water. It is simple to follow the steps involved in the derivation of (9), and it should be noted that propagation takes place through the air above the sea water. The dipoles have the figure-eight directional pattern, i.e., turning a dipole 90° around a vertical axis should give a "null" (except for field distortions caused by supporting structures).

Sheet E shows the effects of having the insulated dipole wires above the surface of the water and of lowering the dipole spheres in the water.

Sheet F, which covers transmission between one-turn loops, introduces the subject on sheet G which gives the transmission loss between "grounded" loops over sea water.

Sheet H is presented for information only.

It is believed that experimental studies will verify the transmission formulae given on sheets E and G.

Fig. G-(A)-1

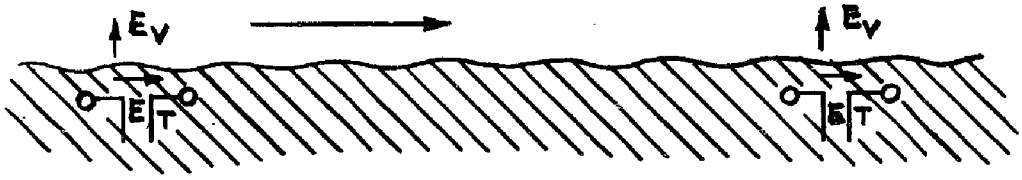


Fig. G-(A)-2

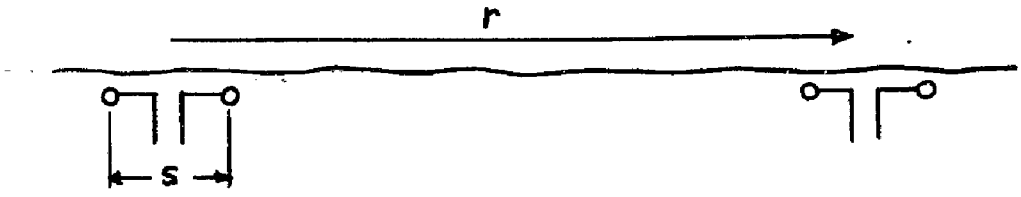


Fig. G-(A)-3

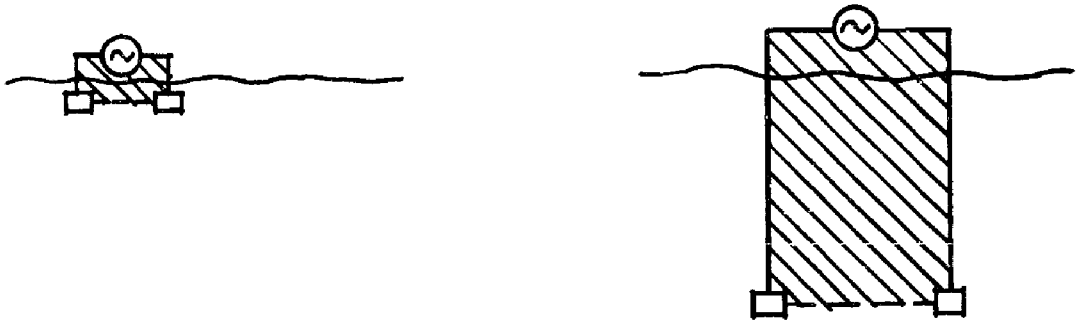
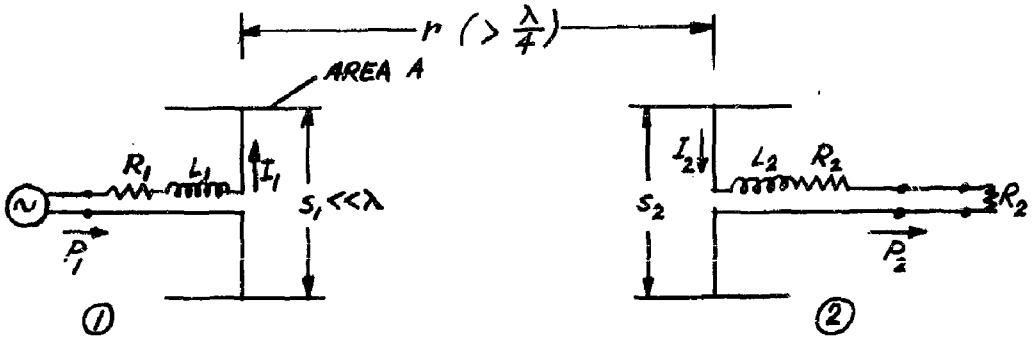


Fig. G-(A)-4



RADIATION RESISTANCE $= R_{rad.} = 80\pi^2\left(\frac{s}{\lambda}\right)^2 \ll R$ (1)

"Q" OF ANT. CIRCUIT $= Q = \frac{\omega L}{R} = \frac{1}{\omega C R}$ OR $R = \frac{1}{Q\omega C}$ (2)

FOR AREA $A = s^2$: $C \simeq \epsilon \frac{A}{s} = \frac{s}{36\pi \times 10^9}$ (3)

SUBSTITUTING IN (2): $R = \frac{60\lambda}{Qs}$ (4)

[MISMATCH LOSS IN ANT. CIRCUIT $= 10 \log_{10} \frac{R}{R_{rad.}} = 10 \log_{10} \frac{\lambda^3}{13.2 Q s^3}$] (5)

FIELD AT 2 $= E = \frac{60\pi I_1 s_1}{\lambda r}$ (6)

INPUT POWER $= P_1 = \frac{1}{2} R_1 I_1^2$ (7)

OUTPUT POWER $= P_2 = \frac{1}{2} R_2 I_2^2 = \frac{1}{2} R_2 \left(\frac{E s_2}{2R_2}\right)^2 \simeq P_1 \frac{\pi^2 Q_1 Q_2 s_1^3 s_2^3}{\lambda^4 r^2}$ (8)

FOR $s_1 = s_2 = s$, $Q_1 = Q_2 = Q$: $P_2 \simeq 2.5 P_1 \frac{Q^2 s^6}{\lambda^4 r^2}$ (9)

[FOR LOSSLESS DIPOLES: $P_2 = P_1 \left(\frac{3\lambda}{8\pi r}\right)^2$] (10)

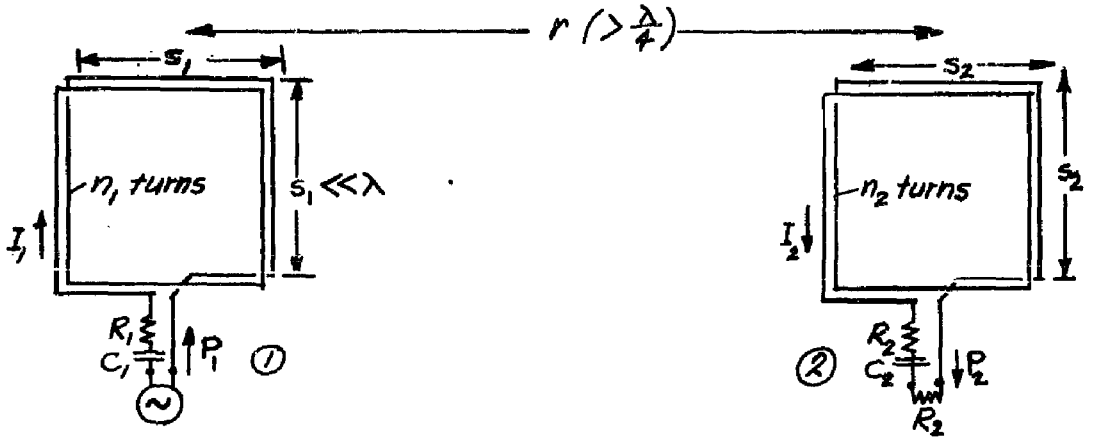
EXAMPLE: $f = 3 \times 10^4$, $\lambda = 10^4$, $Q = 10$, $s = 2$, $r = 10^4$

$10 \log_{10} \frac{P_1}{P_2} = 198$ db

MISMATCH LOSS IN EACH ANT. CIRCUIT = 89.75 db

SHEET A

FREE SPACE TRANSMISSION BETWEEN DIPOLES



LOOP : SQUARE CROSS SECTION WITH SIDES s/10. EQUATION (164) IN B. OF S. CIRCULAR 74 GIVES :

$$L = 0.8\, s\, n^2 (2.303 + 0.0477 + 0.033)10^{-6} \simeq 2 \times 10^{-6}\, s\, n^2$$

"Q" OF LOOP CIRCUIT $= Q = \dfrac{\omega L}{R}$ OR $R \simeq \dfrac{1200\pi s n^2}{Q\lambda}$ (1)

RADIATION RESISTANCE $= R_{rad.} = \dfrac{320\pi^4 s^4 n^2}{\lambda^4}$ (2)

[MISMATCH LOSS IN LOOP CIRCUIT $= 10 \log_{10} \dfrac{R}{R_{rad.}} = 10 \log_{10} \dfrac{\lambda^3}{8.25 Q s^3}$] (3)

FIELD AT 2 $= E = \dfrac{120\pi^2 I_1 s_1^2 n_1}{\lambda^2 r}$ (4)

INPUT POWER $= P_1 = \frac{1}{2} R_1 I_1^2 = \dfrac{\lambda^3 n^2 E^2}{24\pi^3 Q_1 s_1^3}$ (5)

VOLTAGE INDUCED IN LOOP 2 $= E_2 = \dfrac{2\pi s_2^2 n_2}{\lambda} E$ (6)

OUTPUT POWER $= P_2 = \frac{1}{2} R_2 I_2^2 = \frac{1}{2} R_2 \left(\dfrac{E_2}{2R_2}\right)^2 \simeq P_1 \dfrac{\pi^4 Q_1 Q_2 s_1^3 s_2^3}{100 \lambda^4 r^2}$ (7)

FOR $s_1 = s_2 = s$, $Q_1 = Q_2 = Q$: $P_2 \simeq P_1 \dfrac{Q^2 s^6}{\lambda^4 r^2}$ (8)

EXAMPLE 1: $f = 3 \times 10^4$, $\lambda = 10^4$, $Q = 100$, $s = 2$, $r = 10^4$

$$10 \log_{10} \frac{P_1}{P_2} = 182\, db$$

EXAMPLE 2 : $f = 3 \times 10^5$, $\lambda = 10^3$, $Q = 100$
$s = 2$, $r = 3 \times 10^4$

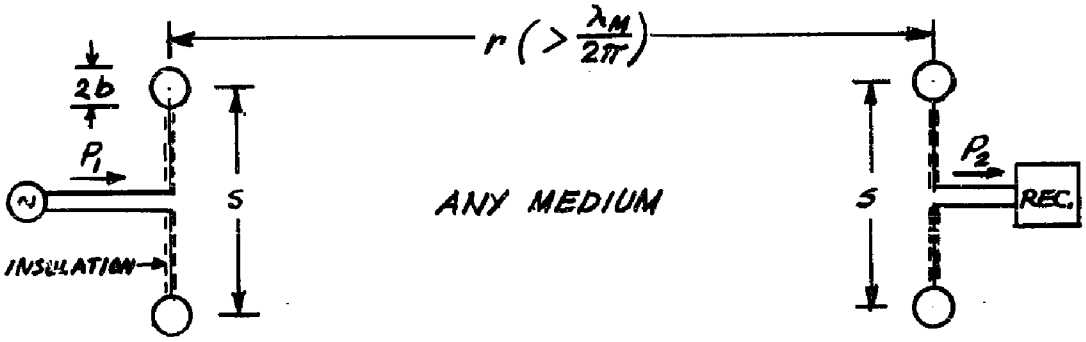
$10 \log \dfrac{P_1}{P_2} = 155\, db$

FOR $E = 10 \times 10^{-6}$ AT 2 REQUIRES

$P_1 \doteq 150$ WATTS

SHEET B

FREE SPACE TRANSMISSION BETWEEN LOOPS



TRANSMISSION FORMULA :

$$P_2 = P_1 \frac{900\pi^2 \mu_r^2 s^4 e^{-2\alpha r}}{R_1 R_2 \lambda_{air}^2 r^2}, \quad r > 0.2\lambda_M \qquad (1)$$

WHERE R_1, R_2 = INPUT RESISTANCES OF THE ANTENNAS

FOR OCEAN WATER : $g = 5$, $\mu_r = 1$, $\alpha = \beta = \sqrt{\pi\mu f g} = \frac{77}{\sqrt{\lambda_{air}}}$

$$\lambda_w = 0.0815\sqrt{\lambda_{air}}, \quad R_1 = R_2 = \frac{1}{2\pi g b}$$

$$P_2 = P_1 \frac{8.75\times10^6 b^2 s^4}{\lambda_{air}^2 r^2} e^{-\frac{154}{\sqrt{\lambda_{air}}} r} \qquad (2)$$

$$\text{TRANSMISSION LOSS} = 10\log_{10}\left[\frac{\lambda_{air}^2 r^2}{8.75\times10^6 b^2 s^4}\right] + \frac{669\times r}{\sqrt{\lambda_{air}}} \text{ db} = \qquad (3)$$

$$= 10\log_{10}\left[\frac{\lambda_{air}^2 r^2}{8.75\times10^6 b^2 s^4}\right] + \frac{r\sqrt{f}}{25} \text{ db} \qquad (4)$$

EXAMPLE : $f = 300$, $\lambda_{air} = 10^6$, $r = 1000$ (1 KM)
$b = 0.1$, $s = 2$
TRANSMISSION LOSS = 119 + 669 = 788 db

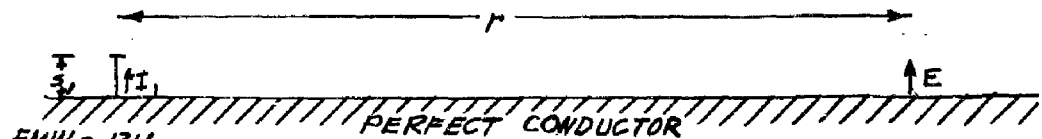
D.C. CASE ($\sigma r \ll 1$). MULTIPLYING (2) BY $\frac{1}{\sigma^2\mu^2}$ GIVES

$$P_2 = P_1 \frac{s^4 b^2}{16 r^6} \qquad (5)$$

FOR IN LINE DIPOLES : $P_2 = P_1 \frac{s^4 b^2}{4 r^6}$ (6)

SHEET C

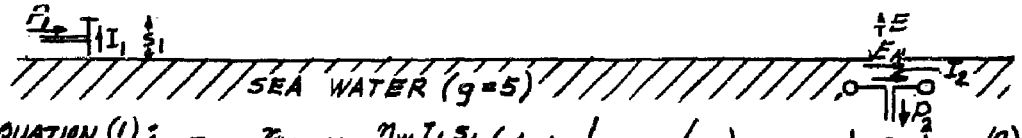
TRANSMISSION LOSS BETWEEN 2 DIPOLES



EMW p. 131:

$$E = \frac{\eta I_1 2 s_1}{2\lambda_{air} r}\left(1 + \frac{1}{j\beta r} - \frac{1}{\beta^2 r^2}\right) \qquad (1)$$

WHERE $\eta = 120\pi$, $\beta = 2\pi/\lambda_{air}$



EQUATION (1): $E_H = \frac{\eta_w}{\eta} \times E = \frac{\eta_w I_1 s_1}{\lambda_{air} r}\left(1 + \frac{1}{j\beta r} - \frac{1}{\beta^2 r^2}\right)$ (2)

WHERE $\eta_w = \sqrt{\frac{j\omega\mu}{g}} = \sqrt{\frac{j 2\pi f 4\pi 10^{-7}}{5}} = \sqrt{j\frac{48\pi^2}{\lambda_{air}}}$ (3)

RECEIVED POWER $= P_2 = \frac{1}{2} R_2 I_2^2 = \frac{1}{2} R_2 \left(\frac{E_H s_2}{2 R_2}\right)^2$ (4)

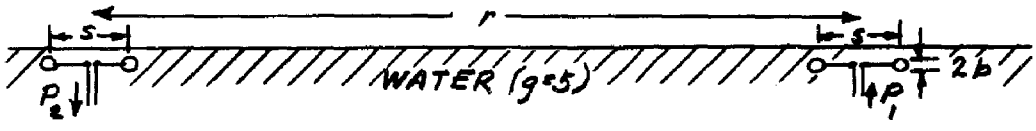
TRANSMITTED POWER $= P_1 = \frac{1}{2} R_1 I_1^2$ (5)

WHERE R_1, R_2 = INPUT RESISTANCES OF THE ANTENNAS

EQUATIONS (2) TO (5) GIVE

$$P_2 = P_1 \frac{12\pi^2 s_1^2 s_2^2}{R_1 R_2 \lambda_{air}^3 r^2}\left(1 - \frac{1}{\beta^2 r^2} + \frac{1}{\beta^4 r^4}\right) \qquad (6)$$

BY RECIPROCITY EQ.(6) GIVES RECEIVED POWER FROM VERTICAL ANT. WHEN POWER P_1 IS FED INTO SUBMERGED DIPOLE. THEN CHANGING FROM VERTICAL ANT. TO SUBMERGED DIPOLE REDUCES RECEIVED POWER BY THE RATIO $\left(\frac{E_V}{E_H}\right)^2 = \left(\frac{\eta_w}{\eta}\right)^2$, OR THE TRANSMISSION FORMULA FOR TWO SUBMERGED DIPOLES IS:



$$P_2 = P_1 \frac{12\pi^2 s_1^2 s_2^2}{R_1 R_2 \lambda_{air}^3 r^2}\left(1 - \frac{1}{\beta^2 r^2} + \frac{1}{\beta^4 r^4}\right)\frac{48\pi^2}{\lambda_{air} 120^2 \pi^2} \qquad (7)$$

FOR $s_1 = s_2$, $R_1 = R_2 = \frac{1}{5\pi b}$ WHERE b IS RADIUS OF DIPOLE SPHERES

$$P_2 = P_1 \frac{\pi^4 s^4 b^2}{\lambda_{air}^4 r^2}\left(1 - \frac{\lambda_{air}^2}{4\pi^2 r^2} + \frac{\lambda_{air}^4}{16\pi^4 r^4}\right) \qquad (8)$$

FOR $2\pi r < \lambda_{air}$: $P_2 = P_1 \frac{s^4 b^2}{16 r^6}$ (9)

EXAMPLE: $s = 2$, $b = \frac{1}{10}$, $r = 1000$ (1KM)

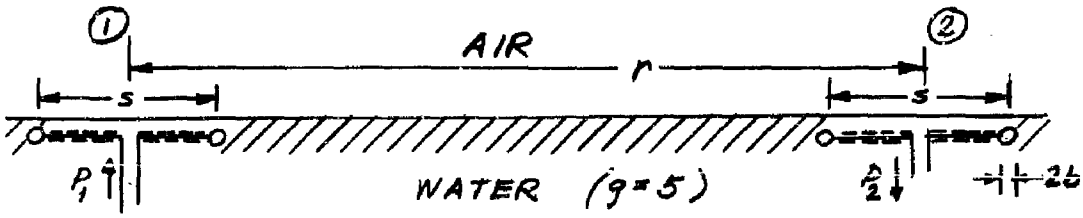
$P_2 = P_1 \times 10^{-20}$ OR

$10 \log_{10} \frac{P_1}{P_2} = 200$ db

SHEET D

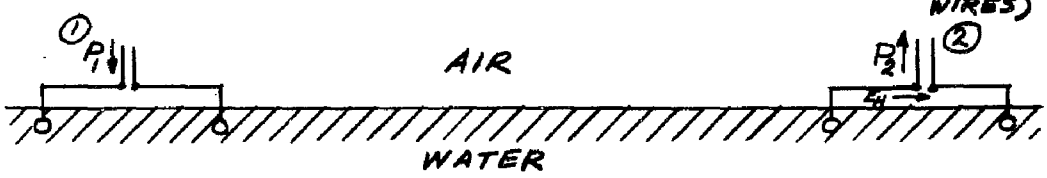
PROPAGATION FORMULA

CASE 1. DIPOLES SLIGHTLY BELOW SURFACE.



EQUATION (9) SHEET D: $P_2 = P_1 \frac{s^4 b^2}{16 r^6}$ (1)

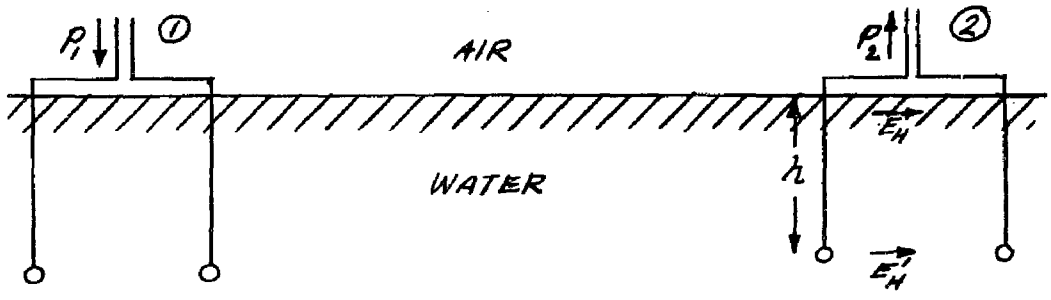
CASE 2. DIPOLE WIRES SLIGHTLY ABOVE SURFACE (INSULATED WIRES)



THE HORIZONTAL COMPONENT OF THE FIELD AT 2 IS CONTINUOUS ACROSS THE BOUNDARY SURFACE. THEREFORE:

$$P_2 \simeq P_1 \frac{s^4 b^2}{16 r^6} \qquad (2)$$

CASE 3. METAL SPHERES LOWERED.



THE MAIN EFFECT IS A CHANGE OF DIPOLE IMPEDANCE (INPUT OR OUTPUT). THIS CHANGE IS BELIEVED TO BE SMALL. THEREFORE:

$$P_2 = P_1 \frac{s^4 K}{16 r^2}, \quad K \simeq b^2 \qquad (3)$$

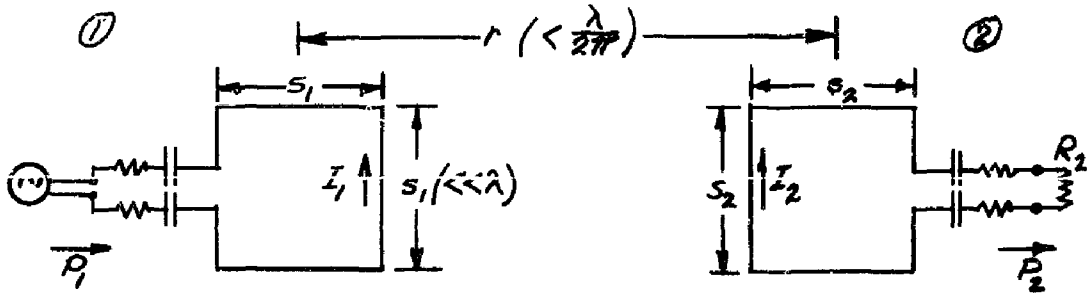
A WIRE BETWEEN THE SPHERES SHOULD NOT AFFECT THE TRANSMISSION APPRECIABLY WHEN $E_H' \ll E_H$.

$$\left(10 \log_{10}\left(\frac{E_H}{E_H'}\right)^2 = \frac{669 h}{\sqrt{\lambda_{air}}} = \frac{h\sqrt{f}}{25}\right)$$

SHEET E

TRANSMISSION BETWEEN 2 DIPOLES

CASE A: LOOPS IN SAME PLANE.



LOOP: 1 TURN, WIRE RADIUS $= a$, $L = 1.84 \times 10^{-6} \times s \times \log_{10} \frac{0.6s}{a}$ (1)
(FORMULA 137, B. OF S. BULLETIN 74)

"Q" OF LOOP CIRCUIT $= Q = \frac{\omega L}{R}$ (2)

INPUT POWER $= P_1 = \frac{1}{2} R_1 I_1^2$ (3)

MAGNETIC FIELD AT ② $= H_2 = \frac{s_1^2 I_1}{4\pi r^3}$ (4)
(EMW P. 163)

VOLTAGE INDUCED IN LOOP ② $= V_2 = \omega \mu H_2 s_2^2$ (5)

OUTPUT POWER $= P_2 = \frac{1}{2} R_2 I_2^2 = \frac{1}{2} R_2 \left(\frac{V_2}{2R_2}\right)^2 = P_1 \frac{Q_1 Q_2 s_1^3 s_2^3}{1350 r^6 \log_{10} \frac{0.6 s_1}{a_1} \log_{10} \frac{0.6 s_2}{a_2}}$

FOR $s_1 = s_2 = s$, $a_1 = a_2 = a$, $Q_1 = Q_2 = Q$: (6)

$$P_2 = P_1 \frac{Q^2 s^6}{1350 r^6 \left(\log_{10} \frac{0.6s}{a}\right)^2} \quad (7)$$

EXAMPLE: $Q = 1, s = 2, a = 0.01$, $r = 1000$ (= 1 KM)

$$P_2 = P_1 \times 1.1 \times 10^{-20} \quad (8)$$

CASE B: LOOPS IN PARALLEL PLANES.

THE RADIAL FIELD AT ② IS NOW $= H_2 = \frac{s_1^2 I_1}{2\pi r^3}$ (TWICE THE VALUE GIVEN BY (4)) (9)

AND THE TRANSMISSION FORMULA IS NOW:

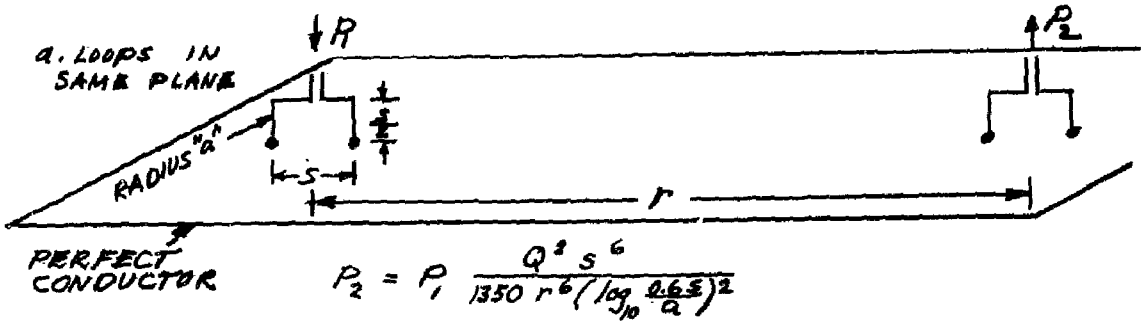
$$P_2 = P_1 \frac{4 Q^2 s^6}{1350 r^6 \left(\log_{10} \frac{0.6s}{a}\right)^2} \quad (10)$$

SHEET F

FREE SPACE TRANSMISSION BETWEEN ONE TURN LOOPS. SMALL SEPARATION ($r < \lambda / 2\pi$)

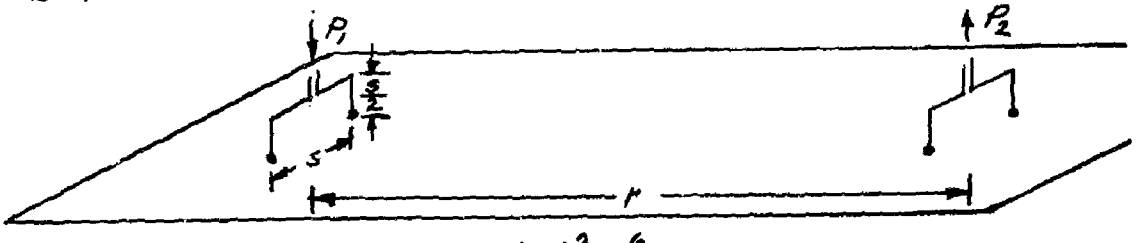
A HORIZONTAL SHEET OF PERFECT CONDUCTOR THROUGH THE CENTERS OF THE LOOPS SHOWN ON SHEET "F" WILL NOT DISTURB THE FIELDS. WE HAVE, THEREFORE, FOR GROUNDED LOOPS:

a. LOOPS IN SAME PLANE



$$P_2 = P_1 \frac{Q^2 s^6}{1350\, r^6 \left(\log_{10} \frac{0.6 s}{a}\right)^2}$$

b. PARALLEL LOOPS



$$P_2 = P_1 \frac{4 Q^2 s^6}{1350\, r^6 \left(\log_{10} \frac{0.6 s}{a}\right)^2}$$

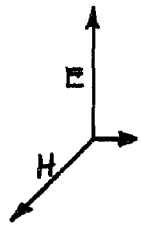
SUBSTITUTING SALT WATER FOR THE PERFECT CONDUCTOR AND "GROUNDING" THE LOOPS BY METAL SPHERES ETC. SHOULD NOT INCREASE THE TRANSMISSION LOSS A GREAT DEAL.

SHEET G

TRANSMISSION BETWEEN GROUNDED LOOPS

FREE SPACE

$\eta = 120\pi$



WATER ($g = 5$)

$\eta_W = \sqrt{\frac{j\omega\mu}{g}}$, $\lambda > 1$

$E_W = E\frac{2\eta_W}{\eta + \eta_W} \simeq 2E\frac{\eta_W}{\eta}$

$H_W = H\frac{2\eta}{\eta + \eta_W} \simeq 2H$

PHASE ANGLE BETWEEN E_W AND H_W IS 45°

POWER FLOW $= \frac{1}{2}EH$

POWER FLOW $= \frac{1}{2}|E||H|\cos\frac{\pi}{4}$

$= \frac{1}{2}EH\,2\sqrt{2}\,\frac{|\eta_W|}{\eta} = \frac{1}{2}EH\frac{1}{6.11\sqrt{\lambda_{air}}}$

REFLECTION LOSS $= 10\log_{10}\frac{\text{POWER FLOW IN FREE SPACE}}{\text{POWER FLOW IN WATER}} = 10\log_{10}\left[6.11\sqrt{\lambda_{air}}\right]$ db

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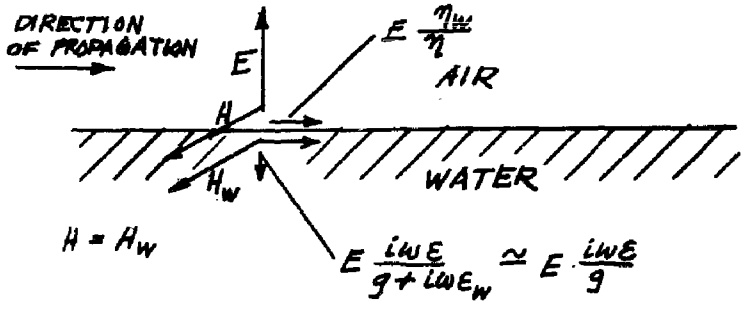
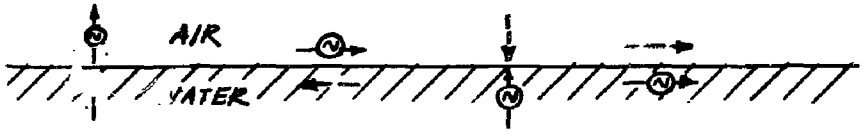


IMAGES



SHEET H

APPENDIX D

DETECTION AND IDENTIFICATION

I. SONAR

A. Introduction

The functions of anti-submarine sonar equipment are at least four in number:

1. Detection at long range;
2. Identification;
3. Tentative location at moderate range;
4. Precise location for fire control.

It is becoming increasingly evident that no single piece of gear can perform all four functions well. In fact, it is difficult enough to design an equipment that will perform any one of them adequately.

In the past, there has been a tendency to reject specialized developments on the ground that they would not perform all the functions. During World War II, passive listening was not exploited fully because it would not give the range of quiet targets; short pings and FM pings were not used because they sacrificed Doppler information; low-frequency echo ranging was not developed because of the difficulty of obtaining bearing accuracy.

Many factors, as discussed under Operational Need (Section D-1), make it necessary to increase greatly the range of detection and identification, as well as accuracy of localization and fire control. This can be done only by turning our attention from the compromise-limited multipurpose sonar to a system of high-performance specialized sonars. Each member of the system must be designed for optimum performance of one function. At the same time, the several specialized devices must be integrated, with the weapons of attack, into a flexible, effective system.

B. A Proposed Sonar Listening System for Long-Range Submarine Detection

1. General

With radar detection of snorkeling submarines becoming more difficult, we may be forced to depend more and more on sonar listening. Detection of transiting submarines by listening gear is very well adapted to a quiet submerged SSK submarine. Picket lines of such submarines extending from Iceland to Norway would preserve the advantage of ambush surprise against enemy submarines in transit. If assured listening ranges of 50 to 100 miles could be achieved, an SSK submarine fleet consisting of only our present submarines (snorkel-equipped) could be a damaging threat to the enemy submarine fleet. Surface search craft will also benefit from improved long-range listening equipment.

We feel that the greatest promise for extreme listening ranges lies in the low-frequency region--those frequencies below 500 cycles per second. As will be discussed under "Research on the Medium" (see Section C-1), this frequency region has many peculiar advantages.

It appears that the low-frequency listening system described below could capitalize on the various aspects of submarine noise.

2. Size Requirements

It is felt that the most important single item in achieving extended listening ranges is to employ the largest possible hydrophone array. This is comparable to the use of a larger antenna for increased range obtained in the case of radar. In the acoustic case, furthermore, the listening range

is often limited by sea noise so that the greater directivity of a large transducer extends the range because it discriminates against sea noise coming from all directions.

The inability to provide high directivity at low frequencies, even with extremely long arrays, can be overcome to some extent by going to superdirective arrays (discussed subsequently in this Appendix). These would provide moderately high directivity, and are quite feasible here because of the fact that the signal-to-noise ratio in the receiver is determined by the external noise from the sea.

3. Design Considerations

The proposed listening equipment would consist of a long array of low-frequency hydrophones, which are presently available commercially. These would be mounted along the full length of the hulls of present fleet-type or guppy submarines, or along the hulls of surface craft. (The submarine, incidentally, has the advantage of being able to take its 200-foot array to greater depths as demanded by thermal layers and the Lloyd's mirror effect. At 50 cycles, the wavelength is approximately 100 feet.) The hydrophones could be protected against damage in harbors by steel extensions on the hulls.

As to the number of hydrophones required, suppose it is assumed that the highest frequency to be employed would be 250 cycles. The hydrophones could then be spaced as far as 10 feet apart (1/2 wavelength) so that an array 200 feet long would consist of only 20 hydrophones. Such an array at 62 cycles would actually

have an effective length of 800 feet if placed in the 1/8 wavelength superdirective condition. Even in the non-superdirective condition, this array at 250 cycles would have approximately 13 db more gain than a 10 ft. x 10 ft. ring or broadside array employing many more hydrophones. If spherical spreading is assumed, the range would thus be increased by about 4, whereas if the expected cylindrical spreading is realized, the range would be increased by 16 times (over that of a 10 ft. x 10 ft. array).

The individual hydrophones should be equipped with electrical or mechanical delay lines so that the entire hull-length array could be steered through an angle of 10° or 20°. This amount of angular scan should be sufficient if the expected detection range of 50 to 100 miles for a snorkeling submarine is achieved.

This array should be supplemented with 2 JT type gear for tracking use and triangulation ranging as the target approaches at closer ranges. The maximum range of the JT gear extends only up to 20,000 yards under the best conditions, but it is quite flexible, and the added advantage of triangulational ranging would be of great help in the later stages for closing the target.

4. Conclusions

The listening gear described above appears, with the information now available, to be so certain of success that tests on such an array should be made without delay. If the expected results are realized, it would appear to be desirable to equip at once as many of our fleet-type or guppy submarines as possible for SSK service, by outfitting them with: (a) the long hydrophone array for long-range detection, plus (b) the two JT equipments for use in short-range tracking and triangulation ranging.

C. Research on the Medium

1. Low-Frequency Region

One of the most promising developments in underwater listening appears to be the use of audio frequencies below 500 cycles. At these frequencies, sounds apparently penetrate the shallow thermal layers and propagate to great distances in the deep sofar channel. This frequency range is particularly important for submarine detection, because there is evidence that there are strong peaks in machinery noise both from Diesels and battery-operated submarines at these frequencies even when propeller cavitation is absent. The low frequencies are also known to have a very low attenuation.

Unfortunately, very little is known about the transmission of these low-frequency sounds in the open sea. The need is very great for information on: (a) how such sounds propagate; (b) whether correlation exists in time and also in space for sound waves at these frequencies; (c) the question of ambient and self-noise *versus* target noise; and (d) how large one can make listening arrays that will give the expected increase in gain with size.

The important phases of a research program on the medium at these low frequencies would therefore appear to be the following:

a. Propagation

This should include an investigation: as to how well transmission is aided by the deep channel; to what extent skip distances are encountered; and whether sounds originating near the surface can penetrate into the sound channel, propagate for great distances, and then emerge so as to be detected by hydrophones also near the surface. The extent of temperature variations in the deep channel and their influence on propagation should be studied, as should the variations in angle of arrival, both vertical and horizontal, of sound from a fixed source.

It is important to know how uniformly sounds propagate in the open sea. It is known that there are variations in temperature and salinity in sea water which affect the value of the velocity of sound. If these variations occur rapidly, sounds arriving at one hydrophone might not be coherent with sounds arriving at a hydrophone 100 or 1000 feet away. This is the question of correlation in space. Furthermore, a steady sound arriving at a single hydrophone might travel over many paths, and with variable velocity over any one path. The received sound would appear to possess both phase and amplitude modulation and would not have ideal correlation in time. The extent of these two factors will determine whether large-size listening arrays and correlation techniques are suitable to the problem. This phase modulation would also determine how narrow our filters can be made in receiving the narrow-band noise peaks caused by the submarine machinery. Certain proposed sonar communication systems would depend for their success upon the extent of this phase or amplitude modulation, likewise the use of binaural listening in large split arrays.

These various aspects of propagation should be determined by experiments using both single-frequency (continuous wave) sources and pulses (such as explosive sounds). For CW experiments, improved sound generators are needed in the low-frequency region; motor-driven sources should be useful here. Investigation of correlation may be implemented with signal storage on magnetic tape for later laboratory analysis. Pulsed sound will be useful in determining the arrival times and energy division for various paths of propagation. Observation of successive pulses can give information on the stability of the transmission paths. Both CW and explosive sounds can be used to determine the type of sound spreading (spherical or cylindrical). Theoretical

analysis of the ray and mode theories of propagation in the deep channel should be continued.

b. Characteristics That Distinguish Target Noise from Ambient Noise

Additional ambient-noise measurements in the low-frequency region are needed. Measurements of the intensity in very-narrow-frequency bands are needed for prediction of the performance of autocorrelation methods. The cause of ambient noise in the ocean is unknown. Certain components are caused by fish and other organisms, and wind waves contribute others. In the low-frequency region where sound is not appreciably attenuated, it is probable that much of this ambient noise is due to distant ships. In any case, the study of ambient noise should be coordinated with work on the sound output of ships (especially submarines at different speeds and under various conditions), since many of the useful techniques will be identical, and the primary purpose of the work is to invent means for distinguishing between the two sounds.

It is to be noted that sofar stations have had difficulty with self-noise in cables. For long-range listening, such bottom-mounted installations will become important, and studies of the source of this noise should be undertaken at an early stage. Self-noise may also be countered with more-directional hydrophones; it appears possible to make significant improvements here.

c. Maximum Transducer Size Permitted by the Medium

Experiments should be made with very-long transducers. There are available, commercially, 300-foot long, oil-filled, hose-type transducers* which could be employed in such

* For a description, see "Oil and Gas Journal", April 15, 1950, p. 82.

experiments to determine the feasibility of large transducers and transducer arrays at various frequencies. Recent work on superdirectivity suggests that a listening array can have its effective length or size increased by proper phase and amplitude adjustment. If it thus turned out that a 1000-foot-long transducer was quite feasible at these frequencies, superdirective arrays could be built which would be only 100 or 200 feet long, but would have an effective length of 1000 feet. This means that they would have a signal-to-noise ratio equal to a receiving array of that size if the noise is due to ambient or self-noise of the ship. Their bandwidth would be limited, however.

2. Higher Frequencies

At higher frequencies, the important facts to learn about the medium again concern wave coherence. The extent of this coherence will determine the feasibility of larger transducers, correlation techniques, and certain sonar communication schemes. It is important to know, for example, whether the JT transducer (5 feet long) could be doubled or quadrupled in size to advantage. It is important to learn under what conditions single-sideband speech transmission on sonar voice transmission has a superior range to code on a pinging-sonar system. Perhaps single sideband code transmission using wide audio bands would be more effective than voice transmission. If correlation can be used, many new schemes for picking the target echo out of the noise might be possible.

Propagation research at high frequencies should, therefore, be carried out with the objective of obtaining information on the coherence of waves separated in space and time.

D. Correlation Techniques Applied to Sonar

1. Operational Need

Long-range, pattern-running, and nuclear-explosive torpedoes make it imperative to increase the range and accuracy of submarine and torpedo detection, location, identification, and tracking. Snorkels make it more difficult than it once was for radar to fulfill those sensory functions of anti-submarine weapons systems for which it is in principle adapted. These two facts emphasize the need for extremely sensitive and accurate sonar.

Two interrelated factors limit the sensitivity and accuracy of present sonars: (1) their integration times are short; (2) their spatial discriminatory capacities are poor. Without long-time integration, full advantage cannot be taken of the fact that submarine signals are in part coherent, whereas water noise is incoherent. Without sharp spatial discrimination, it is not possible to minimize background noise by focusing the equipment upon a small, distant region of the ocean.

The application of narrow-band filtering techniques (an example of which is given in Annex A) or correlation techniques provides means of increasing the integration time beyond that inherent in the ear or eye. In addition, correlation can be used to obtain spatial discrimination. If correlation techniques can be employed, a marked improvement in the detection and location functions is possible, and some improvement in identification and fire control might also result.

A third limitation of present sonar effectiveness is imposed by compromise. An all-purpose, single-package sonar cannot be expected to provide optimal fulfillment of every function. Only a system of specialized equipments can do that. Correlational techniques lend themselves most readily to specialization. They

suggest methods and tactics quite different from those that have evolved in interplay with past sonars. There is definite need for study and development of such methods and tactics, designed in relation to correlational and related specialized techniques, and aimed at integrating the best possible use of sonic underwater signals into over-all anti-submarine weapons systems.

The degree of improvement realizable cannot be calculated precisely because not enough is known about the relevant characteristics of sound transmission through the ocean. A gain of 10 db in recognition differential (over a conventional sonar plus listener) appears to be a conservative estimate for a simple correlator, and it appears reasonable to think in terms of detecting a submarine at 20 miles and locating it within a 500-yard square with a highly specialized correlational system involving two helicopters and a ship.

Correlation techniques may be applied to both active and passive sonar. Either autocorrelation or crosscorrelation may be employed. Precisely what is done will depend upon the nature of the specific system employed. The techniques lend themselves most readily to specialized methods and tactics of search and location. Some possible uses of the method are described in the following recommendations.

2. Recommendations

a. Research should be pushed vigorously to determine the upper limits of integration time that can be employed to advantage with signals of various frequencies, bandwidths, etc. transmitted over water paths of various lengths, etc. It is essential to know more about the propagation of low-frequency sounds and about the preservation of waveform and envelope-form at all frequencies.

b. A number of correlational and integrational schemes should be tried out empirically. Since correlators are essential tools in the research recommended in (a), efforts (a) and (b) will interact.

c. Experimentation should be carried out with ships, submarines, buoys, helicopters, remote-controlled vessels, and shore stations to determine the optimal organization of search sonar teams. The essential feature of the search team using correlational techniques is that the signals picked up by the receiving members of the team are relayed to a central point where they are subjected to correlational analysis.

d. Further experimentation should be carried out to determine the best way of integrating search sonar into the overall weapons system. This will involve the coordination of detection, location, identification, and fire-control functions of sonar with the anti-submarine attack. It is important, for example, to keep the noise of the attack from disrupting the sonar functions.

E. Sonar Presentation Methods

Present sonar presentation methods are inadequate, and little is being done to improve them. The data presented to the sonar operator are obtained very slowly, because of the low propagation velocity of sound, and are presented only fleetingly on the PPI. The time between scans is so long that little frame-to-frame comparison is possible. The chemical record does provide a permanent record but it is poor and difficult to interpret. Not all the data present in a sonar return are utilized in evaluating a target. In addition, the bright flash that accompanies the writing on the P-7 scope causes rapid eye fatigue. Finally, in most ships the operators work under very poor conditions; the quarters

are cramped, poorly air-conditioned, and noisy. Since the entire utility of an ASW ship depends upon the performance of the sonar gear and the sonar operators, a determined effort should be made to improve sonar presentation methods and to provide satisfactory working conditions for sonar operations.

The factors that influence the ability of an operator to detect targets successfully amid noise and clutter are not thoroughly understood; thus, any attempts to improve the "operator factor" will obviously be educated guesses. Nonetheless, the following ideas should be carefully evaluated.

(1) The NRL visual Doppler indicator should be exploited. It provides a good method for target identification and an extremely useful method of holding a target once contact is made. It is not expected to materially increase the detection range obtained with sonar listening.

(2) A data-storage system, probably using magnetic tape, could be developed to permit storage of several past frames of information. This would permit the operator to re-examine fleeting contacts and ascertain whether or not they were just noise or actually a target. We have witnessed dozens of situations where contact was lost because of the inability of the operator to evaluate the data in just the moment that the signal appears on the screen.

If the information is stored on magnetic tape in the form in which it is received, it would be possible to expend considerable effort to evaluate a suspicious signal. Time would be available to examine it carefully for Doppler, and possibly to perform other operations on it (e.g., correlation).

(3) The relatively low velocity of sound restricts the rate at which a sonar set can pulse, and thus the rate at which target information can be obtained. The pulsing rate is generally so slow that only a few scans of a weak target may be obtained before it disappears. The data so obtained may be insufficient to permit target identification. An effective higher repetition rate is possible by transmitting and receiving interleaved pulses on different frequencies. Use of two transmitters would double the amount of information obtained, and three transmitters would triple it, and so forth.

(4) In order to detect a signal in the presence of noise, it is necessary to bring together observations that are separated in time. This requires temporal integration. The integration that is inherent in human vision and hearing covers only a very short interval of time. Much better integration can be provided by suitably designed equipment.

> One of the most promising ways of improving the over-all performance of detection sonars is, therefore, to build temporal integration into the sonar gear. Correlational techniques permit just that; a correlational sonar would present the sonar data to the operator in predigested form, and thereby relieve him of the responsibility for doing something he is not equipped to do well.

While it is believed that the four schemes mentioned above have considerable merit and should be tried, it is more important to realize the existence of the general problem of improving the "operator factor" by every means possible. To accomplish this, it will be necessary to set up a group to establish and evaluate the various factors that are significant to this problem. When this is done, an attempt can be made to build data systems that improve operator performance.

F. New Identification and Detection Methods

The necessity for distinguishing between submarine contacts and false contacts has long been recognized. It is closely related to the problem of regaining or keeping contact. In the past, great reliance has been placed upon the recognition of Doppler and echo quality by the operator; this has made great demands upon the ability of the operator and has necessitated specialized selection procedures and training programs. The innate abilities required of operators are very similar to those of a good musician, and the training procedure is lengthy. Even in wartime, it is difficult to find enough men with the requisite abilities for this work, and the training program is costly in time. It is therefore very desirable to investigate the possibility of other means of identification that do not require specialized abilities.

There are many characteristics that distinguish a submarine from a false target, and all of these can be exploited for the present purpose. The following discussion will consider these characteristics primarily as means of identification; but some of

them may be useful for initial detection, and such uses will occasionally be mentioned.

1. Doppler

The ability of the human ear to perceive the Doppler change of frequency diminishes rapidly as the ping length is decreased. The ping length is an important design parameter for many other reasons. In the past, it has been determined primarily by the ability of the human ear to detect a Doppler shift, and sonar designers have been prevented from exploiting it for other purposes.

This design handicap may be removed either by replacing Doppler with other means of identification or by developing devices that can measure the Doppler shift in the echo of short pings. It appears quite feasible to construct devices that will give a visual presentation of the frequency of a strong echo. Some developments of this sort are being actively pursued by NRL and others were explored by NDRC; it is possible that they will give a more precise estimate of range rate than can the ear.

Doppler also makes it easier to hear weak echoes in the presence of stationary targets or reverberation . This contributes to the detection function rather than to the identification function. Exploitation of Doppler to improve detection probably requires less training and aptitude than does its exploitation to improve identification. These two functions of Doppler should therefore be considered separately.

2. Echo Quality

The "quality", an intangible property of the echo, has often been discussed as a means of detecting the submarine's evasive maneuver of producing a wake "knuckle". Its perception requires a very good musical ear.

It would be highly desirable to develop an instrument to indicate or measure this characteristic of the echo; while the use of correlational techniques appears promising, no development in this field can be promised for the immediate future. Research on the subject has not progressed in any way, and it is not known what physical properties of the echo correspond to the quality, often referred to as "mushiness".

The tactical importance of the countermeasure to the wake knuckle makes it imperative to initiate research in this field. Such a program will require the close cooperation of operational staff and facilities with psychologists and physicists. A scientific task group should be assembled for this purpose to work at Key West with Opdevfor, even though the project is research and not development. It is very probable that the returns from such a project may have unexpected implications for other problems.

3. Magnetic Effects

The magnetic field of the submarine has been exploited by magnetic airborne equipment. Because of its inherently small range, this equipment is not well suited for accomplishing the detection function, but it is very valuable for distinguishing a submarine from a non-magnetic target and for locating the submarine precisely. Further development in this field is possible; it appears probable that the range can be considerably increased and that magnetic devices can be installed on vehicles other than aircraft.

4. Electric Effects

Submarines (and surface vessels also) are surrounded by variable electric fields. These fields can be detected at ranges of at least a thousand yards, and are not affected by thermal

conditions in the surface layers. The electric fields can certainly be exploited for identification purposes. The necessary equipment can be installed on radio buoys, dunked sonar, and anti-submarine vessels. The possibility of obtaining bearing information from an electric field should be explored. Electric signals may also be useful for IFF. It is important to determine whether or not the electric field exists when the submarine is balanced on a layer with propellers stopped.

Work in this field is under way at various activities and should be continued.

5. Exhaust Trails

A snorkeling submarine leaves a trail of exhaust gases that can be detected in various ways. Chemical components, such as carbon monoxide or carbon dioxide, can be detected with the mass spectograph. Electrically charged molecules can be detected with ionization chambers.

6. Infrared and Thermal Detection of Wakes

In moving through the water, a submerged submarine produces a disturbance of the water surface. This may consist in the displacement of the original surface water by cooler water from below. The effect is likely to be most pronounced when there are strong temperature gradients between the submarine and the surface.

Early experiments showed that, while this effect occurs, it is obscured by the background of irregular temperature differences that always exist in the ocean. The present application of airborne infrared techniques is especially promising because the equipment scans an area of the sea surface rather than a line. It appears to be possible to perceive the wake against the irregular background more readily in this case than when a

surface vessel tows a thermometer through the wake. Infrared detection of wakes should continue to be actively explored, with special effort made to determine the maximum distance astern and maximum depth of submergence at which detection is possible. It is probable that both will depend on the vertical temperature gradients existing in the ocean.

Wake detection may be important for initial detection. However, even if the sweep rates should prove to be too small for this purpose, it may still be useful as a method of identification. As other methods of long-range detection improve, it is likely that the false-target problem will become increasingly important. Wake detection may be one of the easier methods of investigating suspected contacts.

7. Detection of Bubbles in Wakes

A cavitating propeller produces many bubbles which, in turn, affect the acoustic properties of the water. This effect has frequently been considered as a means of detecting submarine wakes. Recent technical developments have greatly increased the sensitivity of bubble detectors. It has also been found that there are surprisingly few bubbles in the open sea, so that this sensitivity can be exploited. Research in this field should be directed toward determining the structure of a submarine wake. It is possible that the bubble-filled water rises to the surface. Even in this case, the wake of a submarine may differ from the wake of a surface vessel in its vertical dimension. It is also possible that these devices may develop into a countermeasure for the knuckle maneuver.

8. Active Electromagnetic Methods

The non-acoustic methods discussed above are all passive. The possibility of active electric and/or magnetic means of detecting

a submerged submarine has often been discussed. Such methods are successfully used in prospecting for ore bodies and buried pipes in the solid earth. Their feasibility at sea has not been established, although some work has been done towards their application to mine detection. Interest in them has not been great because they do not give promise of long detection ranges. They may, nonetheless, be useful for identification and keeping contact, and therefore should not be completely ignored.

9. Passive Listening

As a means of long-range detection, passive listening is discussed in detail elsewhere, but it may also be used as a means of identification either in conjunction with echo ranging or by itself.

Passive listening as a means of identification is very attractive, primarily because of its long range. Ships and submarines have many properties of acoustic output that distinguish them from natural targets. Among these are propeller beat, cavitation noise, and single-frequency components (such as gear whine). It is probable that there are differences between the acoustic outputs of submarines and surface vessels and that these can be used for identification at long ranges. They can be presented to the operator either as sounds to be recognized by ear or, perhaps better, visually by the use of correlational devices. However, considerable research will be required before development of methods is possible. The work of obtaining the data and devising the methods will require the same sort of research team described above under Echo Quality. Again, the importance of the tactical problem will justify a considerable expenditure on research of this kind.

G. Improvements in Echo-Ranging Gear

Echo-ranging methods are unique in that they can provide numerical range data on quiet targets. They are at a disadvantage, however (compared to passive listening), for long-range initial detection, because the longer round-trip transmission path makes the echo intensity decrease more rapidly with range than does the listening signal. As the range increases, it becomes increasingly difficult to overcome this inherent disadvantage of echo-ranging methods considered as a means of initial detection.

Any consideration of ways and means for improving the performance of echo-ranging gear should therefore be explicitly divided into two parts: improvements in detection sensitivity; and improvements of range accuracy. In this discussion, it will be assumed that initial detection and bearing determination have been made by other means.

1. Improved Detection Sensitivities

For increased range, the low-frequency, high-power systems appear to have the greatest promise, and the NRL program in this field should be vigorously prosecuted. It is possible that echo ranging with frequencies below 500 cps is feasible; it has been suggested that extremely long ranges (out to the 35-mile sofar peak, or even to ranges of 1000 miles) might be achieved in this way. Research on long-range listening gear at these very-low frequencies (proposed in Section C of this Appendix) should indicate the feasibility of such pinging (bonging) sonars.

Scanning sonars have the basic advantage of broad angular coverage (usually 360°) but present types sacrifice some range in order to gain this angular coverage. Thus the QHB radiates an omnidirectional pulse of long duration, but scans the echoes from a given bearing in a relatively shorter interval so that only about

1/35th of the pulse energy is used in receiving. These short received pulses require a wideband receiver with its poor signal-to-noise ratio (reduced detection range). However, PPI-type sonars need not sacrifice range for angular coverage. Thus, a battery of many individual searchlight-type sonars could give a PPI presentation and yet have the same detection sensitivity as one single searchlight sonar. If this battery of transducers were furthermore multiple-phase-connected, so as to produce a multiplicity of "preformed" beams, its detection sensitivity would be greater still. For example, for a given receiving direction, the transducers would be phased so that the whole array would "look" in that direction (corresponding to all the searchlight sonars being pointed in that one direction). This particular receiving connection could be made to control the intensity of a spot moving radially outward on a cathode-ray tube, echoes from that direction appearing as bright spots along this radial line. For another receiving direction, the same transducers would have interconnections that cause the receiving beam to "look" in that direction; this receiver connection would be made to control the intensity of the same (or another) spot on the cathode-ray tube but moving outward along another radius (corresponding to that direction). The number of such preformed beams would correspond to the total angular coverage desired divided by the receiving beam width (all transducers contributing to the beam sharpness). In this way, the array would have the same radiation efficiency as a battery of searchlight sonars covering an equivalent angular sector, but would have a receiving "gain" equal to all the searchlight sonars pointing in one receiving direction. This would be many times the receiving "gain" of the multiple-searchlight system if many searchlight sonars were involved.

Thus it is felt that preformed beam arrays and multiple-

searchlight sonars offer great promise and should be exploited.

The use of Doppler for target identification is not very effective with the present QHB because of the rather short pulse length. With the multiple-searchlight or preformed-beam arrays, longer pulses could be used to enhance the Doppler effect and thus increase the detection sensitivity (target recognition).

Identification may be made by other means also. The use of frequency-modulated pulses might reduce the number of false targets, and additional processing of the signal after rectification might be desirable. Special presentation methods (described in Section E of this Appendix) would be useful for picking a true target out of clutter and noise.

2. Improved Range Accuracy

Improved range data will generally be obtained through the use of shorter pulses. The preformed beam and multiple-searchlight devices would permit the use of very-short pulses when they are desired for accurate ranging, since the received pulse is not scanned. The large number of transducers involved in such arrays would permit high transmitting powers to be employed, since the power is divided among many transducer elements. It is felt that such high-power short-pulse sonars should be exploited.

H. Helicopter Sonar

The concept of using a helicopter as a sonar vehicle offers a number of advantages, principally the following:

1. It places the air-water interface between the sonar and the propulsion machinery, resulting in reduction of self-noise.
2. It may allow the sonar to be placed below the surface layers in which there may be sharp downward refraction. If the sonar can be lowered beneath

the mixed layer, the layer effect may be avoided also, although this may not be possible in the open ocean.

3. The irregular motion of the sonar caused by the effects of surface waves should be reduced.

4. It gives the sonar high mobility and, thus, an increased sweep rate.

5. In addition, since helicopters can be launched from the decks of merchant vessels, they could be used for defense of independents as well as for the A/S screen of a convoy.

6. Finally, helicopters are invulnerable to torpedoes.

Helicopters, however, suffer the following disadvantages:

1. A helicopter with the requisite lift, navigational and all-weather-flying characteristics does not exist.

2. A suitable helicopter weapon does not exist. A helicopter is vulnerable to gunfire from a surfaced submarine, although such action, since it would betray the submarine's presence, is unlikely.

3. It is possible that a helicopter, relying only on its own sonar for information, could not close the range on an evading submarine. However, MAD may be developed for helicopter use.

The advantages listed above are so great that a very vigorous program for the development of helicopters with the necessary characteristics should be initiated immediately.

Simultaneously, it will be necessary to develop A/S weapons for the helicopter. Several types should be considered:

1. Homing torpedoes;
2. Underwater rocket-propelled missiles;
3. Wire-guided torpedoes;
4. Towed charges.

The question as to whether the sonar and weapon should be carried by the same vehicle or different vehicles must be considered. The answer may be that both alternatives must be developed. It is also uncertain whether the ultimate weapon should be launched from the air or under water.

The relative merits of the three types of torpedoes will depend on the ability of the helicopter to close the range on the submarine; this cannot be determined in advance of helicopter development. At present, it appears that priority should be given to the development of a light-weight homing torpedo.

During the early stages of an attack, the helicopter's speed, when not echo-ranging, is great enough so that the range can be closed rapidly. During the later stages, the time required for raising and lowering the sonar may so hamper the helicopter that the submarine can successfully evade a close encounter. For this reason, the possibility of towing the sonar under water while the helicopter is in motion should be explored. This would be a great advantage, even if it were possible only at the reduced speed of 15 or 20 knots, and if it were impossible to echo range while towing.

If the helicopter is able to close the range on an evasive submarine to zero, the most effective weapon might be a relatively small charge towed at depth. The cable would be allowed to contact the submarine, drawing the charge up into contact with the hull.

If the range can be made very small, but not zero, the rocket type of missile, launched underwater and aimed with sonar data, may be the weapon of choice. The success of a relatively short-range homing torpedo, launched with sonar data, now appears to be least dependent on the outcome of future helicopter developments and should, therefore, be provided for the first sonar-vehicle helicopters.

I. Towed Sonar for Surface Vessels

Sonar towed by surface vessels has considerable promise of immediate usefulness. It has several of the advantages listed above under helicopter sonar. Both passive and echo-ranging types should be developed.

Echo ranging and passive sonar towed at depth from specially constructed patrol craft also appear very promising. Since such craft can be heavily armed with A/S weapons and will have both range and bearing information, they can themselves attack a submarine. Used in conjunction with other barrier devices, they should be very useful.

The overside, binaural listening device developed during World War II should be subjected to further development for use from sailing vessels and small craft. Consisting of two hydrophones mounted on a rigid cross-piece at the end of a length of flexible shaft, it enables rough bearings to be obtained. The use of sailing vessels as the platform for this and similar passive sonar devices should not be dismissed without serious consideration. Used in this manner, sailing vessels have many of the advantages of a submarine as a quiet listening platform -- in fact, all except stability for the operator and ability to stay at sea in all weather. While these are serious defects, the availability of civilian craft for the establishment of emergency and special-purpose barriers may offset them.

II. DIRECTION FINDING

ABSTRACT

Flash transmissions having durations of the order of one second are to be expected from enemy submarines, but more subtle and complex methods of communication are relatively improbable, at least for some years. We do not recommend that effort be spent at present in an attempt to deal with methods more complex than flash, because the probability of their use is low and because the large expenditure of manpower that would be necessary can be better used on positive rather than negative programs.

The present direction-finding networks cannot deal adequately with flash transmissions. A satisfactory network must be able to fulfill the following minimum requirements: (1) identify enemy flash transmissions; (2) record their message content; and (3) fix the positions of the transmitters. The natural ways to obtain these kinds of information are, to some extent, mutually exclusive. We therefore think it not desirable to try to develop equipment that would carry out all these functions on a single flash.

We believe it better to divide the functions as follows. Some or all the stations in a network are to operate panoramic receivers, with specialized methods of data presentation and storage to identify the radio frequencies at which enemy transmissions occur. No attempt is to be made to fix position or to record message content until the <u>second</u> time a frequency is used. These latter functions are to be carried out by continuously guarding each frequency that has a history of enemy activity by the use of multiple-channel position-fixing equipment. Although the proposed method would fail if the enemy submarine had a large number of channels available and used a new frequency for each new transmission, such action is deemed unlikely, as discussed under "Basic Requirements".

Both sets of apparatus must make full use of storage devices because human operators can do little or nothing within the duration of a flash transmission. Display methods must be designed to increase the probability of interception and to decrease the number of false interceptions that must be submitted to analysis.

Data are at hand to show that an inverse SS loran position-fixing network can be made to give fixes with average errors of the order of ten miles, in contrast with average errors of fifty to one hundred miles obtained by direction-finding methods. Much of the basic equipment necessary for such an inverse SS loran network is already in existence, while the storage and recording devices that must be developed are perhaps less complex than the corresponding ones that would have to be developed for a direction-finding network capable of dealing competently with flash transmissions.

We believe that an inverse SS loran network can be in operation in late 1952 or early 1953 and that its construction should not involve more than three or four million dollars of development time and equipment.

The current "interim DF" program (which, in its presently planned form, could not deal satisfactorily with flash) would not be in operation at a significantly earlier date. We therefore recommend that this program be modified to permit guarding of multiple frequencies by abandoning the concept of tuning to a frequency <u>after</u> a signal is heard. This should make its development somewhat faster and should permit some degree of interception on flash. The presently planned network will be necessary, however, in case the enemy should use a technique, the opposite of flash, that would defeat inverse SS loran fixing by the narrowness of the emitted spectrum.

An inverse SS loran network of the kind we recommend can give valuable navigational aid to our surface vessels or submarines

whenever they can break radio silence to the extent of transmitting even a single pulse and can wait a few minutes for determination of the corresponding position. If administrative procedures can be set up to permit the position-finding network to requisition such transmissions from our vessels, the position of an emitting submarine relative to that of a vessel within a hundred miles can be determined with an error of the order of three miles.

The network we envisage will be equipped to detect and identify enemy flash or other transmissions and to record the messages for deciphering. The time required to deduce a fix should not differ materially from that now required by the present direction-finding networks.

A. Introduction

Even if instantaneous direction-finding equipment were available, the present Navy networks would fail to measure the positions of the sources of flash transmissions. The most severe deficiency is one of procedure: the present networks are based upon the concept of alerting the DF stations when a signal is heard. The stations must then set continuously tunable receivers to the appropriate frequency before bearings can be taken.

Under this limitation, the networks succeed, under favorable conditions, in obtaining bearings on a good majority of transmissions having a duration of 30 seconds, but successful bearings are few when the duration is 15 seconds or less. Recent development has been concentrated on the order circuit for alerting the DF stations. By making the tuning controls automatically adjustable from the control center, the entire network can be tuned to a signal with great rapidity. The so-called "interim DF" that is now being developed should, by using this kind of technique, reduce the time required for bearing determination to five or ten

seconds after the control station has discovered a transmission on which a fix should be obtained.

This kind of operation would have been perfectly successful against transmissions of the type made by enemy submarines for almost the entire duration of World War II. Unfortunately, neither the present equipment and methods nor those now under development can deal with the very-short flash transmissions that we shall probably have to face in the event of further hostilities.

Flash (or squash) transmissions are very short bursts of signal which can be emitted in approximately the minimum reaction time of a human being. The amount of information that can be transmitted in a short period is limited by the non-linear characteristics of the radio transmission path. For the moment, it is sufficient to estimate that, by relatively crude methods, it is possible to transmit the equivalent of a ten-word telegram in one second, and that, by more nearly optimum use of the characteristics of radio transmission, a fifty-word message could be sent in one-half second.

The feasibility of such communication is indicated by the German development and limited use of Kurier with a transmission not longer than 0.47 sec, and by recent experiments of the Naval Electronics Laboratory indicating teletype transmission of fair accuracy at speeds of the order of 500 words per minute. These matters are discussed in an NEL memorandum, "Memo on Flash Communication Systems" by C. B. Davis, dated June 30, 1950.

Since the U.S.S.R. has had access to the Kurier development -- to say nothing of its designers -- it seems highly probable that this is the sort of transmission for which we must be prepared. So far as we can discover, there has been no detection of radio transmission from Soviet patrol submarines. This may indicate equally well the maintenance of radio silence or the use of flash transmission or some more advanced technique. It seems to

us highly unlikely that any method more subtle than flash is in use or will be used for some time to come. The concepts of information theory, from which the next order of subtlety is to be expected, are of very recent development, and it does not appear probable that the U.S.S.R. will, in the near future, be able to apply them to an operating system that would satisfy military requirements.

One of the characteristics of cross-correlation devices used for transmission of information is that the transmission can, in principle at least, be made completely undetectable by those who do not know the matrix required for reception. Transmission of this kind would (or rather will) be of the nature of a cipher that can be made unbreakable if the code matrix does not repeat itself within the period of examination. Even if we felt that transmissions of this kind might be used against us, we would not recommend that effort be spent in trying to detect them, since it would constitute a massive enterprise and the required intellectual ability would be better occupied on a positive program of our own. It further appears to us that something of this order is the next logical step beyond flash transmission.

The preceding paragraphs may be summarized thus. There are three main lines that enemy transmission may follow.

(1) Use of conventional slow-speed radio transmission, probably limited to bursts of a few seconds duration. This kind of transmission would be vulnerable to the interim DF, if not to the present networks.

(2) Use of flash, or bursts of one-half to one second duration. These transmissions could not be located by our present networks or by the interim DF, and would, in fact, probably escape detection by our present search methods.

(3) Use of cross-correlation mechanisms that would make the very existence of signals difficult or impossible to detect. This type of communication would be, in our opinion, entirely safe since countermeasures would probably involve more effort than would be justified by the problem.

Any of these methods could be modified to make submarine transmission somewhat less risky by various relay expedients. If air cover were available, communication from the ships could be maintained at UHF to SHF frequencies; or free balloons could be released and used as relay points after drifting to some distance from the origin of communication. We do not regard methods of this sort as especially serious because, in one way or another, it is relatively direct to deny their use to the enemy. The attack on the three main methods of communication listed above is, therefore, not greatly affected by any such modifications.

Our summary of the intercept and position-fixing problem is simple. It would be foolhardy to expect a future enemy to use a method less advanced than the flash transmission that was available at the end of the last war, especially since the knowledge that we cannot deal with flash may be expected to be widespread. On the other hand, really complex transmission systems, while hard to develop, would be even harder to intercept; therefore, economic factors inhibit our application of the technical power necessary to defeat them in the unlikely event of their being used. Flash transmission appears, thus, to be both the least we can expect and the most we can deal with.

The Navy has, to date, expended no effort on the detection and fixing of flash transmissions. With some modifications, direction-finding equipment now under development and panoramic receivers that are also nearing production can be used with visual monitoring

and have some chance of locating sources if the DF receivers are installed in sufficient quantity to guard the most probable radio-frequency channels continuously. Because no storage devices are available or easily applicable to these equipments, the probability of interception would always be low, but the service would be better than nothing. This kind of operation can probably be available in one and one-half years.

On the other hand, a completely integrated final system based on the inverse SS loran concept can (because much necessary equipment now exists) be erected in a time we estimate at 2 to 2-1/2 years. This system would have a far higher probability of interception, and would yield fixes of 5 to 10 times the linear accuracy.

We believe that the time schedule and other factors can be summarized roughly as follows.

TYPE OF EMISSION

	Conventional	Flash	Cross-Correlation
When available against us	Now	Probably now	1955+
When we can locate transmitters:			
(a) by present network	Now	--	--
(b) by interim network	1952	1952	--
(c) by hyperbolic network	1952 or 1953	1952 or 1953	--
Fix accuracy of:			
(a) present network	50-100 miles	--	--
(b) interim network	50-100 miles	50-100 miles	--
(c) hyperbolic network	10 miles	10 miles	--
Estimated portion of transmissions intercepted:			
(a) present network	50%*	0%	0
(b) interim network	90%	10%	0
(c) final network based on storage of information (either hyperbolic or DF)	90%	50%	0 ?

*Depends strongly upon duration of transmission

B. Basic Requirements

It seems likely that, in future hostilities, relatively less information on enemy movements will be available to us than we have been able to get in the past. It is important, therefore, that a maximum of information be extracted from interception of enemy communications. On the assumption that such communications are made and that they are audible to us at bases under our control, there are three fundamental operations that we must perform in order to approach the maximum of utility.

Step 1. We must be able to identify an enemy signal that may last only an instant and may appear at a random radio frequency surrounded by a vast number of transmissions of no immediate interest.

Step 2. We must be able to record the message so that decipherment will, if possible, give us the information it contains and identify the individual transmitter.

Step 3. We must be able to fix, as accurately as the nature of radio-wave propagation permits, the position of the transmitter that emitted the signal.

It should be noted that, in our present state of quasi-war, there are no reports that we have as yet completed Step 1 in even a single instance, at least so far as submarine communications are concerned. Without solution of this first problem, no further steps can be taken.

If search is to be conducted over the entire high-frequency spectrum from a number of widely separated points, it is nearly inconceivable that it can be done by operation of enough fixed-frequency receivers to monitor all frequencies continuously. Panoramic reception will certainly be used. A panoramic receiver, however, passes quickly from one frequency to another so that

reception of a single frequency, while occurring many times per second, is not continuous. Thus the recording function (Step 2) could not practically be performed by a search receiver.

It is conceivable that a single unit could be made to perform the search and position-finding functions (Steps 1 and 3) simultaneously, but it would be a complex unit, and a prediction that it could satisfactorily be developed cannot safely be made. It is easier to plan equipment to carry out Steps 2 and 3 (message recording and position fixing) together, and to expect that the search function will be carried out independently.

The same conclusion can be reached through a somewhat stronger argument. It has been suggested that the great merit of flash transmission is that the duration is less than the human reaction time -- that is, the transmission is over before an operator can do anything. This fact must be faced in identifying the enemy signals (Step 1), but Steps 2 and 3 (especially 2) require only that a receiver be listening to the transmission frequency before any transmission occurs, and that the message and fix information be recorded and stored for a time at least long enough to let an operator decide what he must do.

If, for instance, espionage or other methods could reliably tell us that an enemy transmission would occur near a certain time and at a certain frequency, Step 1 could be omitted and a single tunable receiver with high-speed recording and instantaneous direction-finding characteristics would solve the problem. Unfortunately, however, the enemy has a large (but not nearly infinite) choice of frequencies at which he may communicate, and we are not likely to receive prior information about his choices.

It is unlikely that a flash transmission can be used successfully for communication except in a channel that is clear of

other operations, at least for the instant occupied by the flash. There are three primary methods the enemy might choose for finding such a frequency.

1. Simple multiple choice. In theory, transmission is possible in any one of thousands of radio-frequency channels, and rotation among them might be controlled by a complex cipher. In practice, however, the available number is reduced by several factors.

a. Ionospheric limitations. At a specific distance, time of day, and time of year, propagational factors limit the useful band to some three or four megacycles.

b. Interference by other services, friendly or enemy. In a general way, the high-frequency spectrum is well filled. At any instant, half or more of the channels may be vacant; but, if the existence of a clear channel must be predicted months in advance, the number of spaces available is greatly limited.

c. Coding limitations. If a flash transmission is to be useful, the intended receiver must be tuned to the proper channel in advance. A complex code system is likely to break down through human failure to be at the right place at the right instant. This factor may be serious or not, depending upon tightness of discipline.

d. Pressure for frequency allocations. For the available clear channels that can be predicted, competition will be severe. Headquarters will reserve some for emergency use, the air force will demand some, etc. The number finally assigned to the submarine force is not likely to be large.

It is difficult to assign a numerical value to any of these factors. We have studied them at some length and have

collected as many opinions as possible. All considered opinions lie in the range between 4 and 80 channels available at any one time and place. The smaller numbers come from submariners and others with an operational and administrative viewpoint, while the higher numbers represent the opinions of communications engineers who examine the problem primarily from its technical aspects. We are adopting the view that 20 channels may be available to a fairly large submarine enterprise such as six months' effort in the North Atlantic.

The only way to defeat short transmissions at multiple frequencies is to have a position-finding receiver (at each station) operating at each frequency in advance of the transmission. The number of these parallel units that must be built and operated can be kept to a minimum by filling some of the detected channels with either jamming or signals useful to us. Thus, if the position-fixing network were equipped to handle only ten channels and it were found that the enemy had twenty available, ten of the twenty could be filled with our signals.

2. Pilot frequency. This second potential enemy method consists in the use of frequencies related in some simple way to an adjustable frequency used by one of his shore stations. Thus, one flash of a sequence might be fifty kilocycles below the movable standard and the next might be one hundred and twenty kilocycles above it. This method is somewhat limited by the necessity of finding two sufficiently clear channels at the predetermined separation, but it has the advantage of permitting the final choice to be made shortly before the time of transmission rather than months in advance.

The pilot-frequency technique can be defeated only be recording the population of the spectrum as a function of

time and by searching for correlation between the appearances of submarine transmissions and changes in the operating frequency of enemy shore stations.

3. Guarded-frequency hole. There is a strong possibility that flash transmissions may be inserted into silent intervals in otherwise innocuous transmissions. This technique offers certain advantages of synchronization of recording equipment and stabilization of transmission frequency which makes its use very attractive.

This method requires either predetermination of times of transmission or frequent pauses in the shore station emission. Fortunately for us, the flash transmission must require either a greater bandwidth than the concealing transmission or a rather pronounced break in the continuity of that transmission. In general, also, the signal intensity will be different and the agreement of the two frequencies may be less than perfect. Properly designed search equipment can recognize these variations in character, but a careful watch over the habits of enemy shore stations must be maintained.

We have suggested above that Steps 1, 2, and 3 cannot be carried out simultaneously on a single flash without the use of thousands of receivers with somewhat complex indicating and recording equipment for each one. It appears better to us to rely upon the fact that the enemy must repeat the use of any frequency because only a few will be available to him. We therefore think it best to abandon the idea of obtaining the message and fix information on the first flash transmitted on a given frequency, and to try to plan a network that will obtain all the desired information whenever a radio-frequency channel is used for the second time or any subsequent time.

Thus, we envisage the use of two networks, perhaps comprising

some or all of the same stations. One of these is equipped with panoramic receivers and specialized equipment for presentation and storage of frequency and time information so that flash transmissions can be recognized with high reliability. The second network is made up of stations with a considerable number (say 20) of tunable receivers equipped for rapid position finding (preferably through the use of storage devices) and prepared to provide permanent records of the message content of any intercepted transmission. The second, or position-finding, network would put receivers into continuous watch on each of the various frequencies as fast as the first, or identification, network provided the information that an enemy transmission had been detected at that frequency. With the passage of time, the enemy would have used each of his allowable and operable frequencies at least once. After that, while the identification network searches for new frequency assignments, the position-finding network should be able to intercept most communications.

We have now a clear picture of the steps that must be taken by a simple pair of functional networks to extract a maximum of information from enemy flash transmission. There is one further way in which these networks can cooperate which can either simplify the functioning of the position-finding network or enhance the probability of obtaining a fix on a flash transmission. If the position-finding network is designed to operate from stored information with storage of at least 30 or 40 seconds, that network can be alerted by the identification network after the flash by techniques now or presently in practice. It might not be wise to depend entirely upon this kind of operation, but it could well be used as a second line of defense in case the flash is not detected by the operators when it occurs.

Before discussing the technical way in which these requirements

may be satisfied, we will recite the argument that convinces us that a hyperbolic network should be used for position fixing.

C. Inverse SS Loran

Since about 1943, there have been many proposals that the hyperbolic principle should be used for location of non-cooperating transmissions. This is, in effect, applying the principles of acoustic ranging to electromagnetic radiation, and is frequently called inverse loran. These proposals have usually been abandoned after examination of the degree of instability of the F-layer transmission which is nearly always effective for long distance communication. An example of this instability, as applied to standard loran, is given in the book "Loran" where it is shown that a series of experiments at a distance of 625 miles gave average line-of-position errors of 18 miles. Similar conclusions have been reached by other investigations and the result, as in the Hazeltine Corporation report, is usually negative.

In spite of this negative history, let us examine the possibilities a little further. So far as we know, the studies made so far have envisaged the use of relatively short base lines, presumably because of the difficulty of synchronizing widely separated stations with the required precision. For the moment, let us neglect this difficulty and assume that relative time can be maintained at any distance to within a few tens of microseconds. If the signal from a mobile transmitter located, roughly, between two observing stations is observed at both, the relative times of arrival will change by 10 or 12 microseconds per nautical mile that the transmitter moves parallel to the line connecting the stations. This maximum of the geometrical accuracy of a time-difference system is obtained only by surrounding the operating area with synchronized stations.

We must now examine the degree of uncertainty of the time of transmission of a radio signal propagated by F-layer reflection. The signal normally arrives by a number of modes (say between one and six), with the modes separated in time by from 200 or 300 microseconds to 1000 or 1500. The total wave train corresponding to a short element of signal is not likely to exceed five milliseconds in duration. The time of transmission of each mode varies with the height of the reflecting layer which, in turn, varies with time of day, magnetic activity, and other factors. Some data on this variability at typical frequencies and distances are available from work done by the Raytheon Manufacturing Company for the Air Force. The standard deviation for a single mode of transmission, including data over nearly a year, may be set at about 70 microseconds at a typical distance of 1500 miles.

Short-term variations of the transmission time observed at Cruft Laboratory (Harvard) indicate much smaller variations: about 20-microsecond standard deviation at 500 miles. This shows that the F-layer for a period of an hour or two lies at a fairly definite height, but that the height varies considerably from day to day.

If a short signal, say a pulse, be transmitted over a long distance, the energy will reverberate between the earth and the reflecting layer for several milliseconds in a typical case. If the signal be complex and last for more than a millisecond or so, the arriving signal will be even more complex. Without careful study, little can be made of all the details that compose it; but, with any ordinary signal, the time at which it begins can easily be noted with considerable accuracy. This time will, in general, be the time of arrival of the first effective mode and will be subject to the sort of statistical variation mentioned above. At short distances (say, less than 1500 miles), there is little doubt

that this first mode will be a single-hop transmission. From, say, 2200 to 3000 miles, it is highly probable that the first mode will be propagated by two hops. Between 1500 and 2200 miles, however, the first mode might be either, and additional uncertainty in the relation between distance and time of arrival is introduced.

At the limiting distance, where first-hop transmission fails, the time difference between the first and second hop is of the order of 300 to 400 microseconds, depending upon the height of reflection and distance. We may thus suggest that approximate solution of the relation between distance and transmission time may be obtained, even in the zones of ambiguity, by assuming intermediate values, without introducing errors of more than ± 200 microseconds.

We visualize the process of fixing the position of an enemy transmission as consisting of three steps.

1. Without regard for ambiguities, the observed time differences are plotted in accordance with an average sky-wave correction to give a rough fix. In this case, the standard deviation of a line of position will probably not exceed 250 microseconds or 25 miles. Assuming that some five or six stations report the signal, the error of fix should be of the same order, provided that the observing stations properly surround the operating area.

2. Using this rough fix as a guide, any time differences obtained from transmissions at ambiguous distances can be laid aside, so that only lines having standard deviations of the order of 70 microseconds are used. To these lines may be added pairs of lines derived from the ambiguous readings. Since the difference between the two ambiguous values is 300 microseconds or more, and the standard deviation of either value is about one-fourth as much, one of the two ambiguous lines

should agree with the fix derived from the unambiguous ones and the other may be discarded. This process, incidentally, gives additional data on whether transmission at a certain distance is, in fact, by one hop or two hops (for instance), and thus serves to reduce the area involved in future ambiguities. This second step should yield fixes having a standard deviation of about 10 miles.

3. If one of our vessels is in the neighborhood of the enemy ship, and if administrative procedures are set up so that the fixing network can immediately request the transmission of even a single pulse or a CW dot at a frequency near that used by the enemy, this friendly transmission can be used, in effect, to calibrate the ionosphere. Since the transmission times would be very similar in the two cases, the relative fix of the enemy with respect to the friendly vessel can be given with considerably greater precision than the absolute position of either. It is difficult to assign an exact figure to this precision, but we estimate that if the friendly transmission is within 100 miles in distance, one megacycle in frequency, and 10 minutes in time, then the relative fix should have a standard deviation of not more than 3 miles.

The order of precision of even the first step is equivalent to that of a DF network working at distances of only 400 miles. At actual working distances of one or two thousand miles, the hyperbolic network, whose errors do not vary much with distance, would

therefore give absolute fixes of five to ten times the accuracy of the DF network.*

To deal with flash transmission, a hyperbolic network must meet the same problems that face a DF network. Enough parallel receivers and recorders must be used so that each potential channel is continuously guarded. This in itself is not a major problem. Storage must be continuous and done with a fair bandwidth, say 25 kc, and provision for recording a family of accurate time marks must be made. Reporting would be done by slow-speed retransmission of the received flash and appropriate time marks. Reading of times of arrival and the plotting of time differences would be more complex than treatment of the corresponding quantities in direction finding, but the methods are direct and do not constitute serious problems.

The major technical difficulty lies in the development of time standards for the various stations that will maintain relative phase to the necessary accuracy. Here, fortunately, we can call upon the fact that the rate of flow of information required to maintain the rate and phase of a clock approaches zero, if the clock is not moving with respect to the standard. In other words, signals from WWV, or any other standard, can be received and integrated to whatever degree is required to reduce the excursions from the mean time of arrival from those inherent in high-frequency transmission to those required for the system. Recent experiments

* We recognize the possibility of using the self-coherence of a number of lines of position as a means for testing the height of reflection and thus reducing the errors of the system. This is the technique called "envelope time difference ratio" in the Hazeltine Corporation reports. We are doubtful, however, that the low degree of correlation between the heights of reflection at widely separated points will permit any great advantage to be gained from the use of this technique. We therefore prefer to assume, so far as performance estimates are concerned, that no improvement is to be obtained from this source. It should be noted, moreover, that the relative-fix technique, when possible, does all that self-coherence can do, and more.

at Cruft Laboratory indicate that moderately good crystal clocks furnish a sufficiently stable base to permit integration with a time constant of two or three days. This order of integration appears to give an output phase constant within 50 microseconds with respect to that of the distant transmitter. If clocks controlled by molecular resonances are to be available, the problem becomes more simple because it is the ageing rate of a crystal oscillation that sets the limit to the integration time constant at present.

An alternative method of providing synchronism is simpler to visualize, but suffers from the required transmission of synchronizing signals from each of the fixing stations. This method is that of loran (or, rather, SS loran). A master station would transmit pulses that would be repeated back from the other fixing stations. From the total time of transmission, the one-way time can be found and used to provide an instantaneous correction that can be applied to the apparent time at each station. This method fundamentally requires very little storage, but, in practice, it would be advisable to provide very good clocks to ride through the various interruptions to be expected. In the first stages of a hyperbolic fixing network, this method is to be preferred, since the instrumentation can be provided by relatively minor modifications of standard loran timers.

We believe that the technical and operational difficulties to be surmounted in setting up a hyperbolic fixing network are not greater than those, for example, of setting up the loran system -- that is, the method proposed is simple and direct and suffers only from the necessity of requiring good collaboration between groups of operators at widely separated points. Fortunately, much of the necessary equipment is in existence, or can be developed and supplied easily because it is required in limited quantity. The training problems should, however, be minimized by

use of automatic methods wherever feasible. Careful training of the operators who "decode" the information and plot the fixes must be undertaken, in any case.

It is worth while to consider whether such a system might not furnish a useful additional navigational aid to our forces, for those cases in which it is possible to break radio silence. With some foreknowledge of the desirability of a fix, very little transmission and little equipment or operational complexity is required to provide this service.

D. Equipment Details

Note: This section is written so that it constitutes a series of footnotes that may be read in conjunction with the system diagram of Table I; it is, therefore, in outline form.

(A) Search Program

(A1) Interim Search

We envisage the temporary use of a panoramic receiver with spiral-scan presentation, as developed under Air Force contract W28-099ac-163. This equipment may be ready in moderate quantity in 18 months. Unfortunately, no provision can readily be made for storage of information. Manual operation must therefore be used, and the fatigue factors will be large. Energetic steps must be taken to maintain a high order of discipline, and operators must be relieved after short watches. At best, the relative number of flash transmissions detected will be small, probably a few per cent. The efficiency can be raised by providing a number of parallel equipments and operators, and by limiting the frequency coverage of each operator to a megacycle, more or less.

(A2) Final-Search Equipment

The equipment must be designed around a presentation

adapted to provide maximum visibility of expected signals. We propose a rectangular presentation of data in the frequency-time plane, using essentially a slow-speed television scan. The output of a panoramic receiver will modulate the intensity of a horizontal sweep synchronized with the beam, while successive scans appear adjacent to each other in the vertical plane. Since we are searching for signals that may occupy a few kilocycles of bandwidth and a half-second or more of time, these quantities should represent at least one per cent of the linear dimensions of the display. Thus, one minute would be a convenient time for a complete frame, and a megacycle or less would be an appropriate length of sweep.

Unfortunately, the resolution bandwidth of a panoramic receiver is approximately the square root of the range surveyed in cycles per second multiplied by the repetition frequency in the same units. The repetition frequency cannot be less than about 10 per second to give several hits during a half-second transmission, while 20 cycles would be better. At 20 cps and with a range of one megacycle, the limit of resolution would be about 4 kc bandwidth -- that is, all signals of narrower bandwidth would appear identical. The flash transmission might be of only a few hundred cycles bandwidth, in which case there would be no way to make its width one of its primary distinguishing features with this kind of receiver. It is quite likely, however, that, like the NEL versions, the transmissions may consist of a number of modulated subcarriers, in which case its width would be conspicuous.

On the presentation we recommend, a burst of noise would appear as a horizontal line, while a continuous wave transmission would appear as a vertical line. The length of the horizontal lines would be limited by the finite duration of the noise bursts,

and the vertical lines would be interrupted somewhat by keying.

A flash transmission, if of wide band, would be represented by an area one or two per cent of the linear dimensions of the display along each side -- an area containing perhaps 25 to 100 picture elements. Such an area would be relatively distinguishable, if not obvious.

Storage of this frequency-time population diagram should be by photography, a single frame for each cycle of one minute. Rapid development should be provided so that scaling of frequencies can be checked on the photograph. These records should be kept permanently, perhaps at headquarters, so that, in the event of enemy use of transmissions other than those expected, prior records can be consulted. For instance, if reason is found to suspect that submarine frequencies are being changed in accordance with variations in the frequency of a shore station, an intercomparison of flash frequencies and other signals can be made in order to find the key to the method.

(B) DF Fixing

The basic unit should be the new "interim DF" receiver, used in numbers sufficient to guard the required channels continuously. Provision must be made for operation of a number of these units from a single antenna (and single goniometer*) through multicouplers. Because currently available multicouplers permit some mutual interference from local oscillators, steps must be taken to identify these fictitious signals by temporarily disconnecting other receivers as requisite. This feature should not be serious, since most operation will be at fixed frequencies.

The DF network should be set up for purely manual operation under the same conditions as the interim search equipment --

* This necessitates synchronization of all the indicators from the one goniometer.

namely, good discipline and frequent relief of operators. As a second step, provision might be made for remote control of receiver frequency, for whatever advantage that might give, and for elimination of local-oscillator interference through the multicouplers. An automatic trigger, capable of recognizing a flash, and a recording camera might also be added.

This interim network might be of particular value in case the enemy suspected the use of hyperbolic methods for flash location and used the opposite technique which we have called "sneak". Essentially, by using slow speeds and a "key thump filter" with a long time constant, he could produce signals of such slowly varying amplitude that time-of-arrival methods would be impossible. In order to defeat the hyperbolic method, it would be necessary to hold signaling speeds down to a few tens of elements per second. At such a speed (a word or two per second), the duration of a message would be long enough to make the interim DF network quite effective.

It should be noted that, since the interim DF equipment will only sample the received signal a number of times per second, it will be necessary to use a family of fixed-frequency communication receivers to record the messages. The recording might well be done in two stages, as discussed below, to minimize the amount of material sent to the deciphering room.

(C) Hyperbolic Fixing

(C1) Synchronism

The primary requisite is a set of good crystal oscillators with provisions for frequency division and generation of the required families of markers. The UE-1 loran timer will do very well for this purpose, with the addition of further frequency division so that standard time signals can be used for calibration and checking. Equipment for compensation of the ageing rates of the

crystals should also be added.

These time standards must be provided at least in duplicate and preferably in triplicate in each station. They must be operated with standby power available and preferably with floating batteries and other precautions that would make interruption of service very rare indeed.

A new system of marker families must be developed so that time can be recorded against whatever signals are received. These markers must be identified, presumably in binary code, often enough so that search over a long strip of record is not necessary. We suggest that each second in an hour carry its own identification. Enough families of markers should be provided to permit reading records to a precision of at least 10 microseconds. These markers may, if desired, occupy several channels on the magnetic tape used for temporary storage.

Pulse transmitters must be provided (assuming that the one-way-transmission technique discussed above is not used or is deferred for later development) to operate at enough radio frequencies to insure reasonably continuous communication with the master station; this is in addition to the ordinary teletype communication circuit, whose existence is assumed.

(C2) Guard Receivers

In each station, there must be a sufficient number of receivers to guard as many channels as may be judged necessary. These can be normal communication receivers*, but should have adjustable bandwidth to make the best use of whatever channel width is available at the various frequencies. They must be sufficiently stable to stay accurately on the assigned channels, and frequency-

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* They may well be the same receivers procured under the interim DF program.

calibration equipment must be provided. These receivers may be used with multicouplers and a common antenna system, but steps must be taken to reduce mutual local-oscillator interference below the level attained with present receivers and multicouplers.

(C3) Storage System

For each guard receiver, there must be provided a temporary storage device in the form of a recorder using a continuous loop of magnetic tape. We suggest storage for a period of one minute with a bandwidth of 25 kc. Receiver output and time marks are to be stored together. Whenever a noise that might be an enemy transmission is heard, the operator starts the permanent storage mechanism -- a film recorder with provisions for very rapid development. If this record reveals the "noise" to be, in fact, a wanted transmission, the information contained on it is sent to the control station by slow-speed facsimile or teletype.

The processes of recognizing a flash and reporting its time of occurrence to the control station can be simplified by introducing another form of temporary storage. This might resemble the visible speech presentation developed by the Bell Telephone Laboratories. In this instrument, a persistent cathode-ray image moves laterally across the field of view so that a few seconds' prior information is continuously visible. If this device, as well as a loudspeaker, were attached to each receiver output, visible as well as audible recognition would be possible. Further, an index could be provided, say, at a point reached by the image three seconds after reception. The operator would press a key when the image reached this point. This impulse would then be combined with one or more members of the binary time-mark family to signal to the control station the time of the flash and the radio frequency at which it occurred. This message would then be repeated to the other stations in the network. The same impulse

would start the camera for transferring the enemy signal to permanent storage.

Other stations in the network might or might not have noticed this flash. If not, the sixty seconds' storage comes into play. During this interval, the message would be received from the control station, indicating the frequency and time of an interesting event. The code number of the desired second would then be punched on the keyboard of the film record starter, so that a permanent record would be made when the desired interval came to the end of the magnetic storage.

When the network is first set up, the film recorder should exhibit the data as amplitude against time. The film strip would then be projected upon a coordinate grid and the information would be manually transmitted by teletype by simply allowing various letters to represent corresponding amplitude and by reading off the amplitude at appropriately spaced intervals. An automatic encoder will be more desirable, but can be added later if its early inclusion would delay operation of the network.

If the message must be forwarded for possible deciphering, it must be sent in toto, but this can be a somewhat delayed service. For position fixing, the control station need only receive the first part of the wave train and the time marks, and these can be transmitted at even the lowest speed in a minute or two.

(C4) Control-Station Equipment

At the control point, a teletype receiver and recording camera must be provided to complete the circuit from each station in the network, because information should come in from all of them simultaneously. Here it will be most convenient if the amplitude information be converted into light intensity so that the message, or at least the beginning of it, can be recorded as a variable-density pattern, given as a function of time after some

identified time mark. The process of time-difference reading would then (at first) consist simply in superimposing the records from two stations over a light source and sliding one laterally until coincidence is detected by observation of maximum contrast. Then the time difference is obtained by reading off the separation between time marks. Again, at a later date, an automatic comparator can easily be added.

This method of reading the data is a simple form of cross-correlation procedure and serves to minimize the instrumental error in reading time differences. It will be especially efficacious in the case of low-speed signaling. To attain maximum effectiveness, the control-station recording camera should have its speed (the time scale of the record) adjustable to fit the various conditions that might be encountered.

(C5) Computation of the Fix

At least initially, the time differences determined at the control station should be used to enter precomputed charts similar to those used for loran navigation. These charts should be constructed with lines of position that include the sky-wave corrections for the most probable mode of transmission over each path. In ambiguous areas, the correction needed to convert the lines of position shown to those for a mode of secondary probability can be given as numbers, as the loran sky-wave corrections are presently shown.

Thus, the operator determining the fix interpolates his lines of position between those shown on the chart and, in ambiguous cases, draws two alternative lines. With this quantity of precomputation, the plotting operation should not take more than a minute or two.

While a computing machine capable of dealing with the hyperbolic lines could certainly be made, there is no reason

to believe that it would improve the quality of the resultant fixes, and the time saved would be small. We do not recommend the expenditure of effort on this development.

If the third step discussed above (fixes relative to friendly vessels) is to be undertaken, the officer in charge of plotting the fixes must be given the authority and the communication facilities necessary so that he may request friendly transmissions as requisite. We regard this feature as of great value, and strongly recommend that such a procedure be set up.

Our discussion of the methods and equipment necessary to obtain useful fixes on enemy flash transmission has been given above in skeletal form because of the limited time available to the Hartwell group. We believe, however, that all the necessary steps have at least been mentioned.

l spare contract W28-099-ac163
l spare
ver frequency range system system be modified to avoid mutual ator interference and remotely tuned from control
that several can be synchronized meter)
as at present (later should e tuning of receivers)**

SECRET

TABLE II-1

	No. at Master or Control Station	No. at Slave Stations	Development Status
(A) SEARCH (for Conventional Transmissions, Flash Transmissions or Sneak Transmissions)			
(A1) Interim Search Equipment Spiral scan display 2-20 Mc Searched bandwidth proportional to frequency 25% efficiency (search cover/max. scan rate) No permanent record	4	4X	#
(A2) Final Search Equipment 2-30 Mc Slow TV scan display Searched bandwidth roughly constant 66% efficiency (search cover/max. scan rate) Camera record (1 frame per minute)	9	9X	**
(B) DF FIXING (for Conventional Transmission or Sneak Transmission)			
(B1) Receiving		4X 4X 4X 7X	# # # *
(B2) Indication		7X	*
(B3) Reporting		X	#

SECRET

TABLE II-1

	No. at Master or Control Station	No. at Slave Stations	Development Status	
[illegible]				
	4	4N	#	3 to cover frequency range; 1 spare As developed under Air Force contract W28-099-ac163
	9	9N	**	8 to cover frequency range; 1 spare
		4N 4N 4N 7N	# # # *	antennas — 4 bands to cover frequency range goniometers — 1 per antenna system multicouplers — 1 per antenna system receivers — (later should be modified to avoid mutual local oscillator interference and preferably be remotely tuned from control center)**
		FN	*	indicators — (modified so that several can be synchronized from 1 goniometer)
		N	#	alerting and reporting links as at present (later should be modified to provide remote tuning of receivers)**

TABLE II-1 (cont.)

	No. at Master or Control Station	No. at Slave Stations	Development Status	
(Flash Transmissions or Conventional Transmissions)				
(C1) Synchronism				
(1a) Clock equipment (time-keeping)	3	+ 2N or 3N	#	"cry
	1	+ N	#	rail
	1	+ N	*	
(1b) Re-setting equipment (time-finding)	1	+ N	*	lora
	3 or 4	+ N	#	HF s but
(1c) Encoding equipment (time-telling)	1	+ N	**	spec phas
(C2) Receiving		FN	#	
		5N	#	
		5N	#	
(C3) Recording		FN	#	
		FN	#	
	N	+ N	#	
		N	**	
(C4) Reporting		N	#	
		N	#	may
(C5) Special Master Station Functions	N		*	
	1		#	

*Requires some development effort. **Requires substantial development effort. #Essentially a matter of pro

N=Number of slave stations in network. F=Number of radio-frequency channels guarded.

	No. at Master or Control Station	No. at Slave Stations	Development Status	
[illegible]tions'				
	3	+ 2N or 3N	#	"crystal clocks" (for duplicate or triplicate installation)
	1	+ N	#	fail-proof installation (to insure against interruption of operation of clocks)
	1	+ N	*	motor-driven frequency-varying gear-box (manually chosen gear ratio)
	1	+ N	*	loran timer (modified to resolve 1/25 second ambiguities)
	3 or 4	+ N	#	HF communication units (standard HF transmitter and receiver but reserved for this use)
	1	+ N	**	special pip generators (identified seconds, plus tenths, plus hundredths)
		FN	#	HF receivers (later should be modified to avoid mutual local oscillator interference and preferably to be remote-tuned by master station)**
		5N	#	antennas
		5N	#	multicoupler
		FN	#	loudspeakers (later should be supplemented by visual "moving phosphor" display)*
		FN	#	tape recorders
	N	+ N	#	film recorder with quick development
		N	**	film starter (responds to selected code on magnetic tape)
		N	#	projector for manual encoding (later to be replaced by automatic coders)**
		N	#	teletype transmitter and circuit (any existing facility may be shared)
	N		*	teletype receivers (modified for recording on film)
	1		#	set of loran charts

[illegible]ires substantial development effort. #Essentially a matter of procurement and installation.

[illegible] or radio-frequency channels guarded.

III. RADAR

The following report is by no means a complete analysis of the anti-submarine radar problem but rather a list of the strongest impressions gained through our discussions with those at present concerned with the development and use of snorkel-search radar.

It is evident, first of all, that the development of radar under the Bureau of Aeronautics since the War has been prosecuted with much imagination and boldness and that, considering the necessary limits of the scale of the effort during these years, the situation in which we find ourselves today could be far worse than it is. Roughly speaking, one can say that the advance in radar techniques represented by the APS-20 (and subsequent developments stemming therefrom) has nearly compensated for the initial advantage that the development of the snorkel gave to the submarine. We can see snorkels about as far now as we could see surfaced submarines in 1944. We have every reason to try to improve the performance of our radar since it is more likely that the snorkel will continue to become more elusive. Indeed, we have no assurance that the ranges we are now obtaining against our own snorkels and copies of the German snorkel can be duplicated against the Soviet snorkel. Evidence regarding the efficacy of snorkel camouflage is still fragmentary, but we feel that a moderately vigorous Russian effort to exploit geometrical camouflage could probably reduce our ranges seriously. In the long run, then, we see the radar-vs.-submarine contest as an unequal one, with the submarine eventually the winner. This by no means implies that we should slacken our effort to improve our radar. <u>On the contrary, it is absolutely essential to keep the radar in the fight as long as possible</u>.

The present status of anti-submarine radar development has two aspects, the technical and the tactical, which have been interacting with one another for some time, so that it is a little hard to separate cause and effect. An example of this is the emphasis we

seem to find on the "single package system", in which one plane carries the search radar, the localizing and identifying equipment, and the weapons. This tactical doctrine is reflected in the equipment under development, where we note some compromise between size and radar range. In particular, there appears to be a tendency to feel that the improvement in the radar and its demonstrated success against snorkels at modest ranges has reduced the necessity for carrying very large antennas. We believe that, although the single-package doctrine may have its place in many circumstances, it is not the only, and probably not even the best, approach to the problem that we shall face.

The search problem and the attack problem are different. At present, the search problem does not look hopeless but it will never stay solved for long. We shall have to be improving our search radar continually, usually by adding more gadgets and increasing the size and complexity of the equipment.

The identification and attack problem is even further from an ultimate solution. To impose the condition that these problems must be solved by equipment capable of being carried in one plane is to sacrifice flexibility of planning and development. Moreover, the tactics to which the single package lends itself are such as to make the problem of radar flooding considerably more difficult (see Section No. IV). We are, therefore, interested in encouraging the other approach, which starts with the ambition of building and flying the best snorkel-search radar we can possibly devise.

There are several directions in which one might proceed in trying to make a better search radar. The present radar is seriously limited by sea clutter at short ranges while its long-range limit, at least in seas of State No. 3 or less, appears to be receiver noise. These limits refer to the actual signal-to-noise or signal-to-clutter ratio, as the case may be, in the set. An additional and very important limit under all conditions is the "operator factor"

which accounts for the difference between targets actually visible on the screen and targets detected unmistakably by the operator. While we do not wish to underemphasize the importance of improving the discrimination against sea clutter, we believe that it is perhaps more important for the search radar to increase the maximum range of detection. This offers, we believe, the bigger possible gain in sweep width. Moreover, improvements in snorkel camouflage might well drop the snorkel return irretrievably below the sea clutter at short ranges while still allowing a detectable echo in the region where the Lloyds-mirror reflection has reduced the sea clutter but not the snorkel echo. There is an additional consideration that we should not forget: the enemy may resort to floating decoys; even if he does not, the problem of radar echoes from flotsam and jetsam may be serious. The snorkel differs from decoys and flotsam by being relatively higher above the surface, and the place to take advantage of this is at the longer ranges where the angle of incidence is small and the Lloyds-mirror effect suppresses the echo from objects on the surface.

To increase the radar range we need high power and a big-dish antenna. The Constellation Project PO-1W, although intended for a somewhat different purpose, is a bold step in the right direction. We would like to see explored the possibility of putting large antennas on smaller aircraft, and we believe that one promising attack on this problem is the "sideways-looking" antenna which would have a long rectangular aperture extending along the fuselage and presenting very small frontal area. The antenna would have to scan over a sector of perhaps 50° or 60°. We visualize an antenna of this type on each side of the plane. A search plane of this type would be accompanied by one or perhaps several attack planes which would be vectored by the search planes to identify and, if necessary, attack suspicious targets. Of course, this calls for a suitable relay or communication link with the attack planes. The latter may themselves carry radar to be used at

short range for location and attack, but this radar would be designed for that purpose, and not primarily for long-range search.

We are encouraged by the progress that has been made in adapting large antennas to aircraft. We believe that it is not at all unreasonable to fly an antenna as long as 30 or 40 feet on a carrier-based plane, and an antenna of 75 to 100 foot length on a land-based plane. For example, the P2V in one modification carries a droppable lifeboat underneath the belly in an enclosure that looks pretty much like a radome for a 28-foot antenna of the sort we visualize. There is no obvious reason why this could not be extended farther forward to accommodate a 35-foot antenna. Such an antenna would have at least 4 times the effective area of the APS-20 antenna. The flying boat P5Y has enough space along its side to accommodate an antenna nearly 100 feet long. The Lockheed L-168 transport, the pod-carrying version of the Constitution, is designed to accommodate a pod that would house a pair of reflectors back-to-back each 77 feet long by 7 feet high in an ideal location for side-looking search radar. Such an antenna has more than 20 times the effective area of the APS-20 antenna. In each of these cases, the antenna would presumably be fed by a scanning line source similar in function, if not in method of operation, to the Eagle antenna. We have not encountered any brilliant new ideas that promise to solve this problem in an elegant and simple manner. Nevertheless, we feel that it can be solved by fairly straightforward engineering methods, possibly at the price of some complexity and clumsiness. It is probable that an antenna as large as the land-based plane could carry—say, 50 to 100 feet -- should be designed to work at S-band. Whether this is the best choice for a 30-foot antenna we cannot say. We recommend that a design study be initiated, having as its objective a long scanning line source capable of handling the highest available power and capable of forming, with a suitable lens or reflector, a scanning antenna for a long-range search.

Even if the sideways-looking antenna here proposed should prove impractical, we wish to emphasize strongly the general desirability of large antennas and to deplore any tendency to reduce antenna sizes. The APS-44 should be used wherever possible with no less than an 8 x 3 foot dish.

The information on sea clutter that has been gathered by NRL and to some extent by the Philco laboratory shows that there is much to be gained by clever utilization of storage and correlation techniques. The striking improvement reported for the Philco delay-line integrator is only one hint that work in this direction can be very fruitful. We believe that further fundamental studies of sea clutter should be vigorously supported. There is much of a very practical nature to be learned by direct observation and data analysis.

It is not hard to see why the operator factor should be so discouragingly low, as it is, and it will probably be worse in actual wartime operations unless we do something about it. Bona fide snorkel targets will be discovered at best only very rarely, and these occasions will be separated by long hours of tedious observation and many investigations of driftwood and fruit crates. It was generally agreed at our discussion of the radar presentation problem that the conventional PPI with the P-7 screen is responsible for part of the trouble. The dynamic range of the tube is low, the flash is distracting and when information fades from the tube it is gone forever. There is no doubt that rapid scanning, where feasible, is much better, especially for picking up targets against clutter. The possibility of rapid scan, even for the long-range search radar, should be kept in mind; it looks difficult but someone may have a bright idea. On the other hand, we believe there may be ways of obtaining some of the advantage of a fast-scan presentation on a slow-scan radar. One method for doing this has been suggested. It consists of photographing every complete PPI scan and re-projecting the picture at movie speed, recycling for each sequence of pictures, continuously. This would give the operator leisure to examine over

several minutes, a screen on which the relatively slow-moving targets such as a snorkel would appear, repeatedly, as a quickly darting spot. No information would be thrown away until it had been on view before the operator's eyes for at least two or three minutes. Methods now exist by which this could be instrumented, although doubtless more elegant methods could be devised. We believe that considerable effort in the direction typified-- but not necessarily defined-- by this method might increase, very significantly, the operator factor for long-range search as well as detection in sea clutter.

We have not thought very much about the radar needed by the attacking aircraft. Obviously the attacker could be vectored close enough to the target to avoid using radar at very long range and thus disclosing its approach. He will be faced with the sea-clutter problem no matter how short the range, and it is probable that the ideal radar for this purpose would be a rapid-scan high-resolution forward-looking radar on 3 cm or shorter wavelength. It may be that an APS-33 will do. We have not seen information on the capability of the APS-33 against snorkels at short range and very low altitude; possibly this information exists. This is only one of the components of the hunter-killer team that should really be studied as a complete system. The use of GPI, of radar relay, of secure communication, and so forth, are all involved in the problem.

IV. RADAR FLOODING

A. The Problem

Airborne snorkel-finding radar can play an important part in anti-submarine warfare if it is protected against countermeasures. Two obvious radar countermeasures available to the submarine are passive listening and decoying. This discussion is concerned only with listening, but the threat of decoys--that is, snorkel-like targets dotted over the ocean in sufficient numbers to foul up search operations--bears indirectly on the problem of countering radar listening, and will be referred to in the appropriate place.

Few prospects are more certain than the employment of passive radar listening by the Soviet submarines. The apparatus required is of the most rudimentary sort, the Germans had developed microwave listening gear, and the result of their failure to develop and use it soon enough is well known. One must assume that Russian submarines will go to war already equipped with microwave listening gear, with crews trained in its use and indoctrinated with its importance. They will be able, while running at snorkel or periscope depth, to monitor any bands we could conceivably use for long-range search radar, at the cost of exposing an antenna not much larger than the periscope itself. Direction finding also is possible without any significant increase in antenna size.

If these assumptions seem overly pessimistic in view of the way the Germans fumbled around,* one should recall that the Germans were handicapped in several ways: microwave techniques were new to them, and, in particular, they did not have good crystal detectors; they were forced to improvise hurriedly in a desperate situation; and their submarine personnel had lost confidence in listening receivers generally as a consequence of the futile meter-wave listening they had tried earlier. None of these considerations applies

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*See OEG Report 51, Part 2, pp. 280 ff.

to the Russians. On the contrary, the well-documented experience of the Germans, and the Russians' familiarity with our microwave methods, make it very likely that they will be adequately prepared.

Radar listening is easy. Wide-band pulse receivers of the crystal-video type can be made to have a sensitivity of the order of 10^{-8} watts by techniques now well known.* It is no trick to make the instantaneous acceptance band as wide as 15 per cent in frequency. These figures doubtless could be, and probably have been, bettered by a little development work.** But that is not very important, as the following example shows. Consider an APS-20 antenna (8 feet x 3 feet aperture) radiating pulses at 3000 Mc/sec with 10^6 watts peak power. Let the listening antenna have a gain of 10 which corresponds to a physical aperture about 0.2 feet^2 in area (making reasonable allowance for the illumination factor). If the associated listening receiver has a sensitivity of 10^{-8} watts, pulses can be detected in free space at a range of 6,000 miles. This implies that, in all practical cases, the distance at which radar pulses can be heard will be limited by the microwave horizon rather than by the sensitivity of the listening receiver. In every case, the listener can outrange the radar.

We can't fool the Russians, as we fooled the Germans, by developing radar in an entirely new part of the spectrum. The last window is at 8 mm wavelength, and even there the radar range would be severely limited by atmospheric absorption. Moreover, it would

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*See Rad. Lab. Series, Vol. 3, §§ 8.17 and 8.18; Vol. 15, Chap. 11; VHF Techniques, Vol. 2, §§29-16 ff.

**For reasons not clear to the writer, the U.S. development of RCM receivers for submarines has concentrated almost exclusively on elaborate superheterodyne frequency-scanning devices, typified by the AN/BLR-1, which contains 158 vacuum tubes. Not much has been done to improve wide-open direct-detection receivers, apparently, and 10^{-8} watts is still typical of what we can do.

be relatively easy to make an 8-mm listening receiver which would outrange any 8-mm radar; it could probably be done with existing crystals. To switch our radar frequencies around in the useful part of the microwave spectrum--say 2 to 20 cm wavelength--will not cause the listening enemy much inconvenience, in the present state of his knowledge. In fact, it would probably change the situation very little to announce in advance the radar bands we intend to use.

If any snorkel-seeking radar can be heard at near-horizon ranges (as we must assume it can), the submarine has only to dive when he hears radar pulses and surface when the ether is quiet in order to be entirely safe from detection by radar. In this situation, the radar has only a nuisance value, measured in terms of the frequency of radar alarms aboard a given submarine. Our obvious task now is to increase the rate of alarms aboard a given submarine to a level at which the submarine cannot dive at each alarm without serious loss of its offensive power. Then the submarine can either remain safe and impotent, or it must choose to ignore the alarms; in the latter case, the situation is equivalent to one in which the submarine has no listening gear aboard. To bring this about requires a flooding operation. In the following pages, we shall examine some of the technical and tactical requirements of radar flooding in order to find out how much effort it is likely to cost, and how to go about it. Of course, we shall have to oversimplify the situation in order to subject it to arithmetic.

It should be understood that the immediate object of the flooding operation is not to find and sink submarines, but solely to nullify the value of the submarine's listening gear, so far as airborne radar is concerned, by creating a situation in which the decisions of the submarine commander will not be influenced by what his listener hears. We are trying to satisfy a necessary, but not sufficient, condition for the successful use of radar in anti-submarine operations. It would be senseless to embark on a flooding operation

if we were not, at the same time, able to find and kill submarines by methods involving radar.

B. Requirements for Successful Flooding

The flooding operation ought to succeed if it meets these two requirements:

1. The signals heard by the submarine must be indistinguishable, by any reliable means, from potentially dangerous signals, even assuming, as we must, that the enemy knows the general characteristics of our A/S radar, such as approximate frequency, type of scan, beam width, pulse repetition frequency, and approximate range.

2. The frequency of occurrence of radar alarms in any given submarine must be so high that to dive after every alarm would seriously hamper the submarine's operations. This is a requirement on the density of flooding and on the total area flooded. We shall use S to denote the total area flooded, in square miles, and r to denote the average alarm rate in alarms per submarine per day.

The implications of requirement (1) depend strongly on the ability of the submarine listening gear and its operator to make the most out of the information received. It is certainly possible for the listener by relatively simple means to determine the approximate pulse repetition frequency, the number of pulses per beam width, the frequency of scans, and whether the beam sweeps over him at regular intervals (as it would if the radar antenna were continuously rotating) or at alternately long and short intervals (as it would if the antenna were rocking to and fro with the target off the center line). He may be able to recognize the side lobes in the antenna pattern; this is not so hard as it sounds because of the large reserve of sensitivity that the listening receiver has, and the advantage of one-way transmission. It would not be very hard to determine the pulse length. To measure quickly and precisely the

microwave frequency would require more elaborate equipment, and the information would not be worth much to the listener. All these features of the radar signal we may call collectively the signature of the radar.

In addition to recognizing the signature, the listener will be able to make rough estimates, at least, of the intensity of the signal, and, if he dares to wait around long enough, he can ascertain whether the signal is increasing or decreasing in intensity.

A trainable antenna--even a fairly small one--will enable the listener to fix the bearing of the pulse transmitter, and to obtain a bearing-rate. (Our AN-BPA-1 achieves a bearing accuracy of $\pm 5^{\circ}$, in S-band, with a continuously rotating antenna housed in a 17-inch diameter radome; a trainable antenna of considerably smaller dimensions should be capable of the same accuracy if the signals are strong.)

In principle, an accurate measurement of signal intensity under ideal conditions of propagation, coupled with knowledge of the characteristics and performance of our search radar, would enable the operator to decide with certainty whether or not he were safe from detection. In that case, the flooding transmitter would be required to create a field strength at least as high as that in the radar beam at a range equal to the maximum range of snorkel detection. But the actual situation is different for many reasons. First, the submarine antenna is located only a few feet above an irregular, tossing "ground-plane"; for this reason alone, the observed signal will show large fluctuations, not necessarily correlated with fluctuations of the snorkel echo received by the radar. Further fluctuations may be introduced by the propagation path itself and, although these probably will be correlated with fluctuations in the radar echo, the listener cannot be sure that a signal that appears "safe" by a margin of 10 db will not, a few minutes later, rise above the "dangerous" level. Second, the maintenance

of a microwave field-strength meter in a reliably calibrated condition is probably no easier for the Russians than it is for us. Finally, no matter how much he knows about our sets, the listener will have to put in some factor of safety. (The more submarines we find and kill the higher this factor will tend to grow.) I think it is conservative to assume that a flooding signal will be effective if it is not more than 20 db below the signal that would normally be received from a radar at a reasonable snorkel-detecting range. If we take APS-20 as the radar and 20 miles as the range, this is equivalent to requiring 0.001 watts/meter^2 peak power at the listening antenna. For APS-44, at X-band, with one megawatt and an 8 ft. x 3 ft. dish, the figure will be about the same, the effect of increased directivity being compensated by a corresponding increase in detection range.*

What the listener can infer from the observed change of signal strength with time depends on our anti-submarine tactics and his knowledge of them. The signal will ordinarily be increasing, at first, if the listener is alert, for if it were decreasing he should have heard it even earlier. He concludes that something is approaching his general vicinity, but is still beyond snorkel-detection range. As soon as the signal threatens to exceed the "danger level," he will have to take action if he wants to avoid detection. If he is willing to risk detection, providing he can submerge several minutes before a plane arrives over his position, he may take the bolder course of staying up after the signal has reached the danger level to see whether it continues to increase or instead begins to fade. This tactic is useless, however, if our radar can make proper use of the Vixen technique, or if the

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*If the maximum snorkel-detecting range is limited by receiver noise, and if the target cross section is independent of wavelength, the power density required by the above criterion depends <u>only</u> on the effective area of the radar antenna.

search plane and the attack plane are not the same. In either case, a fading of the radar pulses may be the prelude to an attack. Hence, the growth or fading of the received signal need actually provide no reliable distinction between harmless and dangerous pulses.

How much the listener can infer from the measured bearing rate and its change with time depends on the precision of his measurement and on our tactics. There are two situations in which he might profit from bearing-rate information: (a) if our tactics called for the search aircraft, having detected a target, to fly directly toward it to investigate and possibly attack, the listener would be justifiably alarmed by a small or zero bearing rate and reassured by a moderately high bearing rate; (b) if our search radars are always flown on a straight course, and the listener knows this fact and the approximate speed of our aircraft, he might be able to infer the course and range of the aircraft from a good bearing-time plot. It is pretty obvious that we can avoid helping him in either of these ways, if we keep the problem in mind.

So far as requirement (1) is concerned, we conclude that the signature of the flooding signal must be a reasonable facsimile of that of the radar, and its strength should be about 0.001 watts/meter^2, or greater, at the submarine. If we want to use two or more recognizably different types of radar for snorkel search, each type ought to be imitated by some of the flooding signals. This would not, however, increase the total number of flooding transmitters required.

Under requirement (2), the flooded area S can be taken as large as we please; in general, the results of our oversimplified analysis will simply be proportional to S. Merely as a basis for discussion we shall take S=8 million square miles. Figure 1 shows how much of the North Atlantic an area of this size can include. To require uniform flooding of the particular region shaded in Figure 1 would, of course, be unrealistic. Parts of this region,

during a given period, will include neither shipping routes nor submarine transit routes. In the north, especially, rough seas will often prevent effective radar search over large areas; it is probably a waste of effort to flood manifestly unsearchable areas. But other areas outside the region shown will call for some attention and, on the whole, 8×10^6 square miles does not seem much too high a goal for the entire Atlantic operation. An operation of equal scope in the Pacific, confined to selected areas and routes, ought to be effective, but that is another story.

It is more difficult to estimate r, the alarm rate required for effectiveness. It depends on the submarine's characteristics and tactics, eventually upon our success in killing submarines, and upon psychological factors we can assess only after the event.

In 1943 the British attempted to flood a strip in the Bay of Biscay across which U-boats in transit from French ports would have to pass. The barrier, or strip, was somewhat wider than the distance (60 miles) that a U-boat could travel in one submergence. In a preliminary study of the problem by ORS Coastal Command,* it was estimated that, if the submarine heard signals every 15 minutes, on the average, it could not afford to dive at every signal, and would then have to take the risk of detection by ASV. In the actual operation, which was very successful, it was found that an alarm rate much <u>lower</u> than the assumed 4 alarms/hour was, in fact, adequate.

Our problem is somewhat different, not only because we are dealing with a different submarine, but because we are proposing to flood a very large area rather than a narrow barrier. To cross a barrier or run a gantlet safely, a submarine will put up with considerable inconvenience, and the alarm rate over the barrier strip will have to be fairly high before the alarms will be ignored,

*ORS/CC Report No. 210, dated 27/11/42

whereas a situation that persists day in and day out, wherever the sub goes, should become intolerable at a much lower average rate. Arguments such as these lead us to guess that an average alarm rate of 0.25 alarms per hour might be a reasonable one. Signals will be heard, in general, more frequently than this; an alarm is a signal above our assumed "danger level."

One could approach the problem differently and inquire, not about the alarm rate, but about the fraction of the time the alarm is on, which is the alarm rate times the average duration of an alarm. One might hope to make this fraction so large that the submarine simply could not spend enough time snorkeling without ignoring the alarms. Now, an alarm will ordinarily last from a few minutes to perhaps half an hour, and an alarm rate of 0.25/hr corresponds still to a rather small fraction of the total time. Therefore, unless 0.25 alarms per hour is far too low to be adequate, as a rate, it is better to stick to the alarm rate as the criterion, rather than to the fraction of time occupied by alarms. In other words, as the number of flooding transmitters over a large area is increased, they first become a serious nuisance because of the frequency of alarms rather than the duration. These remarks do not apply to certain tactical situations in which intensive flooding of a small area is called for ("hold-down" tactics).

C. Flooding from the Air

If an airborne transmitter has a sweep width, for effective flooding, of W miles and is carried by an aircraft at V knots, it sweeps out VW square miles of ocean per hour. Assuming N flooding aircraft, cruising at random over the area S, the average alarm rate for one submarine in the area is $r = \frac{NVW}{S}$ alarms per hour. With the figures we have more or less arbitrarily assumed, $S = 8 \times 10^6$ square miles, $r = 0.25$ alarms/hour, and, taking $V = 200$ knots, we have $N = \frac{rS}{WV} = \frac{10,000}{W}$. A sweep width of 100 miles, for example, would require 100 planes in the air at one time.

We now consider, individually, various ways in which the operation might be carried out.

1. Flooding by Snorkel-Finding Radar Engaged in Hunter-Killer Operations

An obvious way to satisfy requirement (1) is to make every signal dangerous in fact as well as in appearance. We simply expand the scope of our airborne H/K operation until requirement (2) is satisfied.

With the assumed 20 db margin of uncertainty in the listener's interpretation of the signal strength, the range for effective flooding would be 10 times the snorkel-detection range, were it not for the curvature of the earth and the Lloyds-mirror interference. If we assume the listening antenna is 6 feet above the surface, the APS-20 flown at 5000 feet would fade out pretty rapidly beyond 50 miles, its signal dropping below the specified level at about 75 miles. The APS-44 (on X-band) flown at 5000 feet could reach close to the horizon (100 miles) with an adequate flooding signal, and it could reach the horizon (140 miles) from 10,000 feet also (see Figure 2). If we adopt 100 miles as a typical flooding range, the sweep width being twice this* and 160 knots vs. the aircraft's speed, we require 60 radars over the area at all times to maintain the specified alarm rate.

This is a formidable operation if, as we assume, each radar aircraft is the nucleus of a hunter-killer group. It means several hundred specialized aircraft, loaded with fancy equipment and trained personnel, in the air around-the-clock. We can't do the whole job, or even a substantial part of it, this way.

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*It is fair to use the factor 2 here. The problem is quite different from that of detecting snorkels; the "operator factor" should be nearly one, since the "dangerous" signal level is far above the threshold and, in most cases, the operator will have heard the signal somewhat beyond the effective flooding range.

2. Flooding by Snorkel-Finding Radar Not Associated with Attack Groups

The operation contemplated in (1) is less expensive if we send the plane out alone with its high-power radar. It can't kill submarines, but it can find them when they don't hide; the intelligence thus provided might justify the expense of the operation. The expense is still very high, for a snorkel-finding radar is a costly device and likely to become even more costly. If the enemy resorts to decoys, for example, we may have to add elaborate equipment to the radar to cope with them.

3. Flooding with Ordinary ASV or Navigation Radar

The effective flooding range with APS-30-type radar, if we assume 100 kw peak power at X-band and an antenna gain of 32 db, should be about 60 miles, if it is flown at 4000 feet or higher. Complete coverage could be provided by about 80 such sets flown at 200 knots (that this is only a little higher than the number of high-power sets arrived at in (1) is due to the fact that the flooding range of the high-power set was limited not so much by inverse-square law but by the horizon and Lloyds-mirror interference). These APS-30-carrying planes can't find snorkels and unless they have other business in the area their mission is a dull one. Nevertheless, we ought to count on doing at least part of the job this way. Every plane over the area, whatever its primary mission, can contribute its bit to the flood, providing its radar signature does not give it away. With foresight, and in most cases, the matter of signature can be taken care of without compromising the usefulness of the radar to the plane carrying it.

To the extent that we get our flooding done "free" by planes, tactical or transport, whose primary mission is something else, we necessarily lose control over their routes and schedules. Certain limited areas, such as the transatlantic routes, can be flooded cheaply and thoroughly this way; other areas will require special missions.

4. Flooding from High Altitude by High-Power Radar

An X-band radar with an 8 ft. x 3 ft. dish and one megawatt--the APS-44 specifications--could flood effectively out to 230 miles* from 35,000 feet. This gives a sweep width of 460 miles or a sweep rate of 140,000 square miles per hour, if we assume the aircraft can make 300 knots. Fifteen of these planes could flood 8 million square miles to our specified alarm rate of 0.25 per hour. Even if the plane doesn't go anywhere, but merely circles at its station, it floods continuously an area of 160,000 square miles. The radar could be used to keep track of shipping, a function that might at least pay the freight of the receiver and operator. Alternatively, or perhaps also, the plane might be a station in the "Navy ionosphere," with the function of relaying electromagnetic signals.

The Atlantic barrier patrol discussed in Appendix B, under the title "Aggressive Defense of Eastern Seaboard and Coastal Waters" easily takes care of its own flooding requirements. In fact, the planned density of search aircraft over the 500 x 1200 mile strip is so high that a submarine in the area would hear strong radar signals all the time, and frequently would hear several transmitters at once.

5. Flooding by Airborne Transmitters Only

If a plane is to carry a high-gain scanning antenna and a high-power transmitter for flooding purposes, there is not much point in leaving out the receiver and indicator needed to make a complete radar. However, it is possible to duplicate the signature of a scanning radar with a non-scanning transmitter-antenna combination. One system that does this is sketched in Figure 3. A fixed beam is radiated from the side of the aircraft. The pulse repetition

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*This figure is based on the curves of Figure 2 and an assumed snorkel-detection range for APS-44 of 35 miles. Its apparent precision is, of course, spurious. Nevertheless, because of the rapid decrease of signal strength near the horizon, almost any reasonable assumptions would lead to a flooding range between, say, 180 and 260 miles.

frequency is the same as that of the radar to be imitated, but pulses are fed to the antenna only for an interval as long as the radar beam would require to scan over a target. To make it still more lifelike, the pulse amplitude is modulated by a cam-driven attenuator, or other means, so that the train of pulses the listener hears has an envelope of the appropriate shape--with sidelobes, if desired! The cycle is repeated at regular intervals, matching the scanning rate of the radar. The other antenna is fed from the same transmitter.

The actual width of the beam radiated determines, in this case, the length of time during which signals of maximum strength are heard by the listener. It is perhaps desirable, and not difficult, to shape the beam so that the contours of constant field strength are roughly parallel most of the way. Then, as the beam passes over the listener, the variation of signal strength with time is more or less independent of his distance from the transmitter and will not betray the signal as a counterfeit.

In Figure 4, equal-intensity contours have been plotted for an antenna of this sort. With one megawatt output power, the flooding range, according to our standard criterion, is about 90 miles. The antenna aperture required is about 20 x 30 inches at S-band, or 5 x 10 inches at X-band.

Figure 4 also emphasizes the fact that the listener will hear the signal long before it reaches the "danger level"; if the plane is flying high enough to avoid cutoff by horizon or Lloyds-mirror interference.

The fixed-antenna flooder can be installed with relatively little modification of the aircraft; the antennas could be mounted flush with the skin, on either side of the fuselage or could project as a single streamline span below the fuselage. The device would require no operator and no attention in flight. The <u>average</u> power <u>radiated</u> is considerably less than that radiated by a radar

transmitter of the same peak power, but it does not seem easy to take advantage of this saving. The transmitter will not be much lighter than the transmitting section of the equivalent radar. In APS-20, for example, the transmitting equipment amounts to 500 pounds, roughly, or one-third the weight of the entire equipment, and requires 2500 watts of 3-phase a-c.

It seems wiser to sacrifice some flooding range in order to reduce the weight and power requirement. We ought to be able to transmit 100-kw pulses at X-band, with a signature imitating APS-44, at the cost of 75 pounds of transmitter, 25 pounds of wave guide, antenna and radome, and 250 watts of electrical power. Equipment of this size could be carried, if desired, in a detachable "bomb," as is APS-4. The flooding range according to our standard criterion, and using the pattern of Figure 4, would be about 30 miles. A plane cruising with this equipment at 250 knots could flood 60,000 square miles at the rate of 0.25 alarms/hour. These figures probably underestimate the effectiveness of the low-power flooder; its signals will be heard far beyond the assigned 30-mile range, and will cause considerably more than 0.25 alarms per hour unless the listener can make full use of intensity measurement.

D. Air-Transport: Traffic Density and Flooding Capability

In 1949, about 10,500 scheduled transatlantic flights were completed by civil airlines, 60 per cent of them by U.S. lines. Most of this traffic was concentrated close to the Gander-Shannon Great Circle or rhumb line (Fig. 5). The alternate Gander-Shannon routes shown in Fig. 5, which are used by American Overseas Airlines, show how widely the traffic might spread if pressure-pattern flight procedures were in use by all lines. The area covered by these routes is roughly 600,000 square miles. (We are neglecting flights along southern routes, which are actually included in the 10,500 flights, but form a relatively small fraction of the total.) At the wartime peak, there were about 50 transatlantic transport

flights daily (25 eastbound, 25 westbound) and 400 tactical ferry flights, mostly eastbound. The limitation was then, and still is, traffic-handling capacity at the terminals.

Fig. 6 shows the present scheduled civil traffic over the major North Atlantic routes. There are 26 scheduled transatlantic flights daily (13 eastbound, 13 westbound) by U.S. lines (PAA, AOA, TWA), and 42 foreign flights. Most of them travel by the Gander-Shannon route. Including the New York-Puerto Rico, and New York-Bermuda flights, this amounts to about 170,000 miles of flight over North Atlantic waters per day.

If each of these planes carried a radar transmitter of 50 miles effective flooding range, the total area swept daily would be 2 x 50 x 170,000 or 17 million square miles. This is about one-third of the total daily requirement we have set up (6 alarms per day over 8 million square miles). Actually this traffic, so equipped, would reach only a fraction of the North Atlantic, but that part would be very effectively flooded. The exact numbers here are, of course, not meaningful, but two conclusions are fairly clearly indicated: (1) the total airlift required for adequate flooding of the North Atlantic is not fantastically large compared to civil air operations over the Atlantic in peacetime; (2) air transport, in wartime, can make an important contribution to the flooding effort if a substantial fraction of the transports carry suitable radars or flooding transmitters.

Transatlantic transports are not now equipped with radar, but according to authoritative opinion they could make good use of it, if they had it, for navigating through and around storms. The APS-42 development, which was aimed at a radar suitable for transport aircraft, has progressed slowly, but we understand that the equipment has finally reached the type-testing stage and that procurement of several hundred sets by the Air Force and Navy is contemplated. We have heard of no plans to introduce this equipment

on commercial lines.

Unfortunately, the electrical power situation in transport aircraft has grown more critical than ever, chiefly because of pressurization. On the Boeing type 377 used by American Overseas Airlines, there is available, for additional equipment, 100 amperes at 24 volts d-c and 500 volt-amps at 110 volts, 400 cycles. This represents about 6 per cent of the total generator capacity (six 300-amp generators). It would be barely adequate to supply an APS-33 or APS-42 radar. The situation on the Lockheed Constellation type L-49 is even more critical, but could be eased by replacing the present 200-amp generators by 300-amp generators.*

The 100-kw flooding transmitter described under (3) above requires considerably less power than a navigation radar; it might be possible to install such transmitters even if the supply of power cannot be much improved. But it would be far better to give the plane a radar it can use, rather than to require it to carry equipment of no tangible value to the plane's mission. This is one good reason, doubtless not the only one, for doing something about the electrical power situation. There appears to be no serious incompatibility in signature between a radar suitable for storm detection and long-range snorkel-detecting radar.

E. Flooding from Ships

Under standard propagation conditions, shipborne transmitters would be of little use for flooding large areas. The range would be even less than the horizon distance, because of the Lloyd's-mirror interference, and because the ship moves slowly; its effective flooding rate, in square miles per hour, might be no more than one or two per cent of that of an airplane. More important, a ship, being a potential target for torpedoes, would not want to advertise its presence and location.

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*Information supplied by D. S. Little, Supervisor of Airway Aids American Airlines.

Nevertheless, situations may develop in which judicious use of ship radars for flooding purposes would be relatively safe and relatively effective. There is reason to believe that in the region 10° to 30° N. Lat. the normal conditions correspond not to standard propagation but to superrefractive, or trapping, conditions because of a relatively stable evaporation duct at the surface.* Microwaves are then bent around the earth for considerable distances, and, as an uncertain estimate, an effective flooding range of 30 miles might be obtainable from a ship's radar. Now suppose we were running fast ships over a southerly route in fairly small, and hence fairly numerous, groups. A fast ship could flood a sector astern, which might be as large as 1000 square miles in area, without much risk, since submarines astern would not be in a position to close and attack. This could be done by turning the transmitter on for, say, 10 minutes every two hours. Should the submarine in the flooded sector hear the signal, suspect it of being a ship's signal, and attempt to report it to base or to a confederate lying ahead, we could make this unprofitable by being well prepared to DF on his signal, and by changing course after the flooding transmission. This is a special situation, and obviously not one on which to base long-range plans. It serves chiefly to remind us that a flooding campaign will be a battle of wits; we shall have to be alert to recognize and exploit every opening--often by unorthodox tactics.

F. Flooding from Shore Stations

Transmitters fixed on shore can help very little in flooding the North Atlantic, but in one area, the Caribbean, it may be possible to do part of the job in this way. The Caribbean is unique in providing attractions for submarines, meteorological conditions favoring trapping, and plenty of islands. Without trapping, shore

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*See Radio Wave Propagation Experiments; Summary Technical Report of the Committee on Propagation, NDRC, Vol. 2, Chap. 4.

stations would probably not be worth while, even in the Caribbean; to be sure of this, we would need a survey of the high sites available. But if the trapping conditions prevail a good part of the time, so that a high-power transmitter might have a flooding range of 40 to 50 miles from a low site, one or two hundred transmitters scattered from the Bahamas down to the Lesser Antilles could thoroughly flood a small but possibly very critical region.

One disadvantage of a shore station, conceivably a fatal disadvantage, is its fixed location. This provides a distinguishing clue to a submarine equipped for direction finding. In fact, a few high-power flooding transmitters more or less permanently sited, might be welcomed by the submarines as a navigational aid! To counter this, we must have many stations and change their sites frequently. The periods of transmission from any one station should be of short duration and irregularly scheduled. The aim is to create the impression of woods full of fireflies, in the twinkling confusion of which it will be hard to distinguish a moving firefly (our ASW search plane) from the stationary fireflies (the flooding transmitters). Whether this can be done will depend on the rapidity and accuracy of the submarine listener's measurement of bearing rate, and his knowledge of our methods. It might be worth while to have the transmitted signal increase gradually in strength, over a period of many minutes, an effect that, in conjunction with the zero bearing rate, might appear alarming. If the submarines learn to ignore such alarms, we adapt our local search tactics accordingly, emphasizing direct approach to suspicious targets.

We shall have to meet the situation as it arises, of course. Fortunately, an operation of this sort, involving transmitters only, operating from temporary sites, should require little advance preparation. Almost any mobile or portable radar transmitter could be made to serve as a flooder, and its operator has only to keep

it running on an irregular, intermittent schedule.

G. The Danger of Self-Jamming

The spatial density of radar pulses will still be quite low, even if we succeed in flooding the Atlantic at several times the rate we have assumed. With the flooding density assumed in Section C. if the flooders were more or less uniformly scattered, a search plane operating among them would seldom be within range of more than one or two transmitters, and would be out of range of any of them more than half the time. If we compare this with the density of transmitters in any naval task force, and remember how little difficulty the presence of a few unsynchronized pulses actually causes, it is evident that we can go a long way in confusing the enemy before we hamper our own radars. Further insurance against this danger, if it were needed, may be provided by storage-integration techniques which show considerable promise for snorkel detection and have incidentally proved very effective in reducing interference by "wild-catting" radar transmitters.

H. Interdependence of Radar and Radar Counter-Countermeasures

It is easy to design a radar that is useless as a flooder because its signature is wrong. It is possible also to design an anti-snorkel radar that betrays its identity by alternating pulse lengths (as in APS-44) or some other cute trick that can't be imitated by an ordinary radar. Such mistakes can be avoided without much sacrifice, but will probably not be avoided unless radar, RCM, and RCCM developments are closely coordinated. The relation of radar and RCCM is especially close. So far as anti-jamming features built into the radar are concerned, these come more or less automatically within the cognizance of the radar designer. But flooding, the only effective anti-listening measure, involves above all the relation of one piece of equipment to another, one tactical doctrine to another, perhaps even one branch of the service to another. It calls for broad planning at a higher level as well as

close technical cooperation in design and development.

What is the best method of flooding--and indeed whether flooding is feasible--will depend on our ASW tactics. If, for example, ASW tactics were to develop around the "single-package" hunter-killer plane exclusively, the submarine could with impunity ignore any transmitter whose behavior showed that it was not approaching him. This would make the flooding problem much more difficult. We can hardly hope to predict the best ASW tactics in advance of actual operations; the enemy will have something to say in determining them. For the same reason, we cannot specify a complete design for our flooding tactics in advance. Both plans must be kept flexible--but we must try to keep them at least consistent with one another, and we must learn to regard radar and radar counter-countermeasures as two aspects of the same weapon.

I. Comments and Conclusions

We believe that radar flooding will be an important, probably an indispensable, element in anti-submarine warfare so long as the submarine offers a detectable radar target. The analysis in this report suggests the scope of the campaign that is likely to be required against a resourceful, well-informed enemy, and indicates ways in which the operation might be carried out. But it would be a mistake to rely heavily on the numerical results or to assume that the pattern of operation we have described will be exactly what the situation calls for. Our assumptions may prove wrong, and the situations we encounter may be different in many ways. For example:

(1) The "alarm-rate" we have assumed may be inadequate. If it takes one alarm per hour on the average, rather than one alarm every four hours, to do any good, the job is four times bigger than we have indicated. This may mean that we would have to reduce the area flooded.

(2) It may be that the area flooded ought to be reduced

anyway; that is, with a fixed number of flooders, however large, at our disposal, it may prove best to concentrate them in certain areas where the undersea war is intense. Or it might turn out that our flooding and search forces could be deployed more effectively over barrier strips, rather than over the whole ocean.

(3) Our assumption that the enemy can measure and correctly interpret the intensity of the signal with a 20-db allowance for fluctuations, etc., may be too pessimistic (it is not likely to be too optimistic). If the listener can't make that much use of intensity, our job is easier and, in particular, the relative advantage of high-power over low-power flooders is less than we have indicated.

(4) It has been assumed that propagation between an airborne flooding transmitter and a listening antenna obeys the simple theory in which the sea is treated as a perfect mirror. Experimental tests under the rather extreme conditions of our problem (the antenna only a few feet above the water) would be desirable; any departure from theory will imply a larger flooding range than we have assumed.

Questions like (1) and (2) need further study, but probably cannot be reliably answered until we actually observe the enemy's response to our tactics. A most essential part of the flooding campaign will be the operational research that accompanies it. Most of what we need to know we shall have to learn by experience; the most effective tactics will be those that we improvise in the light of operational analysis.

Questions such as (3) and (4) can be attacked at once, experimentally. We can learn much by trying simulated radar signals and flooding tactics against our own submarines. It is important to find out what, from the submariner's point of view, are the most reliable identifying features of the radar signal, and how accurate

a facsimile we need to present. The submarine, incidentally, should be equipped with the sort of listening gear a clever and sensible Russian would use--not the BLR-1. Experiments and trials of this sort can carry the problem a long way beyond the armchair theorizing of this report.

That a variety of transmitters and vehicles will be involved in a flooding campaign seems likely enough to warrant our taking immediate steps to develop a flooding transmitter of the widest applicability, to investigate and if possible expedite the progress of air-transport radar, and to promote the development of high-altitude, high-power radar for flooding, as well as other purposes.

Radar flooding has applications wider than the one we have been concerned with here. A listening receiver can be used by the enemy both defensively and offensively; it can tell him when to hide, and it can disclose to him the location of a target, if the target is a ship using its radar. As a by-product of an intensive flooding campaign, we might gain more freedom to use ships' radar. We have not analyzed this possibility carefully. It depends on many unknown factors.

Even the value of achieving fairly free use of ships' radar in the open ocean is hard to specify. In waters where radar is an important navigational aid, flooding might be worth while for this purpose alone. Nevertheless, the possibility of these secondary benefits must not be allowed to complicate or confuse our planning. Our first task is to mullify the defensive value of the submarine's listening receiver. It is a big job and an important one.

J. Recommendations

1. Radar flooding should be treated as an essential element in ASW.

2. Responsibility for RCCM planning should be assigned in such a way that close coordination of radar, RCM, and RCCM is possible. We emphasize especially the importance of coordinating radar

search and radar-flooding instruments and tactics at all stages of planning.

3. Experiments should be made at sea, using submarines equipped with suitable listening gear, to get more answers to such technical and tactical questions as: How does the received signal vary with distance, under typical conditions? How large are the fluctuations in intensity? What are the most revealing features of the signal? What combinations of search and flooding tactics are most deceptive? (A direct-detection receiver suitable for these trials has been developed at Airborne Instruments Laboratories under BuShips contract. Flooding transmitters of various characteristics can be assembled from standard radar components.)

4. Steps should be taken to encourage the installation of navigation radar in any transport aircraft likely to be used over the sea, and to insure that such radar is usable, or could be made usable with minor alterations, for flooding purposes.

5. Development of a single, light-weight airborne flooding set of the sort described in Section D, should be initiated. Eventually, a set on S-band and one on X-band will probably be needed; the development might begin with the S-band set. Subject to further study, the specifications might be something like this: peak power, 100 kw; signature, capable of imitating APS-20 but with maximum flexibility of characteristics; beam width, 30° (horizontal) x 8° (vertical); packaging, one or two units plus spar antenna, or complete single-package externally carried unit; controls, on-off switch (all other adjustments pre-set); weight, 100 pounds; power requirement, 300 watts. Final specifications, including peak power, should be adapted to standard radar components now in production, as much as possible, and should emphasize ease of installation and maintenance. It is not contemplated that this set would be ordered in large quantities at this time. The object is to have satisfactory prototypes, fully tested and shaken down, which could go into

production quickly if necessary.

6. Developments such as the PO-1W Constellation that point toward the operation of high-power, big-dish radar at high altitude should be encouraged for radar flooding as well as for other reasons. Even if there is no other military requirement for very-high-altitude operation of such a system, an effort should be made to make the transmitter, antenna, etc., operable above 30,000 feet, for flooding purposes.

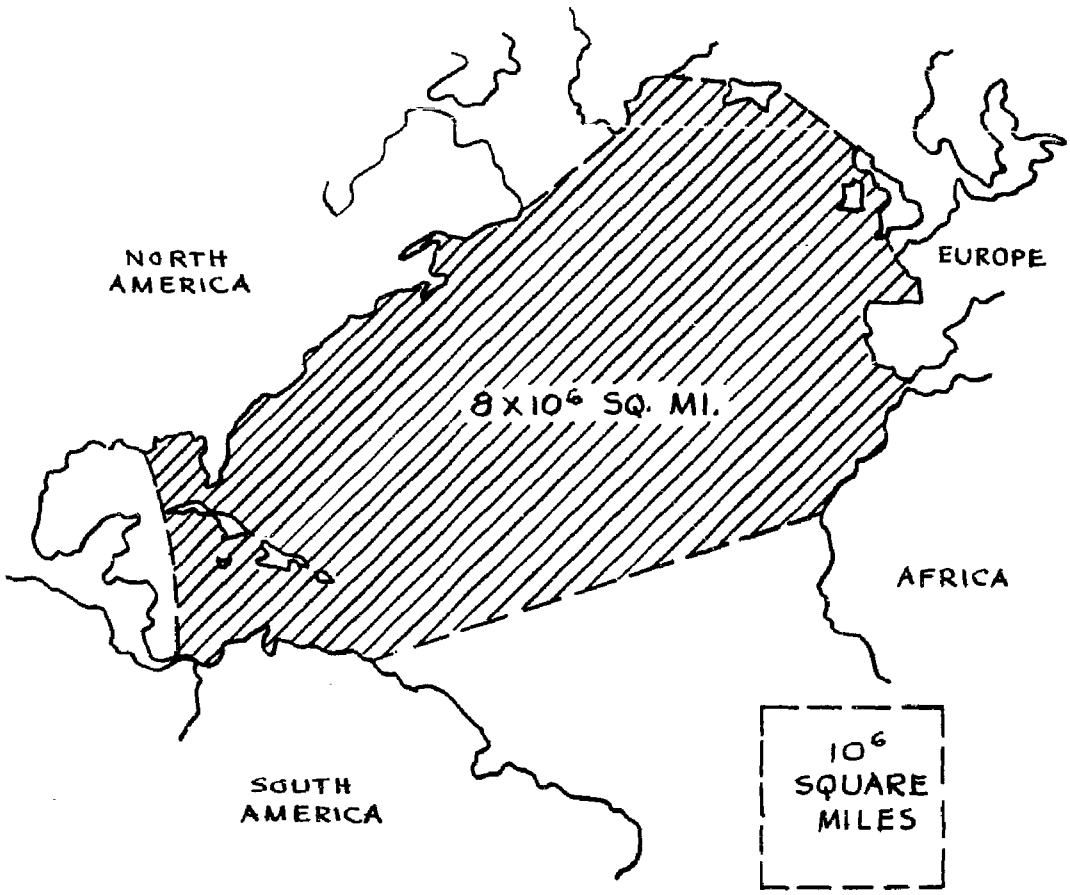
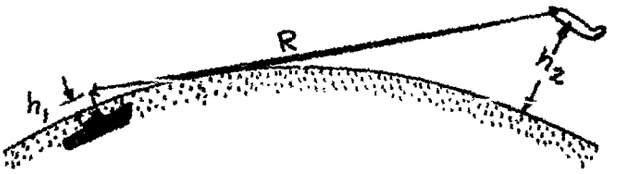


Fig. IV-1. The North Atlantic, on an Equal-Areal Projection, Showing Approximate Extent of 8 Million Square Miles.



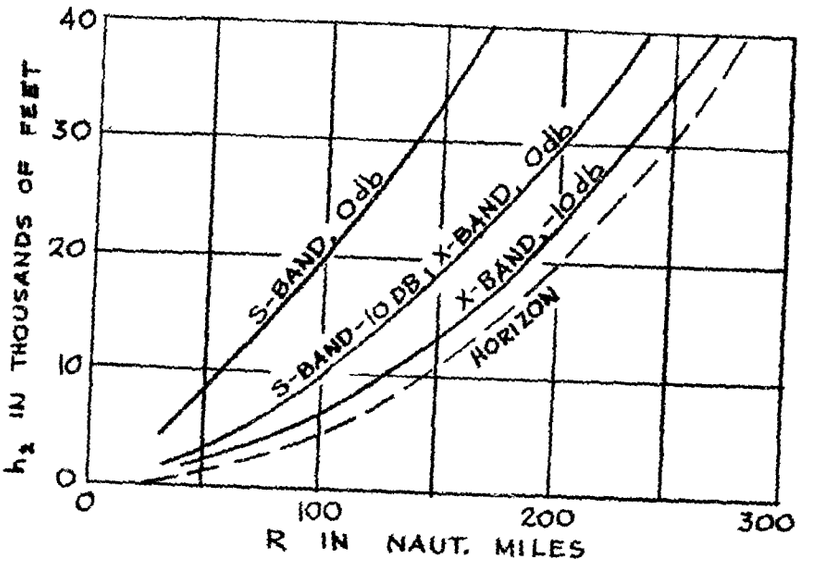


Fig. IV-2. Curves Showing Range at which Signal from Transmitter at Height h_2 is Equal to, or 10 db Below, Its Free-Space Value at the Same Range. Assumptions: receiving antenna 6 feet above totally reflecting smooth surface; method of calculation crude but adequate; more-refined theory would shift curves toward horizon (dotted curve) slightly; actual sea conditions will have similar effect, by reducing reflection coefficient.

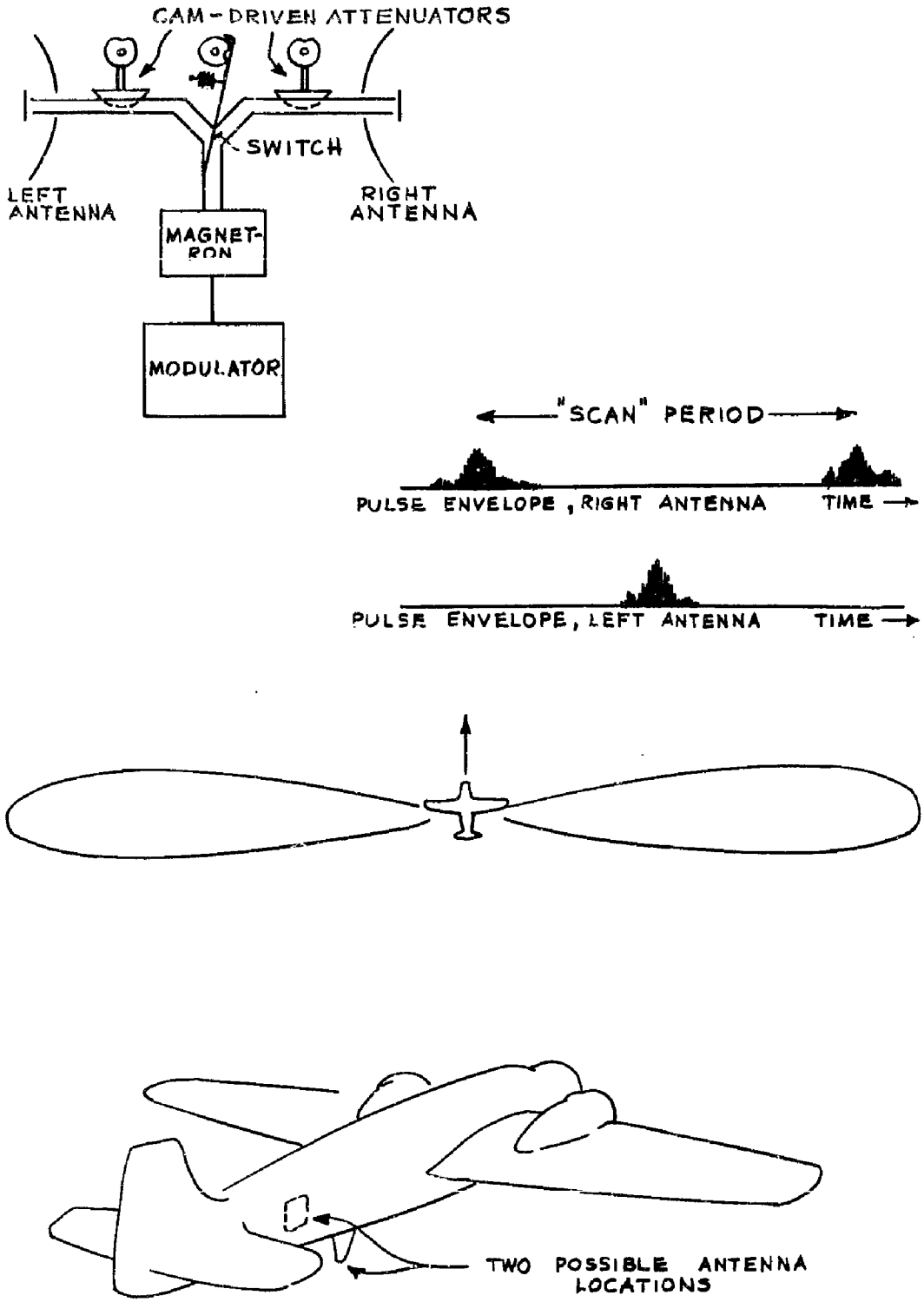


Fig. IV-3. Fixed-Beam Flooder

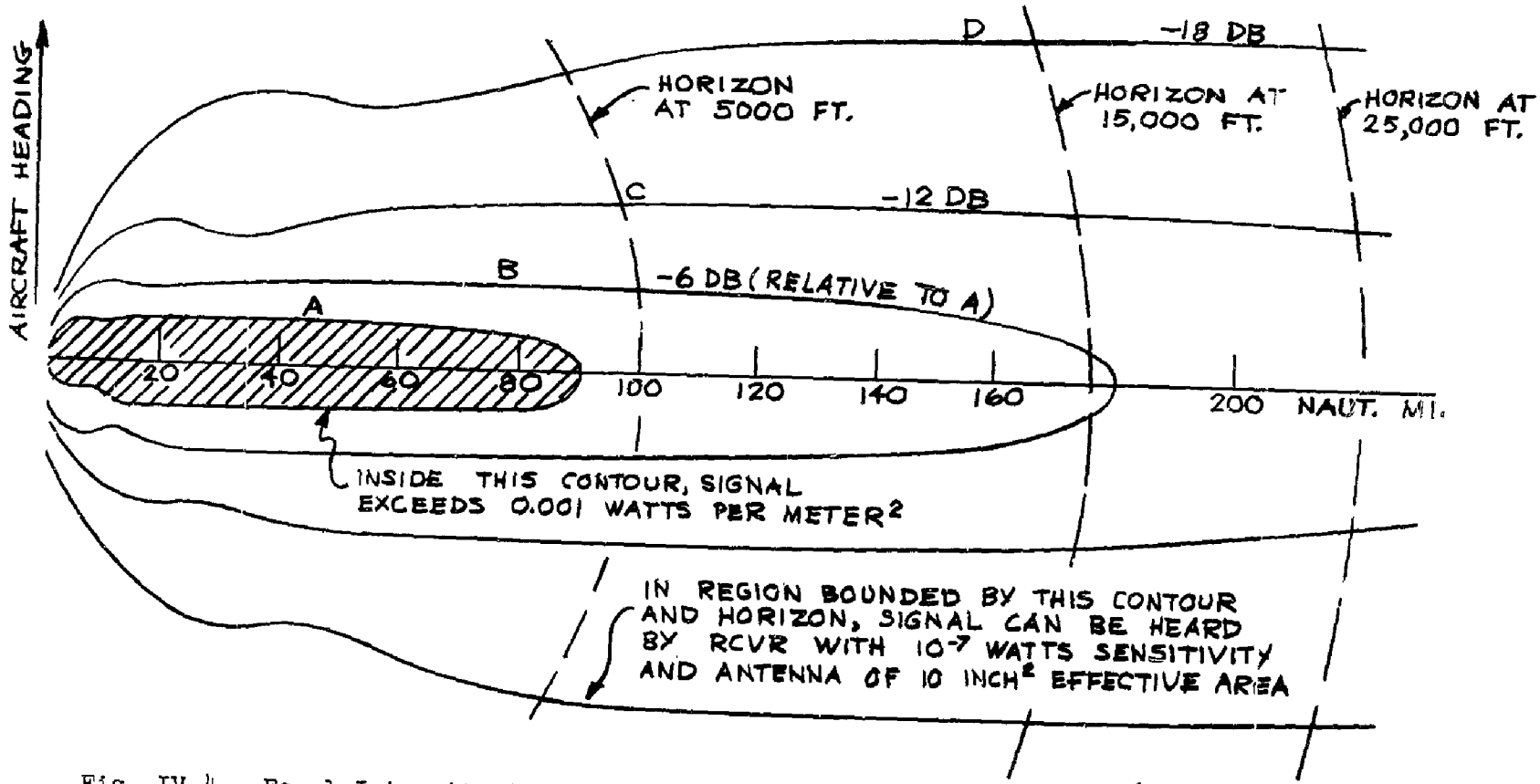


Fig. IV-4. Equal-Intensity Contours for a Flooding Transmitter of 10^6 Watts Power. The antenna pattern assumed here has an effective beam width of 15°, but has been shaped to spread out the contours at short ranges. It could be achieved with an aperture about 20 x 30 inches at S-band, or 5 x 10 inches at X-band; in either case, the peak gain is 200. This plot is based on free-space propagation and ignores Lloyd's mirror effect; for S-band, signal would be cut off long before horizon is reached, for low altitudes (see Fig. IV-2).

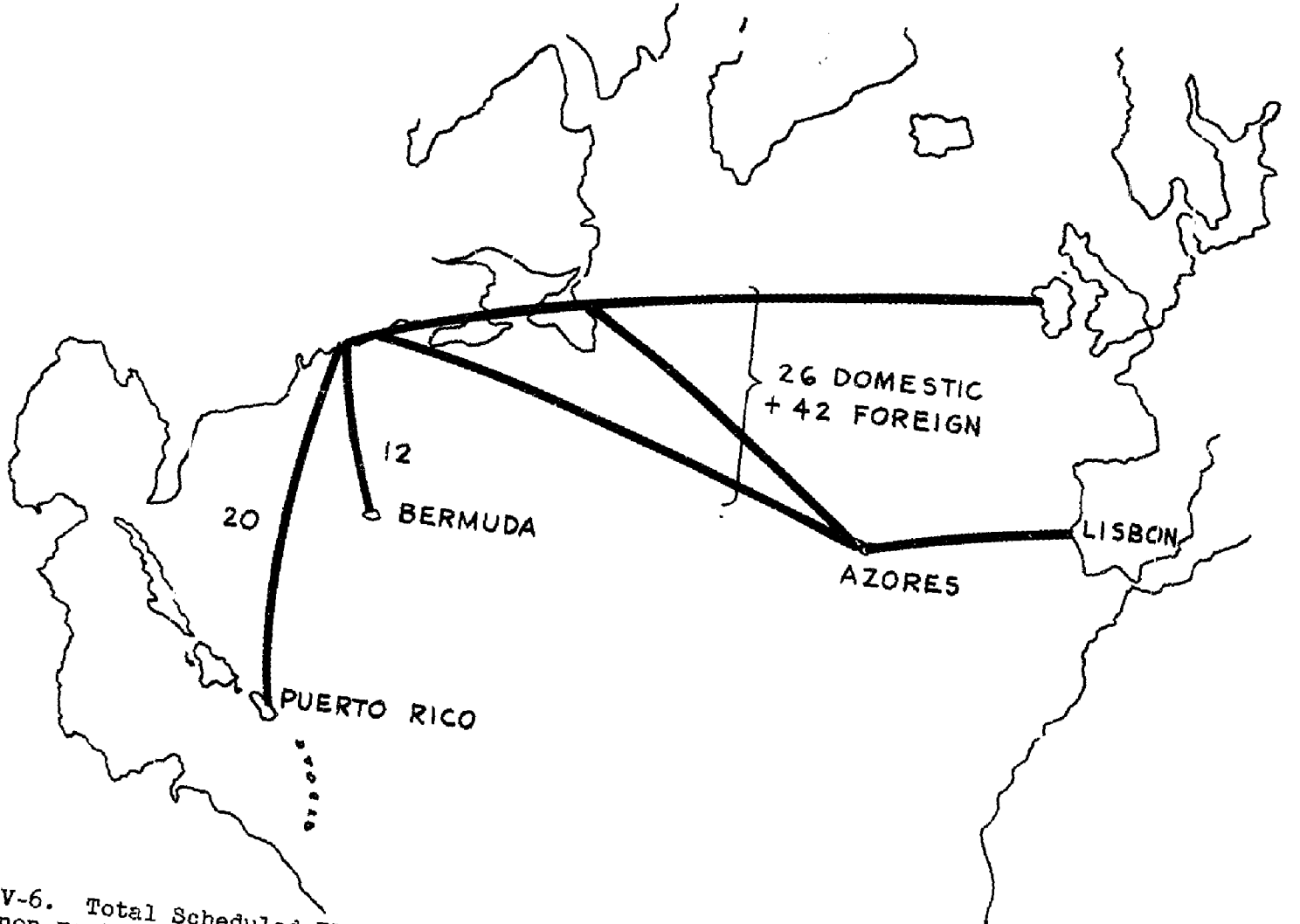


Fig. IV-6. Total Scheduled Flights Daily Over Routes Shown. Most of the transatlantic flights use Gander-Shannon route. Total overwater mileage per day on these routes = 170,000 N.M.

APPENDIX D

ANNEX A

Introduction

This Annex describes a system for very-narrow-band reception at low signal frequencies which may extend substantially the listening range of "passive sonar" and provide means for both hidden communications between submarines and underwater "loran". The advantages of this method over the usual narrow-band schemes are comparative simplicity and flexibility. There is nothing speculative about the technical features described below. Similar equipment is in use in the Bell Telephone Laboratories for other purposes. The only question concerns effectiveness of the system in the contemplated uses. Since the equipment is not complicated to build and operate, the most practical way to evaluate effectiveness probably would be to construct and test a unit.

For a fixed level of background noise, the range of "passive sonar" would be increased in direct proportion to signal attenuation. Effective improvements around 20 db of S/N ratio would seem reasonable for the frequency selection available. If the added attenuation for double the range were y db, and the S/N improvement were x db, the range improvement would be

$$R = R_o(2)^{x/y} .$$

If the signal attenuation for double the distance is 10 db and the S/N improvement 20 db, the range would be extended fourfold.

At high underwater sound frequencies, the loss due to effects of temperature gradient and other irregularities may be such as to limit the improvement in range. But, at low frequencies, it is entirely possible that the advantage would be substantial. Although the very-low frequencies have been at a

disadvantage in the past, due to high noise and lack of directivity, they may become the most useful for long-range work when narrow-band reception is employed.

Listening

In Fig. D-(A)-1 there is shown at the left a magnetic-tape arrangement in which signal and noise from a transducer (1) is impressed upon a recording head (2) that records the signal and noise upon a relatively slow moving magnetic tape (3).* A rapidly rotating scanning head (4) picks up the noise and signal and, because of the increased scanning rate, steps up the frequency of these components. For low-frequency recording, it is not difficult to obtain a step-up ratio of more than 100:1. If signals of as low as one cycle per second are being recorded, they could easily become 200 cycles per second in the scanning process. By making the rate of the scanner driving mechanism (5) variable, the frequency of the output may be shifted.

At the output of the scanner (4) is shown a bank of harmonically related filters (6). If a very-low-frequency signal containing harmonically related components is received, it may be "tuned into" this filter bank by varying the adjustable drive(5). When so tuned, all the filters would show outputs simultaneously. These outputs (which would be in the range of hundreds or thousands of cycles per second) would be rectified by elements (7), commutated by (8) and spread out on the CRO screen (9).

An operator watching for enemy vessel sounds would tune the adjustable drive and watch the CRO screen. Normally, the different filter outputs would jump around in uncorrelated

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* Spools of tape are assumed because it would seem worth while to keep the records of contacts for later reference.

fashion. When a signal is received, a correlated movement would appear. With reasonable S/N margin, a comparatively fixed displacement of all the filter outputs would show on the screen. Relation of the displacement would tell something about the characteristics of the source (identification).

By combining the rectified harmonic filter outputs, a single over-all indication may be obtained. In Fig. D-(A)-2, such an arrangement is indicated. The adjustable drive (5) is now varied by an automatic scanning drive (10) which also provides a horizontal sweep for the CRO tube. A submarine sound would show as a comparatively persistent peak in the A-type display. Obviously, a threshold device (11) and an alarm bell (12) could be used to alert an operator automatically when a signal is received.

Use of very-low signal frequencies is preferable for narrow frequency selection by the above methods. For a given, physically reasonable, gap length in the recording head, the tape speed is directly proportional to signal frequency. Then, for a given maximum rotational speed of the scanner, the frequency step-up ratio is in inverse proportion to the signal frequency. This means that the effective filter bandwidth available is in proportion to the signal frequency.

Communications

The type of receiver described above could be used for hidden underwater communications of the sort that would be effective in SSK operations. For this purpose, a calling scheme would be very desirable. One possibility would be that of using a particular non-harmonic filter bank (e.g., simple tuned circuits) for each submarine in the group. The outputs of these would be combined and arranged to actuate an alerting bell or other mechanism as in Fig. D-(A)-2. Comparison of the full-band input level with

the combined outputs of the filters would eliminate effects of intensity change. When the bell operates, a recognition "dot" would be sent by the receiving operator. At the transmitting end there would be several very-low-frequency oscillators which could be adjusted to any calling combination. Very-slow code would be sent by operating combinations of the frequencies set up to contact a particular submarine. The transducers used for this very-low-frequency work would need to be of special design. A conventional transducer, 6 inches in diameter, can provide some output down to 5 cycles, but frequencies below this would be "in the noise" for ordinary uses. Perhaps a jet-type transducer would be indicated. A simple version of such a transducer appears in Fig. D-(A)-5.

Another calling arrangement could utilize coded sequences of very-low-frequency marks and spaces. Coincidence of the elements in such coded signals could be accomplished in a number of ways, all of which would involve what amounts to storage in a record or in delay elements. The magnetic tape already provides a storage; thus, some means for using this feature would seem in order. This could be done by means of a multigap (or multihead) scanner as symbolized in Fig. D-(A)-3. The separate outputs of these heads could be combined in various ways to produce a maximum output for particular code combinations. The best calling code for this purpose would probably be one with a fixed number of marks and spaces.

Underwater "Loran"

The techniques described above might also be employed in a desirable form of underwater "loran". Codes would be sent from spaced stations at particular times. These would be on very-low frequencies, and would be essentially hidden due to their low

levels. When these "loran" signals are received on the submarine, they would actuate a time marker that would permit a determination of position if the sending time is known. Different code could be used for the different transmitting stations. By means of a prearranged code for timing the transmissions, such "loran" could be made useless to the enemy. If the added equipment could be justified, the position could be computed automatically.

Balancing Against Self-Noise

Another advantage of very-low-frequency listening is that it may be practical to introduce a substantial balance against self-noise. If so, the listening submarine would be able to hear sounds from distant sources while moving at comparatively high speeds.

A balancing arrangement is illustrated schematically in Fig. D-(A)-4. If the major very-low-frequency self-noise components are related to the propeller-shaft rotation cycle, a record of these could be made on a reentrant disk attached to the shaft and fed back into a balancing network. Of course, self-noise conditions would vary with speed; this could be taken into account by different recordings at progressively different speeds and a shift of the reproducer head with speed along the surface of a reentrant recording cylinder. Or conditions could be recorded momentarily for any running condition, using the transducer output for the purpose. Then when a signal appears, the balance would be upset. The latter possibility amounts to a "departure-from-status-quo" recognizer. It could take a number of forms in which a balance against self-noise is set up at intervals in time and any deviation therefrom detected. The magnetic tape simply serves as a storage medium in the comparison of present and past conditions.

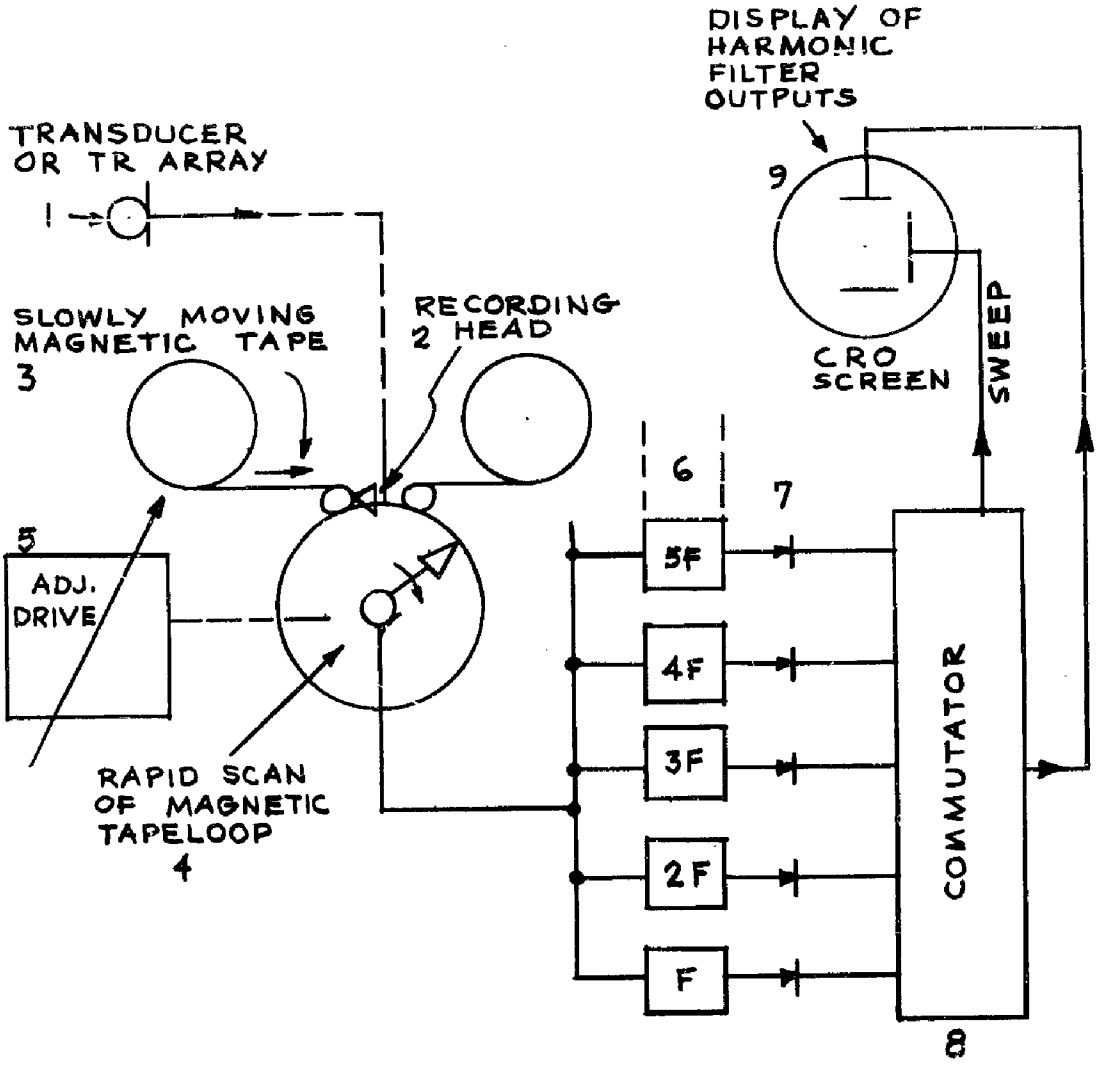

DISPLAY OF
HARMONIC
FILTER
OUTPUTS
9
TRANSDUCER
OR TR ARRAY
1
SLOWLY MOVING
MAGNETIC TAPE
3
RECORDING
2 HEAD
CRO
SCREEN
SWEEP
6
7
5
ADJ.
DRIVE
5F
4F
3F
2F
F
COMMUTATOR
RAPID SCAN
OF MAGNETIC
TAPELOOP
4
8

Figure D-(A)-1

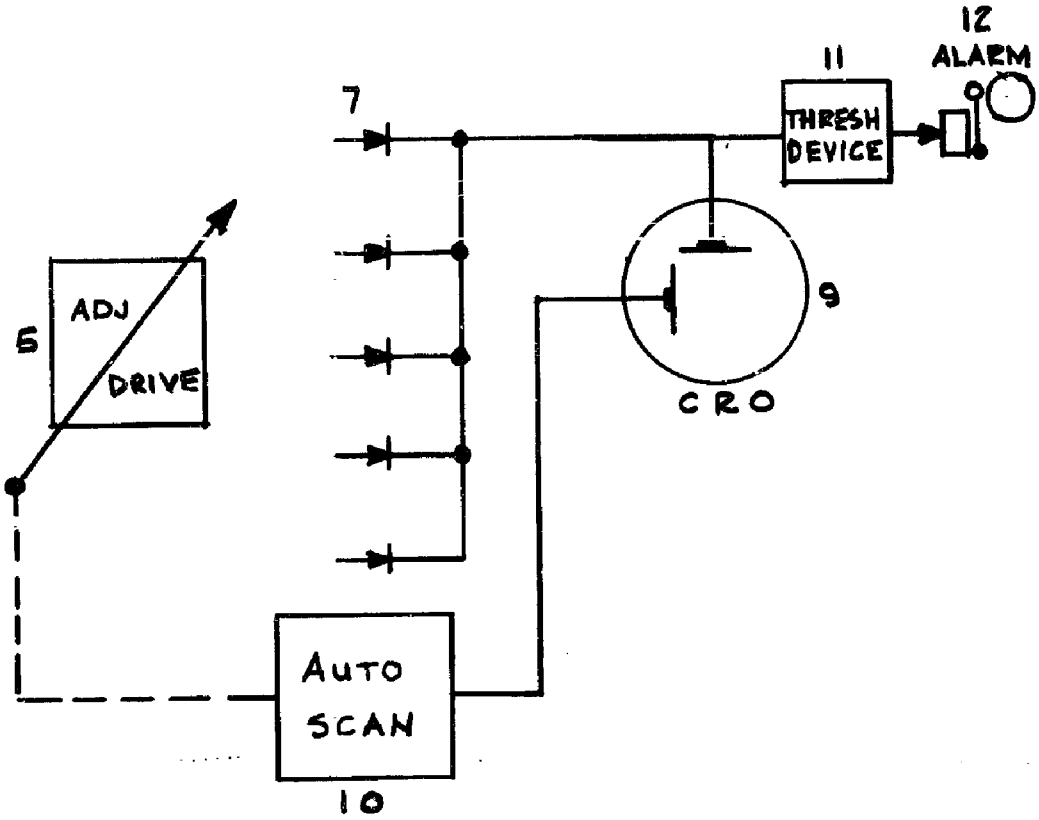


Figure D-(A)-2

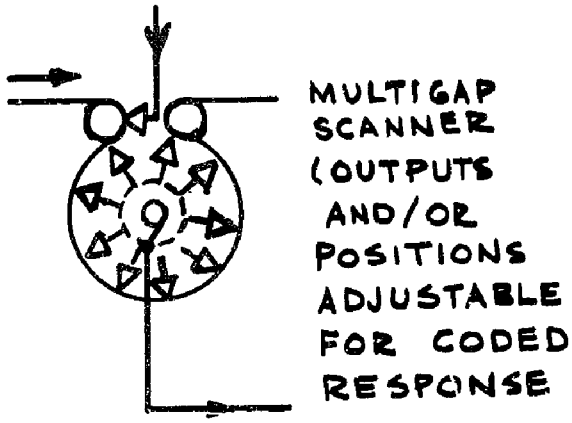


Figure D-(A)-3

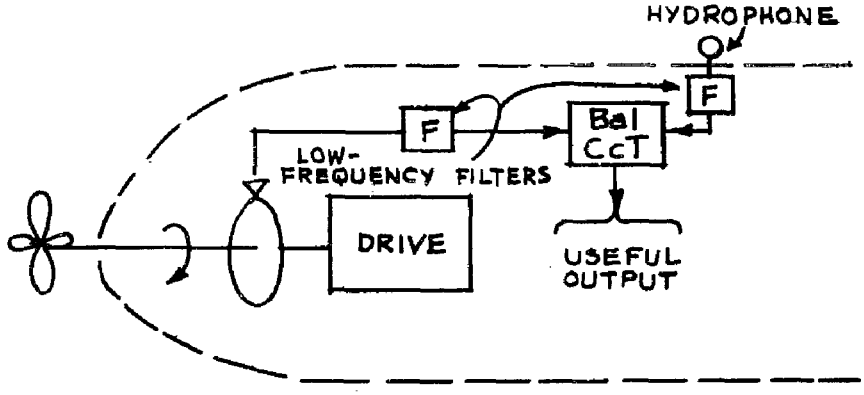


Figure D-(A)-4

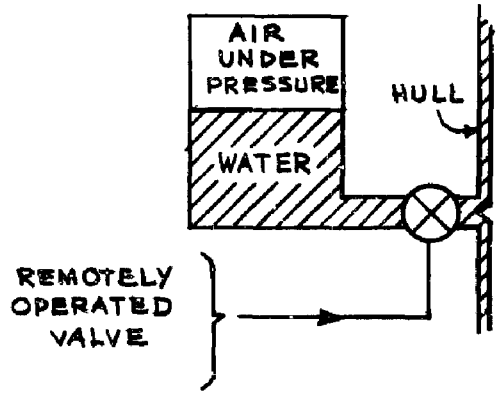


Figure D-(A)-5

APPENDIX J

PARAMAGNETIC RESONANCE ABSORPTION IN A MAGNETOMETER FOR MAGNETIC AIRBORNE DETECTION

I. INTRODUCTION

The possibility of employing paramagnetic absorption in a magnetometer for weak magnetic fields has been considered. The paramagnetic medium required is one for which the magnetization is produced almost wholly by the electron's magnetic moment; that is to say, the orbital motion of the electron has a negligible effect upon the magnetization. The reason for this requirement will be considered later.

Paramagnetic resonance absorption is a phenomenon connected with the electron's spin. Electrons are known to be in continuous rotation with an angular momentum of $h/2\pi$ where h is Planck's constant. As a result of their being charged particles, this rotation causes them to act as elementary magnets whose moment expressed in cgs units is $eh/2\pi mc$ where e is the electronic charge, m the electron mass, and c the velocity of light.

The electron is analogous to a spinning gyroscope, the shaft of which is magnetized along its axis. If such a gyroscope is placed in a magnetic field, there will be a torque acting upon the gyroscope tending to line up the shaft with the magnetic field. Of course, the gyroscope fails to line up with the magnetic field but instead precesses about the magnetic field. So also the electrons, when placed in a magnetic field, precess without lining up with the magnetic field. This precession will continue until the electron is disturbed by some outside agency such as a close encounter with another electron. A coil filled with a paramagnetic medium of this type, suddenly energized by a constant current, would find the magnetization of the medium building up slowly rather than appearing coincident with the magnetizing field.

For a magnetic field with a strength of the earth's field, the electrons precess with a frequency of about 2 Mc/sec. Because of this characteristic frequency of precession, the paramagnetic medium has some unusual properties near this frequency. If a coil filled with the medium were oriented perpendicular to the earth's field, the Q of the coil would be found to be abnormally low at the precession frequency. Furthermore, slightly above and below the frequency of precession, the reactance of the coil would have anomalous values. It is this effect of the magnetic field upon the properties of a coil having such a paramagnetic core that permits the measurement of a weak magnetic field. It should be noted that it is possible to make such a magnetometer directionally insensitive because the frequency at which the anomaly occurs is independent of the direction of the field.

The apparatus to detect this effect would be very similar to that

introduced by Purcell, Torrey and Pound (Phys. Rev. 69, 37, 1946) and described in considerable detail in an article by Bloembergen, Purcell and Pound (Phys. Rev. 73, 679, 1948). Purcell et al. used the apparatus to detect nuclear spin resonances, rather than electron resonances. The chief components of the apparatus are a coil containing the paramagnetic material and a second coil to modulate the magnetic field acting on the first coil. The anomalous resonance thus acts to cause the modulation frequency to appear as a modulation upon the frequency used to excite the first coil when this frequency is in the vicinity of the precession frequency of the electron.

Whether or not a magnetometer of sufficient sensitivity could be constructed depends upon whether or not a suitable paramagnetic medium could be found. The preferred medium is one for which the electrons are essentially free insofar as their spin axes are concerned. It is a medium for which the main disturbance that acts on the electron's spin direction comes from the magnetic field produced by other electrons. It is a medium for which the electrons are in rapid motion with respect to each other. This motion tends to average-out local fields produced by neighboring electrons.

A medium of low electron density would have a narrow absorption resonance, since electrons would be rarely disturbed in their precessional motion. Because of the narrow resonance, the frequency accurately defines the magnetic field. However, a medium of high electron density works equally well. This results from the fact that there are more electrons to absorb energy and, furthermore, any one electron can absorb more energy because it is disturbed more often by neighboring electrons. Hence, a larger power can be dissipated in the medium, and the available signal power from the coil is greater. Thus, from the standpoint of the ratio of signal power to thermal noise power, an electron-dense material (not too dense) is as good as an electron-dilute material.

In one respect, however, the concentrated material with its broad resonance is superior. A broad resonance allows a high modulation frequency. If this frequency is sufficiently high, the background fluctuation effects caused by mechanical vibrations of the components, etc., are unimportant. It should be possible in such a case to realize essentially thermal noise as a background.

Such a magnetometer could be made directional-sensitive only in the deviation of the earth's field from a norm rather than in the total field itself. Thus, only rough stabilization of the magnetometer would be required.

The chief unknowns are connected with the paramagnetic material. Three possibilities have been considered. A solution in benzene or other suitable solvent of an organic free radical of the type previously investigated at microwave frequencies would seem to be the best known material. A better medium, but one at present unknown, would be a paramagnetic gas with weak

coupling between the electron spin and the molecule. If found, such a material would be decidedly superior to the solution. A third material, also unknown, would be a concentrated paramagnetic substance with very strong electron exchange narrowing. This would be the best of all, but also least likely to be found.

The performance that might be expected in the case of the solution is, for a coil 20 cm in diameter by 50 cm long, an rms fluctuation of about 0.02 gamma for a bandwidth of one cycle/sec. In the case of a suitable paramag netic gas, this would be reduced considerably. There is a great deal of uncertainty in the above figure. The actual performance would depend greatly upon the properties, so far unknown, of the paramagnetic substance employed. The above performance figure assumes that only thermal noise is limiting performance. This is an ideal that cannot be completely reached. However, it is believed that, at a modulation frequency of 100 kc, it should be possible to closely approach this ideal. It should, however, be realized that obtaining the ultimate in performance might require a fairly elaborate electronic device

The proposed magnetometer outlined above has an interesting connection with a proposed magnetometer submitted to the Navy by Varian Associates on 27 August 1948. The Varian device employs protons instead of electrons. The protons are oriented by a magnetic pulse, then allowed to precess in the earth's field. The precessing protons induce a voltage in a coil. The precession frequency is measured to determine the field strength. This device is also relatively insensitive to orientation of the earth's field. However, as has been pointed out by Purcell, there is a velocity-stabilization requirement which could be serious. Because of the relatively low precession frequency of the proton, a rotation of the magnetometer about the direction of the field at a velocity of 10^{-3} revolutions/sec would contribute an error to the field measurement of about 2×10^{-7} gauss.

It has been suggested by Purcell that the cyclotron frequency of free electrons in the earth's field could be used to produce a directionally insensitive magnetometer. Although this cannot be definitely ruled out, there are difficulties that should not be overlooked. The earth's field is so weak that even quite-weak electric fields, such as would accompany a variation in the work functions among electrodes, produces marked variations in the cyclotron frequency. These variations would, of course, be directional-dependent. Furthermore, if it is desired to stabilize electron orbits by employing an electric field, this field would have an axis characteristic of the apparatus and hence would make it difficult to achieve results independent of orientation.

A preliminary survey of solutions of organic free radicals in non-polar solvents should be made to see if one can be produced with a sharp enough

resonance. The resonance width needed is 300 kc or less. If such a solution is found, a sensitivity measurement is needed. If this is found satisfactory, the device should be turned over to a development laboratory.

The substantial improvement to be gained by going to a gas or concentrated material warrants considerable effort in trying to produce these materials. It is felt, however, that the first steps should be taken in the direction of investigating the solution.

Section II contains a theoretical development of the basis for employing paramagnetic resonance in a magnetometer. There are two preliminary parts to the section. The first deals with magnetic disturbances produced by ocean waves. It is found that these disturbances are important only in the case of low-flying planes.

The second preliminary section discusses the possibility of so shaping the element of the detector presently used in MAD as to reduce its directional sensitivity. It is shown that all such linear detectors, independent of shape, have the same directional sensitivity.

II. THEORETICAL DEVELOPMENT

A. Wave Noise

No systematic study of natural magnetic disturbance that would serve as a limitation of MAD was made; however, one disturbance, believed not to have been previously considered, was investigated theoretically. The surface waves of the ocean, since they constitute a conducting medium moving in the earth's magnetic field, have associated with them electric currents. These currents generate varying magnetic fields. The result of a calculation made in collaboration with E. M. Purcell, and independently by C. Eckart, is that the magnetic field produced by currents generated by a deep-water wave is given by

$$\overline{H'} = \pi\sigma \frac{aV}{c^2} H e^{i(kW-\omega t)} , \quad \text{for } \frac{a}{\lambda} \ll 1 \quad . \tag{1}$$

H and H' are complex numbers, the real part being the component of the magnetic field in the direction of propagation of the water wave; the imaginary part is the component in the upward direction. $\overline{H'}$ is the complex conjugate of H'. H is the unperturbed earth's magnetic field. The perturbation H' is measured at the point W at the time t. W = x + iy where y is the positive distance above the surface of the water. x is the position coordinate in the direction of propagation of water wave. Further,

a = amplitude of water wave;

V = velocity of water wave = $\sqrt{g\lambda/2\pi}$;

k = $2\pi/\lambda$ = propagation constant of wave;

$\omega = 2\pi\nu$ = angular frequency of wave;

c = velocity of light;

σ = conductivity of sea water expressed in sec^{-1} (Gaussian units).

In order to see the order of magnitude of this disturbance, the factor $\pi\sigma(aV^2/c^2)$ has been calculated under the assumption that

$$\sigma = 3 \times 10^{10}\ sec^{-1} \quad ;$$

$$a = 10^2\ cm \quad ;$$

$$V = 1.3 \times 10^3\ cm/sec \quad .$$

Then

$$\pi\sigma\frac{aV^2}{c^2} = 1.4 \times 10^{-6} \quad . \tag{2}$$

This means an rms fluctuation at sea level of about 0.6 gamma, or 6×10^{-6} gauss. This would represent a serious limitation except for the fact that the magnitude of the fluctuation falls off exponentially with height. For example, the velocity of 1.3×10^3 cm/sec corresponds to a wavelength of 8.3×10^3 cm. The mean square fluctuation at a height of 10^4 cm is

$$0.6 \cdot e^{-2\pi \frac{10^4}{8.3 \cdot 10^3}} = 0.6\, e^{-7.6} = 3 \cdot 10^{-4}\ \text{gamma} \quad . \tag{3}$$

The oceanic wave disturbance may, for low-amplitude waves, be considered as a superposition of plane waves. The mean square magnetic disturbance of such a superposition is equal to the sum of the mean square disturbances of each of the individual plane waves.

In conclusion, wave-generated magnetic disturbances are serious only in the case of a low-flying plane. A moderately good MAD may be flown at such a height as to make these effects unimportant.

B. Directional Sensitivity of the Saturated-Core Magnetometer

It might be thought possible so to shape this type of magnetometer as to make its indication insensitive to position, at least over a limited range in angles.

The saturated-core magnetometer is a linear device – that is, the output signal from a superposition of two magnetic fields is equal to the sum of the signals from the fields taken separately. It may be shown that all such magnetometers have the same directional characteristics. Hence no improvement can be obtained by shaping the coil or iron parts. This statement may be proved as follows.

Consider such a magnetometer in a magnetic field H and giving a signal of magnitude I. Now rotate the field vector through an angle of 180° in some

plane P. The output signal is now $-I$. During this rotation, the signal must have gone through zero. Call the direction of the field vector for which this occurs $\vec{d}$. Now repeat this operation by rotating in a plane P_2. This leads to a direction d_2 for which the signal vanishes. The directions $\vec{d_1}$ and $\vec{d_2}$ determine a third direction d_3, perpendicular to d_1 and d_2. Now, for an arbitrary magnetic field, the magnetometer measures only the component of the field in the direction of d_3. This follows from the linearity of the detector, since an arbitrary field may be expanded in components in the directions $\vec{d_1}$, $\vec{d_2}$, and $\vec{d_3}$.

If the signals from several detectors are combined linearly, the over-all device is still linear and hence measures a component of the field. However, by squaring signals and combining, a non-linear detector may be obtained for which the above rule does not hold. However, a single detector can only give a measure of one component of the magnetic field.

C. Resonance Absorption in Paramagnetic Substances

This section contains material well known in the fields of paramagnetic and nuclear resonance absorption. In general, little attempt has been made to give references. One paper, however, should be acknowledged. Much of the section on line breadth runs parallel in a very crude fashion to the elegant paper on nuclear resonance line widths by Bloembergen, Purcell and Pound (Phys. Rev. 73, 679, 1948).

The paramagnetic substance considered here is such that the electron's magnetic moment interacts mainly with the earth's magnetic field. The interaction of the electron moments upon each other may be reduced to arbitrarily small values by dilution of the substance. Whether the remaining interactions can, in the case of liquids, be reduced sufficiently is at present unknown. However, the organic free radicals investigated by Townes and Turkevich (Phys. Rev. 77, 148, 1950), also by Holden, Kittel, Merritt, and Yager (Phys. Rev. 77, 147, 1950) look promising. These could be put in solution in benzene or some other solvent to produce a dilute material. If the substances so far investigated are not satisfactory, there are, no doubt, many other possibilities among similar materials.

Another medium showing promise is a paramagnetic gas. In this case, the pressure may be reduced to lessen the spin-spin interaction effects. Another possibility is to dilute the paramagnetic gas with an inert gas such as argon.

The magnetization of the paramagnetic substance considered here is assumed to be produced wholly by the electron's magnetic moment. The magnetic moment per unit volume in a static field of strength H is given by

$$p = H \frac{N\mu^2}{kT} \quad . \tag{4}$$

Here μ is the electron magnetic moment and N is the electron density (counting only electrons with unpaired spin). This leads to a static permeability given by

$$\eta = \frac{B}{H} = \frac{H + 4\pi P}{H} = 1 + 4\pi \frac{N\mu^2}{kT} = 1 + 4\pi\chi \quad , \tag{5}$$

where the susceptibility $\chi = N\mu^2/kT$.

Because of the angular momentum of the electron, the simple linear connection between H and P disappears when one considers time-dependent fields. For example, in a magnetic field, the electron's spin axis precesses. If a second oscillating magnetic field acts at right angles to the first, the magnetization it induces depends in a critical way upon the frequency of oscillation. In particular, at the spin precession frequency, energy is absorbed by the medium.

The problem then consists of considering the effect upon the radio-frequency magnetization of the paramagnetic substance of having the earth's field act at right angles of radio-frequency field. The problem of the two fields not at right angles will be considered separately.

There are several simplifying general properties that the time-dependent field has in this case. First, if the time-dependent field (acting at right angles to the earth's magnetic field) is weak compared with the earth's magnetic field, the magnetization is linear in the following sense. Any simply periodic field produces a simply periodic magnetization of the same period. The magnetization produced by a superposition of periodic fields is a linear superposition of the separate magnetizations.

Thus it follows that, for any time-dependent field, there is a time-dependent magnetization such that

$$\underline{H}(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} H(\omega)\, e^{i\omega t}\, d\omega \quad , \tag{6}$$

where

$$H(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \underline{H}(t)\, e^{-i\omega t}\, dt \quad ,$$

and

$$\underline{p}(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} p(\omega)\, e^{i\omega t}\, d\omega \quad , \tag{7}$$

where

$$p(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \underline{p}(t)\, e^{-i\omega t}\, dt \quad ,$$

and also

$$p(\omega) = \chi(\omega)\, H(\omega) \quad .$$

Here $\chi(\omega)$ is a complex number which is a function only of ω and does not depend on the particular type of time dependence. It will be called the complex susceptibility.

Thus the magnetization produced by a given time-dependent field may be calculated if $\chi(\omega)$ is known.

$$\underline{p}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \underline{H}(\tau)\, e^{-i\omega t}\, d\tau\, \chi(\omega)\, e^{i\omega t}\, d\omega \quad . \tag{8}$$

It should be noted that, since $\underline{H}(t)$ and $\underline{p}(t)$ are real numbers,

$$\overline{\chi}(-\omega) = \chi(\omega) \quad , \qquad \text{for real } \omega, \tag{9}$$

where the bar signifies complex conjugates. It is evident that χ plays a role similar to impedance in a-c network theory.

The definition of χ may be extended to complex values of ω by considering exponentially increasing periodic fields and magnetization. This extends the definition to the negative imaginary half-plane of ω. By considering the magnetization produced by a field which is a delta function of the time, it may be seen below that $\chi(\omega)$ satisfies the Cauchy-Riemann conditions for an analytic function in this half-plane, for all finite values of χ. In this case,

$$\begin{aligned} \underline{p}(t) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \delta(\tau)\, e^{-i\omega\tau}\, d\tau\, \chi(\omega)\, e^{i\omega t}\, d\omega \quad , \\ &= \frac{1}{2\pi} \int_{-\infty}^{\infty} \chi(\omega)\, e^{i\omega t}\, d\omega \quad . \end{aligned} \tag{10}$$

From which

$$\chi(\omega) = \int_{-\infty}^{\infty} \underline{p}(t)\, e^{-i\omega t}\, dt \quad , \tag{11}$$

since $\underline{p}(t)$ is zero for all negative time (the magnetizing pulse occuring at the time $t = 0$). The above equation is valid in the bottom half-plane of ω including the real axis. That $\chi(\omega)$ as defined above satisfies the Cauchy-Riemann equations for finite χ may be easily verified by considering real and imaginary parts. Note also that $\overline{\chi}(\omega) = \chi(-\overline{\omega})$.

The process of analytic continuation may be used to extend the definition of $\chi(\omega)$ to the whole finite plane of ω.

The second general property of $\chi(\omega)$ follows from a consideration of the magnetization produced by a field which is a delta function of the time. As the magnetization cannot occur before the magnetizing pulse appears, $\chi(\omega)$ must have certain properties to assure this. In this case, as above,

$$\underline{p}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \chi(\omega)\, e^{i\omega t}\, d\omega \quad . \tag{12}$$

where $\underline{p}(t) = 0 \quad \text{for } t < 0$.

For negative t, the integral may be closed about the bottom half-plane of ω with a vanishing contribution over the closing arc. Thus $\underline{p}(t)$ would be given by the residues of poles in the bottom half-plane. Because of the factor $e^{i\omega t}$, any pole, simple or not, will have a non-vanishing residue for some negative t. This is only compatible with the above if χ is free of poles in the bottom half-plane of ω, real axis excluded. Thus we conclude that $\chi(\omega)$ has no poles in the bottom half-plane.

The third general principle comes from the conservation of energy. If the magnetizing field is taken as an exponentially increasing periodic field, the medium can at most, on the average, absorb energy. The energy absorbed by the medium is

$$E(t) = \int_{-\infty}^{t} \dot{\underline{p}}(t)\, H(t)\, dt$$

$$= \int_{-\infty}^{t} \left[i\omega\chi(\omega)\, e^{i\omega t} - i\bar{\omega}\bar{\chi}(\omega)\, e^{-i\bar{\omega}t}\right] \times \left[e^{i\omega t} + e^{-i\bar{\omega}t}\right] dt \tag{13}$$

$$= \left[i\omega\chi(\omega) - i\bar{\omega}\bar{\chi}(\omega)\right] \frac{e^{i(\omega-\bar{\omega})t}}{i(\omega-\bar{\omega})} + \frac{1}{2}\left[\chi(\omega)\, e^{2i\omega t} + \bar{\chi}(\omega)\, e^{-2i\bar{\omega}t}\right] \quad .$$

A value of t may be chosen for which the second bracket vanishes. Since E(t) can be negative for no value of t, it follows that

$$\left[i\omega\chi(\omega) - i\bar{\omega}\bar{\chi}(\omega)\right] \geqslant 0 \tag{14}$$

or the real part of $\left[i\omega\chi(\omega)\right] \geqslant 0$ for ω in the bottom half-plane, real axis included.

These general principles are a guide in selecting a function $\chi(\omega)$ that corresponds to the physical case. Thus, the most general form for χ is

$$\chi(\omega) = \sum_{n,q} \frac{A_{nq}}{(\omega - \omega q)^n} + \sum_n B_n\, \omega^n \quad . \tag{15}$$

Here ωq must lie in the top half-plane or on the real axis. The coefficients A and B must be so chosen as to make the real part of $\left[i\omega\chi\right]$ positive in the bottom half-plane, real axis included. In addition, they must be so paired and adjusted that

$$\bar{\chi}(\omega) = \chi(-\bar{\omega}) \quad .$$

This is about as far as one can go without making more specific assumptions about the paramagnetic medium. The first thing to be noted in this direction is that, because of the angular momentum of the electron, one would expect that a periodic magnetic field at very high frequency would

produce little magnetization, and that the higher the frequency the less the magnetization. From this it seems likely that the coefficient B should vanish. Thus $\chi(\omega)$ consists wholly of poles.

Consider again the magnetization produced by a magnetic field which is a delta function at t = 0.

$$\underline{p}(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \chi(\omega)\, e^{i\omega t}\, d\omega \quad . \tag{16}$$

For positive t, this integral may be closed about the top half-plane in which case $\underline{p}(t)$ may be expressed as a sum of residues

$$p(t) = i \sum_{q} A_{1q}\, e^{i\omega q t} \quad . \tag{17}$$

The poles are so paired that for every ωq there exists another

$$\omega q' = -\overline{\omega} q \quad .$$

Furthermore,

$$A_{1q}' = \overline{A}_{1q} \quad .$$

Thus $\underline{p}(t)$ consists, at most, in a superposition of a set of damped oscillations.

Again we must concern ourselves with the medium. It is evident that a magnetic disturbance at t = 0 will set the electrons precessing about the constant earth's magnetic field. In the case of no damping, they will precess at the Larmor precession frequency of the spin in the earth's field. It is clear, therefore, that we are concerned with a single pair of poles, in this case lying on the real axis at $\pm$ the Larmor precession frequency. If one considers a small circle in the ω plane with one of these poles at the center, it is evident that, for the bottom half of this circle, the condition Real $[i\omega\chi(\omega)] \geqslant 0$ implies that the pole is simple and has a residue purely real and negative. In the case of damping of the spin precession, it is clear that the electron again precesses and that this precessional motion is damped. Thus we are again concerned with a single pair of poles. It is now not possible to rule out a pole of higher order than the first.

However, it can be easily seen that a simple exponential damping is obtained if, and only if, the pole is simple. Furthermore, as will be seen, a simple pole leads to a simple Lorentz shape of absorption line. Although there are many broadening mechanisms that can lead to different line shapes and, consequently, more complex singularities, it will be assumed for simplicity that one is dealing with a simple pole and consequently with a Lorentz-shape absorption line.

Thus, it is assumed finally that

$$\chi(\omega) \sim \frac{A}{\omega - \omega_o} - \frac{\overline{A}}{\omega + \overline{\omega}_o} \quad , \tag{18}$$

where ω_o is complex, the real part being the Larmor precession frequency and the imaginary part giving the damping constant.

We must now consider two cases, the case of small damping and the case of large damping. In the case of small damping, the poles lie close to the real axis in comparison with their distance apart. In this case, the phase of A is determined as for the case of no damping. In other words, A is very nearly pure real and negative. This follows from the energy condition. The magnitude of χ may be obtained from the condition that $\chi(0)$ has just the static value

$$\chi_o = \frac{N\mu^2}{kT} \quad . \tag{19}$$

Thus

$$\begin{aligned} \chi(0) &= -A\left[\frac{1}{\omega_o} + \frac{1}{\bar{\omega}_o}\right] \quad , \\ -A &= \frac{N\mu^2}{kT}\,\frac{\omega_o\bar{\omega}_o}{\omega_o + \bar{\omega}_o} \quad . \end{aligned} \tag{20}$$

In the case where the damping time is comparable with the period of the Larmor precession, the situation is slightly more complicated. The energy condition is not sufficient to determine the phase of A. If however, we again consider a magnetizing pulse which is a delta function of the time, the magnetization immediately after the pulse may be written as

$$\underline{p}(t) = \frac{N\mu^2}{kT}\,\frac{1}{\tau} \quad , \tag{21}$$

where τ is the damping time. This may be seen as follows. Assume that the magnetizing pulse has a strength $\frac{1}{t}$ and lasts for a time t. The delta function is obtained as a limit as $t \rightarrow 0$. As the pulse is excited, the electron spins, and starts to precess about the new direction. This contributes a term to the magnetization which increases quadratically with the time for small times. Thus this effect cannot contribute to the magnetization produced by a sufficiently short pulse.

The only contribution to the magnetization immediately following a delta function must be connected with the damping. It is convenient to introduce an explicit mechanism for damping, although the results are probably independent of this mechanism so long as one has a Lorentz-shaped line. We assume that the electron suffers a series of strong disturbances randomly distributed in time, and that, after such a disturbance, an electron has its orientation distributed between the two possible orientations with respect to the field in accordance with the Boltzmann factor. Thus the magnetization after the magnetizing pulse may be written as

$$p(t) = \frac{N\mu^2}{kT} \frac{1}{t} \cdot \frac{t}{\tau} \quad . \tag{22}$$

The factor $(N\mu^2/kT)(1/t)$ represents the static magnetization produced by a field of strength $1/t$. The factor t/τ represents the fraction of the electrons that have had their magnetization altered through damping disturbance. Here τ is the mean time between disturbances. It should be emphasized that this equation is valid only for times t much less than the Larmor period or the damping time τ, whichever is the shorter.

One would expect the damping time to be related to the location of the pole ω_o through the relation

$$\tau^{-1} = \left[-i\omega_o\right] \text{real part} \quad ,$$

in other words, that τ^{-1} is equal to the damping constant. This may be verified for a special case. If the earth's static field is eliminated, the two poles move together and coalesce into a single pole lying on the imaginary axis. This pole must be simple if the magnetization following an impulse is to decay exponentially with time. Thus, for this case,

$$\chi = \frac{B}{\omega - \omega_o} \quad . \tag{23}$$

It is clear that B has the value

$$B = -\chi(0)\,\omega_o = -\frac{N\mu^2}{kT}\,\omega_o \quad . \tag{24}$$

The magnetization following an impulse function is

$$\begin{aligned} \underline{p}(t) &= \frac{1}{2\pi}\int_{-\infty}^{\infty} \chi\, e^{i\omega t}\, d\omega = \frac{2\pi i}{2\pi}\left[-\frac{N\mu^2}{kT}\,\omega_o\right] e^{i\omega_o t} \quad , \\ &= \frac{N\mu^2}{kT}\,(-i\omega_o)\,, \quad \text{for } t = 0 \quad . \end{aligned} \tag{25}$$

By comparison, remembering that ω_o is purely imaginary,

$$\tau^{-1} = \text{real part } (-i\omega_o) \quad .$$

We return again to the case of a static magnetic field acting at right angles to the time-dependent field. The magnetization following an impulse disturbance $H = \delta(t)$ is given by

$$p(t) = i\left[A\, e^{i\omega_o t} - \bar{A}\, e^{i\bar{\omega}_o t}\right] \quad , \tag{26}$$

where

$$\chi = \frac{A}{\omega - \omega_o} - \frac{\bar{A}}{\omega + \bar{\omega}_o} \quad .$$

From which we have, for $t = 0$,

$$\frac{N\mu^2}{kT}\,\frac{1}{\tau} = i\left[A - \bar{A}\right] \quad ; \tag{27}$$

where

$$\tau^{-1} = (-i\omega_o)_{(\text{real part})} \quad .$$

Also, we have

$$\chi(0) = \frac{N\mu^2}{kT} = -\left[\frac{A}{\omega_o} + \frac{\bar{A}}{\bar{\omega}_o}\right] \quad . \tag{28}$$

Eliminating $\bar{A}$ from these two equations, we obtain

$$-i\,\frac{N\mu^2}{kT}\left[\frac{1}{\tau} - i\bar{\omega}_o\right] = A\left[1 + \frac{\bar{\omega}_o}{\omega_o}\right] \quad . \tag{29}$$

Then substituting

$$\frac{1}{\tau} = \frac{1}{2}\left(-i\omega_o + i\bar{\omega}_o\right)$$

in Eq. 29 above,

$$-\frac{N^2}{kT}\,\frac{1}{2}\left(\omega_o + \bar{\omega}_o\right) = A\,\frac{\omega_o + \bar{\omega}_o}{\omega_o} \ ,$$

$$A = -\frac{1}{2}\,\omega_o\,\frac{N\mu^2}{kT} \quad . \tag{30}$$

Thus, our general expression is

$$\chi(\omega) = \frac{1}{2}\,\frac{N\mu^2}{kT}\left[\frac{-\omega_o}{\omega - \omega_o} + \frac{\bar{\omega}_o}{\omega + \bar{\omega}_o}\right] \quad . \tag{31}$$

It should be noted that this expression reduces to the correct ones considered earlier in the case of ω_o purely real or imaginary. The above expression is valid for all damping times and field strengths, at least to the extent that the collision damping mechanism is valid.

1. Equivalent Circuit

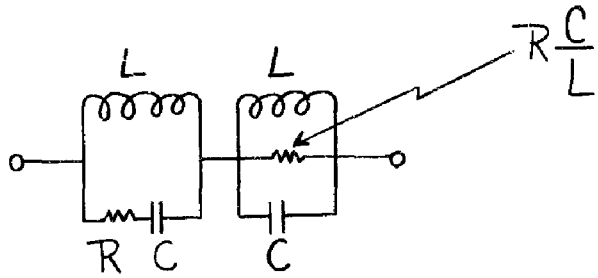
Assuming a coil of inductance L_c and resistance R_c it is desired to calculate the effect upon the coil of immersing it in the paramagnetic medium. In this case, the reactance becomes

$$R_c + i\omega L_c\eta = R_c + i\omega L_c\,(1 + 4\pi\chi) \quad . \tag{32}$$

The contribution to the reactance having its origin in the paramagnetic medium is

$$4\pi i\omega L_c\chi = 2\pi i\omega L_c\,\frac{N\mu^2}{kT}\left[\frac{\omega(\omega_o - \bar{\omega}_o) + 2\,\omega_o\bar{\omega}_o}{-\omega^2 + \omega(\omega_o - \bar{\omega}_o) + \omega_o\bar{\omega}_o}\right] \quad . \tag{33}$$

The circuit



has the reactance

$$Z_M = \frac{iL\omega(iRC\omega + 2)}{-LC\omega^2 + iRC\omega + 1} \quad . \tag{34}$$

It may be seen by examination that this is the same form as the above, and that if

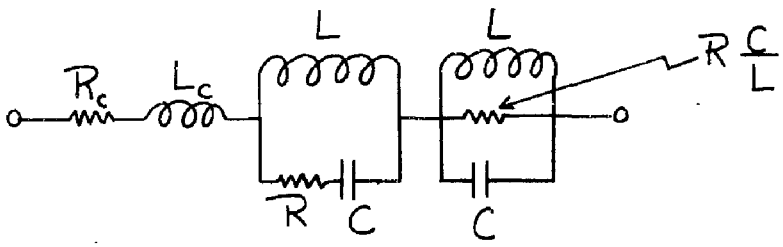
$$Z_M = 4\pi\, i\omega L_c \chi$$

for all ω, one has

$$LC = \frac{1}{\omega_o \bar{\omega}_o} \quad , \quad iRC = \frac{\omega_o - \bar{\omega}_o}{\omega_o \bar{\omega}_o} \quad ,$$

$$L = 2\pi L_c \frac{N\mu^2}{kT} \quad . \tag{35}$$

The equivalent circuit for the coil including the effect of the medium is



The relations for the circuit parameters may be conveniently expressed in terms of the spin precession frequency ν and damping time τ or, alternatively, the damping constant

$$\Delta\nu = \tau^{-1} \quad ,$$

$$\omega_o = \nu + i\Delta\nu \quad .$$

Then

$$LC = \frac{1}{\nu^2 + \Delta\nu^2} \quad , \quad RC = \frac{2\Delta}{\nu^2 + \Delta\nu^2} \quad . \tag{36}$$

From which

$$R = 2\Delta\nu \cdot L = 4\pi L_c \frac{N\mu^2}{kT} \Delta \quad ,$$

$$C = \frac{1}{\nu^2 + \Delta\nu^2} \frac{kT}{2\pi L_c N\mu^2} \quad , \tag{37}$$

$$L = 2\pi L_c \frac{N\mu^2}{kT} \quad .$$

As a check on the correctness of these constants, note that near our zero frequency the only effect of the medium is to multiply the inductance by the static permeability of the medium.

Since ν is proportional to the earth's magnetic field strength, and $\Delta\nu$ is independent of the field strength, it is evident that only C depends upon the earth's field strength. If the frequency ω is adjusted to be in the vicinity of the resonance of the parallel tuned circuits, it is evident that the voltage developed across the coil (assumed to be excited by a current source) will depend upon the earth's magnetic field.

The frequency to be chosen should be so selected that the magnitude of the rate of change of Z_M with respect to ν is a maximum.

Instead of making the detailed calculation in general, we shall limit ourselves to two special cases:

$$\text{Case I} \quad \nu >> \Delta\nu \quad ;$$
$$\text{Case II} \quad \nu << \Delta\nu \quad .$$

At first glance, Case II would not seem to be of interest, since the sensitivity would seem to be low. However, as shall be seen later, a wide band allows a large power dissipation in the medium and a correspondingly larger signal. Hence, it is necessary to include Case II.

$$Z_m = 4\pi i\omega L_c \chi = 4\pi i L_c \chi(0) \left[\frac{-\omega\omega_o}{\omega - \omega_o} + \frac{\omega\bar{\omega}_o}{\omega + \bar{\omega}_o}\right] \quad ,$$
$$\omega_o = \nu + i\Delta\nu \quad . \tag{38}$$

This may be written

$$Z_m = 4\pi i L_c \chi(0)\omega \left[2 - \frac{\omega}{\omega - \omega_o} - \frac{\omega}{\omega + \bar{\omega}_o}\right] \quad . \tag{39}$$

Thus

$$\frac{\partial Z_m}{\partial \nu} = -4\pi i L_c \chi(0)\, \omega^2 \left[\frac{1}{(\omega - \omega_o)^2} - \frac{1}{(\omega + \bar{\omega}_o)^2}\right] \quad . \tag{40}$$

For Case I ($\nu >> \Delta\nu$),

$$\left|\frac{\partial Z_m}{\partial \nu}\right| = 16\pi L_c \chi(0) \frac{\omega^3 \nu}{(\omega^2 - \nu^2 - \Delta\nu^2)^2 + 4\Delta\nu^2\omega^2} \quad . \tag{41}$$

In this case, it is clear that, to first order in $(\Delta\nu/\nu)^2$, the maximum value occurs for $\omega^2 = \nu^2 + \Delta\nu^2$. The maximum is

$$\left|\frac{\partial Z_m}{\partial \nu}\right|_{max} = 4\pi L_c \chi(0) \frac{\nu^2}{\Delta\nu^2} \quad . \tag{42}$$

For Case II ($\nu << \Delta\nu$),

$$\left|\frac{\partial Z_m}{\partial \nu}\right| \cong 16\pi L_c \chi(0) \frac{\omega^3 \nu}{\left[\omega^2 + \Delta\nu^2\right]^2 - 2\nu^2(\omega^2 - \Delta\nu^2)} \tag{43}$$

to zero order in $(\nu/\Delta\nu)^2$ the maximum occurs for $\omega^2 = 3\Delta\nu^2$.

To zero order, this maximum value is

$$\left|\frac{\partial Z_m}{\partial \nu}\right|_{max} = \sqrt{27}\ \pi L_c \chi(0) \frac{\nu}{\Delta\nu} \quad . \tag{44}$$

2. Damping Constant[1]

The reciprocal damping time $\Delta\nu = \tau^{-1}$ and its relation to other parameters of the system must now be considered. It may be broken into two parts: a part caused by mutual action of the electron spins, and the remainder. This spin breadth has its origin in the magnetic field produced by the magnetic moment of one electron acting on another.

The contribution to the damping having its origin in spin interactions is denoted by

$$\Delta\nu_s \quad .$$

It is of importance for two reasons. First, the spin damping is dependent upon the electron density, hence the electron density cannot be increased indefinitely without broadening the resonance line indefinitely. The second importance comes from the fact that, under certain conditions, it is a particularly damaging type of damping. Under these conditions, the spin energy of the electrons is merely passed about without appearing as lattice energy or heat. Thus, spin damping may under certain conditions be ineffective in disposing of the absorbed energy.

It is evident that because of the inverse cube dependence on distance, the magnetic field that acts on one electron has its origin mainly in those electrons that are near. Thus, for purposes of approximation, only the near neighbors will be considered. For a fluid, which is the only medium being considered, the electrons are always in random motion with respect to each other. This motion plays an important role in determining the line breadth. In the following analysis, no attempt has been made to derive formulas valid to the extent of correct numerical factors.

If two electrons are at a distance a apart, the precessing field of the one affects the other to turn its spin over in a time of the order of

$$\frac{\hbar a^3}{\mu^2} \quad .$$

[1]The paper by Bloembergen, Purcell and Pound, Phys. Rev. 79, 679 (1950) is the source of most of this section.

It is assumed that a is the closest distance of approach in the fluid. The time spent by the electrons at this range is of the order of the time required by the molecule to move this distance. There are two cases to be considered: a gaseous medium, or a solution. For the gas, the duration of the interaction is of the order of

$$\tau_g = \frac{a}{v} \quad ,$$

where v is the molecular velocity.

In the case of the solution, the characteristic interaction time is

$$\tau_s = \frac{a^2}{D} \quad ,$$

where D is the coefficient of diffusion of the molecule in its inert medium. If one takes as a model of the molecule a sphere of radius a, Stokes law leads to the expression for D:

$$D = \frac{kT}{6\pi\eta a} \quad , \tag{45}$$

where η is the viscosity of the fluid. These expressions are valid only for mean free paths small compared with a (i.e., liquids).

The first factor to be considered is the role played by the strength of the collision. A collision will be said to be strong if

$$\frac{\tau\mu^2}{\hbar a^3} \gg 1 \quad .$$

A weak collision is one with the opposite equality. Note that for solution this becomes

$$\frac{\mu^2}{\hbar kT}\,\eta \gg 1 \quad . \tag{46}$$

It is assumed that, in the case of strong collisions, the electron spin orientation is so badly disturbed during the collision that all phase information is lost. The effective radius for a strong collision is defined as r such that

$$\frac{\tau'\mu^2}{\hbar r^3} = 1 \quad , \qquad r > a \quad , \tag{47}$$

where, for solutions,

$$\tau'_s = \frac{r^2}{D} \quad ,$$

for gases,

$$\tau'_g = \frac{r}{v} \quad . \tag{48}$$

The collision width of the resonance line is given by the reciprocal time between collisions,

$$\Delta\nu_s = \frac{Nr^3}{\tau'} \quad , \qquad \Delta\nu_s \ll \frac{1}{\tau} \quad . \tag{49}$$

Combining these equations

$$\Delta\nu_s = N\frac{\mu^2}{h} \quad \text{for } a^3N \ll \left(\frac{a}{r}\right)^3 \quad ;$$

$$\frac{r^2}{a^2} = \frac{\mu^2}{ha^3}\tau_g \quad , \text{ for gases}$$

$$\frac{r}{a} = \frac{\mu^2}{ha^3}\tau_s \quad , \text{ for solutions} \tag{50}$$

In the case of a weak collision, the spin axis is tipped slightly by the interaction. The line width is determined by the time (hence number of collisions) required to completely disorient the electron spin axis. The angle turned through as a result of a single collision is of the order

$$\left[\frac{\tau\mu^2}{\hbar a^3}\right]^2 \ll 1 \quad .$$

The mean square angle after n collisions is

$$\left[\frac{\tau\mu^2}{\hbar a^3}\right]^2 n \quad . \tag{51}$$

If n represents the number of collisions to completely disorient the spin axis,

$$n = \frac{h^2a^6}{\tau^2\mu^4} \quad . \tag{52}$$

The reciprocal time required for n collisions is

$$\Delta\nu_s = n\frac{Na^3}{\tau} = \frac{\mu^4}{\hbar^2a^3}N\tau \quad . \tag{53}$$

For gases, this becomes

$$\Delta\nu_s = N\frac{\mu^4}{\hbar^2a^2v} \quad . \tag{54}$$

For liquid solutions,

$$\Delta\nu_s = N\frac{\mu^4}{\hbar^2aD} = N\frac{\mu^4n}{\hbar^2kT} \quad . \tag{55}$$

All these results, the effects of electron exchange during the collision have been neglected. Electron exchange should make the line more narrow.

A Lorentz line shape is obtained when the various collisions that a molecule suffers are uncorrelated in time. However, in a dilute solution there is, in general, some correlation between collisions. If a collision between two paramagnetic molecules in a dilute solution occurs, the probability of another collision between the same molecules in the immediate future is quite high. This correlation probably has no great effect upon line shape in the case of a weak collision. However, in the case of a strong collision, the

correlation should have a rather marked effect. In general, the line should be more narrow and peaked with broad low-lying wings. Thus, the width of the central peak should be somewhat less than the value calculated earlier for a Lorentz broadened line.

The effectiveness of the spin-spin interaction in dissipating the spin energy must next be considered. If the fluctuation in the magnetic field at an electron is caused essentially by the random displacements of the neighboring electrons, then the spin energy lost by the electron appears essentially as heat energy. If, on the other hand, the fluctuation is caused by precession of the spins of surrounding electrons, the energy is merely transferred from one electron spin to another. Thus, if the spin-spin interaction is to be effective as a means of transferring the absorbed spin energy to molecular heat energy, it is necessary that

$$\nu\tau \ll 1 \quad .$$

3. Power Dissipation

The medium can absorb energy only to the extent that it gives it up to the lattice by damping collisions. The energy stored in the medium in the earth's magnetic field is

$$4\pi\chi(0)\, H^2 V \quad , \tag{56}$$

where V is the volume of the liquid. The maximum power that could be absorbed by the medium without serious saturation may be taken to be

$$P = 4\chi(0)\, H^2 V\,(\Delta\nu - \Delta\nu_b) \quad .$$

Here $\Delta\nu_b$ is that part of the line width corresponding to mutual interchange of spin energies. This power seems to be on the conservative side (see Bloembergen, Purcell, and Pound, Phys. Rev. 73, 690 (1948)). Let I be rms alternating current which flowing in the coil will produce this dissipation in the medium. This current may be calculated from

$$|I|^2 \left[Z_m\right]_{\text{real part}} = P \quad . \tag{57}$$

There are again two cases to be considered.

Case I: $\nu \gg \Delta\nu$, $\omega = \nu$.

$$Z_m = 4\pi i L_c \chi(0)\,\omega \left[\frac{-\omega_o}{\omega - \omega_o} + \frac{\bar{\omega}_o}{\omega + \bar{\omega}_o}\right]$$

$$= 4\pi i L_c \chi(0)\,\nu \left[\frac{-\nu}{-i\Delta\nu} + 1\right] \quad , \tag{58}$$

$$Z_m = 4\pi L_c \chi(0)\,\frac{\nu^2}{\Delta\nu} \quad .$$

Case II: $\Delta\nu >> \nu$, $\omega^2 = 30\nu^2$.

$$Z_m = 4\pi i L_c \chi(0)\sqrt{3}\,\Delta\nu \left[\frac{-i}{\sqrt{3}-i} + \frac{-i}{\sqrt{3}-i}\right]$$

$$= 8\pi\sqrt{3}\left[\frac{\sqrt{3}+i}{4}\right] L_c \chi(0)\,\Delta\nu \quad , \tag{59}$$

$$\left[Z_m\right]_{\text{real part}} = 6\pi L_c \chi(0)\,\Delta\nu \quad .$$

4. Signal

Assuming a phase-sensitive detector so phased as to detect the change in voltage produced by a change $\delta\nu$ in ν, the signal voltage squared may be taken as

$$|\delta e|^2 = |I|^2 \left|\frac{\partial Z_m}{\partial\nu}\right|^2 \delta\nu^2 \tag{60}$$

$$= \frac{P}{\left[Z_m\right]_{\text{real part}}} \left|\frac{\partial Z_m}{\partial\nu}\right|^2 \delta^2 \quad .$$

It is assumed that ω is selected to maximize the signal as was previously indicated

Case I:

$$|\delta e_s|^2 = \frac{16\pi L_c \chi^2(0) H^2 V (\Delta\nu - \Delta\nu_b)\nu^2}{\Delta\nu^3}\,\delta\nu^2 \quad . \tag{61}$$

Case II:

$$|\delta e_s|^2 = \frac{18\pi L_c \chi^2(0) H^2 V (\Delta\nu - \Delta\nu_b)\nu^2}{\Delta\nu^3}\,\delta\nu^2 \quad . \tag{62}$$

Surprisingly enough, these two expressions are nearly identical.

5. Signal-to-Noise

The mean square thermal noise voltage developed across the coil has the value per unit frequency

$$\overline{|\delta e_\eta|^2} = 4R_c kT = \frac{4L_c\omega}{Q}\,kT \quad . \tag{63}$$

For Case I, the ratio of squares of signal-to-noise voltage is:

$$\frac{|\delta e_s|^2}{\overline{|\delta e_\eta|^2}} = 4\pi \frac{Q}{kT}\chi^2(0) H^2 V \frac{\Delta\nu - \Delta\nu_b}{\Delta\nu} \frac{\nu}{\Delta\nu^2}\,\delta\nu^2 \tag{64}$$

For Case II, $\omega = \sqrt{3}\,\Delta\nu_{II}$:

$$\left|\frac{|\delta e_s|^2}{\overline{|\delta e_\eta|^2}}\right|_{\text{Case II}} = \frac{9}{8}\frac{\nu}{\sqrt{3}\,\Delta\nu_{II}} \left|\frac{|\delta e_s|^2}{\overline{|\delta e_\eta|^2}}\right|_{\text{Case I}} \quad . \tag{65}$$

6. Choice of Paramagnetic Medium

An inspection of the expressions for the signal-to-noise voltages indicates that Case I is superior to Case II by essentially the ratio of the two operating frequencies. This need not be a very large factor. However, there are more compelling reasons connected with the directional sensitivity of the field detector for limiting oneself to Case I. These will be considered briefly later.

In order to maximize signal-to-noise, it is evident that $\chi(0)$ should be as large as possible, $\Delta\nu$ as small as possible, and $(\Delta\nu_b/\Delta\nu) \ll 1$.

To what extent these conditions are mutually compatible must now be considered.

The line breadth $\Delta\nu$ is composed in part of the spin-spin contribution and, possibly, in part of other causes such as spin-orbit interactions. It is desirable that these interactions be absent provided they are not needed to obtain the requisite spin-lattice relaxation. Let it be assumed, therefore, that one is concerned only with the spin-spin interaction. In this case, the line width is proportional to the electron density N, and consequently the signal strength is independent of line width and of N since $\chi(0)$ varies directly as N. The choice of line width must, therefore, be on other grounds than signal-to-thermal noise. This problem will be considered later.

In order to satisfy the condition $(\Delta\nu_b/\Delta\nu) \ll 1$, it is necessary that the collision time be short compared with $\nu^{-1} = 10^{-7}$ seconds. For a molecular diameter of 10^{-8} cm, the collision time for a gas such as oxygen is

$$\frac{a}{v} \sim 3 \times 10^{-13} \text{ sec} \quad .$$

For a liquid such as water, it is

$$\frac{a^2}{D} \sim 5 \times 10^{-12} \text{ sec.}$$

Hence it would seem that the spin interaction would be effective in dissipating the absorbed spin energy in all cases except solids and viscous liquids.

The next problem to be considered is the strength of the collision. Assuming $a = 10^{-8}$ cm, $\tau = 10^{-12}$ sec,

$$\frac{\tau \mu^2}{\hbar a^3} \sim 0.1 \quad . \tag{66}$$

Therefore, the collisions may be usually taken as weak. In order that the ratio $N/\Delta\nu$ should be large in the case of a liquid, the viscosity of the liquid should be low. In the case of a gas, the product $a^2 v$ should be large. In general, a gas should be superior to a liquid.

One condition that is probably essential is that the magnetic moment of the atom or molecule should arise almost wholly from the electron's magnetic moment. If the electron spin is coupled to orbital motion, then a single

collision is apt to strongly disturb the spin via a change in the orbital motion.

There are two fairly obvious approaches. One, as mentioned earlier, is to try to find a molecule such as an organic free radical that would be satisfactory, either in solution or as a gas. The other possibility is to use a monatomic gas with an S-state for its ground state. An example of such a gas is sodium vapor or some other alkali metal.

There is a third possibility that should be mentioned, although it appears unlikely that it is feasible. If a paramagnetic solid such as the free radicals mentioned earlier could be found for which the spin exchange narrowing is sufficiently pronounced to give a sufficiently narrow line, this would probably be the most satisfactory medium of all.

There are experimental difficulties connected with each of the monatomic gases that are suitable. The gases of chief interest are monatomic hydrogen, nitrogen, phosphorus, and the alkali metals. The high temperature necessary to get a suitable vapor pressure of the alkali metals is a difficulty. Monatomic hydrogen and possibly nitrogen may be obtained by collisions of the second kind with excited mercury vapor. To get a sufficient quantity in this fashion might be difficult.

There is a further difficulty connected with the employment of monatomic gases. There does not seem to be a single example of a stable isotope with a suitable ground state which has a zero nuclear spin. The coupling of the electron spin and the nuclear spin causes a difficulty to which we shall return shortly.

One possible way out of this difficulty should be mentioned. If helium is excited to its metastable triplet S-state, it would be suitable. The chief difficulty here seems to be the continuous production of metastable helium at a rapid enough rate. According to Mitchell and Zemanski ("Resonance Radiation and Excited Atoms", Cambridge Press, p. 245), the life time to e^{-1} of metastable helium in helium is 1/100 p sec, where the pressure p is in mm of mercury. This is sufficiently long at a pressure of a few mm that it would, in principle, be possible to continuously recycle helium through a generator of metastable helium. However, to maintain 10^{20} metastable atoms at a pressure of 10 mm normal helium would require a power of about 100 kw. It must be concluded that, for such a system to be feasible, a much longer lifetime for the metastable atoms would be required.

To return to the difficulties connected with nuclear spin, it should be noted that, in general, the hyperfine separation of the ground state would be large compared with the Zeeman splitting in the earth's magnetic field. In other words, F and m_F are good quantum numbers. The g-factor would be essentially that of a free electron modified by the angular momentum of the nucleus. Thus, aside from change in resonance frequency, the nucleus has caused no trouble. However, there is a difficulty connected with collisions. Consider,

for example, a collision between two sodium atoms. In a close collision, electron exchange can take place. This normally causes no difficulty, since an exchange of two electrons does not change the magnetic moment of the medium. However, with a coupling to the nucleus, an interchange of two electrons can completely change the coupling scheme. Thus, the effect of exchange in a collision is generally one of throwing the system from one F-value to another. These are certainly to be considered strong collisions. It would seem that, because of electron exchange, a gas such as sodium would not be a suitable material.

A medium consisting of a solution of an organic free radical would seem to be promising. There seems to be very little coupling of the electron's spin to the molecule's angular momentum. In order to calculate a minimum detectable signal, an expression connecting the line width $\Delta\nu$ with electron density N is needed. The appropriate one is that given earlier for weak collisions in solutions. However, it is now necessary to improve things by adding a numerical factor that is reasonably reliable. The value chosen is 4/3, the factor calculated by Bloembergen, Purcell, and Pound for the contribution to proton resonance width arising from interactions of the molecule with its neighbors, namely,

$$\Delta\nu = \frac{4\pi}{10} \cdot 2^4 \frac{\mu^4 N}{\hbar^2 aD} \quad . \tag{67}$$

Using Stokes relation for aD, this becomes

$$\Delta\nu = \frac{3}{5}\pi^2 \cdot 2^6 \frac{\eta N \mu^4}{\hbar^2 kT} \quad . \tag{68}$$

To produce a line width such that

$$\frac{\Delta\nu}{\nu} = 0.1 \quad ,$$

$$\Delta\nu = 10^6 \text{ sec}^{-1} \quad .$$

For a liquid similar to water,

$$\eta = 10^{-2} \quad .$$

which leads to

$$\begin{aligned} N &= \frac{5}{3}\frac{1}{\pi^2} \cdot 2^{-6} \frac{\hbar^2 kT}{\eta \mu^4} \Delta\nu \quad . \\ &= 2.6 \times 10^{17} \text{ electrons/cm}^3 \quad . \end{aligned} \tag{69}$$

This is roughly 1/100 the molecule density of a gas at N.T.P. If this is substituted in the expression for the ratio of signal-to-noise voltages, remembering that $(\Delta\nu_b/\Delta\nu) \ll 1$, one obtains,

$$\frac{|\delta e_s|^2}{\overline{|\delta e_n|^2}} = \frac{5^2}{3^2 \cdot 2^6 \cdot \pi^3} \frac{QVH^6}{kT\nu\eta^2} \left(\frac{\delta\nu}{\nu}\right)^2 \quad . \tag{70}$$

It should be noted that this expression is independent of μ. It would seem, at first glance, that the use of protons might even be superior to electrons. However, even with protons packed as tightly as possible, a substance such as water has a line too narrow to be useful. It is, of course, detrimental to the sensitivity to broaden the line by any method except increasing the concentration. The proton resonance in water has a width of about

$$\Delta\nu = 0.3 \text{ sec}^{-1} \quad .$$

As will be evident later, it is extremely difficult to reduce fluctuations to the limits set by thermal effects if the line is this narrow. Thus, protons are ruled out because their concentration cannot be made sufficiently high.

Assuming that the smallest discernible signal is for signal-to-noise voltage ratio equal to unity, the smallest discernible change in magnetic field is given by

$$\frac{\delta H}{H} = \frac{\delta v}{v} = \frac{24\pi^{3/2}}{5} \left[\frac{kT\nu}{QV}\right]^{1/2} \frac{\eta}{H^3} \quad . \tag{71}$$

Assume the following values:

$V = 10^3 \text{ cm}^3$,

$Q = 500$,

$\eta = 10^{-2}$ dyne sec/cm^2 (viscosity of water at 20° C) ,

$\nu = 10^7 \text{ sec}^{-1}$,

$H = 0.6$ gauss .

Then, according to Eq. (71), $\delta H/H = 1.1 \times 10^{-6}$, or $\delta H = 6.6 \times 10^{-7}$ gauss, that is, 0.066 gamma. This result is encouraging; it suggests that with a sample volume of only one liter, sensitivity comparable to that of the most highly refined MAD equipment might be achieved. By increasing the volume of the sample, the sensitivity could be further increased. If we assume that Q scales as $V^{1/3}$, a volume of 17 liters would be required to make δH as small as 0.01 gamma, and a volume of 540 liters to make $\delta H = 0.001$ gamma.

7. Balanced Systems

A gradiometer would have the advantage of balancing out time-dependent

variations in the earth's field. In addition to this advantage, it has two disadvantages: a reduced sensitivity, and a field strength that varies as an inverse fourth power of the range.

It is possible to attain some of the advantages of the gradiometer without its disadvantages. If a magnetometer were so sensitive that time variations in the earth's field strength were limiting its performance, then there would be a decided advantage in having planes search in pairs, flying a mile or two apart. Each plane would be supplied with two indicators. One indicator would give a measure of the earth's field at the plane, the other would give the difference in field strengths at the two planes. The second indicator would, of course, not be influenced appreciably by time-dependent field variations. Upon the receipt of a signal on the difference indicator, the sign of the signal would give the clue as to which plane is near the submarine. In case the sign should be unreliable, each plane could maneuver as though the signal were its own. If maneuver is not a source of fluctuation, then the fact that the wrong plane is also looking for the submarine does not influence the difference signal. Of course, as soon as the plane is sufficiently close to warrant attack, the signal appears on its second indicator, leaving no doubt as to which plane has found the submarine.

If a suitable paramagnetic material could be found such as a solid with sufficiently strong exchange narrowing, then a sensitivity of better than 0.001 gamma might be realized with a system of 10^3 cm^3 capacity. In such a case, time-dependent fluctuations in the earth's field would be a serious limitation. If it should be necessary to use the magnetometer as a search device, then there would be real advantages in searching in pairs.

8. Modulation Method

The device, as it is so far described, presents a signal as a static unbalance produced by the field strength dependence of the permeability of the core of the coil. It would be impossible to realize a fluctuation as small as thermal noise with a system of this type. In particular, microphonic vibrations, temperature variations, mechanical strains, etc., would be very serious. To eliminate these troubles, a modulation scheme similar to that used by Purcell, et al. is introduced. The strength of the static field is caused to fluctuate periodically through the action of a second coil at right angles to the first, and having its axis in the direction of the earth's magnetic field. This modulation frequency then acts as a carrier, and the signal appears as sidebands on this carrier frequency. Thus, the only fluctuations such as microphonics, which can cause trouble, are in the vicinity of the modulation frequency. This modulation frequency may be as high as $\Delta\nu$. This indicates that there are advantages in making the absorption line wide. The wider the line, the higher the modulation frequency may be and,

consequently, the less serious the microphonic difficulties.

In order to simplify calculations, square-wave modulation and demodulation will be assumed. Thus the Larmor frequency will be shifted back and forth, spending half-time at each of two values.

In the ordinary static case, the contribution to the impedance of the coil having its origin in the medium is

$$Z_m^{(\omega)} = 4\pi i L_c \chi(0)\, \omega \left[\frac{-\omega_o}{\omega - \omega_o} + \frac{\overline{\omega}_o}{\omega + \overline{\omega}_o}\right] \quad . \tag{72}$$

The coil voltage having its origin in the medium is proportional to this quantity. The signal voltage resulting from a change is proportional to the quantity

$$\frac{dZ_m}{d\nu} \cdot \delta\nu \ .$$

The analogous quantities in the case of the modulation-demodulation method are, for the carrier voltage,

$$\frac{1}{2}\left[Z_m(\omega, \omega_o + d) - Z_m(\omega, \omega_o - a)\right] = Z_{mm}^{(\omega)} \quad , \tag{73}$$

which simplifies to

$$Z_{mm}^{(\omega)} = 4\pi i L_c \chi(0)\, \omega^2 \left[\frac{1}{(\omega - \omega_o)^2 - a^2} + \frac{1}{(\omega + \overline{\omega}_o)^2 - d^2}\right] \quad . \tag{74}$$

In a similar way, with modulation, the signal voltage is proportional to

$$\frac{dZ_{mm}}{d\nu}\, \delta\nu \quad . \tag{75}$$

Assuming Case I, $\nu \gg \Delta\nu$, this is maximum absolute value for $\omega = \nu$ and becomes:

$$\frac{dZ_{mm}}{d\nu} = -8\pi L_c \chi(0) \nu^2 \frac{a\,\Delta\nu}{\left[\Delta\nu^2 + a^2\right]^2}\, \delta\nu \quad . \tag{76}$$

Maximizing the absolute value of this with respect to a (the modulation swing), leads to

$$a = \frac{1}{\sqrt{3}}\, \Delta\nu \quad . \tag{77}$$

Substituting:

$$\frac{dZ_{mm}}{d\nu}\, \delta\nu = -\frac{9}{2\sqrt{3}}\, \pi L_c \chi(0)\, \frac{\nu^2}{\Delta\nu^2}\, \delta\nu \quad . \tag{78}$$

This is approximately 0.65 times the corresponding static quantity. The thermal noise voltage is the same in the two cases. Therefore, the expression for ratio of signal-to-noise voltages squared for unit frequency bandwidth becomes:

$$\frac{|\delta e_s|^2}{|\delta e|_n^2} = 1.7\pi \frac{Q}{(kT)^3} N^2\mu^4 H^2 V \left[\frac{\Delta\nu - \Delta\nu_b}{\Delta\nu}\right] \frac{\nu}{\Delta\nu^2} \delta\nu^2 \quad . \tag{79}$$

The sensitivity calculated by Bloembergen, Purcell and Pound should be comparable to the above, providing $\delta\nu$ is set equal to $\Delta\nu$. The two expressions are in agreement in form, but differ considerably in numerical factor

9. Directional Sensitivity

It should be noted that, with the modulation method, the frequency of maximum sensitivity ($\omega = \nu$) is also very nearly the frequency of zero carrier. In other words, at this frequency the modulation frequency fails to appear at the output of the second detector. A small change in the earth's field will cause it to appear. This leads one to suspect that it is only the unbalanced signal (or deviation of the field from the norm) that will vary with direction. That this is so may be seen from two special cases. If the earth's field is in the direction of the axis of the radio-frequency coil, the modulation field acts to change the direction and strength of the field However, only the second harmonic of the modulation frequency appears at the output. The second case is where the earth's field is at right angles to the axis of both coils. In this case also, only the second harmonic of the modulation frequency appears. Thus, since only the unbalance signal is directionally sensitive, only a crude stabilization is necessary. In fact, for those regions where the earth's field is fairly vertical, stabilization is probably not required.

Purcell has pointed out* that there is a velocity stability requirement in addition to the position requirement discussed above. If the apparatus is caused to precess about the magnetic field with a frequency $a/2\pi$, the electrons will react as though the magnetic field were changed by an amount

$$\Delta H = H \frac{a}{\nu} \quad .$$

A crude position stabilization will also reduce this effect sufficiently to make it unimportant.

*In a private communication.

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