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Georgia Institute of Technology
ENGINEERING EXPERIMENT STATION
Atlanta, Georgia

FINAL REPORT

PROJECT A-267

OPERATIONAL ANALYSIS OF PROPOSED DESIGNS FOR RADAR SET AN/TPQ-5( ) SERVICE TEST MODELS

PERIOD 12 JANUARY 1956 TO 12 JULY 1956

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OPERATIONAL ANALYSIS OF PROPOSED DESIGNS FOR RADAR SET AN/TPQ-5( ) SERVICE TEST MODELS

By

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ABSTRACT

An analysis was made of several proposed counterbattery radar configurations to aid the designer in selecting the best arrangement and to examine whether or not even this arrangement is a practical system. Although gaps in knowledge of tactics and of some physical aspects prevented application of a single measure of effectiveness, each influential factor was considered. Expert opinion was solicited whenever possible in such areas as photo-interpretation and camouflage.

The separated antenna system with equipment and operators in a van type trailer was judged the best of the proposed alternatives, primarily because of greater flexibility in its use, better mobility, and better adaptability to camouflage, protection and efficient operation. Even this system however, shows promise of only low effectiveness. Furthermore, as has been emphasized in an earlier study, a CBR must be a very accurate device or it will have no effectiveness at all.

Although a CBR with low effectiveness might have sufficient military value to be considered worth-while, it appears unwise to invest heavily in production of the proposed system when the rewards of increased effectiveness from improved designs would be so great. The recommendations of a previous study still appear valid and timely: an intensive development and testing program is needed with particular attention to miniaturization (for mobility, protection, and ease of camouflage), reliability and achievement of effective target locations at greater rates.

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1. Introduction

1.1 Objectives

The objectives set forth for this study were to provide the basis for decision: first, in the choice between a counterbattery radar (CBR) with a combined search and track antenna system and a CBR with separated antenna systems; second, in the choice of packaging the remainder of the system; and last but most important, in the question of feasibility and practicality of the system.

1.2 Conduct of Study

It was recognized at the outset by General Electric (GE) and the Engineering Experiment Station (EES) that the study proposed would suffer from a severe handicap: the dearth of input information of the sort needed to conduct an analysis with confidence and necessary to develop suitable models for study. Nevertheless, the decisions which must soon be faced in the course of the CBR development program were judged to be of sufficient importance to warrant an effort to make the most out of the few facts and considerable expert opinion available.

The greatest void is in the information needed to develop a satisfactory tactical model incorporating concepts which will dictate the environment of the CBR. The mission and environment of CB artillery in this era of atomic weapons apparently are not yet sufficiently well defined in the military system to permit detailed estimates to be set forth. It must be borne in mind that no real CBR has ever been used, there has been no modern military experience in which our forces were engaged with an artillery-minded enemy, and no battle has yet been fought that employed the concepts of tactical atomic weapons. It is evident that actual field data and experience are lacking.

Extrapolation of related experience and the application of opinions can only be carried so far before confidence in results and predictions wanes rapidly. Therefore, to attempt to evaluate the performance and usefulness of a system not yet designed (and with no field-tested predecessor), in a new military role, and in tactical situations and environments that cannot be well defined is certainly an unappetizing task that has little promise of producing reliable specific results.

However, certain things can be done that might enhance the background of information available to the system designer. Expert opinion in specialized fields can be assembled along with known facts to help make comparisons where the problem is to choose one of several alternatives. To help answer the question of general feasibility or practicality, one can attempt to estimate the performance of a given system in all important aspects, and then one can compare this with an estimate of the performance demanded by the mission in these same aspects. The extent to which such comparisons are favorable or unfavorable should give a basis for decision.

The method of approach selected was that of outlining all the influential factors that should be considered in choosing a packaging arrangement and in deciding feasibility. These factors were organized into groups and subgroups as follows: (1) Performance with subdivisions of Coverage and Time factors, (2) Cost and (3) Flexibility and Other Factors. Each of these groups contains a number of factors which are basically important in analyzing the systems presented.

It would be desirable to relate all these factors on the same scale of measurement so that a single measure of effectiveness could be applied to the various configurations presented for consideration. However, lack of data and lack of reliable models prevent such a classical treatment. The alternative, a qualitative argument supported by some quantitative studies and by consultation with experts, was necessarily chosen.

2. Discussion of Influential Factors

There are two objectives for the discussions that follow, namely, (1) to present the facts that are known about each factor, and (2) to state why and in what way the factors are important.

2.1 Performance

Performance is examined here assuming that specification requirements of range and accuracy will be achieved and that the alternative configurations will be equal in these respects. This stipulation permits consideration to be concentrated on two primary areas of performance: factors involved in coverage and factors involved in operational time.

2.11 Coverage

Coverage in the geographical and geometrical sense for a given physical environment defines that portion of an artillery environment that is potentially "engageable" by a CBR. It was recognized in previous studies that the physical environment introduces a tremendous influence on the usefulness of a specific CBR. This influence is directly discernible in the reduction in the number of trajectories that are potentially usable for location purposes as mask angles are increased and as a CBR is moved away from the zone of contact.

Two important factors contribute to the coverage capability of a CBR. One of these is the range and sector capability which is determined by the technical characteristics of the system. The other is the siting capability which is determined partially by technical characteristics such as the ability to discriminate between targets and ground clutter, and partially by physical aspects such as the ability to move into desirable sites and the ability to be camouflaged and protected there in such a way as to give a reasonable expectation of survival in a battlefield environment.

2.111 Range and Sector Capability

The range to which a CBR can operate effectively is, of course, determined by the target characteristics, the usual radar parameters of peak power, antenna gain, receiver characteristics, etc., and the ability to extrapolate. All of the CBR configurations presented for consideration are assumed to have equal range performance and therefore this important factor is not decisive in comparing the various alternatives. However, it is more difficult to determine if this degree of performance is sufficient for a practical system.

A previous study (1)[†] indicated that a capability of making locations out to a range of about 15 km would enable a CBR to cover most of the important problems in most of the situations involving World War II tactics. A recent Fort Sill study pointed out a need for a location range of 18 km for 75 mm or larger shells or rockets and at least 25 km or preferably 35 km for 100 mm or larger projectiles. It is not possible to evaluate the importance of these range requirements because the tactical background is not available to us. However, if we accept the Fort Sill figures as valid criteria, the range capability of the proposed Service Test Model CBR falls short (and, of course, it has no capability for extrapolation of rocket trajectories).

[†]Numbers in parentheses throughout the report indicate the appropriate work in the list of references.

The sector of coverage of a CBR is the angular sector which can be kept under surveillance and within which target acquisition can be accomplished. The system designers have indicated that the separated-antenna system would permit a sector of coverage of about 30° compared to 20° for the combined antenna arrangement and a "first round acquisition" probability 1.4 times greater for the separated system than for the other. The advantage of the separated system is greatest in these respects when enemy activity is low and when there is great interest in individual rounds. Separation of search and tracking functions permits uninterrupted surveillance during tracking operations, thereby effectively increasing coverage of this type. It is true that where artillery activity is more intense and where the artillery strength is greater, a CBR will be kept busy with acquisitions provided within a smaller sector. However, the separated system can perform as well or better in both situations and therefore appears superior from the standpoint of coverage. The emphasis on this better coverage depends, of course, on the importance attached to the tactical situations. Some military opinions have given considerable weight to the ability to handle light activity. Although this does not seem justified in light of World War II tactics, it cannot be challenged now because of the void in background on tactics in an atomic era.

Lack of this same information makes it virtually impossible to describe quantitatively what the optimum angular sector coverage should be in a practical situation. Certainly the sector of surveillance and acquisition should not be smaller than that necessary to provide sufficient targets to keep the time between effective locations reasonably short for any given tactical situation, and it need not be larger than necessary to cover the area of interest in low activity periods with an economical number of systems. Ideally it appears that the system should have an <u>acquisition</u> sector variable in size between these limits while the area under <u>surveillance</u> is maintained at a maximum.

2.112 Siting Capability

The efficiency and effectiveness of a CBR system that uses a trajectory extrapolation scheme is critically dependent upon the choice of a good operating site. A site which is masked from most of a trajectory by terrain features may not permit the CBR to acquire enough data to adequately reconstitute the initial part of the trajectory in an extrapolation process. The CBR design is important here in eliminating clutter interference and in establishing the criteria for what the CBR must "see" to extrapolate successfully. A CBR that could acquire sufficient data in 2 seconds would be far more flexible in siting than one that requires 8 seconds of smooth data time; likewise, a CBR that could reconstitute 10 seconds of trajectory (in time back towards its origin) would be far easier to site effectively than one that could only reconstruct 4 seconds. However, the nature of a hostile artillery complex is expected to be such that one could not arbitrarily afford to take "second choice" sites even if the CBR performance was greatly improved over that contemplated in the Service Test Model. Every bit of improved performance would be needed to increase the overall CBR effectiveness, which promises to be low at best.

Tables in Annex A show the tremendous influence of mask angle upon the percentage of trajectories that can be used in the artillery model with prospects of successful location for the presently proposed criteria of minimum smooth data time and maximum extrapolation time. The mask in these tables is the combined terrain and radar mask: the terrain and its features contribute a physical line-of-sight barrier, and the technical characteristics of the radar such as the beam width and clutter rejection contribute an additional increment of effective mask. Even for the most optimistic set of CBR technical characteristics, the only way to get moderate effectiveness is to choose optimum sites that have the least mask.

Several severe problems arise in making use of optimum sites. First, it must be possible to physically transport the CBR system to the site. Second, it must be possible to conceal or camouflage the system well enough to prevent deliberate hostile detection and counteraction for a reasonable period of time. Third, it must be possible for the system to be protected well enough to have a reasonable chance of survival in the battle area where it must be used.

The terrain studies show that it is possible to find radar sites with sufficiently small mask angles in almost all landforms provided that hilltops and ridge crests are used. This means that the system must be capable of reaching elevated sites, usually by off-road routes. To do this, the system will need to be even more mobile than the artillery in rugged terrain because the artillery weapons will generally have a much greater choice of sites in more favorable areas. In general, the system can operate in an area if it is sufficiently mobile to reach the optimum elevated site. Thus mobility and not visibility can be expected to keep the system from operating in mountainous terrain. Data showing the relation between terrain roughness and visibility are given in Annex B.

Mobility aspects emphasize the importance of equipment packaging. Where the choice between vehicle types for prime-movers is concerned, these studies supply some assistance in choosing those which will be most mobile. For example, the soils trafficability work discussed in Annex B permits a comparison of performance on slopes as a function of soil type. However, in answering questions on an absolute basis, there are gaps that prevent good quantitative results. These gaps are in the influence of micro-relief and vegetation and in the frequency of occurrence of soil types.

Because optimum CBR sites involve exposure to detection and enemy action, another important physical aspect is the adaptability of the system to camouflage and protection. The application of good camouflage practices will disguise the nature of the system, will conceal it from certain forms of direct observation and will delay the detection of the system by photo-interpretation. Since the CBR must operate on the battleground, these are exceedingly important points.

Good camouflage in the field depends on small size, care in emplacement, care in concealing or disguising approach routes and good general camouflage discipline at all times. Disguise enroute is important in concealing the presence of the system from enemy intelligence; this requires that vehicles with a distinctive appearance be avoided. During operation of the system, moving antenna reflectors would invite detection; therefore, a radome over the track antenna, though difficult to hide with present materials, is preferable to the exposed antenna.

Although there will be many times when track-laying prime movers will be essential, the use of such vehicles enroute and in emplacement invites detection because of the way they disrupt the natural appearance of the area. Personnel of the Camouflage Branch, ERDL, favor emplacement (digging in) by hand labor; experience and studies have shown that this procedure is only slightly more time consuming and far excells in the concealment provided in that there is less disruption to the natural appearance of the site.

The problem of protecting a CBR on the battleground is a serious one inasmuch as sites will be located in areas subject to hostile shelling, strafing and other action even if the system is not detected or recognized. Physical protection can be provided by "digging in," by shielding with sandbags and by making use of natural protective features of the terrain wherever possible. A vehicle configuration that is small and has a low silhouette will, of course, be easier to protect than a larger arrangement. Certainly the system should be well enough protected that operations can be conducted during a battle with reasonable confidence that only a direct hit will seriously disable the system. If this is not done, the system may be put out of action when it is most needed. Annex E gives some insight into the potential vulnerability of a CBR to shell fire.

A short march-order time and a high degree of mobility must be achieved with a CBR if it is to be protected by withdrawal when threatened by enemy patrol action or reconnaissance in force. It must be remembered that the threat of atomic attack may enforce a troop dispersal that would be particularly vulnerable to infiltration by patrols or rapid penetration. An effective CBR would certainly be a high priority enemy target and would have to be defended or withdrawn accordingly.

2.12 Time Factors

It is convenient to classify as time factors several important performance characteristics: transport speed, emplacement and march-order times, reliability, and weather limitations.[†] Each of these factors has an influence on the fraction of total calendar time which can be available for searching and tracking.

The evaluations of these factors which can be made at present do not show up any marked superiority of either of the proposed CBR systems. Time factors are therefore of interest not for comparing systems, but rather for judging the feasibility of either system. In a hypothetical "middle of the road" example described in Annex D it is estimated that as the result of the combined

[†]The CBR system's problem solution rate can also be regarded as a time factor, but one of a slightly different nature. Solution rates are not discussed in this section, but are considered in the model "Battery Acquisition" problem of Annex F.

influences of all time factors, the CBR might be in "ready" condition 66 per cent of the time.

2.121 Movement Time

The process of moving the CBR from one site to another involves three operations: tear-down, transport, and set-up. The times associated with these operations can be lumped together and regarded as "movement time."

Assuming a crew of twelve enlisted men (plus one officer and one noncommissioned officer), GE estimates that under average conditions the time required for setting up and checking the equipment will be about 45 minutes for the combined-antenna system and one hour and 15 minutes for the separate-antenna system.(2) These times do not include allowances for surveying, digging in, or camouflaging. They are therefore limits which might be approached through adequate site preparation prior to the arrival of the radar. Presumably, at least at night, the system could go on the air before the operations vans are dug in and sandbagged and before camouflaging is completed.

As a rough estimate, the time to pack up for an orderly withdrawal can be taken to be about two-thirds of the set-up time: 30 minutes for the combined antenna system and 50 minutes for the separate-antenna system. The figure for the latter system might be shortened if more than twelve men were available. The tear-down time for each antenna unit alone (search, track, or combined) is estimated by Goodyear to be about 30 minutes for a trained crew of eight men.(3)

The time required for transport depends, quite obviously, upon the distance to be traveled, the mobility of the system, and the condition and density of roads in the battle area. Since radar sites must be chosen in elevated postions, the transport route is likely to consist of three legs: an off-road path from the abandoned site to the nearest road, a route by road to a point near the new site, and an off-road path from there to the final position. From studies of road density as a function of population density and local relief, Peltier has concluded that in civilized parts of the world each off-road leg will seldom exceed one mile in length.(4) Even so, the average off-road transport speed can be so slow that the major portion of the total transport time is spent on these legs.

When the movement operation is considered as a whole, it is evident that the march-order and set-up time advantages of the combined-antenna system can be over-balanced by its slower off-road transport speed. The trafficability studies which can be made at the present time, however, lack the detailed "resolution" needed for a meaningful comparison of the two systems in this respect.

Movement time estimates which are too crude to reveal any superiority of one system over the other are nevertheless of value for assessing the general practicality of either system. In the example discussed in Annex D the average movement time is taken to be 3.1 hours and the frequency of movement as once per day. The fraction of total calendar time during which the radar is set up in operating position would then be .87.

2.122 Reliability

In the present study reliability has been given greater attention than other time factors; first, because it is better suited to analytical treatment, and second, because it is spectacularly influenced by design, maintenance, and operation procedures. Without careful attention to such procedures, there appears to be little chance of achieving acceptable performance. A reliability analysis of the AN/TPQ-5( ), made possible by recent studies by Aeronautical Radio, Inc., (5) is presented in Annex C. Reliability predictions have also been made for the AN/TPQ-5( ) by GE.

Among the measures of reliability discussed in Annex C, the following are of particular interest.

(1) Considering breakdown as the only impediment to operation, what is the probability P_e that the radar will be operable at a randomly chosen time? 100 P_e can be interpreted as "per cent operable time."

(2) If the radar is operable at some given time, what is the probability $P(X > \Delta t)$ that it will continue to operate without failure throughout a mission of duration Δt?

The latter probability is determined by the system's mean life between failures (which can be estimated by ARINC's methods), and the former by the mean repair time as well.

Working with the probability of $P(X > \Delta t)$, one can examine the significance of the reliability requirement established for a CBR by the Combat Development Department, Fort Sill: the system "shall be capable of 23 hours continuous operation out of 24 hours, without excessive breakdown." The probability of <u>no</u> breakdown in 23 hours, $P(X > 23)$, is estimated by GE to be 0.9 for a well-engineered AN/TPQ 5( ). This corresponds roughly to a mean life of 10 hours, which agrees with the estimate inferred by ARG, Princeton University, from an analysis of field maintenance data on the M-33 radar.(1) Although "without excessive breakdown" is open to interpretation, this level of reliability is clearly unacceptable. However, GE has further estimated that by providing for preventive maintenance this probability can be raised to .62, corresponding to a mean life of about 50 hours.

While preventive maintenance can thus improve reliability enormously, if one tries to keep the radar on the air continuously there is still a good chance of its being out of order when it is needed most. Suppose, as seems likely, that there will be periods of urgent need of about four hours duration interspersed among longer periods of little or no need. The probability of the radar being operable during all of a randomly occurring four-hour period is the product $P_e \cdot P(X > 4)$ which is listed in the following table.

Mean Repair Time \ Mean Life	10 hours	50 hours
10 hours	.50 x .67 = .335	.83 x .92 = .77
5 hours	.67 x .67 = .45	.91 X .92 = .84

The outlook can be improved if the radar is kept in a standby condition when it is not needed, with only heater voltages applied. The ARINC study indicates that by reducing the heater voltage to .8 of its normal value, standby failures can be made very small. Consequently, if the set is in standby most of the time, P_e approaches unity and the mission survival probability varies between .67 and .92 as the mean life is increased from 10 to 50 hours. The latter figure should be acceptable.

It thus appears that acceptable reliability is attainable through a combination of:

(1) Good design, including component derating and mechanical construction which minimizes susceptibility to shock damage.

(2) Preventive maintenance and built-in testing facilities for detecting incipient failures.

(3) Standby provisions for reducing heater voltages to lower the failure rate during inactive periods.

The differences in reliability for the proposed separate- and combined-antenna alternatives are relatively small; the effects of the measures listed above are much more important than the effects of the slight differences in complexity of the alternate systems.

2.123 Weather Limitations

It has been recognized that a CBR such as the AN/TPQ-5( ), operating on X-band, may be expected to be almost completely useless in the presence of precipitation, even a light drizzle or light snowfall.(6) For this reason the assistance of the Air Weather Service was sought to determine as much as possible about the frequency of occurrence of precipitation on a worldwide basis. Maps of the world which show estimates of the percentage of total time during which precipitation occurs are presented in Annex B, along with a more complete discussion.

In the example of Annex D it is assumed that precipitation occurs 14 per cent of the time, a figure obtained by taking a year-round average over 169 localities in the United States, Europe (including Russia to the Urals), and southeastern Asia. This averaging procedure is a convenient device for arriving at a "typical" figure for purposes of illustration; however, because of the wide variation in climate from place to place and season to season (evident upon inspection of the maps), the result must be interpreted with considerable caution.

2.2 Costs

In passing final judgment on the feasibility of a CBR, someone must compare the cost and effort required to procure and support a CBR with the cost and effort that would be required to achieve the same results by other means. Likewise, a similar comparison between alternate CBR configurations would be helpful in arriving at the optimum choice.

Such comparisons could be very difficult and time consuming if all logistical aspects are thoroughly considered or they could be relatively simple if only rough approximations of magnitude are adequate to supply the basis for decision. In this study, the latter assumption is made. The various cost data and estimates that have been found to be available are assembled in the paragraphs which follow.

2.21 Dollar Costs

The following table summarizes some of the preliminary estimates of CBR cost for the items indicated.

TABLE 1

ESTIMATED DOLLAR COST OF MAJOR ITEMS IN CBR SYSTEM

(Figures Rounded to Nearest $100.00)

Combined System		Separated System	
Radar Equipment	$300,000		$320,000
Prime Movers			
2-M5 Tractors	$ 40,500	6-4 Ton Trucks	$ 64,500
2-4 Ton Trucks	$ 21,500		
Engine Generators			
2-30 kw Diesels	$ 10,000	2-30 kw Diesels	$ 10,000
2-M 18 Trailers	$ 5,300	2-M 18 Trailers	$ 5,300
Total	$377,300		$399,800

The radar equipment costs in Table 1 are preliminary GE estimates of quantity production figures. The engine-generator cost estimates were made after reviewing the costs of somewhat similar Corps of Engineer and commercial power units. Vehicular costs were obtained from the sources indicated in Table 2.

It can be seen that the cost in dollars of the alternative arrangements is roughly equivalent and that the crudity in the estimates of production cost would be large compared to the difference in total costs that are indicated. The small advantages in price of the combined system indicated here could be easily offset as a result of increased flexibility of the separated systems; for example, by operating two trackers with each search system, it might be possible to do the work of 10 combined systems with 10 trackers and 5 search systems. Such examples are merely speculative at the moment since the optimum proportion of systems is yet to be determined, but certainly such considerations must be borne in mind.

TABLE 2

PRIME MOVER COST DATA

Army Designation	Page Number in TM-9-2800-1	Payload Off Highway	Maximum Towed Load (lbs) Off Highway	Procurement Cost†
Tractor, Hi-Speed, 13-Ton M5, A1, A2, A3	124-127	9-11 men	20,000	$20,273.00
Truck, Cargo, 2-1/2 Ton, 6x6, with winch	227	5,350 lbs	4,500	$ 4,818.00
Truck, Cargo, 2-1/2 Ton, 6x6, M35, with winch	231	5,000 lbs	6,000	$ 6,796.00
Truck, Cargo, 2-1/2 Ton, 6x6, M135, with winch	233	5,000 lbs	6,000	$ 6,647.00
Truck, Cargo, 4-Ton, 6x6, with winch	246	8,350 lbs	11,000	$10,745.00
Truck, Cargo, 5-Ton, 6x6, M41, with winch	266	10,350 lbs	15,000	$16,367.00
Truck, Prime-Mover, 6-Ton, 6x6, with winch	276	12,350 lbs	16,500	$15,562.00

†From ORD 5-3-1, 13 October 1955.

2.22 Personnel Requirements

The following table summarizes the estimated CBR personnel requirements to accomplish the functions of emplacement, operation and movement. When the personnel requirements are consolidated, it is evident that a minimum crew size of about 15 men is needed for 24-hour operation of either CBR arrangement. This is consistent with the team size of 15 men for operation of the AN/MPQ-10. It is evident that other specific tasks must be accomplished in addition to those enumerated in Table 3. Camouflage and "digging-in" operations must be carried out during and immediately subsequent to emplacement; security and sentry duty must be performed; and certain "housekeeping" or administrative tasks must be accomplished.

TABLE 3

ESTIMATED PERSONNEL REQUIREMENTS

	Combined System		Separate System	
	Minimum Number of Personnel	Number Rqd. for 24-hour Operation	Minimum Number of Personnel	Number Rqd. for 24-hour Operation
Radar Operations				
(1) Search	1	3	1	3
(2) Track	1	3	1	3
(3) Compute	1	3	1	3
(4) Liaison	1	3	1	3
Power Source Operation	1	1	1	1
Supervisory Personnel	1	2	1	2
Emplacement	12	-	12	-
Prime-Mover Operators	4	-	6	-
Total Men Rqd. for 24-hour Operation		15		15

In addition to the crew needed for operations, personnel will be needed to maintain the CBR. In the past, such technicians were provided in a 2nd and 3rd echelon radar maintenance team of about 6 to 10 men; a team generally maintained a number of radars in a given area and was equipped to move with its maintenance equipment from one radar to another as the need arose. This is the maintenance plan assumed in Annex C. It is not known whether such a plan will be applied to a CBR. However, it might well be that a better arrangement would be to have at least one and perhaps two well trained technicians from a maintenance team stay constantly with each CBR of either configuration. Provisions could be made for assistance and special equipment when needed from the remainder of the team, which could include the better trained and more experienced maintenance supervisors. If the technicians in the depot maintenance shops are also considered, it appears that the prorated requirement for technicians in the field would be about 3 or 4 men per CBR. This number appears consistent with the Naval Electronic Laboratory estimate of "one maintenance technician for each 250 tubes."(7) Certainly the importance of reliability and the key role of preventive maintenance procedures, as described in Annex C, would make it unwise to plan on a weaker maintenance structure.

Thus, the personnel requirements for either CBR configuration add up to a minimum of about 20 men when both operations and maintenance are considered.

2.23 Related Equipment

In addition to basic CBR electronic equipment and the vehicles containing it, an appreciable amount of auxilliary equipment will be required. Two of the major items, prime movers and power units, were considered in paragraph 2.21, Dollar Costs. Other items are: spare maintenance components, tools and test equipment, camouflage material, administrative materials and supplies for "housekeeping," communications and general transportation. Except for the number and type of prime movers, the requirements of either CBR configuration appear to be about the same.

2.24 Resources

Estimates obtained on the amount of manufacturing and material resources required indicate no significant difference for the various CBR configurations.

2.25 Cost of an Artillery Battery

When the end effect of a CBR is interpreted as an increase in effective counterbattery firepower, a CBR can be compared costwise with the equivalent number of batteries it provides.

Table 4 summarizes the cost of Ordnance Corps items issued to an 8-inch howitzer battery. Tools and small arms were excluded from the battery cost tabulation, along with equipment supplied by Quartermaster, Chemical and other services, in the belief that such items would be common to both a radar or a howitzer unit in amounts roughly proportional to the number of men in the units.

Personnel assigned to an 8-inch howitzer battery number 127 men, of which 84 are assigned to the four gun sections.

TABLE 4

ESTIMATED COST OF 8" HOWITZER BATTERY

Description of Item	†Number Issued	††Unit Cost	Total Cost of Item
8-inch Howitzer with Carriage, Limber	4	$60,120	$240,480
Tractor, Cargo Medium (M8E2)	4	56,650	226,600
Trailer, Cargo, 1/4-Ton (M100)	2	271	542
Trailer, Cargo, 1 1/2-Ton	2	978	1,956
Trailer, Water, 1 1/2-Ton (M106)	1	1,132	1,132
Truck, Cargo, 3/4-Ton, 4 x 4 w/w	2	3,757	7,514
Truck, Cargo, 2 1/2-Ton, 6 x 6, lwb, wo/w	1	4,446	4,446
Truck, Cargo, 2 1/2-Ton, 6 x 6, w/w (M34)	2	7,132	14,264
Truck, Cargo, 5-Ton, 6 x 6, lwb, w/w	4	16,367	65,468
Truck, Command, 3/4-Ton, 4 x 4, w/w (M42)	3	3,780	11,340
Truck, Utility, 1/4-Ton, 4 x 4, (M38)	4	2,410	9,640
Aiming Circle	2	516	1,032
Total Cost of Battery			$584,414

†From TO/E 6-417R
††From ORD 5-3-1

2.3 Other Factors

Other influential factors are primarily those in the area of general flexibility. Some of these are in aspects that could have been considered under cost and performance if sufficient quantitative information were available to describe their influence.

The capability of independent surveillance and independent tracking functions provided by the separated antenna systems permits a more efficient and effective utilization of equipment in several respects:

(1) Adjustment missions can be performed with only the tracking system.

(2) General surveillance and "active" battery surveillance missions can be performed with only the search system. Furthermore, search functions are

not curtailed while tracking is in progress. Therefore, surveillance coverage is more continuous.

(3) The ratio of track to search systems can presumably be varied to meet the demands of the tactical situation.

(4) Either the search or the track system can be repaired, modified, improved or replaced independently of the other.

All of the foregoing points support the choice of a CBR with separated antenna systems. There are some features associated with the separated systems that are not particularly desirable, however. Some additional cables are required, thereby exposing the system to a greater risk to damage. A parallax corrector and a survey between the two antenna systems may be necessary if separation of the two systems is relatively large, as might be the case for some acquisition aspects. These undesirable features do not appear to present a serious problem and would be far outweighed by the advantages in flexibility achieved with the separated systems.

3. Evaluation of Influential Factors

Although it was not possible to develop a single measure of effectiveness that would allow the influence of each factor to be introduced in an analytical expression, it has been possible to compare the various alternatives and to consider overall system practicality in light of these factors.

3.1 The Choice of Antenna Systems and Vehicle Types

Two antenna configurations are being considered for the Service Test Model: one arrangement is generally similar to the experimental model AN/TPQ-5(XE-1) in that a combined antenna system is used for both search and tracking functions; the other arrangement provides for completely separate antenna systems for searching and for tracking. The equipment and operations vehicle could be either a van or walk-around type and either of these could be a truck-mounted arrangement, a semi-trailer or trailer.

It is important to keep in mind that only the alternative configurations presented by the equipment designers were considered and compared. In addition, it was necessary to make comparisons by assuming that the performance estimates of the designers would be realized. The choice of either type system on this basis could not be extrapolated to apply unconditionally to all systems purely on the basis of combined or separated antennas. The numerous factors that must be considered could favor either choice depending upon the exact nature and performance of any given configuration.

Impressive arguments in favor of the separated antenna system are presented in the preceding discussions of influential factors. More effective operation can be achieved by the separated system because it is better suited to cope with both the physical and battle environments and because of greater flexibility which permits independent performance of track and search functions.

Experts have predicted greater mobility and better adaptability to camouflage and protection with separated antennas, primarily because smaller vehicle sizes and weights can be achieved with this arrangement. These are extremely important considerations inasmuch as the operational effectiveness of a CBR depends critically on its ability to be located in an optimum site and, once there, to survive in the battlefield environment.

The trafficability studies in Annex B show that when a reasonable choice of wheeled prime-movers is made for both alternatives, the separated system can be expected to negotiate a slope that is about 4 or 5 degrees steeper for the same soil conditions. If both systems are equipped with track-laying prime-movers, the separated system can operate over slopes that are about 5 to 7 degrees steeper. The landform studies in Annex B (Figures B-2 and B-3) show that these differences in negotiable slope may be quite significant in all landform classes, and particularly in the lower land forms characterized by Millen, Georgia and Chocowinity, North Carolina. The frequency of occurence of various slopes is given for six typical terrain types in Annex B, Figures B-2 and B-3. From these figures the reader can determine the slopes that will be encountered in these landforms.

Since enemy counteraction can be expected to cause frequent relocations, it is also important that off-road movement be accomplished with reasonable speed and without elaborate route preparation. It is clear that if all other factors were equal, the system with the greater mobility as evidenced by the greater gradability, lower center of gravity and lesser weight would have a decisive operational advantage when considered over a large number of varied engagements.

Camouflage and photo-interpretation experts have judged the separated system to be better adapted for battlefield survival. Although such a system would eventually be located by the enemy, better adaptability to camouflage would allow a longer time for operation before relocation was forced by the enemy. The system with the smaller equipment size would also be easier to "dig-in" or sandbag for protection against shell fragments.

Figure 1 is presented to display the factor-by-factor comparison of the two types of antenna systems. Plus (+) signs indicate an advantage in the factor concerned, minus (-) signs indicate a disadvantage, and zeros (0) indicate no significant differences. In only one case is the advantage in favor of the combined antenna system, whereas eight of the 17 factors listed favor the separated system. The preponderance of advantage is such that no weighting factors are needed to show the superiority of the separated system.

After the choice of antenna system is made, the method of packaging the rest of the system must be selected. Here again mobility considerations and adaptability to camouflage and protection are primary considerations.

Certainly, flexibility in the choice of prime movers would adapt the system to a wider range of terrain types and situations. Although a truck might be the normal prime mover, micro-relief characteristics in some regions might dictate that a track-laying prime mover be used. General off-road mobility and maneuverability must be achieved through good gradability, low weight, small size, low center of gravity and good suspension characteristics. Some of these same characteristics would, of course, increase the adaptability to camouflage and "digging-in."

Figure 2 presents a comparison of these factors for trailer, semi-trailer and self-propelled vehicle arrangements. As in Figure 1, plus signs (+) indicate an advantage and zeros (0) indicate no significant difference.

The overall advantage of a trailer arrangement is apparent. The greatest flexibility in choice of prime-movers is, of course, achieved with a trailer; a semi-trailer when used with a "dolly" could, of course, be pulled by the same prime-movers but the maneuverability is limited to that of a 2-axle trailer. The self-propelled arrangement is the least flexible.

Off-road mobility is difficult to disassociate from prime-mover performance; the overall height, gradability and center of gravity of the whole combination are important. The advantages of the self-propelled arrangement on smooth

				Separated Antenna System	Combined Antenna System
Performance	Coverage	Siting Capability	Mobility	+	-
			Adaptability to Camouflage	+	-
		Geographical Coverage	Range	0	0
			Sector Size	+	-
	Time Factors		Rapid Emplace and Displace	-	+
			Rapid Movement	+	-
			Reliability	0	0
			Weather Influence	0	0
			Operational Rate, Dense Activity	0	0
			Operational Rate, Light Activity	+	-
Cost Factors			Procurement Cost	0	0
			Personnel Cost	0	0
			Auxilliary Equip. Cost	0	0
			Resources Cost	0	0
Flexibility Factors			Independent Performance of Major Functions	+	-
			Optimum Use of Equipment	+	-
			Adaptability to Other Functions	+	-

Figure 1. Comparison of Influential Factors for Choice of Antenna System Arrangement.

slopes could be offset in more rugged terrain by poor side-slope characteristics and poor clearance of overhead obstructions. For best all-around performance, a trailer with a prime-mover selected to suit the situation at hand seems to be best. Maneuverability is influenced by these same considerations.

	Trailer	Semi-Trailer	Truck Mounted
Flexibility in Choice of Prime Mover	+	-	-
Off-Road Mobility and Maneuverability	+	-	-
Adaptability to Camouflage	+	+	-
Adaptability to Protection and Emplacement	+	+	-
Rapid Emplacement and Displacement	-	-	+

Figure 2. Comparison of Influential Factors for Choice of Equipment and Operations Vehicle Type.

A trailer with its lower silhouette is better adapted to camouflage and "digging-in;" a truck-mounted arrangement with its high silhouette and greater overall size would be the most difficult to protect. However, a self-propelled arrangement would have some advantage in rapid displacement. If the equipment trailer was the slowest part of the system in this respect, some weight would be due this consideration, but the march order time for the antenna trailers appears to be the determining factor in overall system displacement.

In this limited study it was not possible to compare the merits of single-axle trailers with those of other arrangements. Experts have commented on the better riding qualities of multiple axle trailers or trailers with bogie suspensions, but while these arrangements are better adapted to go over rough ground, they are generally not as maneuverable. A track-laying, self-propelled and armored arrangement might be worthwhile for a certain percentage of the CBR's for use in difficult situations; there would be no advantage in this, however, unless the antenna systems were similarly packaged.

There remains the choice between van type or walk-around type trailers. The van type offers obvious advantages in operator efficiency, in ease of maintenance and in rapid emplacement or displacement. Operation under black-out conditions is simplified as are heating and cooling problems, when a van is used. A walk-around arrangement offers some advantage in adaptability to camouflage and protection when comparison is with a large van; this advantage disappears as the van size is made smaller. The comparison of factors in Figure 3 indicates that the van type trailer is the better choice.

	Van Type	Walk-Around Type
Operator Efficiency	+	-
Adaptability to Protection and Emplacement†	0	0
Adaptability to Enroute Disguise	+	-
Adaptability to Camouflage†	0	0
Flexibility in Prime-Mover Choice	0	0
Equipment Reliability and Ease of Maintenance	+	-
Rapid Emplacement and Displacement	+	-
Dollar Cost	0	0

†In this comparison it is assumed that the van size would be relatively small and that special efforts would be made to keep the van height to a minimum (not over about 9 ft.).

Figure 3. Comparison of Influential Factors for Choice of Equipment and Operations Trailer Type.

3.2 Evaluation of Feasibility

To determine whether or not the proposed CBR is a practical military system requires, first, an estimate of the effectiveness of the system, and second, a decision as to whether or not such effectiveness is worth the cost it entails. Unfortunately, serious gaps exist in the definition of the tactical environment and to an extent, in the physical environment. These deficiencies in data preclude establishment of a single measure of effectiveness that would allow a clear-cut rating of a CBR. However, it is possible to present a general qualitative picture, based on the influential factors previously discussed, that should at least permit judgment of whether the effectiveness is nil, low, moderate or good.

Any picture of effectiveness must be based, first of all, on the assumption that the technical performance in accuracy, range, etc. stated in the specifications will be met. Next, a CBR with these technical characteristics and packaged in the better of the alternatives discussed above, (i.e., with separated antenna systems and with van type trailers) can be considered in a physical and tactical environment to answer two important questions: What portion of the time can a CBR be expected to be available for useful operation, and what capacity does it have for providing usable locations during this period of time?

The first question can be conveniently approached by using a "middle-of-the-road" model incorporating the major predictable factors influencing operable time. This was done in Annex D. Under the conditions assumed in the model, it appears that over a long period, a CBR might be in a "ready" condition about 2/3 of the time and that variations in maintenance and standby techniques could cause this figure to be as low as 1/2 or as high as 3/4. (It must be remembered, however, that since advance knowledge and some control exist in the initiation of offensive action, some of the controllable dead times might be scheduled to occur at unimportant time periods.) The average time estimated to be available for operation in the model would be degraded by the amount of time lost as a result of the following:

(1) Time spent in awaiting darkness to emplace the system.

(2) Time out of action as a result of hostile attack or damage.

(3) Time out of action as a result of impassable terrain.

(4) Time out of action for major overhaul.

It is apparent that enemy action, adverse weather, etc. could keep the CBR out of action for considerable periods of time and these periods might be times of great need. Increasing the number of CBR systems assigned to an observation battalion might enable the location capability to be maintained during movement, repair and battle loss, but equipment redundancy would not help during rains or in situations where routes to usable sites were impassable.

The artillery model of Annex A gives indication of what can be expected in operational effectiveness. Even if the very best sites are used (those within 4000 yds of the zone of contact having combined radar and terrain masks of between 50 and 100 mils) only about 20 per cent to 55 per cent of the enemy artillery trajectories might be "visible" to the CBR and, since some of these would not be suitable for extrapolation, a total of about 5 per cent to 55 per cent might yield successful locations. Tables A-4 and A-5 of Annex A show how much this already low ability to engage enemy trajectories is deteriorated as mask angle and CBR distance from the zone of contact are increased.

The outlook is even more grim as a result of several factors which degrade the effective operational rate of producing usable locations:

(1) Part of the CBR time will be wasted with trajectories that are visible and acquirable but which, for various reasons such as multiple target interference, might yield poor tracking data or with trajectories that are seen too late or for too short a time to be successfully extrapolated by the CBR.

(2) Part of the CBR time will be wasted as a result of redundant location of the same batteries. In the model considered in Annex F, the loss of efficiency from this effect is appreciable. Even in those cases where all visible trajectories are usable, location of 90 per cent of the accessible batteries requires acquisition of 2.5 to 4 times that number of projectiles.

(3) Part of the CBR time will be wasted when rocket and mortar projectiles are acquired.

(4) An effective CBR would prompt enemy countermeasures such as those enumerated in the A-108 report,[1] which would interfere with the operational rate of the system.

Although the CBR rate of operation is such that about 1 minute is required for a complete operational cycle, the foregoing factors lead to the estimates that the maximum effective rate of operation in active combat situations, even with good search and acquisition features, might be degraded by a factor of 3 to 5 from the rate established by the equipment alone. This means that a CBR (with one tracker) might be expected to yield on the order of 10 to 20 usable locations in an hour if the enemy exposed his artillery enough for this to be possible. While this location rate may be more acceptable for the "open" type disposition of weapons expected in an "atomic war" than World War II tactics, it shows that a good portion of the hostile artillery can conduct fire for an appreciable time before counteraction can be initiated. Additional trackers could be provided in a given area to compensate for some of the degrading factors so that more batteries are located in a short time. However, there would always remain a large portion of hostile artillery with fire missions that would not yield trajectories suitable for use by a CBR of the type under consideration.

The preceding paragraphs show that the CBR effectiveness can only be described as low. Assuming perfect technical performance, the outlook is discouraging:

1) The system will be completely useless part of the time because of weather, part of the time because it will be immobilized in difficult terrain, and part of the time for major overhaul.

2) It will almost always be difficult to move into position and to emplace the system in effective sites.

3) The enemy can certainly locate the CBR without great difficulty or delay and can attack the system with good probability of success. The very best in camouflage techniques will be required but even these will only "buy time." The vulnerability of portions of the system can be reduced by thorough "digging-in" but the antenna systems must remain exposed.

4) The system will be out of operation a good portion of the time under ideal conditions, especially in fluid situations; even when it is operating it can only deal effectively with a small percentage of the hostile batteries, and this can only be accomplished at a relatively slow rate.

The picture is not complete, however, unless the cost aspects are considered. To do this, it is convenient to consider the CBR as a tool which increases the effectiveness of the artillery it supports. The dollar procurement cost for major items of equipment in an 8-inch Howitzer battery is about $580,000; this could be considered as an investment in firepower which the military planners are willing to make independently of the cost of supporting such a battery in the field. A CBR, including major items of equipment, is estimated to cost about $400,000 with one tracker, or about $650,000 with two trackers. It can be seen, therefore, that a CBR would be a worthwhile investment if it provided an increase in effective firepower equivalent to about one battery of heavy artillery. If the increased location accuracy provided by the CBR enabled a counterbattery battalion, for example, to achieve the same effect on a target with concentrations of 24 rounds instead of 36 rounds, the same battalion could fire on 15 targets in an hour instead of 10 targets. This increase in effective firepower is, at least, crudely equivalent to adding 1 1/2 batteries. An examination of the effect of increasing system accuracy is contained in the A-108 report.(1) (This is the accuracy of the over-all process of locating one weapon of a battery and centering a pattern of fire upon it.) It can be shown from the work there that to maintain a high probability of covering most of a typical target area with a density of fire sufficient for neutralization would require a counterfire concentration of eight battalion volleys if system errors were circularly distributed with a standard deviation of 75 meters; but if the standard deviation could be reduced to 50 meters, only four volleys would be needed.†

A brief glance at some of the other costs involved is enlightening. There are approximately 127 men in an 8-inch Howitzer battery contrasted with about 20 to 25 for a CBR; a battery can fire about $10,000 to $15,000 worth of ammunition in just one hour. It is readily apparent that at least one, and probably several, CBR's could be supported for the costs of maintaining one 8-inch Howitzer battery.

On a dollar basis alone, it is obvious that the expenditure of large amounts of money is justified to gain additional artillery effectiveness for counterbattery artillery. In other words, it appears possible to justify even a CBR with low effectiveness if cost is the criterion. However, there is evidence that, at least on certain occassions, counterbattery efforts have been almost completely ineffective. ORO studied the problem of counterbattery effectiveness for certain periods in Korea(8) and found no evidence

†The estimated shell density required for neutralization has been revised from one round per 400 square meters to one round per 800 square meters at the suggestion of CDD, Ft. Sill. The latter figure is used here.

of appreciable neutralization, although over 10 per cent of the corps artillery and 20 per cent of the division artillery ammunition was expended in counterbattery fire. This poor effectiveness is attributed largely to the inaccuracy of counterbattery fire. It would seem, therefore, that the CBR, even with low effectiveness, would be worth far more than is first apparent: it would not only give the additional effective firepower of one or more batteries, it could conceivably, through both the target location and adjustment roles, give some effectiveness to the entire counterbattery organization in situations where effectiveness normally might not exist. It is critically important to realize that the effectiveness anticipated here is that resulting from attainment of high location and adjustment accuracy; as pointed out in the A-108 report,[1] the effectiveness vanishes if this accuracy is not achieved.

In summary it can be seen that the proposed CBR can be expected to have only a low effectiveness as a target location device. Although even a small increase in effectiveness would be worth much to the artillery forces, it does not necessarily follow that the CBR should be procured in quantity. The rewards of improved designs could be so great that it appears best to suggest that the military procure only the very minimum amount dictated by their estimate of necessity and that great effort should be applied toward the development of a more effective CBR.

Nothing has occurred in the program to date to suggest any changes in the basic recommendations of the A-108[1] report which emphasized the necessity for a strong research and development program coupled with vigorous testing and experimentation.

In suggesting specific ways to achieve greater usefulness, it should be pointed out here that:

1) Many of the reasons for low CBR effectiveness are associated with the physical configuration of the system. All of the problems of mobility, vulnerability and camouflage are those created primarily by equipment size and weight. Although the separated antenna system is somewhat smaller than the combined antenna system, a CBR much smaller than either of these arrangements

is demanded by tactical considerations. A vigorous miniaturization program certainly holds promise of a superior system.

2) Reliability has been shown to be sufficiently important to warrant provisions for preventive maintenance and for methods to give further increases in reliability during stand-by periods.

3) Location effectiveness could be improved by providing the ability to acquire targets closer to the terrain mask, to extrapolate over greater periods of time, and to extrapolate trajectories that are seen for a shorter time. Operational efficiency could be improved by providing means for rapidly recognizing and discriminating against mortar and rocket projectiles and artillery trajectories that are corrupted by multiple target interference.

4) Development work should include attention to the design and testing of features which will give adaptability to camouflage, emplacement and protection. Particular attention should be given to the development and testing of radomes that have good camouflage characteristics.

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(6) Semi-annual Report, Project A-190, Operational Analysis for a Counterbattery Radar, Georgia Institute of Technology, 1955, Secret.

(7) U. S. Navy Electronics Laboratory, NEL Reliability Design Handbook, San Diego, California, 1954.

(8) Operations Research Office, The Effects of Counterbattery Fire, Johns Hopkins University, Technical Memorandum ORO-T-284, June 9, 1954, Confidential.

ANNEX A. THE ARTILLERY ENVIRONMENT

Inasmuch as a CBR is a tool to aid the artillery forces, its design and operation should be patterned by the mission of the artillery to be supported. However, it is not a simple matter to describe the artillery mission in specific terms. The advent of tactical atomic weapons has produced a period of flux both in military organization and in the tactical concepts governing the employment of combat forces and their supporting elements such as counterbattery artillery. Because of these factors, it has not been possible to obtain more than broad generalizations concerning the battle environment which should be considered in designing a CBR. The artillery forces must tailor their operation primarily to accommodate the tactics of the infantry elements; until such time as the friendly and hostile infantry tactics become clear, it probably will not be possible to accurately describe the combat environment in a realistic manner.

For analysis purposes, it is desirable to use an artillery environment model; this was done in a previous study (Project A-108)* utilizing concepts applicable to World War II. Although it was not possible to determine which new concepts should be applied to completely modernize the model, some of the more recent estimates of possible Soviet artillery usage made by personnel at Fort Sill were incorporated.

Artillery Strength of Soviet Field Organizations. The recent study conducted by the Combat Development Department, Ft. Sill, includes an estimate of the artillery strength to be expected in a Soviet Field Army. The organization of the Soviet Field Army is indicated to be very similar to

*Final Report, Project A-108, Operational Research Study for a Counterbattery Radar, Georgia Institute of Technology, 1954, Secret.

that assumed in the A-108 study; it includes an artillery division and three corps of two rifle divisions and one mechanized division each.

Table A-1 is based on the Ft. Sill estimate and shows the numbers of artillery weapons that might be found in a Soviet Field Army.

Table A-2 compares the Ft. Sill estimate and the A-108 study in the numbers of artillery weapons that might be on a division front if all the artillery in a Field Army were equally distributed along the front. The differences are slight and indicate that the same background material was applied in both areas.

Weapon Distribution and Firepower. Ft. Sill estimates that weapon disposition will probably be essentially the same as that previously accepted for extended positional defense. The maximum tube density predicted at Ft. Sill is 125 tubes per 1000 yards of front. This figure, if assumed to include mortars, rocket launchers, and self-propelled guns, implies a minimum Soviet divisional frontage of about 3000 yards for a division slice of about 375 tubes (including mortars, etc.). This density was considered to be an extreme at Ft. Sill and therefore our model here should start with this figure as a maximum in calculating weapon densities. This disposition is generally comparable to the situations shown for "Hostile Defense" in the A-108 report.

By reference to Figure 36 of the A-108 report it is possible to obtain estimates of weapon density for various divisional frontages. The recent Ft. Sill estimate of deployment in depth also corresponds to the estimates presented in Figure 37 of the A-108 report. The similarity in all respects is sufficient to warrant direct use of that portion of the A-108 material dealing with Soviet defensive situations. A tabulation of the number of batteries and firepower per 1000 yards of front for various frontages is given in Table A-3.

The assumptions for combat organization and assignments of fire missions in the A-108 study appear to be valid in this application also since they are based on weapon capability and basic doctrine. The rates of fire used in the artillery model are, of course, those defined by

TABLE A-1

AN ESTIMATE OF TYPICAL SOVIET ARTILLERY STRENGTH

TOWED FIELD ARTILLERY	NUMBER OF TUBES IN SOVIET FIELD ARMY FRONT			NUMBER OF TUBES IN SOVIET DIVISION FRONT		
	Forward Zone	Reinforcing Zone	Total	Forward Zone	Reinforcing Zone	Total
85 mm and 100 mm Guns	312		312	52		52
122 mm How	352		352	59		59
122 mm Gun		64	64		11	11
152 mm Gun/How		63	63		10	10
152 mm How		64	64		11	11
152 mm Gun		64	64		11	11
203 mm Gun/How		48	48		8	8
Total Tubes	664	303	967	111	51	162
Total Batteries (average of 4 tubes/battery)	166	76	242	28	13	41
Mortars and Other Weapons (Does Not Include Anti-tank, Tank or AAA):						
82 mm Mortar	786		786	131		131
120 mm Mortar	270		270	45		45
160 mm Mortar	72		72	12		12
300 mm Mortar	32		32	5		5
132 mm R.L.		36	36		6	6
85 mm S.P. Gun	108		108	18		18
Total Tubes	1268	36	1304	211	6	217

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TABLE A-2. Comparison of Estimates of Soviet Artillery Strength in a Soviet Division Front.

Type of Weapon	Recent Ft. Sill Estimates	Project A-108 Estimates for Defense	Difference in Estimates
76 mm, 85 mm or 100 mm Gun	52 tubes	54 tubes	
122 mm How	59	76	
122 mm Gun	11	---	
Total Light Artillery	122	130	8 tubes
152 mm Gun/How	10	24	
152 mm How	11	10	
152 mm Gun	11	—	
203 mm Gun/How	8	8	
Total, Medium and Heavy Artillery	40	42	2
Total Towed Artillery (tubes)	162	172	10
Total Towed Artillery (batteries of 4 tubes)	40 1/2	43	2 1/2

TABLE A-3. Estimated Battery Density and Firepower for Typical Soviet Artillery Disposition.

Corps Front	Division Front	Battery Density (approx.) per 1000 yds of front.	Max. Rate of Fire per 1000 yds of front (rounds/min.)	Max. Sustained Rate of Fire per 1000 yds of front (rounds/min.)
6,000 yds	3,000 yds	13	600	75
10,000	5,000	9	400	50
20,000	10,000	4 to 5	200	30
30,000	15,000	3	140	20
40,000	20,000	2	60	10

weapon characteristics. In practice, these maximum rates could be expected at times during important situations if the ammunition is available at the weapons. Lesser rates could be expected frequently and these can always be expressed as percentages of the maximum rates to adapt the model to the particular situation desired.

The Artillery Environement as Seen by the Radar. Only a fraction of the trajectories fired by the hostile artillery complex will be visible to a CBR. Estimates of what a CBR might see were made in the course of Project A-108, based on the model distribution in depth and likely fire missions of towed artillery. (Weapons used in a direct-fire role, perhaps 20 to 30 per cent of all artillery, were excluded because their trajectories are expected to be completely masked.) The results of this analysis appear to be generally applicable to the revised artillery model, and are summarized in Table A-4. The percentages listed indicate how many projectiles, of all those fired within a rectangular slice of enemy territory extending back 11,000 yards from the zone of contact (Z/C), are expected to rise above the mask. Here it is assumed that weapons of various types fire at rates proportional to their maximum sustained rates of fire. Figures are given for two opposite extreme cases: first, where all weapons carry out their assigned missions using the maximum possible charges (condition for worst visibility); and second, where all weapons use the minimum possible charges (condition for best visibility). The mask angles considered are the total mask, the sum of the terrain mask and the additional amount by which the radar beam must be elevated to clear the terrain.

Of the trajectories which are visible, not all will be suitable for successful extrapolation. For the presently proposed AN/TPQ-5, a "usable" trajectory is defined by the following criteria: (1) the projectile must be visible long enough for the radar to obtain six to eight seconds of smooth tracking, and (2) for accurate location, the time of flight to the midpoint of the tracked interval must not exceed ten seconds. Again the results of the A-108 study apply. Table A-5 shows an estimate of how many trajectories satisfy these conditions.

TABLE A-4. Estimate of Percentage of Trajectories Visible to Service Test Model CBR.

	Radar Location (from Zone of Contact)			
	4,000 yds.		6,000 yds.	
Mask Angle	Max. charge	Min. charge	Max. charge	Min. charge
50 mils	45 %	54 %	20 %	54 %
100 mils	20	45	6	33
150 mils	6	30	4	20

TABLE A-5. Estimate of Percentage of Trajectories that are Useable by Service Test Model CBR.

	Radar Location (from Zone of Contact)			
	4,000 yds.		6,000 yds.	
Mask Angle	Max. charge	Min. charge	Max. charge	Min. charge
50 mils	20 %	54 %	6 %	45 %
100 mils	4	17	4	4
150 mils	1	2	0	0

These results can be extended to show what a CBR might see within a single wedge-shaped search sector. Table A-6 summarizes the situation for a radar 4000 yards behind the Z/C, with a 30° search sector. The first two columns show how sources of fire within the sector are distributed in depth. The remaining columns show the visible and usable percentages of total sector fire contributed by each class of artillery. The latter figures can also be expressed as percentages of total visible fire, as in Table A-7.

TABLE A-6

MODEL CLASSIFICATION OF FIRE FROM SOURCES WITHIN A RADAR SEARCH SECTOR

Distance from Radar to Zone of Contact = 4000 yards

Search Sector - 30°

ZONE Kiloyards from Z/C	PERCENTAGE OF TOTAL SECTOR FIRE	PERCENTAGE OF RADAR SECTOR FIRE VISIBLE				PERCENTAGE OF RADAR SECTOR FIRE USABLE			
		50 mil Mask		100 mil Mask		50 mil Mask		100 mil Mask	
		Best Case	Worst Case	Best Case	Worst Case	Best Case	Worst Case	Best Case	Worst Case
0 to 2 Direct-Fire; Not Considered									
2 to 5 Light	84.8	42.2	36.4	33.4	12.3	42.2	12.3	12.3	0
5 to 8 Medium	12.4	12.4	9.2	12.4	9.2	12.4	9.2	7.1	4.0
8 to 11 Heavy	2.8	2.8	1.4	2.8	1.4	2.8	1.4	1.4	1.4
Totals	100.0	57.4	47.0	48.6	22.9	57.4	22.9	20.8	5.4

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TABLE A-7

MODEL CLASSIFICATION OF VISIBLE FIRE WITHIN A RADAR SEARCH SECTOR

Distance from Radar to Zone of Contact = 4000 yards

Search Sector - 30°

ZONE	PERCENTAGE OF TOTAL VISIBLE FIRE				PERCENTAGE OF TOTAL VISIBLE FIRE WHICH IS USABLE			
Kiloyards from Z/C	50 mil Mask		100 mil Mask		50 mil Mask		100 mil Mask	
	Best Case	Worst Case	Best Case	Worst Case	Best Case	Worst Case	Best Case	Worst Case
0 to 2 Direct-Fire; Not Considered								
2 to 5 Light	73.5	77.4	68.7	53.7	73.5	26.2	25.3	0
5 to 8 Medium	21.6	19.6	25.5	40.2	21.6	19.6	14.6	17.5
8 to 11 Heavy	4.9	3.0	5.8	6.1	4.9	3.0	2.9	6.1
Totals	100.0	100.0	100.0	100.0	100.0	48.8	42.8	23.6

ANNEX B. THE PHYSICAL ENVIRONMENT

The physical environment of a military system may be thought of as the collection of environmental elements that are not produced by combat activities. Thus the so-called physical environment includes factors such as the landform, the vegetative cover, the soil structure and composition, the weather, the network of roads existing prior to the military engagement, and other similar elements. The physical environment therefore is to be distinguished from the combat environment which is composed of elements produced specifically by combat activities.

If a precise quantitative description of the physical environment could be constructed from maps, aerial photographs, geological data, and other data, then the problems of operational analysis and system design would be greatly simplified. Unfortunately, however, no complete analytical framework exists for studying the effects of physical environment during the design phase of military equipment. Some impressive steps have been taken in this direction, notably by Dr. L. C. Peltier of the U.S. Geological Survey, but there remain many gaps in the quantitative description of the physical environment. Elements of the physical environment such as micro-relief (e.g., local irregularities in the terrain such as ditches, boulders, etc.), vegetative cover, and distributions of soil types have not been studied with a view toward systems-design and operational analysis. Personal judgment and experience must be relied on in assessing these factors. On the other hand, the elements of landform, weather, and the relation between soil strength and trafficability have been analysed and studied in such a way that quantitative data are available for analysis. The following sections of this Annex will describe these data and the methods by which the data were obtained.

1. The Landform Analysis. A most useful method for classifying and analysing landforms has been developed by Peltier[†] at the U. S. Geological Survey. The

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[†]Peltier, L. C., Terrain Components in Operational Research, Military Geology Department, U. S. Geological Survey, unpublished. See also Final Report, Project A-108, Operational Research Study for a Counterbattery Radar, Georgia Institute of Technology, 1954, Secret.

starting point for Peltier's investigation is the definition of a measure of landform structure that is easily obtained from contour maps and which correlates well with the many characteristics of landform that are important in operational analysis and system-design. Such a measure is the so-called local relief. The local relief is defined as the maximum difference in elevation of two points within a one-mile square. A given map, or section of a map, may be said to represent homogeneous terrain if the variation in local relief is small for all the one-mile squares that cover the area under consideration. Once certain areas of homogeneous terrain have been established, other characteristics of the landform may be measured in these areas. Peltier found that the mean local relief for a homogeneous area correlated well with measured values relating to many other landform properties. For example the mean local relief has been correlated with the following landform properties among others:

Distance across valleys
Height of valley walls
Mean slope
Number of drainageways per mile
Extent of visibility

Thus an estimate of the above quantities for a given area may be obtained easily by measuring the mean local relief and using the empirical results which describe the correlation. Regions in which a transition takes place from one roughly homogeneous terrain to another cannot be handled in this way, of course. Such transition regions must be studied separately, and the landform properties must be measured directly on specific maps. If necessary, the analysis could be extended to cover a set of typical transition regions, but this problem has not yet received much attention.

Peltier has organized homogeneous terrain samples into classes numbered one through nine and each of these classes has been given a descriptive title. Table B-1 shows this classification system. As can be seen, the lower boundary of the first class is zero and for each of the other classes the lower boundary is given by

$$B = 2^{N-1} (10).$$

Here B is the value of the lower boundary and N is the class number. A linear relationship between class number and class boundaries was found to be less satisfactory because a very large proportion of the interesting landform types were relatively flat. This resulted in either most of the interesting terrain samples falling into the first few classes or, if the interval was made smaller, extremely high class numbers were necessary for mountainous terrain.

TABLE B-1

HOMOGENEOUS LANDFORM CLASSIFICATION

Landform Type	Landform Class	Class No.	Range of Local Relief	
Plains	Flatlands	1	0-19	ft/mi^2
	Low Plains	2	20-39	"
	Plains	3	40-79	"
	Rolling Plains	4	80-159	"
Hills	Hills	5	160-319	"
Mountains	Low Mountains	6	320-639	"
	Mountains	7	640-1279	"
	High Mountains	8	1280-2559	"
	Very High Mountains	9	2560→	"

Contour maps that provided typical examples of six of these classes were used in the study of landform characteristics important to the CBR problem. These maps and the class they represent are shown in Table B-2.

TABLE B-2

EXAMPLES OF HOMOGENEOUS TERRAIN TYPES

Example (USGS Quadrangle Maps)	Class No.	Landform Class	Local Relief (ft/mi^2) Mean	Std. dev.
Chocowinity, North Carolina	1	Flatlands	13	8.7
Millen, Georgia	3	Plains	70	20
Marble Hill, Missouri	5	Hills	176	47
Mannington, West Virginia	6	Low Mountains	468	58.9
Klondyke, Arizona	7	Mountains	850	310
Montezuma, Colorado	8	High Mountains	1648	400

In the CBR problem it is most important to determine measures of the following quantities from a landform analysis: (1) the visibility of initial portions of the enemy trajectories, (2) the distribution of ground slopes, and (3) the distance across valleys. Measures of each of these three quantities have been defined, and numerical values have been obtained by sampling on each of the homogeneous terrain maps listed in Table B-2.

The visibility analysis was performed by simulating on the maps the selection of a radar site subject to realistic constraints. First, a point was chosen at random on a map and a square, one mile on a side, was drawn with its center on the randomly selected point. Second, a direction was selected at random and a radar site chosen within the one-mile square to give maximum visibility in the randomly selected direction (termed the principal direction). Once the radar site was selected in this manner, the following quantities were measured:

Mask Angle - The angle subtended by some hill or ridge obstruction when viewed from the radar antenna. See Figure B-1. The radar antenna was assumed to be at a height of 15 feet above the ground.

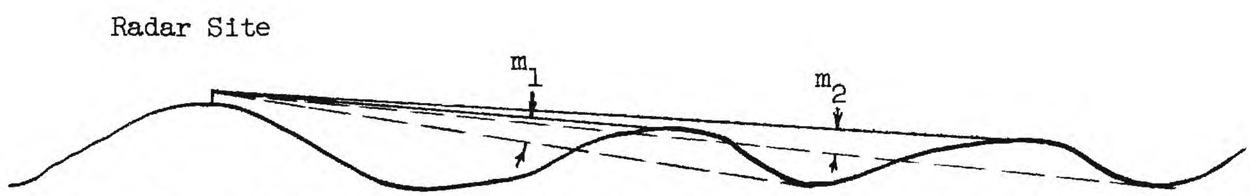

Figure B-1. The Mask Angle. The angles m_1 and m_2 are the mask angles of the first and second hills respectively.

Optimized Mask Angle - The mask angle of some hill or ridge when viewed along the principal direction.

Mean Optimized Mask Angle - The average of the optimized mask angles of hills found on the transect from 1000 to 6000 yards from the radar site.

Greatest Optimized Mask Angle - The largest of the optimized mask angles of hills found on the transect from 1000 to 6000 yards from the point of origin.

The values for these quantities as determined by the sampling procedure are given in Table B-3. The number of sites used on each map was 6 to 10.

Table B-3

RESULTS OF VISIBILITY STUDY

Terrain Sample	Landform Class	Mean Optimized Mask Angle (Degrees)	Greatest Optimized Mask Angle (Degrees)	Greatest Optimized Mask Angle (30° Sector) (Degrees)	Number of Transects Used	
Montezuma, Colorado	High mountains	5.03 2.60	6.45 3.05	7.74 3.16	8	Mean Standard dev.
Klondyke, Arizona	Mountains	1.796 1.72	3.84 2.12	5.54 2.19	7	Mean Standard dev.
Mannington, West Virginia	Low mountains	1.422 .83	3.25 1.09	3.74 1.52	6	Mean Standard dev.
Marble Hill, Missouri	Hills	.638 .56	1.27 .79	1.41 .89	8	Mean Standard dev.
Millen, Georgia	Plains	.155 .108	.27 .10	.44 .18	10	Mean Standard dev.
Chocowinity, North Carolina	Flatlands	.037 .04	.06 .06	.09 .05	10	Mean Standard dev.

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Note that the various types of mask angles increase uniformly with the mean local relief. Also note that the greatest mask angle in a 30° sector is not very different from the greatest optimum mask angle, indicating that the sites give good visibility within the 30° sector centered on the principal direction.

The distribution of ground slopes was also found by a sampling procedure. The slope was measured at a regular pattern of points formed by the intersections of north-south lines and east-west lines spaced one mile apart. This gave about 220 points on each map. The slope was measured by finding the minimum spacing between contour lines in the neighborhood of the point and dividing by the elevation difference indicated by the two contour lines. The resulting slope distributions for each of the six representative maps are shown in Figures B-2 and B-3.

The distances across valleys were obtained by sampling the distance from one high point to the next adjacent high point on randomly placed straight lines. The results of these measurements are shown in Table B-4. These distributions are broad as evidenced by the large values of the standard deviation and skewed as evidenced by the deviation between the mode and the median values.

TABLE B-4

RESULTS OF VALLEY WIDTH STUDY

Terrain Sample	Landform Class	Width of Valleys (feet) Mean	Median	Mode	Std. Deviation
Montezuma, Colorado	High Mountains	3250	2200	1500	2300
Klondyke, Arizona	Mountains	1840	1400	1050	1330
Mannington, West Va.	Low Mountains	2390	2100	1900	1300
Marble Hill, Missouri	Hills	2800	2400	2400	1650
Millen, Georgia	Plains	4110	3350	3500	2770
Chocowinity, N. C.	Flatlands	4670	4350	3500	2380

2. Weather: The Distribution of Precipitation. The weather is an important element in the environment of a radar system such as the AN/TPQ-5( ). This system is particularly vulnerable to spurious echoes caused by precipitation because it must be designed to detect and track a very small radar target at long ranges. It has been recognized for some time that precipitation, including rain, snow, and hail, might disable this radar system. A detailed

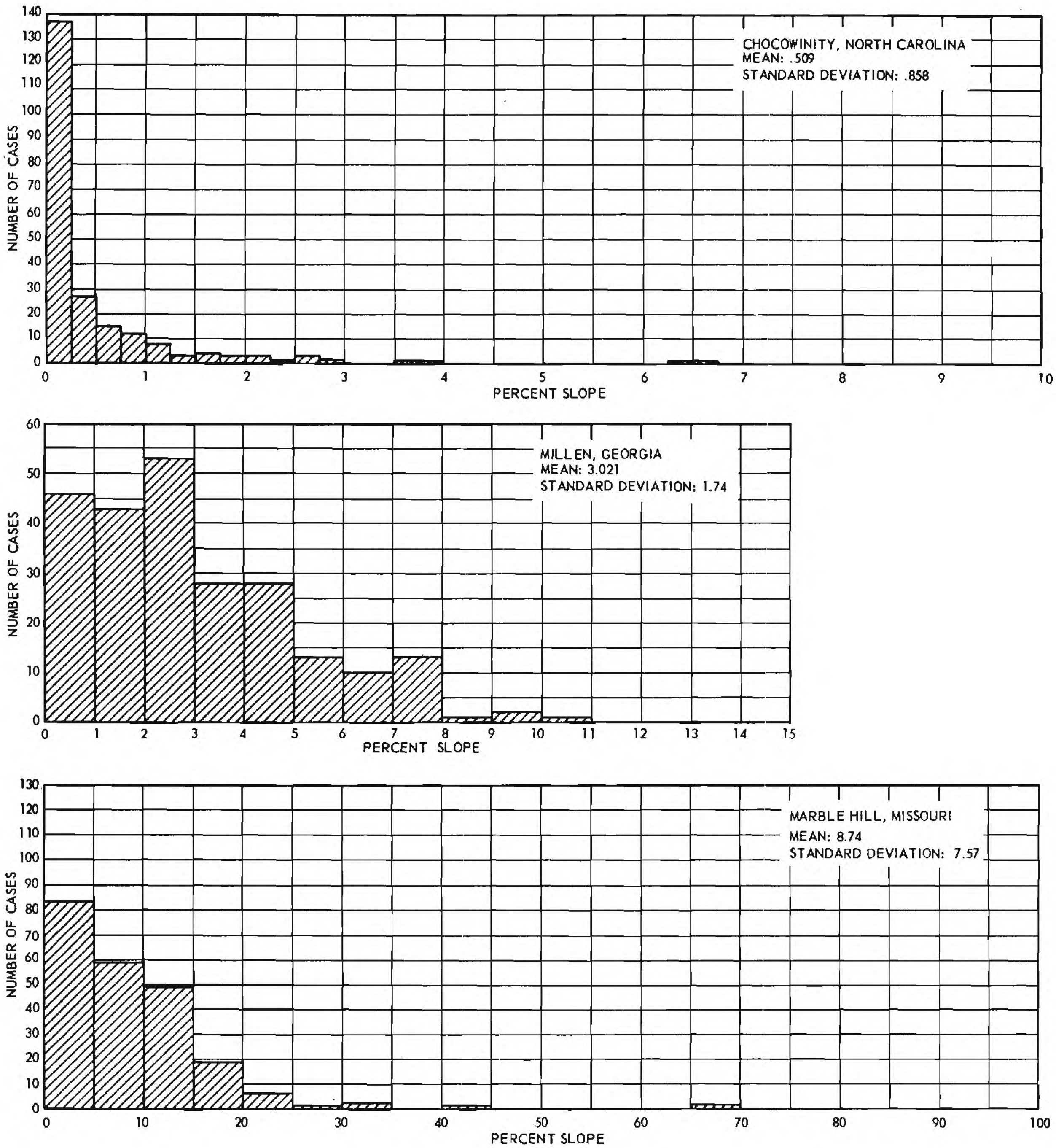

Figure B-2. Distribution of Point Slope Measurements in Per Cent Slope for Chocowinity, North Carolina; Millen, Georgia; and Marble Hill, Missouri.

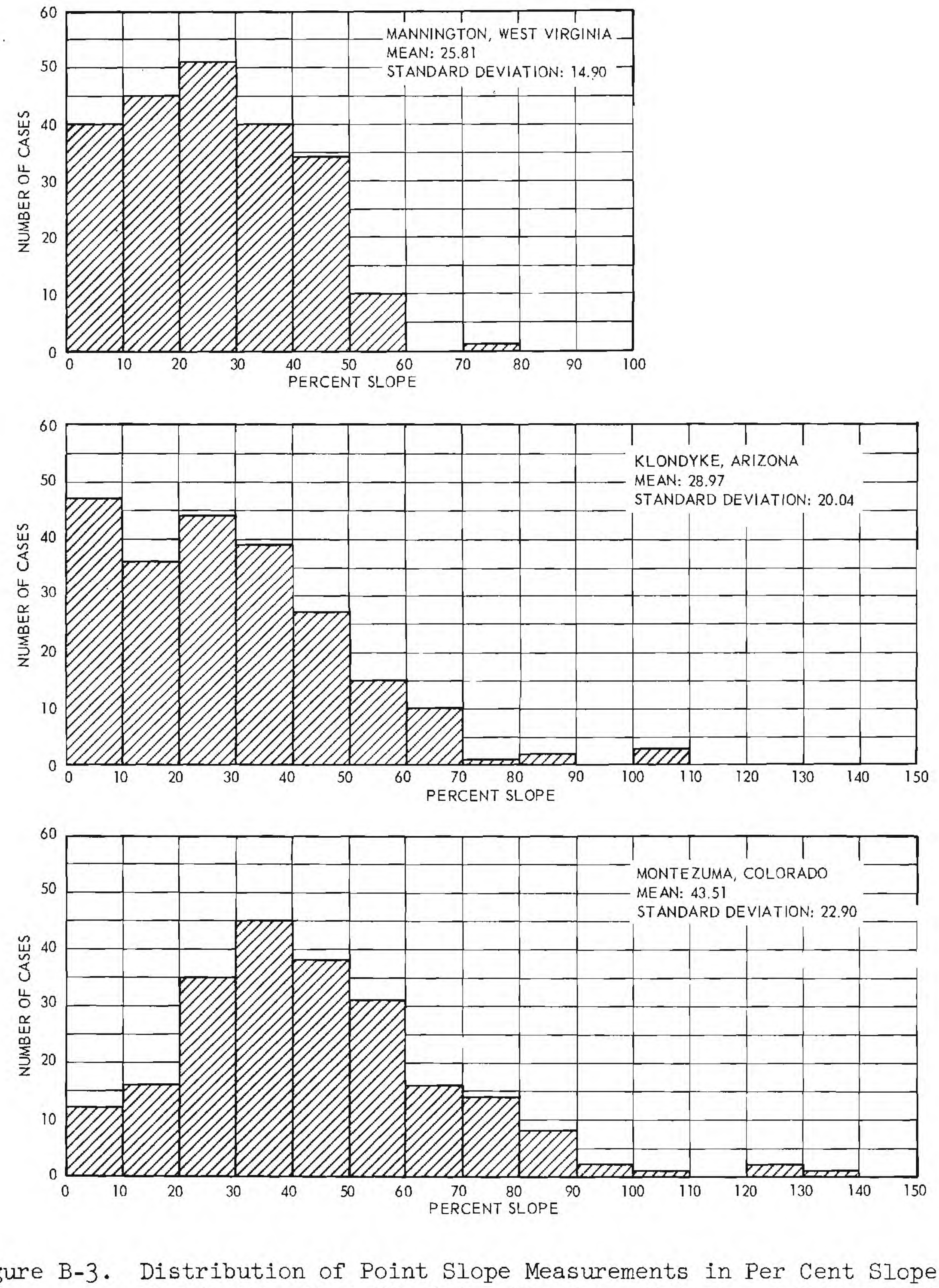

Figure B-3. Distribution of Point Slope Measurements in Per Cent Slope for Mannington, West Virginia; Klondyke, Arizona; and Montezuma, Colorado.

analysis of the effect of precipitation on the XE-1 has been presented earlier.[†] This analysis confirmed the results of unpublished studies by the General Electric Co. The situation may be summarized by saying that a radar system such as the AN/TPQ-5( ), operating on X-band, may be expected to be almost completely useless at any precipitation rate, even a light drizzle or a light snowfall. Field experience with the XE-1 thus far supports this conclusion.

The weather environment of this radar system, insofar as precipitation is concerned, will therefore be extremely important in determining the usefulness of the system. For this reason, the assistance of the Air Weather Service was sought to determine as much information as possible about the frequency of occurrence of precipitation on a worldwide basis. To evaluate the seriousness of the precipitation problem, one would like to know for each part of the world the fraction of time that precipitation occurs during each month of the year. Unfortunately, the percentage of time that precipitation occurs has not been measured directly on anything approaching a world-wide basis. Consequently, it was necessary for the Air Weather Service to perform some degree of objective and subjective manipulation on the available data in order to arrive at an estimate of the distribution of precipitation frequency. In general, precipitation data were taken from two main sources: summarized data from U. S. Air Force stations in the United States and overseas and from various foreign publications. USAF data are summarized in per cent frequency, by months, of hourly observations reporting precipitation. Data from foreign sources are more often than not published in such a form that considerable interpolation is required to obtain a per cent-occurence figure. The length of record for most of the data varies from 5 to more than 20 years.

Estimates were made for areas where precipitation data is completely lacking. These estimates were based on (a) comparison with analogous areas where data were available, (b) personal knowledge, and (c) various theoretical considerations. Estimates were furthermore necessary when the available data were inadequate. However, in spite of the margin of error in these estimates,

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[†]See Semi-Annual Report, Project A-190, Operational Analysis for a Counterbattery Radar, Georgia Institute of Technology, 1955, Secret.

the distributions of precipitation frequency prepared by the Air Weather Service provide a basis for future evaluation which is enormously better than the "off-the-cuff" judgments that would otherwise be required.

As a supplement to the maps prepared for us by the Air Weather Service, a brief report on their study was also submitted. This report provides a good introduction to the maps as well as some valuable guides to interpretation. The report and the distribution maps have been reproduced in full in the next section of this document.

Monthly Percentage Frequency of Precipitation (Prepared by: Headquarters, Air Weather Service, Directorate of Climatology, United States Air Force)

Preface

"This report has been prepared in answer to a request from the Georgia Institute of Technology, Engineering Experiment Station for information on the frequency of precipitation, by seasons, on a global basis. The Institute requires this information in connection with an operational research problem on which it is working for the Signal Corps under Contract No. DA-36-039 SC-64562."

"World-wide charts showing the estimated distribution of precipitation frequency are shown in Figures B-4, B-5, B-6, and B-7. Each figure represents a different season. These charts were prepared on a limited time schedule from immediately available data. They suffer from the scanty data at hand since most precipitation data are not in the form that allows presentation in per cent of time. The data over the world are in number of inches and/or number of days that precipitation occurred. A day of precipitation could be defined as a day that had one-hundredth inch of rain during any period of time, even less than an hour. Data of this nature are not, therefore, readily converted into percentage."

"The observed greatest mean frequency of precipitation (i.e., the greatest per cent of observations with precipitation) is given by the black numbers. The letter subscript designates the month of the season in which this frequency occurred. The red numbers represent the mean monthly frequency of precipitation for the season from factors other than observed data. In some instances a letter subscript designates the month of the greatest mean frequency of precipitation."

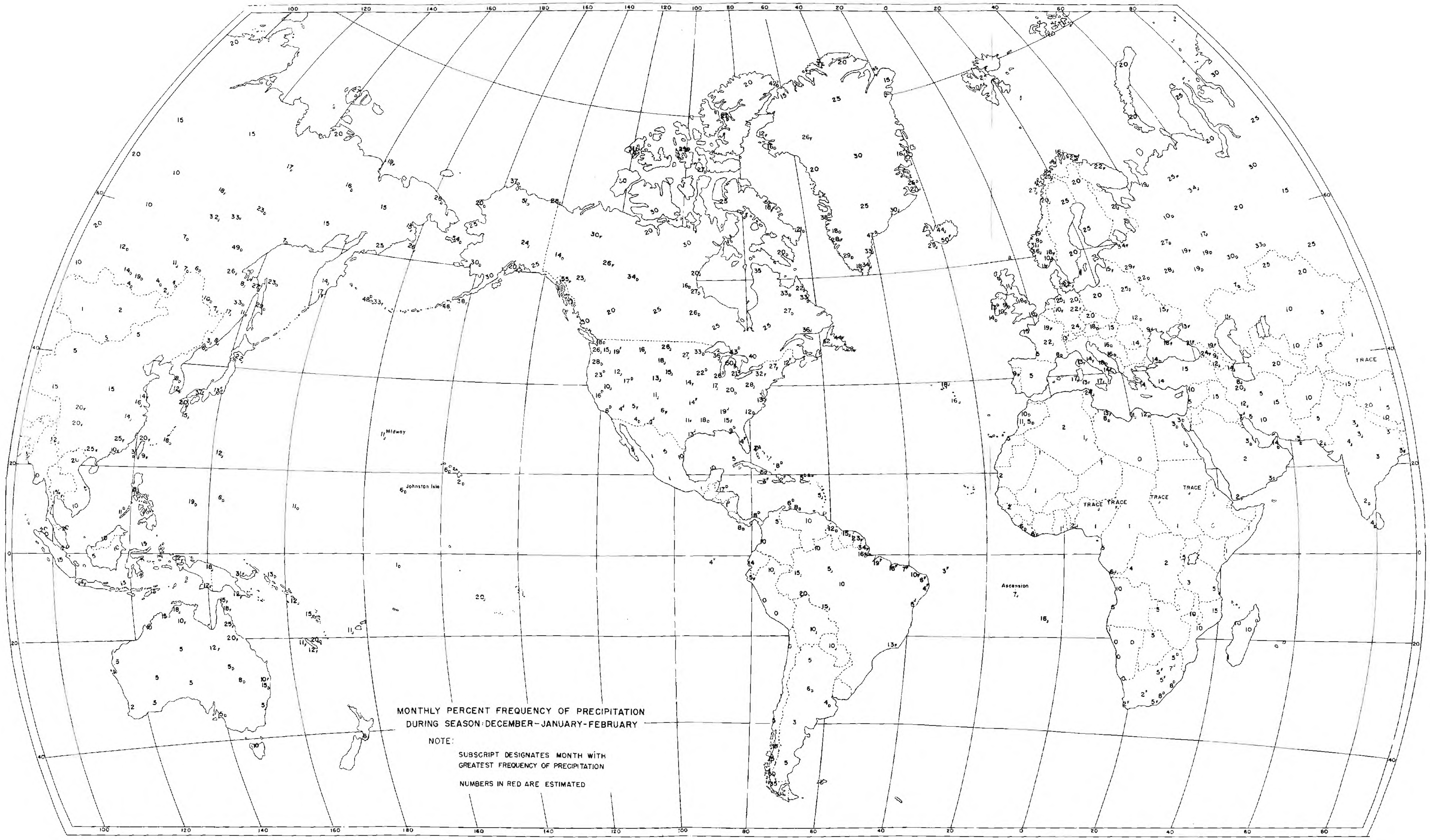

Figure B-4. Monthly Per Cent Frequency of Precipitation During Season: December-January-February.

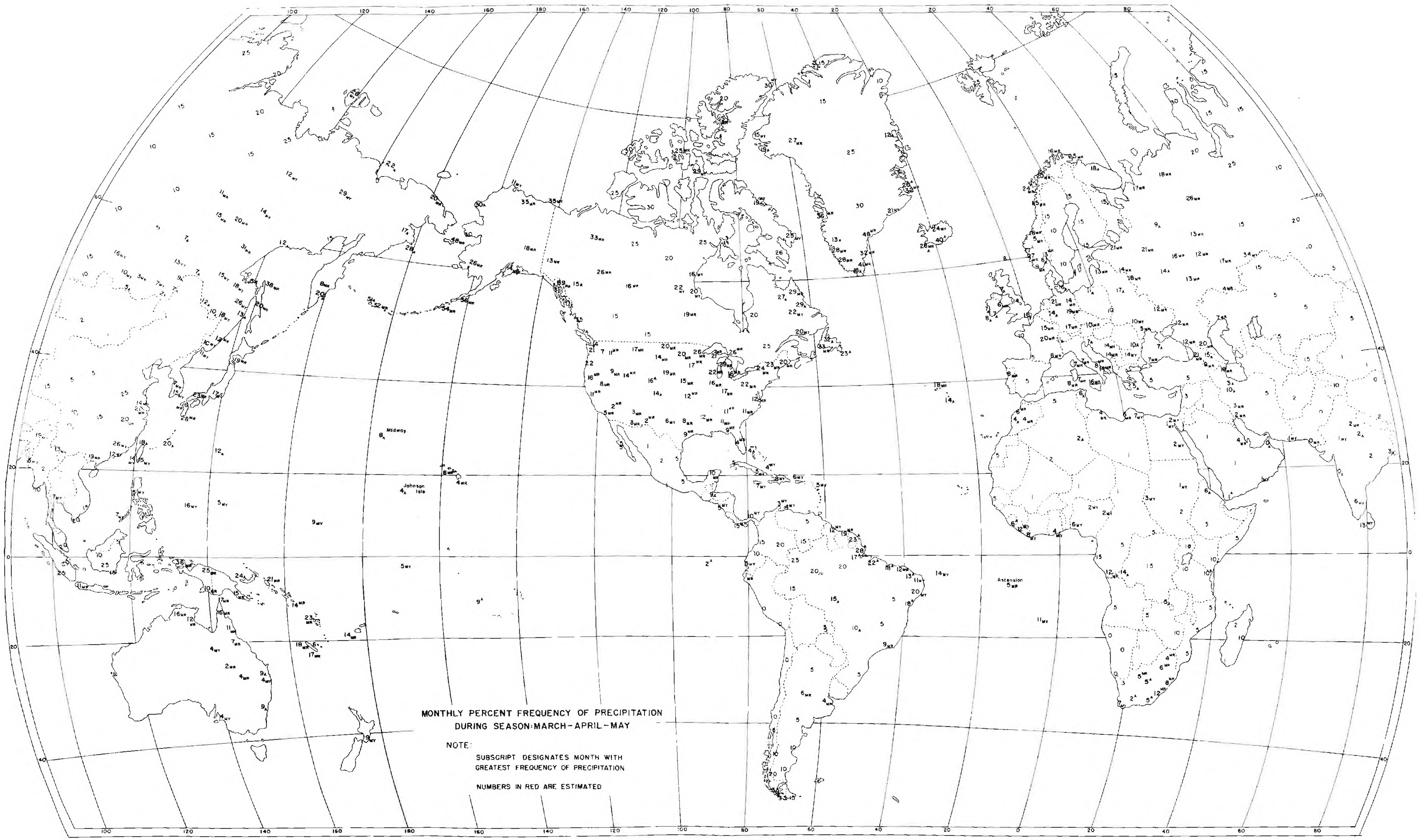

Figure B-5. Monthly Per Cent Frequency of Precipitation During Season: March-April-May.

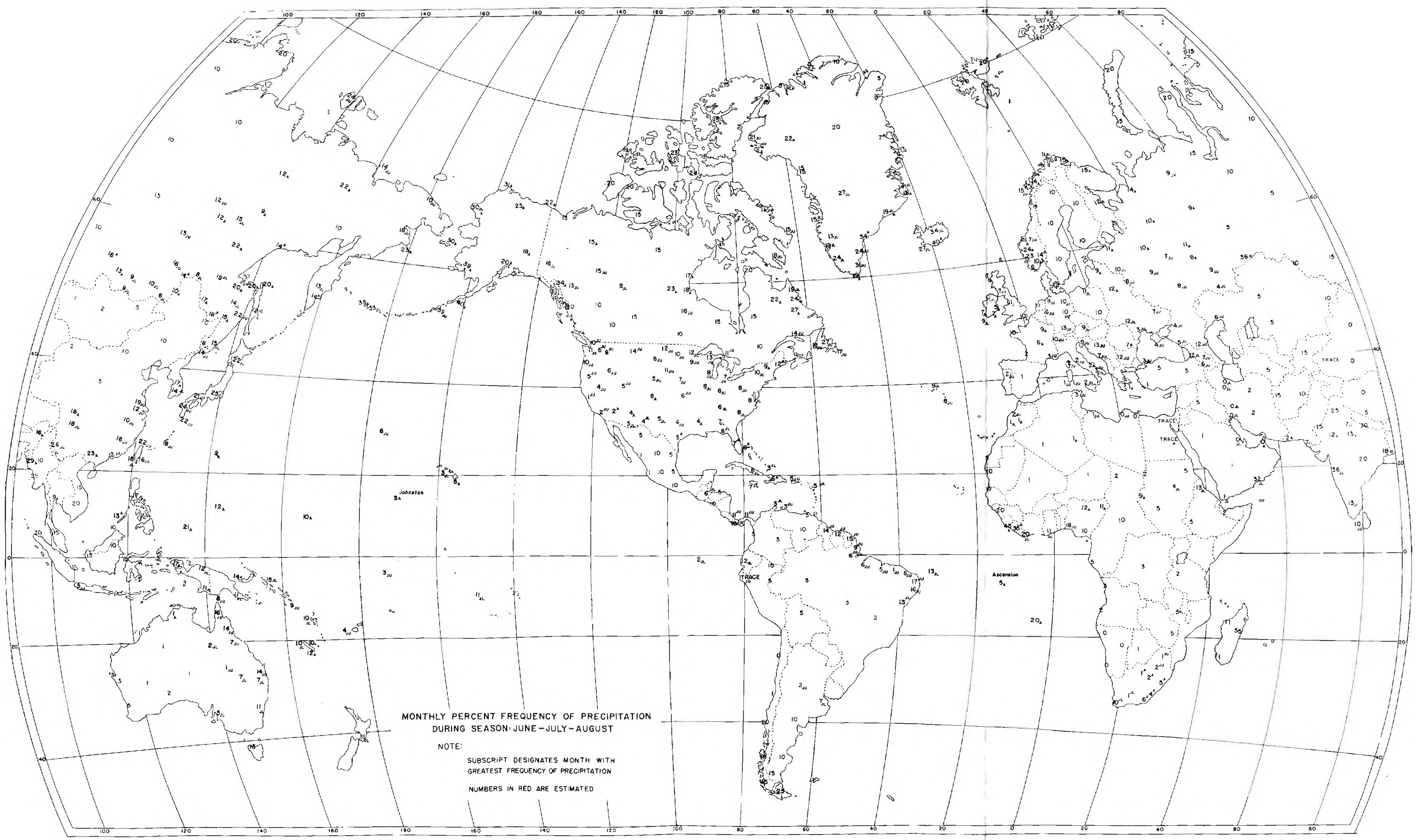

Figure B-6. Monthly Per Cent Frequency of Precipitation During Season: June-July-August.

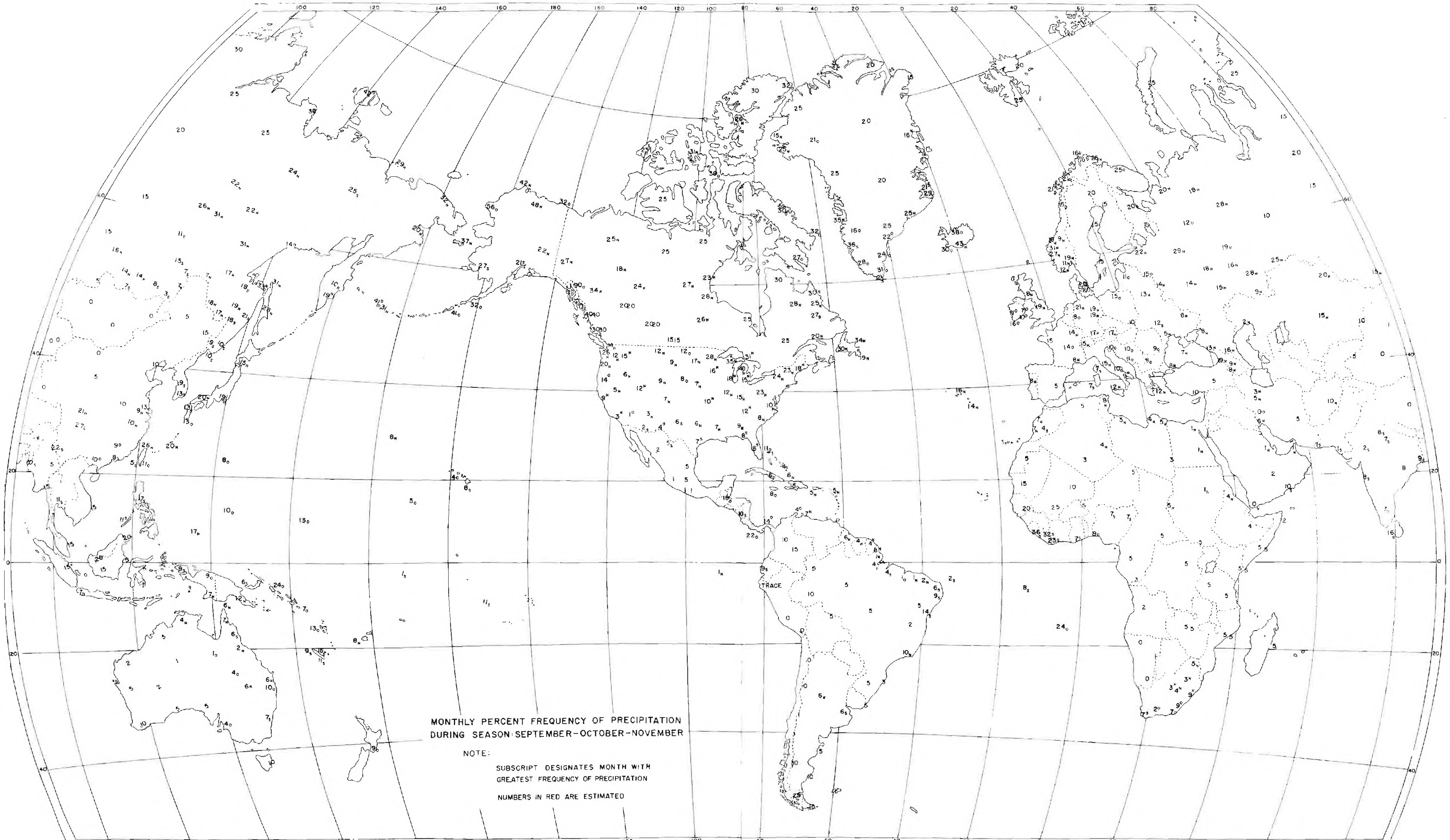

Figure B-7. Monthly Per Cent Frequency of Precipitation During Season: September-October-November.

"Data on the frequency of various intensities of precipitation are unavailable. However, a few general statements can be made about the frequency of intensities on a global scale. Precipitation in the Arctic is light to very light, with most stations reporting less than an inch (water equivalent) per month even though precipitation occurs 40 per cent of the time. In the mid-latitudes during the winter, spring, and autumn most precipitation is light. For example at Kimberly, Union of South Africa, five-sixths of the rain that falls during the entire year is termed light. Moderate and heavy precipitation occur only for short periods of time, mainly in late spring and early autumn. Summer precipitation is usually moderate to heavy, falling mainly in showers. However, coastal areas, such as western Europe, still have considerable light rain in the summer."

"Heavy precipitation occurs most frequently in the Tropics from 20°N to 20°S latitude. Areas where the monsoon is common, such as India, Indonesia and the Gold Coast of Africa, a more steady type of precipitation is noticeable, with light to moderate rain being more noticeable. This is interrupted occasionally with heavier showers."

"Precipitation may differ greatly from place to place (even few miles), month to month and year to year throughout the world. Wind and terrain, such as hills and mountain ranges, have tremendous effect on the amount of clouds and precipitation in very short distances. Therefore, the use of isolines or shading to designate equal areas is not advisable. Interpolation or extrapolation for other purposes than those intended is not recommended."

"This report has been prepared by the Directorate of Climatology, Hq. AWS and will not be reproduced or used for purposes or interpretations other than those intended without concurrence."

3. Trafficability. Trafficability may be defined as the ability of vehicles to move from one point to another through a given environment. Soils trafficability concerns the specific effect of soils on movement. Information on this subject used in this report comes principally from the Waterways Experiment Station of the U.S. Corps of Engineers through discussions, correspondence, and a report being prepared there for the Engineer School, Fort Belvoir, Virginia, titled Soils Trafficability, TB5-550-1, which is as yet in the initial review-draft stage.

The Waterways Experiment Station has divided its investigations of soils trafficability into two phases: (1) the development of instruments and methods for determining trafficability by ground reconnaissance parties, and (2) the development of methods for predicting trafficability from soils and weather data without physical tests. The results of phase (1) of this investigation were taken up in the report Soils Trafficability and will be discussed further in this section.

The factors influencing soil trafficability may be divided into two classes: (1) those which are permanently associated with a given soil type and locality and (2) those which change with the weather. Factors such as soil type, slope, and amount and type of vegetation may be recorded for future reference for a given piece of terrain although the last factor mentioned may vary somewhat with weather and season. Factors which vary with weather are the amount and location of water in the soil, temperature, wind velocity, solar radiation, humidity, cloudiness, etc.

As a first approach to the problem of making a long range prediction as to the trafficability of a piece of terrain, the terrain may be examined under varying conditions and classified as follows:

Terrain Class	Dry	Wet
1	Passable	Passable
2	Passable	Doubtful
3	Passable	Impassable
4	Doubtful	Impassable
5	Impassable	Impassable

The numbers in the column "Terrain Class" refer to terrain having definite soil types and slopes, and the adjectives "Passable," "Doubtful," and "Impassable" refer to movements of some specific type of vehicle. The terms "Dry" and "Wet" are ambiguous to a degree since a given amount of water may be distributed in the soil in several different manners depending on the weather history. The selection of the adjectives "Dry" and "Wet" is dictated by the strong effect of soil moisture on trafficability. For a given moisture content the terrain may be mapped into zones according to terrain classification number. These zones will of course depend on the type of vehicle under consideration.

Considering the complexity of the trafficability problem, it is easy to understand why phase (2) which involves predictions of trafficability, is not yet sufficiently well developed for use in the present problem. Phase (1), however, provides a most useful method of comparing various trailer designs and tractor types in combination. This comparison is possible only on a relative basis as will be seen.

It is necessary first of all to define some measures of soil strength. Two characteristics of a soil are of great interest: (1) the ability of a soil to support a vehicle (not permit it to sink) and (2) the ability of a soil to withstand the shearing stress of a vehicle in motion. If one makes due allowances for vehicle characteristics, the so-called cone index gives a convenient standard for comparing the strengths of various soils. The cone index of a soil is the resistance of the soil to the penetration of a standard cone in pounds per square inch of cone base. This index is usually given with units omitted. The details of the cone index measurement are given later in this section.

A soil that is subjected to continuous mechanical mixing or agitation changes its cone index so that it approaches some new value as the agitation proceeds. A soil that has been changed in this way is said to be remolded. It is assumed that 40 to 50 passes by some heavy vehicle are sufficient to cause the complete remolding of a soil, although most soils are completely remolded by a much smaller number of passes. Agitation or remolding of a soil almost always weakens it. The measure of this effect to be used here is the remolding index which is the ratio of the cone index of the completely remolded soil to the soil's original cone index.

The characteristics under heavy traffic are of considerable interest. The measure of soil strength under this condition is the so-called rating cone index which is the product of the cone index and the remolding index.

None of the above parameters have depended on the characteristics of the particular type of vehicle being studied. In determining the trafficability of a piece of terrain with respect to a particular vehicle one calculates a parameter called the vehicle cone index. This parameter is associated with a giventype of vehicle and indicates the minimum soil strength in terms of rating cone index for 40 to 50 passes of that vehicle. A rating cone index of about 75 per cent of this value is adequate for a single pass. The towing force delivered and the per cent slope negotiable by a given vehicle may be determined for various values of I_c, the rating cone index and I_v, the vehicle cone index. Figure B-8 shows the relationships between these quantities. The vehicle cone index I_v may be determined by means of Figure B-10, if one uses an empirically determined number called the mobility index. The vehicle cone indices and mobility indices for most Army vehicles are obtainable directly from the appendix of the report Soils Trafficability. The mobility indices of vehicles not give there were determined by means of the following empirical formulae:

Mobility Index may be computed in the case of wheeled trailers as follows:

$$I_m = .64 \left(\frac{P_c W}{T} + W_a - C\right) + 10$$

where

P_c = 1/2 tire pressure,

W = 1.0 for 15000 lb/axle or greater,

.9 for 12500 - 14999 lb/axle,

.8 for 10000 - 12499 lb/axle,

.7 for 7500 - 9999 lb/axle,

.6 for less than 7500 lb/axle,

$T = \frac{1}{100}$ tire width in inches for a single tire,

$\frac{1.5}{100}$ tire width in inches for a dual tire,

$W_a = \frac{1}{1000}$ axle load in pounds, and

C = clearance in inches.

For self-propelled tracked vehicles the following empirical formula applies:

$$I_m = \left(\frac{P_c' W'}{T' G} + B - \frac{C}{10}\right) E F$$

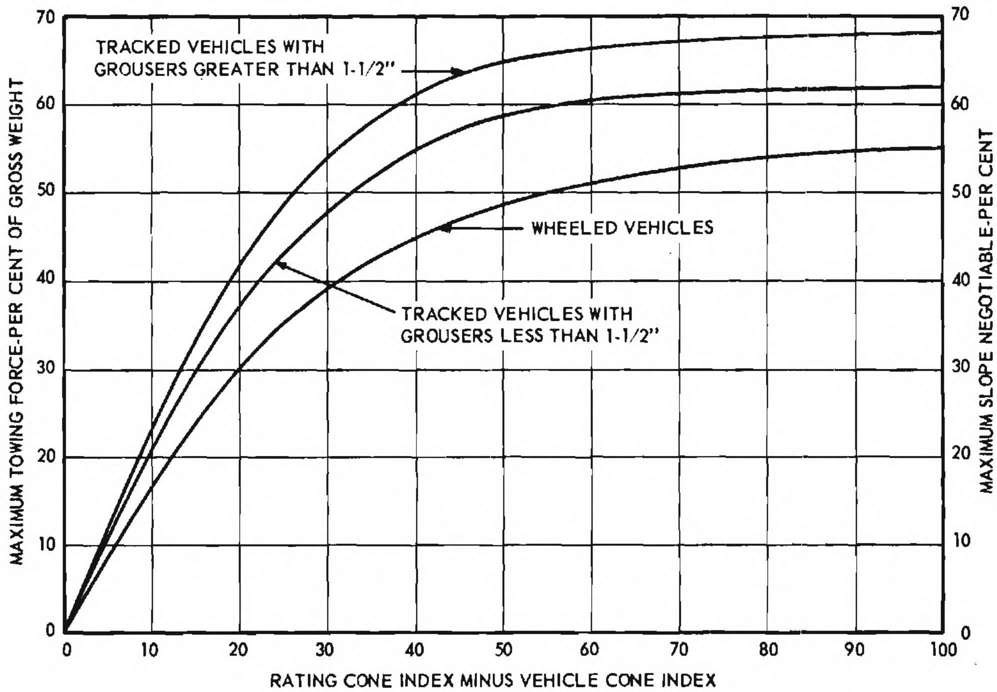

Figure B-8. Maximum Towing Force in Pounds that can be Developed on Level Ground and Maximum Slope that can be Climbed for Various Values of the Quantity I_c-I_v.

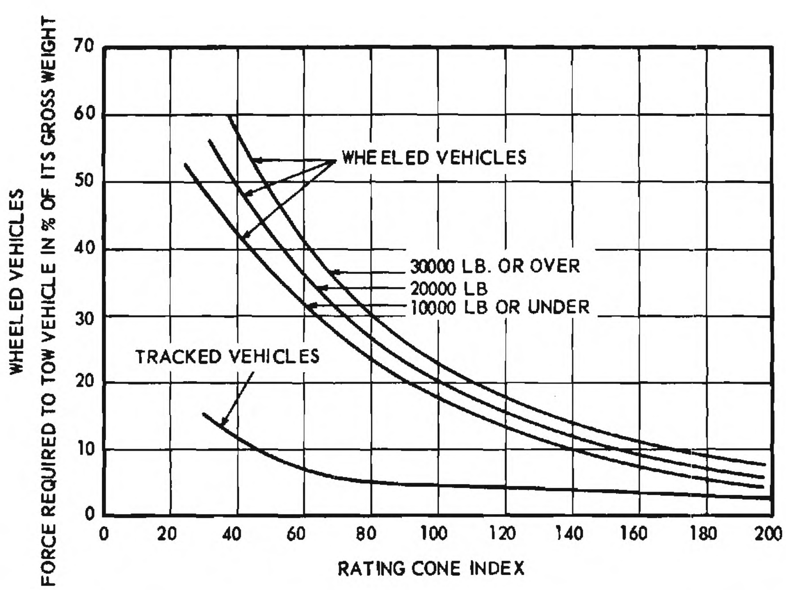

Figure B-9. Force in Pounds Required to Tow Various Types of Trailers on Level Ground.

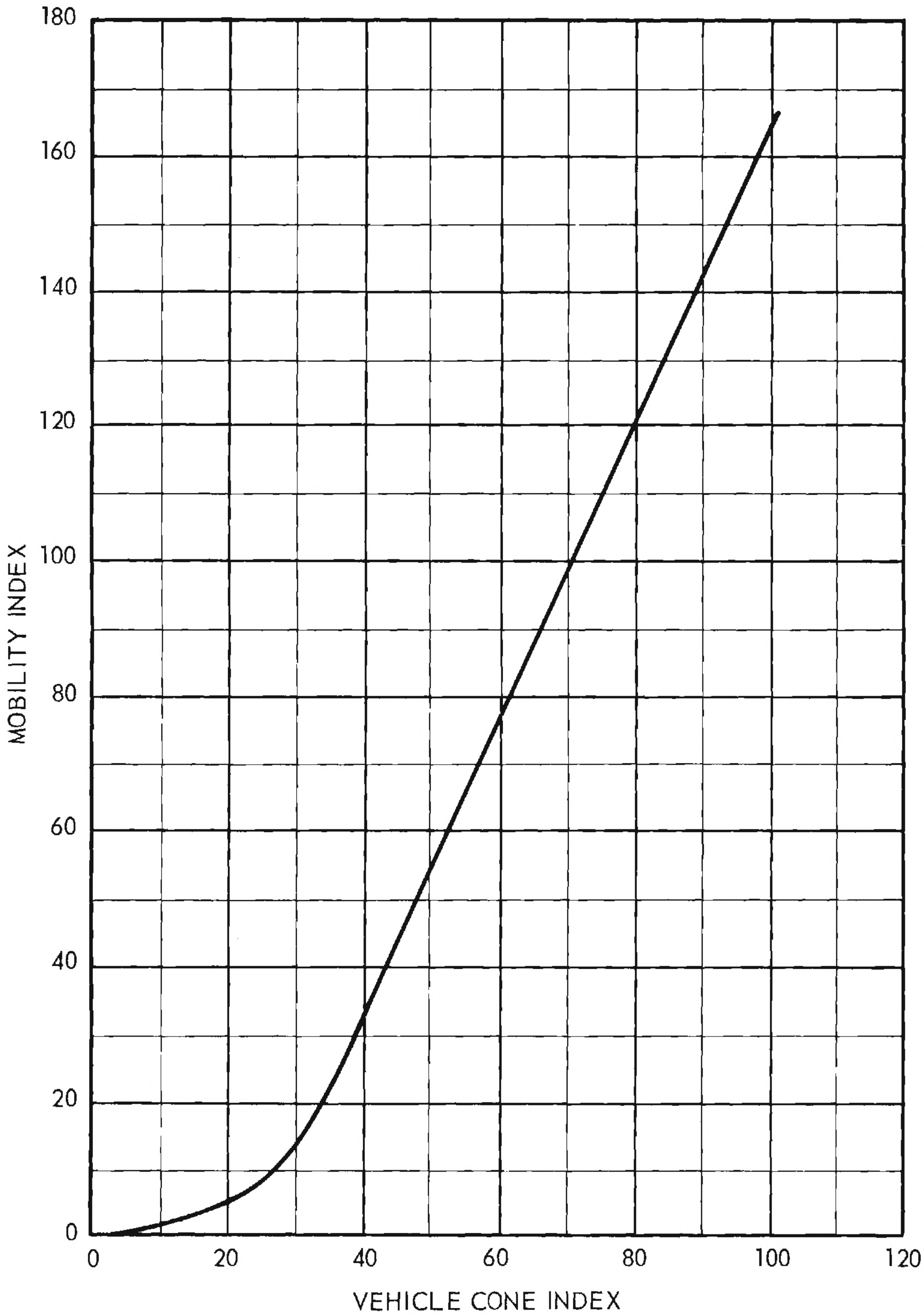

Figure B-10. Mobility Index Versus Vehicle Cone Index.

$P_c' = \dfrac{\text{gross weight in pounds}}{\text{area of track in contact with ground}}$

$W' = 1.8$ for 100000 lb or more

1.4 for 70000 - 99999 lb

1.2 for 50000 - 69999 lb

1.0 for less than 50000 lb

$T' = \dfrac{1}{100}$ track width in inches

G = 1.0 for grousers less than 1.5 in. high

1.1 for grousers more than 1.5 in. high

$B = \dfrac{\frac{1}{10}\text{ gross weight in pounds}}{\text{(No. of bogies on tracks in contact with ground) x (area of one track shoe in square inches)}}$

C = clearance in inches

E = 1.00 for 10 hp per ton or greater

1.05 for less than 10 hp per ton

F = transmission factor = 1.00 for hydraulic
1.05 for mechanical

Soil strength is measured by a device called a cone penetrometer which consists of a 30-degree cone of 1/2-square-inch base, a proving ring, a dial gauge, and a handle. As the cone is forced into the ground the proving ring is deformed by an amount that is proportional to the force on the cone. This deformation is read on the gauge. The gauge is read at intervals of 6 inches as the operator forces the cone into the ground to a depth of about 24 inches, being careful to insure a uniform rate of penetration. For soil layers critical to the vehicles considered here, the gauge readings at 6 and 12 inches below the surface are averaged and the result is called the cone index. It has been found that if 15 sets of readings are taken within a radius of three feet in homogeneous appearing ground, another set of readings will not appreciably change the average. If the cone index is above 150 or below 30, fewer readings are necessary since ordinary inaccuracies in the readings are not enough to change the trafficability estimate of the soil by an important amount.

Equipment for making a remolding test consists of a hollow cylinder 9 inches long and 2 inches in diameter, a 2-1/2 pound drop hammer, a cone penetrometer, and a soil sampler, which is a device used to cut a cylindrically-shaped core sample out of the ground and place it in the 9-inch cylinder. The remolding test is accomplished by reading the cone index as the base of the cone enters the soil sample and after each inch of penetration to a depth of 4 inches. Next, 100 blows are delivered to the sample from a height of 12 inches with the drop hammer. The penetration test is then repeated. The remolding index is the ratio of the sum of five penetration tests before to the sum of five penetration tests after remolding.

In the investigation of an area, enough locations are selected to insure the uniformity of the area and three or four sets of penetrometer readings are made at each location. Remolding tests are made at each location unless, after the first two or three, the remolding index is found to be .90 or more.

The application of these methods is appropriate to fine grained soils only. Sand offers good support at low cone indices especially if wet, whereas the strength of fine grained soils usually decreases sharply with an increase in moisture content. Trafficability studies have not yet progressed to the point where one can determine the distributions of cone indices and moisture content over any large geographic areas or relate cone index to soil type.

The heaviest pieces of equipment to be moved by CBR units are the antenna systems either for separated or combined systems. Attention is therefore concentrated in this section on the ability of these antenna systems, mounted on trailers or truck beds, to be moved from one point to another since this imposes the mobility limitation on the unit as a whole. In order to compare the abilities of various prime mover-trailer combinations, curves were plotted to show the maximum slope negotiable versus rating cone index. These curves are given in Figures B-11 through B-16. In the preparation of these curves, combinations of four different prime movers and three different trailers were considered. The mobility and vehicle indices for the vehicles were found in the Appendix of Soils Trafficability, except for the two- and four-wheeled trailers and the M5A3 tractor. The data for the trailers were taken from the proposed layouts of the separate and combined antenna systems; the data for the M5A3 tractor were

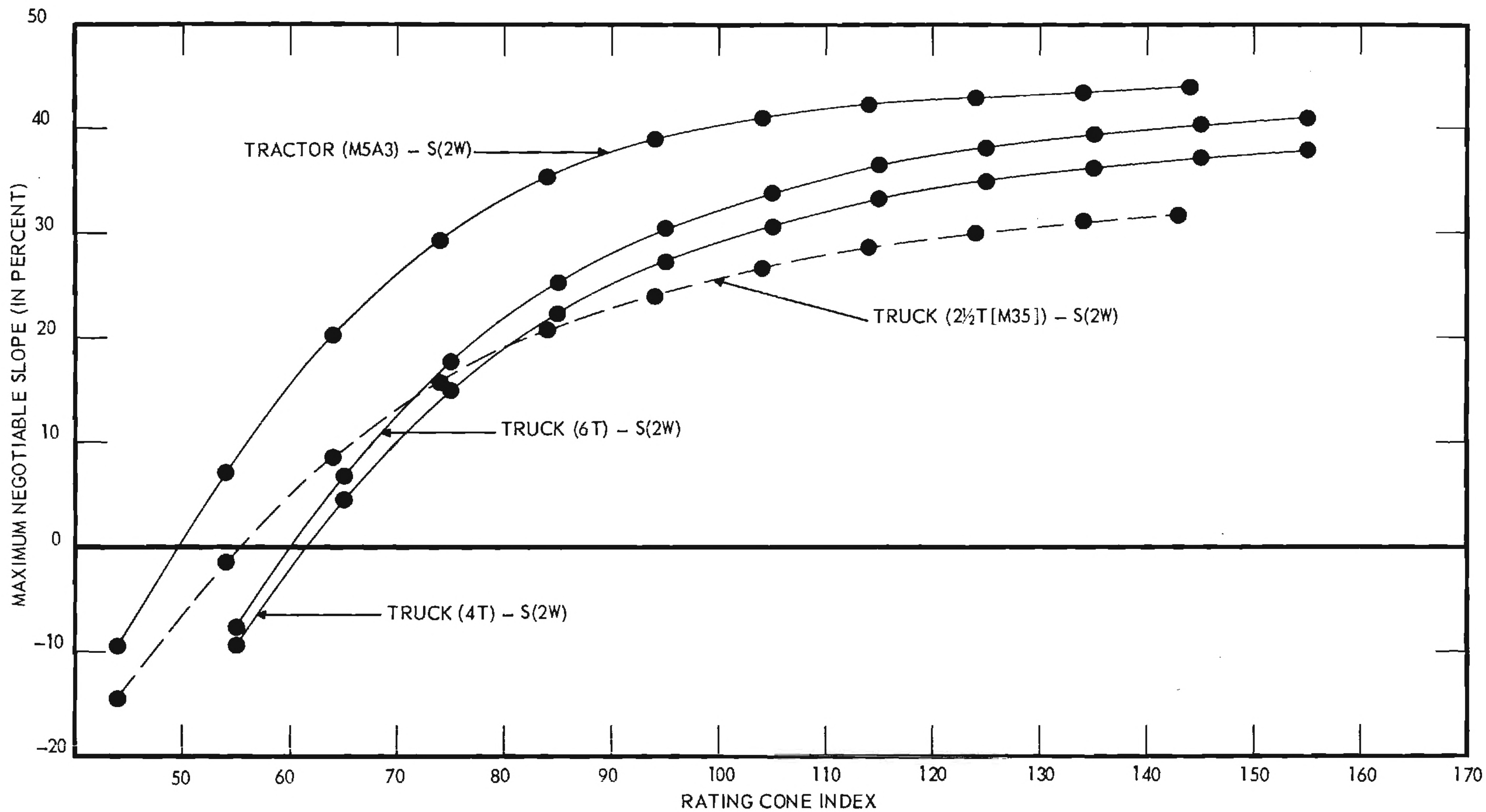

Figure B-11. Maximum Negotiable Slope Versus Rating Cone Index for a Single Pass and for Prime-movers Drawing Two-wheeled Antenna Trailers for the Separate System.

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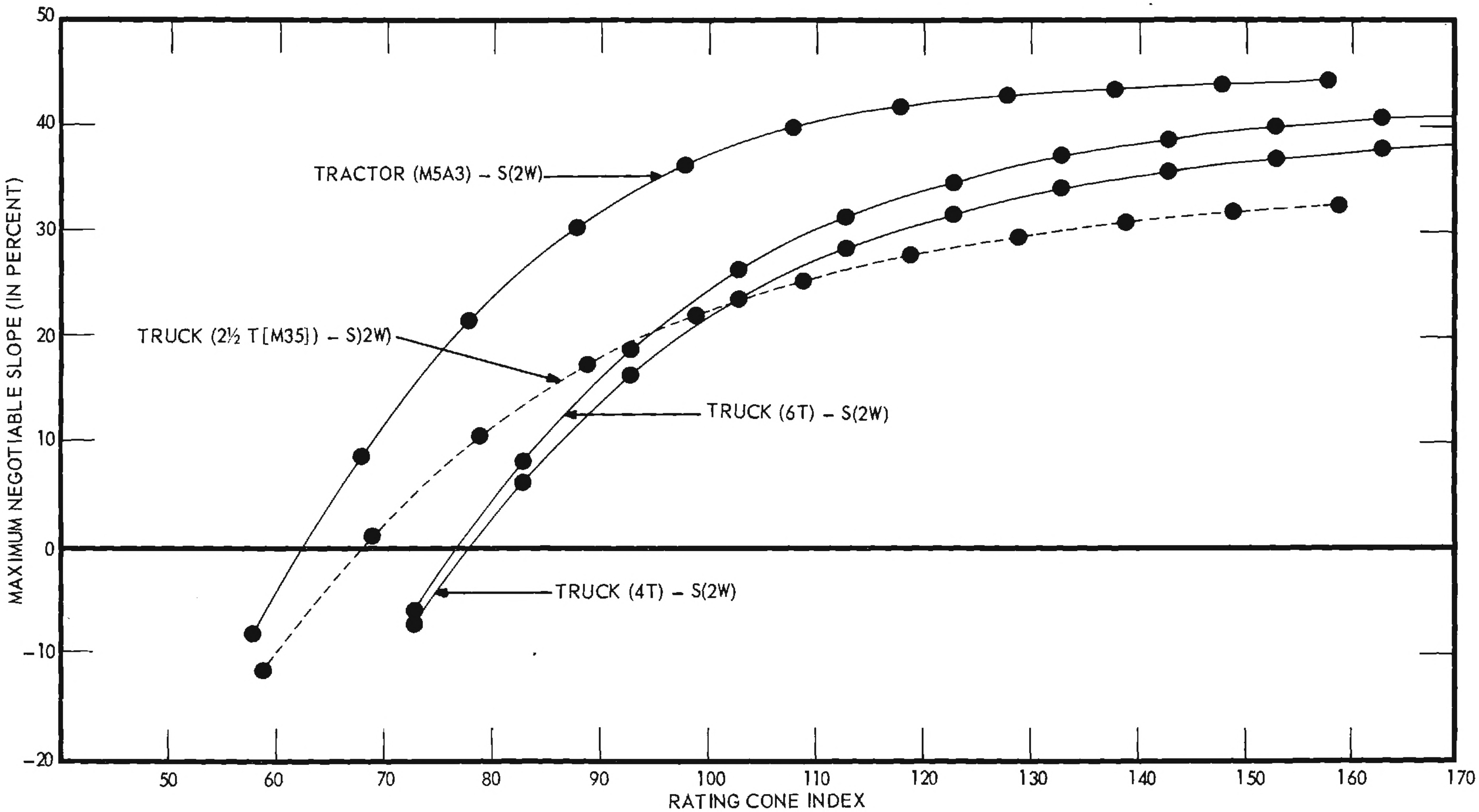

Figure B-12. Maximum Negotiable Slope Versus Rating Cone Index for Multiple Passes and for Prime-movers Drawing Two-wheeled Antenna Trailers for the Separate System.

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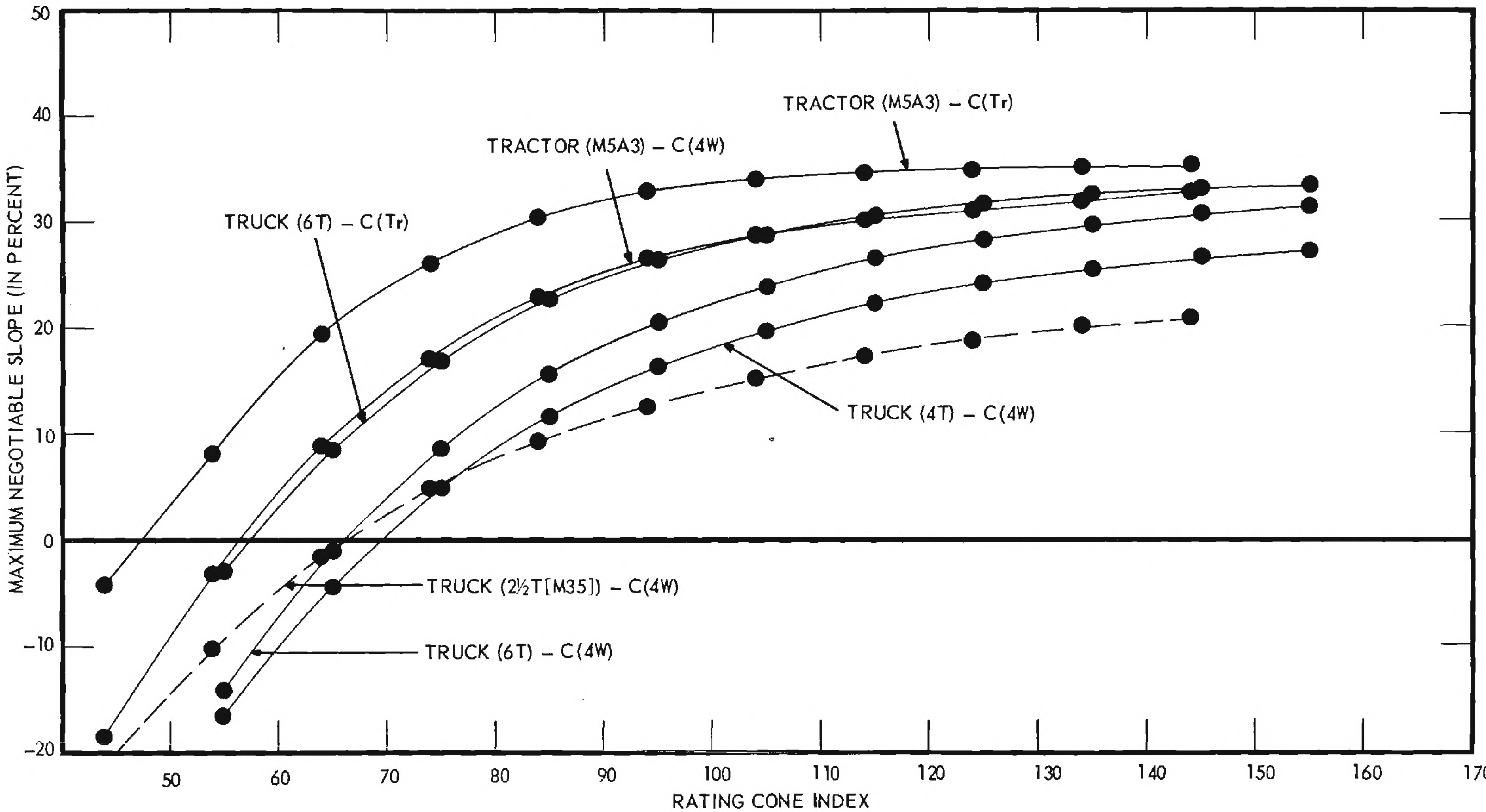

Figure B-13. Maximum Negotiable Slope Versus Rating Cone Index for a Single Pass and for Prime-movers Drawing Four-wheeled Antenna Trailers for the Combined System. Also Curves are Shown for the Tractor M5A3 and the 6-ton Truck Drawing the Tracked Antenna Trailer for the Combined System.

CONFIDENTIAL

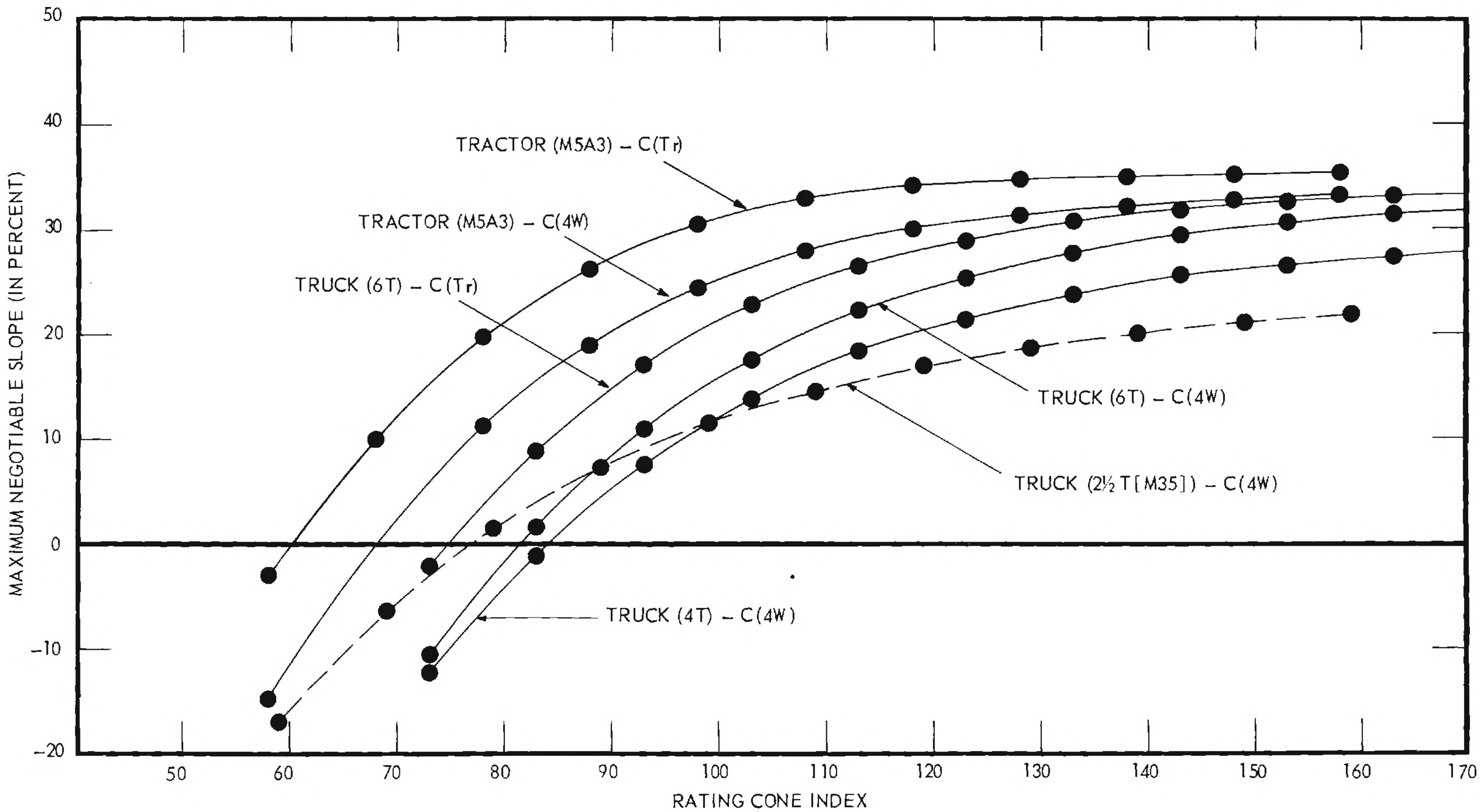

Figure B-14. Maximum Negotiable Slope Versus Rating Cone Index for Multiple Passes and for Prime-movers Drawing Four-wheeled Trailers with the Combined Antenna System. Also Curves are Shown for the Tractor M5A3 and the 6-ton Truck Drawing the Tracked Antenna Trailer for the Combined System.

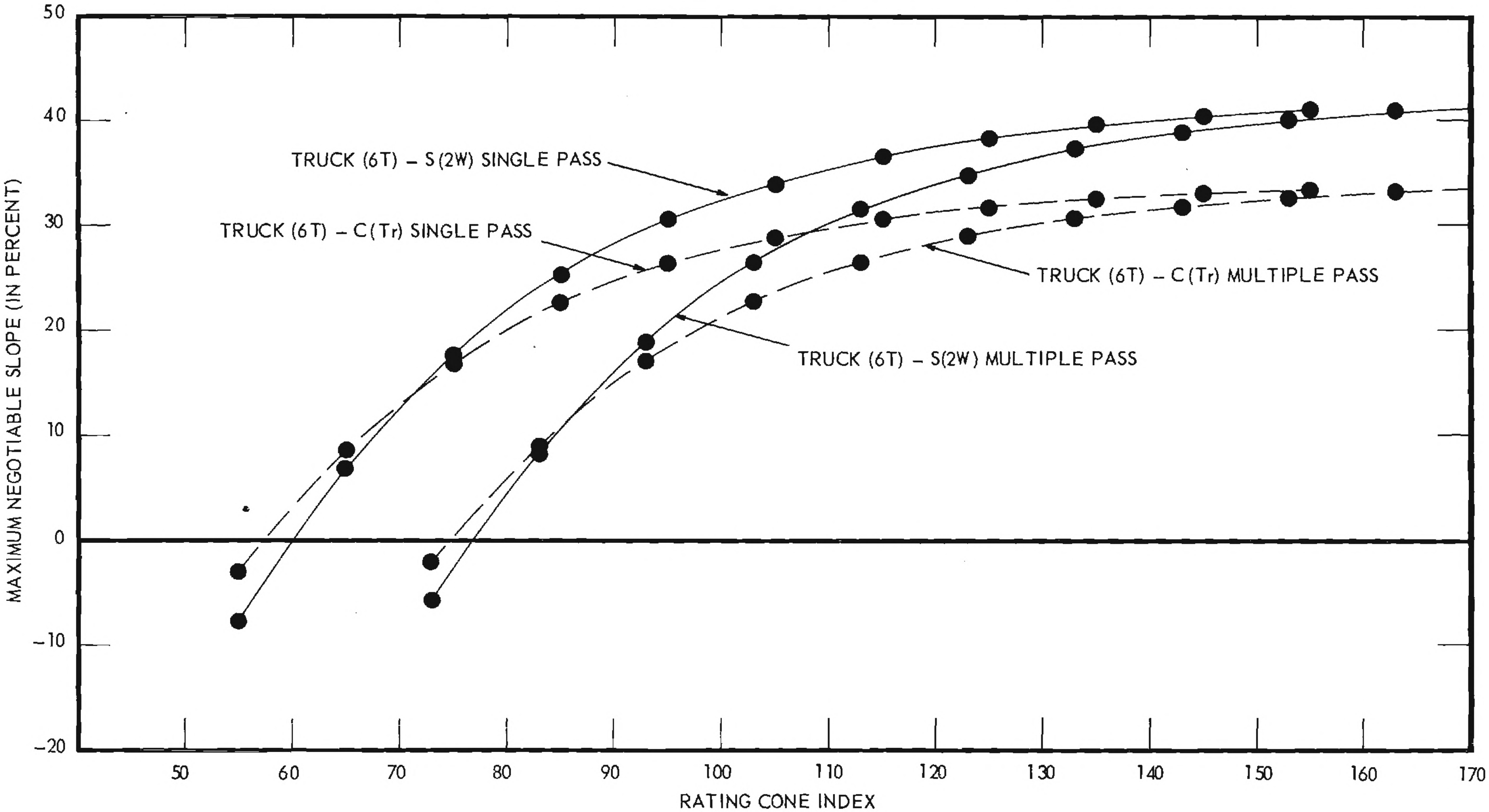

Figure B-15. Maximum Negotiable Slope Versus Rating Cone Index for the Best Separate and Best Combined System Antenna Trailers Using Wheeled Prime-movers for Single and Multiple Passes: Truck (6-ton) + 2-wheeled Trailer. Truck (6-ton) + Tracked Trailer.

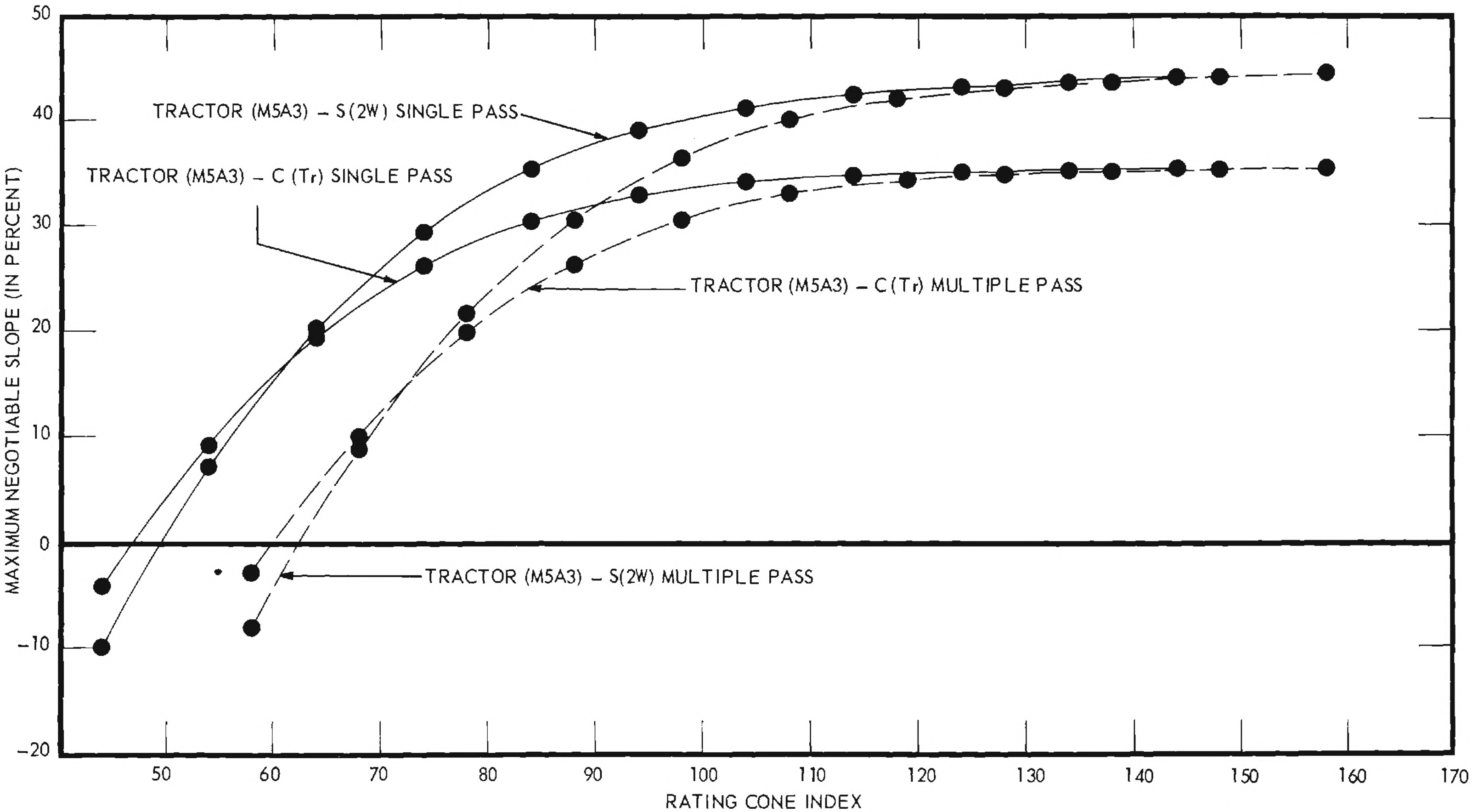

Figure B-16. Maximum Negotiable Slope Versus Rating Cone Index for the Best Separate and the Best Combined System Antenna Trailers Using Tracked Prime-movers for Single and Multiple Passes: Tractor (M5A3) + 2-wheeled Trailer. Tractor (M5A3) + Tracked Trailer.

obtained from TM 9-2800-1, February 1953. These curves represent the best possible performance that can be expected in each case considered. Poor driving technique, unexpected soft spots, slipperiness, etc. could cause the vehicles to become immobilized even under the specified conditions. A tabulation of vehicle characteristics is given in Table B-5.

TABLE B-5

I Vehicle	II Vehicle Cone Index	III Gross Weight (lb)	IV Max. Rec. Payload Off Highway (lb)	V Ref. Page TM 9-2800-1	VI Max. Rec. Towed Load On Highway (lb)	VII Max. Rec. Towed Load Off Highway (lb)
1. Truck, cargo, 2-1/2 ton, 6x6, M35, w/winch	59	17,800†	5,000	231	10,000	6,000
2. No. 1 above w/o winch carrying:						
Search system	60	18,465	5,000	231	10,000	6,000
Track system	58	17,065	5,000	231	10,000	6,000
3. Truck, cargo, 4 ton, 6x6, w/winch	73	26,800†	8,350	246	25,000	11,000
4. Truck, cargo, 4 ton, 6x6, Dia T, Mod 968A, w/o winch carrying:						
Search system	68	23,200	8,350	243	25,000	11,000
Track system	65	21,800	8,350	243	25,000	11,000
5. Truck, prime mover, and cargo, 6 ton, 6x6, w/winch	73	34,900†	12,000	277	40,000	20,000
6. Tractor, high speed, 13 ton, M5A3	58	30,350†	-----	127	20,000	20,000
7. Trailer, cargo, 6 ton, tracked (Athey type)	64	20,540†	12,000	147	------	------
8. Trailer, 4 dual wheels, 9x20 tires	66	20,000†	------	---	------	------
9. Trailer, 2 dual wheels, 9x20 tires	66	10,000†	------	---	------	------

†Includes rated payload.

Columns VI and VII give the maximum recommended weight of the towed load under the worst conditions, the limiting factor being the mechanical capacity of the prime mover. The figures came from TM 9-2800-1 and were presumably based on experience and/or the manufacturers' recommendations. No method for obtaining this data was given.

The curves to be presented here represent the limitation imposed by the load bearing capacity of the soil on various combinations of vehicles. The data used in computing the mobility index for the 2- and 4-wheeled trailers are as follows:

	Tire Pressure (in psi)	Total Weight (in lb)	Tire Width (in inches)	Axle Clearance (in inches)
Trailer, 2-wheeled	45	10,000	13.5	16.5
Trailer, 4-wheeled	45	20,000	13.5	16.5

The force T_2 necessary to tow the trailers for corresponding values of I_c was determined from the graphs in Figure B-9. The maximum negotiable slope is then determined by the formula

$$S = \frac{T_1 - T_2}{W_1 + W_2}$$

where W_1 and W_2 are the weights in pounds of the prime mover and trailer respectively and T_1 is the towing force in pounds delivered by the prime mover. S is plotted against I_c giving the graphs in Figures B-11, B-12, B-13, B-14, B-15 and B-16. In plotting the curves for a single pass, vehicle cone indices were assumed to be 75 per cent of their normal or multiple pass value.

The meaning of the symbols used on these curves are as follows:

S = the separate antenna system (2-wheeled trailers)

C = the combined antenna system (tracked or 4-wheeled trailers)

2-1/2 T = the 2-1/2 ton truck M35 given as item (1) in Table B-5

Tr = tracked trailer

Tr(M5A3) = the tracked tractor

Example: (2-1/2T[M35]) - S(2W) = a 2-1/2 ton truck type M35 towing a 2-wheeled antenna trailer for the separated system.

Consider first the choice between a combined antenna system, where the search and track radars use the same antenna mount on the 4-wheeled or tracked trailers, and the separated antenna systems, where the search and track radars are on separate 2-wheeled trailers. Examination of Figures B-15 and B-16 reveals that the separated system, using the 2-wheeled trailers, is clearly preferable for every prime mover except at cone indices below 70 where the difference is slight.

The tracked tractor M5A3 offers the best choice of prime mover for off-road operation for all rating cone indices and offers special advantages in soft soil (low cone indices) as Figures B-12, B-14, B-15, and B-16 show. The 6-ton truck is the best wheeled prime mover, but it offers only a very small advantage over the 2-1/2- and 4-ton trucks at lower cone indices as Figures B-11, B-12, B-13, and B-14 show. For a single pass over soil of cone index 100, the 6-ton truck can pull the two-wheeled trailers up slopes of 32.3 per cent as opposed to 29.2 per cent and 25.7 per cent for the 4- and 2-1/2-ton trucks. In a choice between the M5A3 and the 6-ton truck, the M5A3 has a considerable advantage in soft ground and a slight advantage at higher cone indices. The tractor M5A3 can be expected to have a considerable advantage in negotiating micro-relief obstacles (ditches, boulders, fallen trees, etc.), but at the same time the disturbance produced by a tracked vehicle will produce camouflage difficulties. Thus it appears clear that the trailers, regardless of type, should be designed to be towed either by a truck or a tracked tractor depending on the trafficability difficulties that will be encountered.

The possibility of having the search and track systems mounted directly on truck beds was also investigated although it is felt that this arrangement had special disadvantages: high silhouette, high center of gravity, possibility of having truck deadlined, etc. Items (2) and (4) in Table B-5, graphs in Figures B-17 and B-18, and columns (4) and (5) in Tables B-6 and B-7 pertain to this arrangement.

Complete tabulations for all systems of the rating cone index allowing motion on level ground and the maximum slope negotiable at rating cone index 100 are given in Tables B-6 and B-7 respectively. The graphs in Figures B-11, B-12, B-13, B-14, B-15, B-16, B-17, and B-18 give the curves from which these values were determined and may be used to get other values.

TABLE B-6

LOWEST RATING CONE INDEX FOR MOVEMENT ON LEVEL GROUND

	Trailer Tracked	Trailer 4W	Trailer 2W	Search System (On truck bed)	Track System (On truck bed)	Number of Passes
Truck, 2-1/2 ton	----	66.3	55.4	44.0	45.0	Single
	----	77.0	68.1	58.0	60.0	Multiple
Truck, 4 ton	----	69.7	61.6	49.0	51.0	Single
	----	84.2	78.0	65.0	68.0	Multiple
Truck, 6 ton	57.5	66.1	60.0	----	----	Single
	74.8	81.5	77.0	----	----	Multiple
Tractor, M5A3	47.4	56.5	49.5	----	----	Single
	60.2	68.1	62.5	----	----	Multiple

TABLE B-7

MAXIMUM SLOPE NEGOTIABLE IN PER CENT AT RATING CONE INDEX 100

	Trailer Tracked	Trailer 4W	Trailer 2W	Search System (On truck bed)	Track System (On truck bed)	Number of Passes
Truck, 2-1/2 ton	----	14.2	25.7	50.1	49.8	Single
	----	11.9	22.5	45.5	44.6	Multiple
Truck, 4 ton	----	18.1	29.2	48.7	48.0	Single
	----	12.1	21.7	42.0	40.3	Multiple
Truck, 6 ton	27.6	22.3	32.3	----	----	Single
	21.4	15.8	24.4	----	----	Multiple
Tractor, M5A3	33.7	28.0	40.4	----	----	Single
	31.2	25.3	37.3	----	----	Multiple

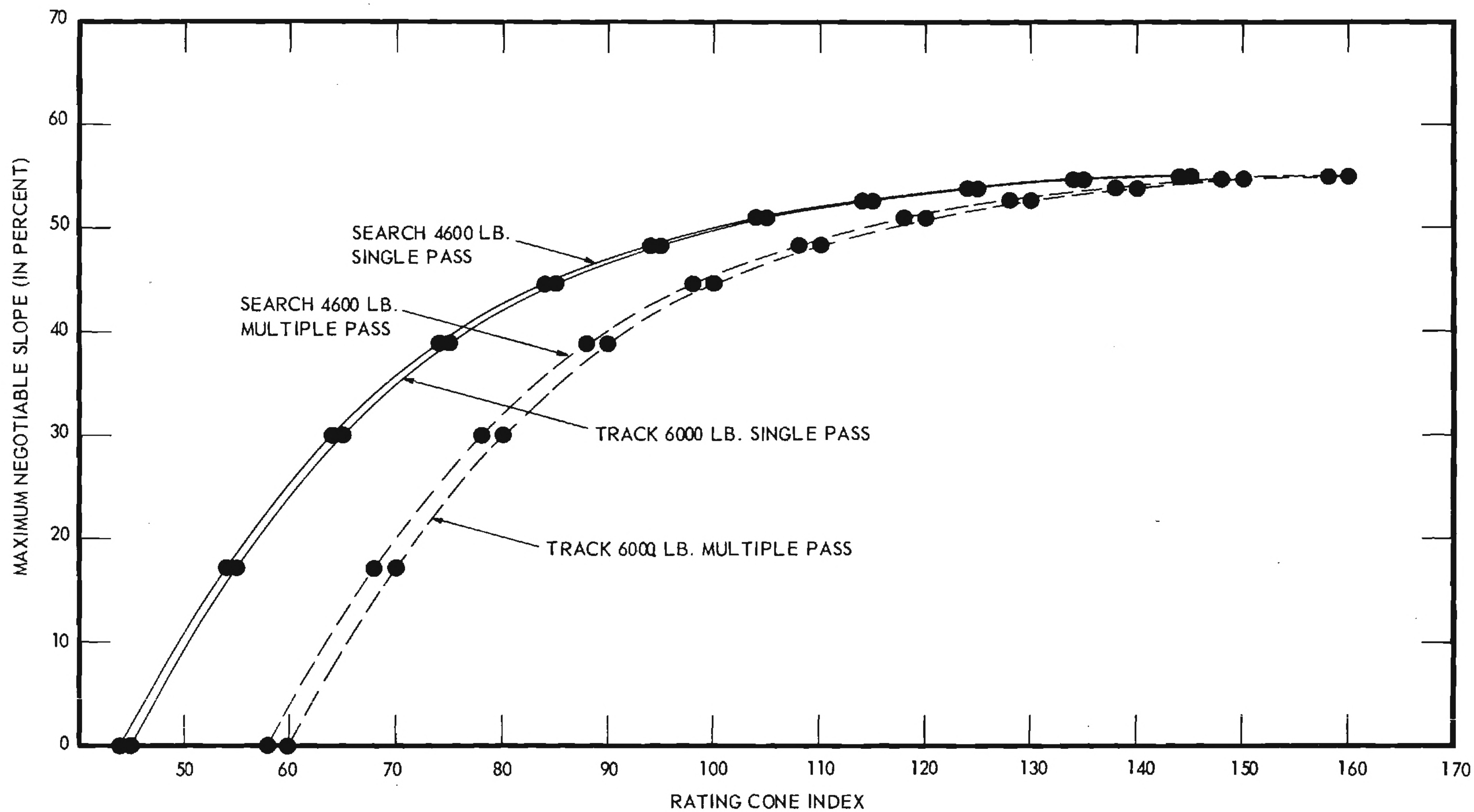

Figure B-17. Maximum Negotiable Slope Versus Rating Cone Index for the 2-1/2-ton Truck (M35) Mounting Either the Separate Track or Search System for Both Single and Multiple Passes.

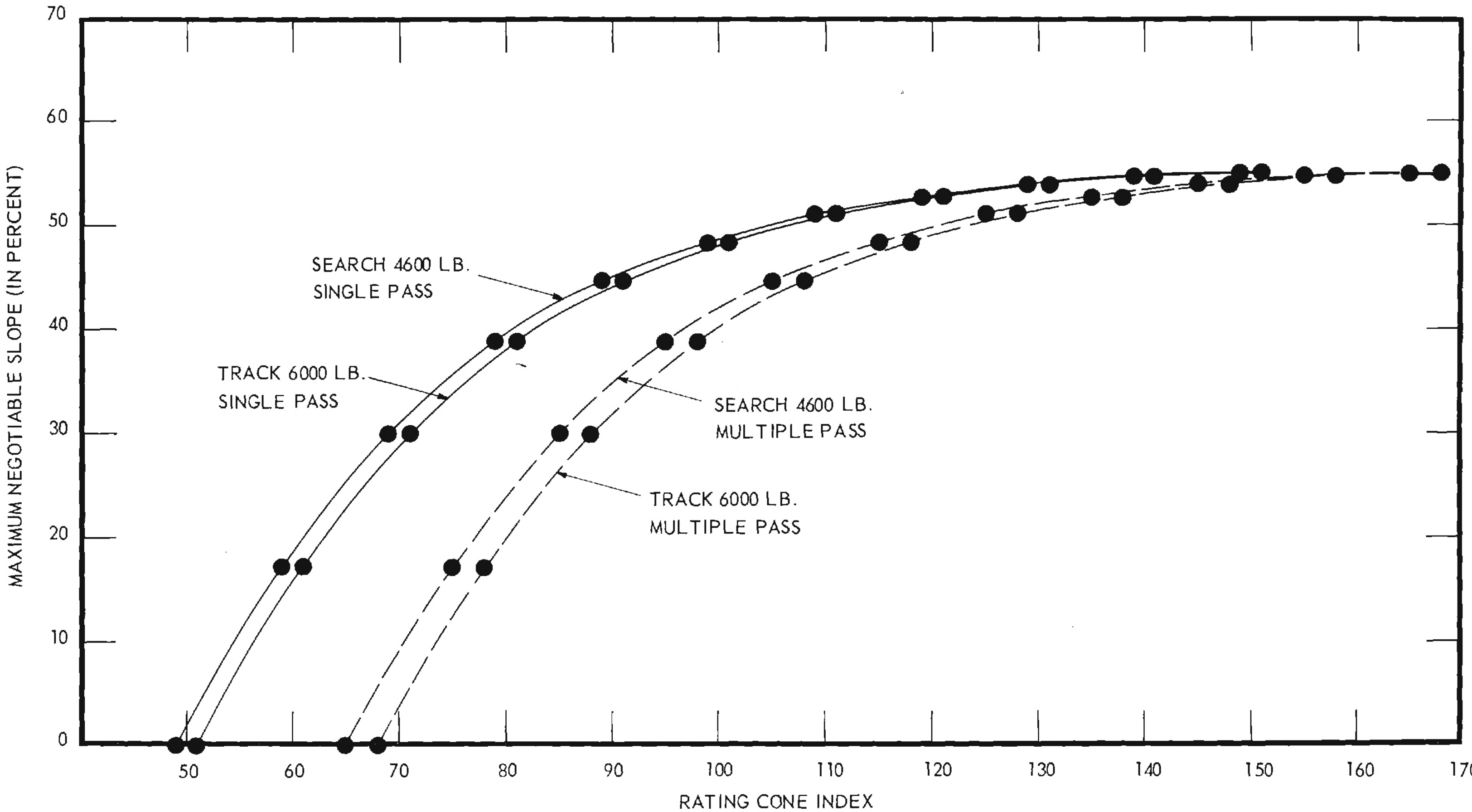

Figure B-18. Maximum Negotiable Slope Versus Rating Cone Index for the 4-ton Truck (Model 968A) Mounting Either the Separate Track or Search System for Both Single and Multiple Passes.

ANNEX C. SYSTEM RELIABILITY

Introduction. In a recent study of the military characteristics of a counter-battery radar made by the Combat Development Department at Fort Sill, Oklahoma, a requirement is stated in regards to reliability that the system should be capable of "23 hours continuous operation out of 24 hours, without excessive breakdown." Although "without excessive breakdown" is open to interpretation, it definitely implies that a high degree of reliability is desired by the military.

The critical nature of this requirement was discussed in an earlier study[†] in which the reliability of the AN/TPQ-5( ) was inferred from an analysis of field maintenance data on the M-33 radar, a similar type system of approximately the same size. This study gives the following estimates of the probabilities of the AN/TPQ-5( ) radar surviving missions of varying lengths, based on a total tube count of 1200.

Length of Mission (hours)	2	4	8	12	24
Probability of Survival	0.78	0.60	0.37	0.22	0.05

Regardless of the interpretation of the above phrase, "without excessive breakdown," these mission survival probabilities are too low. Special efforts must therefore be made to build reliability into the equipment if an acceptable CBR system is to be developed.

The AN/TPQ-5( ) radar system is comprised of electronic circuitry, antennas, inter-connecting cables and engine generator sets. Failure rates of the last two items were discussed with Mr. James Horton and Mr. E. G. Otto of ERDL, Fort Belvoir, Maryland. No quantitative data are available on this subject; however, the general consensus is that failure rates are very low on diesel engine generators and newer type power and multiconductor cables. Practically all failures in this area can be attributed to unpredictable human errors. Similarly, no useable information could be found on failure rates of radar antennas. For these reasons, the following discussion deals solely with the electronic circuitry portion of the AN/TPQ-5( ) radar system. This accounts for a major

[†] Final Report, Project A-108, Operational Research Study for Counterbattery Radar, Georgia Institute of Technology, 1954, Secret.

share of the system failures; however, the other components should receive consideration when information becomes available. In this discussion, no attempt is made to define precisely the degree of reliability required for a feasible CBR system. Such an undertaking is clearly beyond the scope of this project. The purpose here is to determine if a reasonable degree of realiability is attainable and to discuss ways of obtaining it.

ARINC Reliability Prediction Procedure. Aeronautical Radio, Inc. has made extensive studies of electron tube reliability and causes of tube failure. More recent studies, which consider the problem of design-stage prediction of electronic equipment reliability, have been published in a report that also contains information for improving equipment reliability.† A brief summary of the ARINC prediction method is given in Appendix C-1. An application of this procedure indicates that it should be possible to attain a satisfactory degree of system reliability for the AN/TPQ-5( ).

General Electric Co. Reliability Estimates. GE has made reliability predictions for the AN/TPQ-5( ) based on tube failure data from an AN/CPS-6B radar. The AN/CPS-6B is a heavy GCI ground radar employed by the Air Defense Command in its continental radar net. From this data it has been estimated that the probability of the proposed AN/TPQ-5( ) system surviving a 23-hour mission is 0.09; by applying preventive maintenance this figure can be raised to 0.62. These probabilities, based on a tube count of 1200, correspond to mean times to failure of approximately 9.5 and 48 hours respectively.

Per Cent Operable Time of Alternate Systems. In the Project A-108 report cited above, the mean repair times per failure for the M-33 radar system are give as follows:

Total troubles per M-33 system per month. 10

Total troubles per M-33 system per month repairable
by repairman assigned to each system 7

Total troubles per M-33 system per month requiring
higher maintenance (Ordnance Support). 3

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†Investigation of Electronic Equipment Reliability, Aeronautical Radio, Inc., Contract NObsr-64508, Feb. 15, 1956.

Average time spent on trouble by repairman assigned
to each system before repairing it or appealing
to higher maintenance. .5 hrs.

Average time spent on trouble by higher maintenance . . . . .6-8 hrs.

Thus, the overall mean repair time, including higher maintenance repair time, is approximately seven hours with considerable variation expected for the individual repairs. With this figure as a guide, the GE estimates of system reliability given above have been used to compute the per cent operable time, excluding all movement and setup time, for the proposed AN/TPQ-5( ) systems. The results of these computations are shown in Figures C-1 and C-2. Without attempting any quantitative evaluation of these figures, it seems reasonable to conclude that for the systems with no preventive maintenance features, the per cent operable time is unacceptable, varying from 50 per cent to 66 per cent for mean repair times of 10 to 5 hours respectively. Similarly, the systems with preventive maintenance provisions seem reasonably acceptable with the per cent operable time varying from 83 per cent to 91 per cent for mean repair times of 10 to 5 hours respectively. Thus, one might conclude that with preventive maintenance provisions, the lower bound of acceptable operations might be attained.

Consideration of Mode of Operation. For the purpose of making decisions regarding equipment design for improved reliability, it is helpful to consider the probable mode of operation of a CBR. Such operation is characterized by:

(1) Frequent movement, probably once each day under the cover of darkness.

(2) Short periods (approximately four hours) of urgent need interspersed among longer periods of little or no need.

Point (1) is well accepted; frequent movement can be expected because location of the radar by enemy photo-intelligence, if by no other means, is almost inevitable after a period of 24 hours. For this reason, it is expected that movement of the radar will be made daily with at least the emplacement occurring after dark.

Point (2) is not generally accepted by artillery personnel; however, the following arguments can be offered in its support.

(a) Enemy artillery locations made during inactive periods are usually stored for future use, primarily during offensive or defensive engagements.

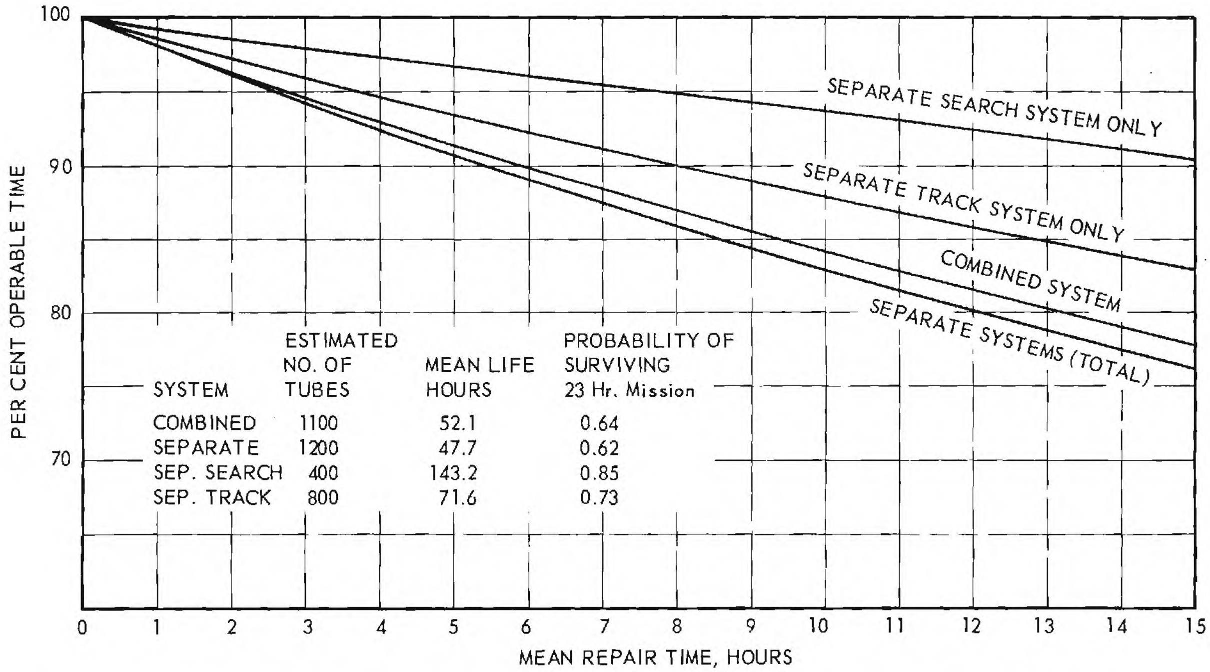

Figure C-1. Per Cent Operable Time as a Function of Mean Repair Time for the Proposed AN/TPQ-5 ( ) Systems with Preventive Maintenance.

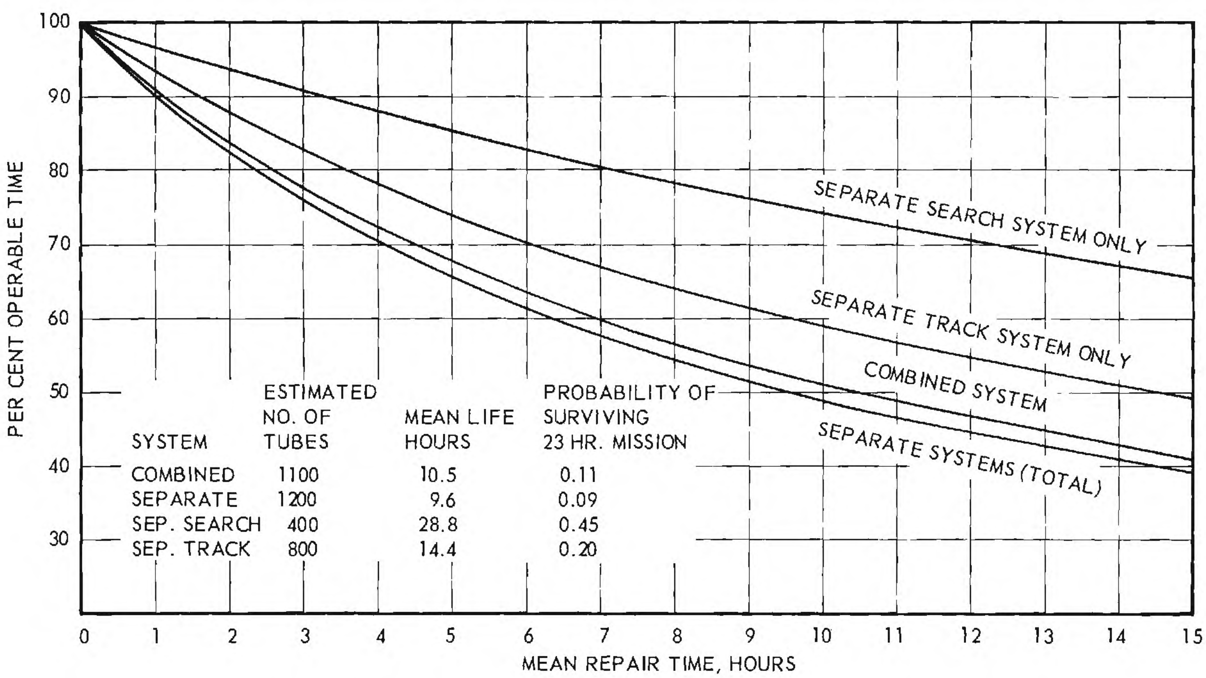

Figure C-2. Per Cent Operable Time as a Function of Mean Repair Time for the Proposed AN/TPQ-5 ( ) Systems without Preventive Maintenance.

Since the Russians are known to employ roving guns and to move or conceal their artillery before offensive action, these stored locations are recognized to be of questionable value.

(b) Importance placed on stored locations is overemphasized because, in the past, it has been the only good source of enemy artillery targets. A good CBR should be able to change this picture by making sufficient locations during the active periods to keep counter-battery artillery fully occupied.

(c) The desire has been expressed to maintain constant vigilance so that first round locations can be made of enemy atomic artillery. For several reasons it does not appear that this information, even if obtainable, would lead to serious restriction of the enemy's capability of delivering atomic warheads. First, the lethal area of an atomic warhead is such that the first round would very likely be an active round which can not be stopped in flight by any presently known means. Furthermore, atomic warheads can now be delivered from rocket launchers, which incidently could not be located by the AN/TPQ-5( ), as well as a number of heavy artillery pieces; thus, destruction of a single enemy source of atomic warheads would have little overall effect. Finally, there is a good chance that a radar which tracks an atomic round will be a casualty of this round before extrapolation of the trajectory is made.

(d) If the enemy utilizes RDF equipment to locate radars, a CBR may be forced to remain "off the air" except during active periods.

(e) By remaining "off the air" except during active periods, the probability of being ready when really needed can be increased.

Accepting the above mode of operation, the reliability requirement for the AN/TPQ-5( ) radar system might, for design purposes, be stated as follows: The AN/TPQ-5( ) radar system should have a reasonably high probability, say ≥ 0.9, of being ready for operation, and when called upon, should have a reasonably high probability, say ≥ 0.9, of remaining operable for at least four hours; such a system would thus have a probability, > 0.8, of being operable during tactically important periods, whenever they might occur, exclusive of radar movement time and periods of inclement weather.

With the special preventive maintenance features referenced above, the probability of surviving a four-hour mission is estimated to be 0.92; this satisfies the above specification of, ≥ 0.9. The problem then is to develop a system which will have a high probability of being operable after movement and will remain so until called upon. Although no quantitative information could be found on the effects of movement of radars, the general consensus is that it should not be an important factor if the equipment is properly designed for shocks.† In regards to increasing reliability during inactive periods, attention should be given to the effect on reliability of operating the equipment in a stand-by condition (heaters energized but all other voltages off) with reduced heater voltages. It is estimated in the ARINC report†† that reducing the stand-by heater voltage to 0.8 of the rated value will decrease the relative failure rate by a factor of 10.

In Appendix C-2, a model which approximates the above mode of operation has been developed. Essentially this model assumes that the radar oscillates between periods of operation and repair; movement of the radar, which is considered to be of minor importance, has thus been omitted. Mission survival probabilities computed for this model are given in Table C-1 below. These probabilities indicate that for a mean repair time of ten hours, the probability of the radar being operable during all of a randomly occurring four-hour period varies from 0.335 to 0.77 as the radar mean life is increased from 10 to 50 hours; similarly, for a five-hour mean repair time, these probabilities vary from 0.45 to 0.84; finally, if the radar has standby provisions which maintain the radar operable at all times, these probabilities would approach 0.67 to 0.92. These probabilities indicate that acceptable reliability is attainable if special provisions are made to build reliability into the system.

Summary. It should be possible by proper design and preventive maintenance techniques to reach an acceptable level of reliability for the AN/TPQ-5( ) radar

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†For example, one should avoid placing heavy parts, such as transformers, near the center of large chassis; Mr. Kapalan of ESL has pointed out that this can increase, by a factor of 10, the effects of shock near the heavy parts.

††Investigation of Electronic Equipment Reliability, Aeronautical Radio Inc., Contract NObsr-64508, pages (xix and xxi), Feb. 15, 1956.

TABLE C-1

PROBABILITIES OF THE AN/TPQ-5( ) RADAR SYSTEM BEING OPERABLE DURING VARIOUS PORTIONS OF A RANDOMLY OCCURRING ACTIVE PERIOD OF LENGTH Δt

Length of Active Periods (Δt) = Four Hours

γ = Mean Repair Time, assumed to be exponentially distributed

ξ = Mean Time Between Failures, assumed to be exponentially distributed

γ (Hrs.)	ξ (Hrs.)	Portion of Active Period During which Radar is Operable		
		All	Part	None
5	10	0.45	0.40	0.15
	50	0.84	0.12	0.04
10	10	0.335	0.33	0.335
	50	0.77	0.11	0.12
With perfect standby provisions which render the radar operable at all times between active periods, these figures become:				
†	10	0.67	0.33	---- ††
	50	0.92	0.08	----

†Mean repair time does not enter into the computations here because of the assumption below.

††These probabilities are zero by assumption that the radar will always be operable at the start of the active period.

system. The differences in the reliability for the proposed separate and combined antenna alternatives are relatively small; the effects of building reliability into the system are much more important than effects of the slight differences in complexity of the alternate systems.

In the process of building reliability into the system, special attention should be given to the mode of operation of the equipment. This leads to the recommendation that special attention be given to the problems of shock so that the equipment will withstand frequent movements without excessive start-up failures. It is also recommended that provisions be made to operate the equipment in standby with reduced heater voltages to increase the reliability of the equipment during the relatively long inactive periods of operation.

APPENDIX C-1

The ARINC procedure for design-stage prediction of system reliability is based on a subdivision of the system into components having different environmental and/or operating conditions with further subdivisions of each component into parts such as tubes, resistors, relays, etc.

The basis of the prediction method is then the reliability of those parts which make an appreciable contribution to unreliability. Reliability is defined as the probability of $(X > t)$, where X is the length of a period of satisfactory operation, and t is the time in hours. Assuming X is exponentially distributed, then

$$P(X > t) = 1 - \int_0^t \frac{1}{\xi} e^{-\frac{X}{\xi}} dX = \int_t^\infty \frac{1}{\xi} e^{-\frac{X}{\xi}} dX = e^{-\frac{t}{\xi}}$$

where ξ is the mean length of a period of satisfactory operation. If a number of statistically independent parts must simultaneously perform satisfactorily, then

$$P(X > t) = \prod_{i=1}^{n} P_i(X > t) = \prod_{i=1}^{n} e^{-\frac{t}{\xi_i}} = e^{-t \sum_{i=1}^{n} \frac{1}{\xi_i}} .$$

It can be shown that the failure rate is approximately $1/\xi$. Thus

$$P(X > t) = e^{-t \text{ (Sum of part failure rates)}} .$$

This expression is applicable to the reliability of components as well as systems of components.

Data are given in the ARINC study on the standard failure rates of parts. Suitable correction factors are given for design conditions such as tube heater voltages, ratio of actual to rated resistor power dissipation, ratio of actual to rated voltage on capacitors, and other operating conditions. The sum of the appropriate parts failure rates gives the component failure rates to which special corrections are applied to allow for the effects of stresses peculiar to each component. These stresses include operating temperatures of parts, circuit margins of tolerance for any characteristic of any part within the component, maintenance conditions, etc. The reliability of the system is then obtained by summing the failure rates of the components. This estimate is modified by consideration of the effects of stresses introduced by the system design which includes allowances for redundancy of components in the system, system margins of tolerance for any characteristic of any component within the system, and system maintenance conditions. A block diagram of this procedure is given in Figure C-3.

Assumptions Involved in Applying Above Procedure

(1) The failure of any part, with the exception of redundant parts, renders the system useless (although it is known that a system may continue to perform its function in spite of the failure of some of its parts).

(2) The failure rate of a specific part is assumed to be that of its class of parts.

(3) Component (or system) correction factors are determined on the basis of the worst situation existing within the component (or system).

(4) The basic failure rates and correction factors listed in the ARINC study are applicable to the AN/TPQ-5( ) under its particular environment.

(5) The length of a period of satisfactory operation is exponentially distributed (constant failure rate).

Assumptions (1) and (3) above tend to make reliability estimates, based on this procedure, pessimistic. However, of the three known applications of this technique made to date, the prediction errors have been 8, 5 and 15 per cent on systems containing 55, 200 and 500 tubes respectively.[†]

Results Obtained from the Above Procedure

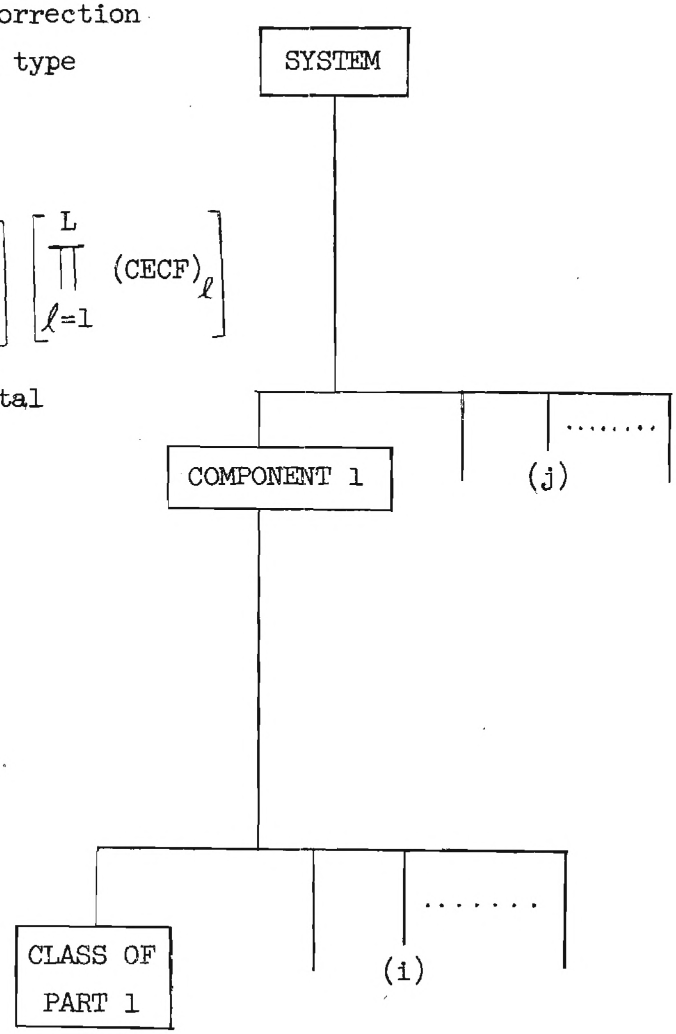
$$P(X > t) = e^{-t\left\{\sum_j C_j \left[\sum_i \frac{K_i}{\xi_i}\right]\left[\prod_{p=1}^{P} (PCF)_p\right]\left[\prod_{\ell=1}^{L} (CECF)_\ell\right]\left[\prod_{m=1}^{M} (SECF)_m\right]\right\}}$$

[†]Private communication with Mr. G. R. Herd, Aeronautical Radio Inc., Washington, D.C.

$$P(X > t) = e^{-t\left\{\sum_j C_j \left[\sum_i \frac{K_i}{\xi_i}\right]\left[\prod_{p=1}^{P} (PCF)_p\right]\left[\prod_{\ell=1}^{L} (CECF)_\ell\right]\left[\prod_{m=1}^{M} (SECF)_m\right]\right\}}$$

$(SECF)$ = the mth System Environment Correction

C_j = no. of components of the jth type



$$P(X > t) = e^{-t\left[\sum_i \frac{K_i}{\xi_i}\right]\left[\prod_{p=1}^{P} (PCF)_p\right]\left[\prod_{\ell=1}^{L} (CECF)_\ell\right]}$$

$(CECF)_\ell$ = the ℓth Component Environmental Correction Factor

$$P(X > t) = e^{-t\left(\frac{K_i}{\xi_i}\right)\left[\prod_{p=1}^{P} (PCF)_p\right]}$$

$(PCF)_p$ = the pth Part Correction Factor

K_i = No. of parts in the ith class of parts

where i = 1,2, ... No. of Classes of Parts in the Component

j = 1,2, ... No. of Different Components in System

ξ = mean life between failures in hours

t = time in hours

Figure C-3. Block Diagram of ARINC Reliability Prediction Procedure.

is the function which gives the probability of the system surviving a mission of length t, assuming the set operates at time t = 0. For reliability statements couched in this manner, this expression can be used directly by substituting the appropriate value of t.

Another useful expression can be obtained from the above function, i.e., the mean life to failure which can be estimated from the reciprocal of the term in the brackets $\left\{ \right\}$.

APPENDIX C-2

Introduction. The purpose of this Appendix is to estimate mission survival probabilities for the AN/TPQ-5( ) radar which is operated as described in Annex C, i.e., frequent movement, and short periods of urgent need interspersed among relatively long periods of little or no need.

The Model. To estimate these mission survival probabilities, the following simplified model is employed.

(1) The radar is considered to be permanently emplaced.

No quantitative information could be found on the effect of movement of radars; however, the general consensus is that it should not be an important factor if the equipment is properly designed for shocks. For this reason, movement of the radar was omitted from this model.

(2) The radar set is "worked" continuously and active periods occur at at random intervals.

Ordinarily the set will oscillate between periods of operation and repair. If special standby provisions are provided, the set will vary among the three modes of operation: standby, operate, and repair.

(Although points (1) and (2) above deviate considerably from the actual mode of operation of the equipment, they should serve as an adequate model for the purposes stated here provided that movement of the radar does not seriously affect reliability.)

(3) Mean time to failure for the radar is denoted by ξ, and the time to failure, t, is assumed to be exponentially distributed with probability density function u(t).

$$u(t) = \frac{1}{\xi} e^{-t/\xi}$$

There is considerable evidence available to support this assumption.[†]

[†]Aeronautical Radio, Inc., General Report No. 1, Investigation of Electron Tube Reliability in Military Applications, Jan. 4, 1954.

(4) Mean repair time for the radar is denoted by γ, and the time for repair, t, is assumed to be exponentially distributed with probability density function v(t).

$$v(t) = \frac{1}{\gamma} e^{t/\gamma}$$

It is felt that this is a reasonable assumption; however, no data are available to substantiate it. Fortunately, this assumption is of secondary importance in the derivation and computations which follow.

Derivation of Prediction Equations. There are three possible outcomes for the radar operation during an active period, assuming the radar is "worked" continuously and active periods occur at random intervals. The radar can operate during (1) all, (2) part, or (3) none, of the active periods. Since these three outcomes are mutually exclusive and exhaustive, they form an additive set with combined probability of one. For convenience then, the probability of (1) and (3) will be computed and (2) will be obtained by difference

$$1 - [P(1) + P(3)] = P(2).$$

For outcome [(1) all] to occur, two things must happen.

(a) The radar must be operable at the start of the active period.

(b) The radar must remain in operation during the entire active period.

Similarly, for outcome [(3) none] to occur, two things must happen.

(a) The radar must be inoperable at the start of the active period.

(b) Repair of the radar must not be completed during the active period.

Following is a derivation of the probability of occurrence of parts (a) in the above description.

ξ = mean working time between failures

γ = mean repair time

N_o = total number of sets under consideration

N = number of sets operable at time t

Then $P_e = \frac{N}{N_o}$ = probability that any randomly selected set will be operable at time t.

If at the moment N sets are operable, failures occur at the rate of $\frac{N}{\xi}$.

If at the moment N sets are operable, repairs occur at the rate of $\frac{N_o - N}{\gamma}$.

Thus, the time rate of change of N is then the difference between the repair and failure rates,

$$\frac{dN}{dt} = \frac{N_o - N}{\gamma} - \frac{N}{\xi}$$

$$\frac{dN}{dt} + \left(\frac{1}{\gamma} + \frac{1}{\xi}\right)N = \frac{N_o}{\gamma}$$

which gives

$$\frac{N}{N_o} = Ce^{-\left(\frac{1}{\gamma} + \frac{1}{\xi}\right)t} + \frac{\xi}{\xi + \gamma}.$$

Let N(0) = number of sets operable at time t = 0

$$C = \frac{N(0)}{N_o} - \frac{\xi}{\xi + \gamma}$$

and

$$\frac{N}{N_o} = \frac{\xi}{\xi + \gamma} + \left[\frac{N(0)}{N_o} - \frac{\xi}{\xi + \gamma}\right] e^{-\left(\frac{1}{\gamma} + \frac{1}{\xi}\right)t}.$$

If we let $t = \infty$, then $\frac{N}{N_o} = \frac{\xi}{\xi + \gamma}$, the steady state value.

Thus $P_e = \frac{\xi}{\xi + \gamma}$ = probability that any randomly selected radar set will be operable at time t.[†] Since the radar must either be operable or in repair, $P'_e = 1 - \frac{\xi}{\xi + \gamma} = \frac{\gamma}{\xi + \gamma}$ = probability that any randomly selected radar set will be in repair.

[†] This same expression has been derived, using a different approach to the problem, by D. P. Gaver of the Analytical Research Group of Princeton University. It appears in Memorandum Report B-6 titled, "Estimated Operability Characteristics of a Radar Artillery Locator."

Following is a derivation of the probability of parts (b) in the above description.

Let $P(A)$ = probability of no failure to time t_o

$P(B)$ = probability of failure during time (t_o) to $(t_o + \Delta t)$

$P(A,B)$ = probability of A and B occurring

$P(B|A)$ = probability of B occurring, given A has occurred,

then

$$P(B|A) = \frac{P(A,B)}{P(A)} = \frac{\int_{t_o}^{t_o + \Delta t} \frac{1}{\xi} e^{-t/\xi} \, dt}{1 - \int_{0}^{t_o} \frac{1}{\xi} e^{-t/\xi} \, dt} = \frac{e^{-t_o/\xi} - e^{-(t_o + \Delta t)/\xi}}{e^{-t_o/\xi}} .$$

$$P(B|A) = 1 - e^{-\Delta t/\xi}$$

$$P\begin{pmatrix}\text{No failure during time } (t_o) \text{ to } (t_o + \Delta t), \\ \text{given that no failure has occurred to time } t_o\end{pmatrix} = 1 - P(B|A) = e^{-\Delta t/\xi}$$

The following can be derived in the same manner as above.

$$P\begin{pmatrix}\text{No completion of radar repair during time } (t_o) \text{ to } (t_o + \Delta t), \\ \text{given that the radar was not operable at time } t_o\end{pmatrix} = e^{-\Delta t/\gamma}$$

From the above, the probability that the radar set will be operable during <u>all</u> of a randomly occurring active period of length Δt is given by

$$P(\text{All}) = \frac{\xi}{\xi + \gamma} e^{-\Delta t/\xi}$$

Similarly, the probability that the radar set will be operable during <u>none</u> of the active period is given by

$$P(\text{None}) = \frac{\gamma}{\xi + \gamma} e^{-\Delta t/\gamma}$$

Finally, the probability that the radar set will be operable during part of the active period is given by

$$P(\text{Part}) = 1 - [P(\text{All}) + P(\text{None})]$$

The above formulae were used to compute the probabilities given in Table C-1 of Annex C.

Effects of Standby Provisions. It has been suggested that radar reliability during inactive periods can be increased by providing for standby operation (heaters energized but all other voltages off) with reduced heater voltage. The limit of the reliability improvement which could be effected by this means would be reached when the mean time to failure (ξ) in standby is infinite. Since it is unlikely that a radar failure occurring during an active period of operation would not be repaired before the next active period, infinite standby mean life would effectively mean that the radar would always be operable at the start of an active period. In this case the probability of the radar surviving all of a randomly occurring active period of length Δt is merely equal to $e^{-\Delta t/\xi}$. Since the probability of being operable during none of the active period is assumed to be zero, the probability of being operable during part of an active period is $1 - e^{-\Delta t/\xi}$. These formulae were used to compute the probabilities given in Table C-1 of Annex C.

ANNEX D. THE READINESS PROBABILITY CRITERION

The "time factors" discussed in Section 2.12--movement time, reliability, and weather limitations--can each be regarded as imposing a restriction on the fraction of total calendar time during which the radar might be in "ready" condition. While this is not the only light in which they can be viewed, such an approach is convenient because it allows several different factors to be tied together on a common basis.

In this annex, time-factor influences will be illustrated by a hypothetical "middle-of-the-road" example. The long-term average effect of each factor will first be discussed as if all other sources of dead-time were absent, and the results will then be combined into an estimate of the system's "readiness probability."

Movement Time. The sum of the system's average tear-down, transport, and set-up times has been called "movement time," M. If the average frequency of movement is denoted by m, the fraction of total time F_m during which the radar is set up in operating position is just

$$F_m = 1 - mM.$$

As mentioned in Section 2.12, the average set-up time for the separate-antenna system is estimated to be about 1.25 hours, assuming adequate site preparation and presuming night-time emplacement so that operation can begin before camouflaging and sandbagging is completed. Similarly, the average tear-down time for an orderly withdrawal is estimated to be 50 minutes.

Military personnel have stated that a CBR will probably have to be moved at least once a day both for tactical reasons and to stay one jump ahead of enemy photointerpreters. At the same time, it appears that it would be difficult to move more often than once per day because opportunity for emplacement seems restricted to night time; the activity involved in setting up in a prominent site would be too conspicuous in daylight. A typical frequency of movement will therefore be taken as once per day.

For an estimate of average transport time, it will be assumed that the route consists of four miles by road, covered at 15 miles per hour, and 1.5 miles off-road at two miles per hour. The transport time would then be 1.02 hours.

Under these conditions, a "typical" movement time is 3.1 hours, which for one move per day gives $F_m = .87$.

Reliability. The quantity P_e derived in Annex C, the probability that a randomly selected CBR will be operable at an arbitrarily chosen time, can also be interpreted as the long-term average fraction of total time during which a single set is in operable condition. If the set is in standby most of the time with negligible failure rate, P_e approaches unity; while if an attempt is made to keep the set on the air continuously P_e is given by

$$P_e = \frac{\xi}{\xi + \gamma} = \frac{\xi/\gamma}{1 + \xi/\gamma}$$

where ξ = mean life to failure
and γ = mean repair time.

From the second expression above it is evident that P_e is really a function only of the ratio of mean life to mean repair time. The behavior of this function is shown in Figure D-1.

Assuming from the discussion of Annex C that preventive maintenance can extend the mean life to 48 hours and that the mean repair time for the residual unanticipated failures is 7 hours, P_e would be .87 if no time were spent in standby. Without preventive maintenance it is estimated that the mean life would drop to 9.5 hours, but the mean repair time might also be shorter because of a greater incidence of relatively simple troubles. For a mean repair time of 5 hours, P_e would then be .66.

Weather Limitations. It is expected that an X-band CBR will be disabled by even very slight precipitation. Estimates of the percentage of time during which precipitation occurs, as determined by season and locality, are shown on the maps of Annex B.

An attempt has been made to obtain a representative figure for purposes of illustration by averaging the map percentages for the United States, Europe (including Russia to the Urals), and southeastern Asia. The results are given in the following table.

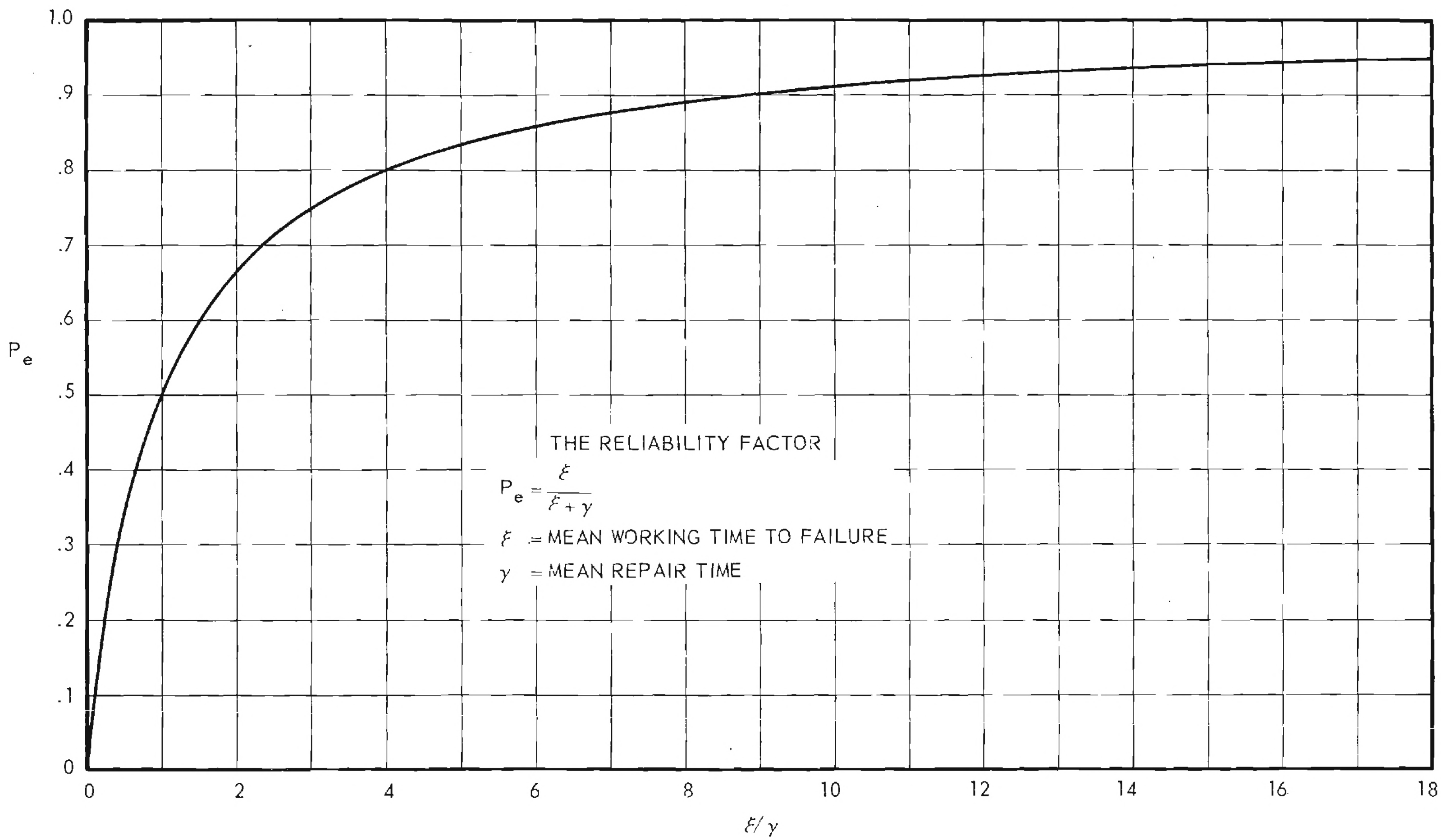


Figure D-1. The Reliability Factor P_e as a Function of the Ratio ξ/γ.

AVERAGE FREQUENCY OF PRECIPITATION (PER CENT TIME)

Months	United States (47 localities)	Europe (85 localities)	S.E. Asia (37 localities)
Dec-Jan-Feb	18.0	17.9	13.5
Mar-Apr-May	14.2	13.1	15.3
June-July-Aug	7.4	8.6	16.9
Sept-Oct-Nov	13.3	14.5	13.5
Year-Round Average	13.3	13.5	14.8

Year-Round Average over all Localities = 13.7

It should be recognized that because of the wide variation in climate from place to place and season to season, the "averages" obtained in this way must be regarded with suspicion and interpreted with caution. Nevertheless, the year-round averages for the three regions considered are nearly the same, and the use in an example of the year-round average over all localities--about 14 per cent--seems not unreasonable.

Accordingly, it will be assumed that the long-term average fraction of total time during which the weather is favorable for CBR operation, F_w, is .86.

Combined Effects. If movement, reliability, and weather effects were non-interacting the over-all fraction of total time during which the radar might be in ready condition (or the "readiness probability") would be just

$$F = F_m \cdot P_e \cdot F_w \, .$$

If other possible sources of dead-time are disregarded, this expression should be nearly correct. Weather and movement can be considered independently, for while it would be desirable to plan moves so as to "conserve" fair weather time for operation, it is unlikely that one could do so with regularity. Movement and reliability are suitably non-interacting, since movement-induced failures are expected to be few and repairs probably cannot be effected while the set is in transit. Therefore, for the expression given above to be correct only one further restriction would be required: confinement of all failures and repairs to periods of fair weather. This condition is evidently not met; failures can be assumed to occur only when the set is operating, but repairs can continue during precipitation. Examination will show, however, that only a slight correction is needed. Depending upon the way in which occurrences of precipitation are distributed in time, F varies between a figure given by the expression above and an upper limit obtained by substituting for P_e the quantity $P_{ew} = \xi/(\xi + \gamma F_w)$. (See Appendix D-1.)

In the example considered here, P_e for a well-designed, continuously worked CBR has been estimated to be .87 with preventive maintenance ($\xi = 48$ hours, $\gamma = 7$ hours) and .66 without preventive maintenance ($\xi = 9.5$ hours, $\gamma = 5$ hours). For the assumed "typical" value $F_w = .86$, the corresponding figures for P_{ew} are .89 and .69. The weather-reliability interaction effect is thus very slight, and it will be sufficient to assume a single set of intermediate figures, .88 and .67 respectively.

The use of the "middle-of-the-road" values

$$F_m = .87$$

$$F_w = .86$$

$$P = \begin{cases} 1; \text{ continuous standby, negligible failure rate.} \\ .88; \text{ good design, preventive maintenance.} \\ .67; \text{ good design, no preventive maintenance.} \end{cases}$$

leads to the following values for the readiness probability F:

(a) Continuous standby, negligible failure rate--F = .75

(b) Good design, preventive maintenance --F = .66

(c) Good design, no preventive maintenance --F = .50

In the role of continuous surveillance envisioned by military personnel, it appears that over a long period a CBR might be found in "ready" condition about 66 per cent of the time. Inadequate attention to preventive maintenance would reduce the figure; operation of the set in standby during inactive periods might increase it.

It should be borne in mind that these calculations apply only to a restricted example, which, while believed to be a reasonable basis for illustrating the long-term average outlook, is entirely hypothetical. Conditions encountered in specific tactical engagements can obviously differ drastically from those assumed. Furthermore, not all sources of dead-time have been considered. The possibility of shell-fragment damage is considerable, as can be seen from the discussion of Annex E. Also, it might sometimes be infeasible to proceed immediately to a new site after a withdrawal, particularly when the withdrawal has been forced in daylight by enemy activity. Periods in which radar operation is curtailed by enemy activity, as well as periods of unfavorable weather, could unfortunately be times of great tactical need.

APPENDIX D-1

The expression $P_e = N/N_o = \xi/(\xi + \gamma)$ is obtained in Annex C as the steady state solution to the differential equation

$$\frac{dN}{dt} = \frac{N_o - N}{\gamma} - \frac{N}{\xi}$$

where N sets, out of an ensemble (actual or imaginary) of N_o sets, are in operable condition. Here N/ξ is the failure rate and $(N_o - N)/\gamma$ is the repair rate.

Now if the influence of weather is to be considered, the failure rate must be replaced by $(N/\xi)\, f_w(t)$ where $f_w(t)$ is a "weather function" such that $Nf_w(t)$ is the number of sets actually operating at any time. (It is assumed that all operable sets are worked continuously during periods of fair weather and turned off during periods of precipitation.) The repair rate, however, remains unchanged. Thus the differential equation becomes

$$\frac{dN}{dt} = \frac{N_o - N}{\gamma} - \frac{N\, f_w(t)}{\xi}$$

Obviously, the form of the solution to this equation depends upon the functional form of $f_w(t)$, so that it is not possible to exhibit a meaningful general solution. However, the weather influence can be examined adequately without formally solving the equation. Let us first observe that if the equation had an <u>equilibrium</u> solution, that solution could be obtained by simply equating the failure and repair rates, since in the equilibrium condition $dN/dt = 0$. Such is the case for the unmodified reliability problem, and the solution $P_e = \xi\ (\xi + \gamma)$ follows immediately from the requirement $(N_o - N)/\gamma = N/\xi$. Now when weather effects are introduced this equilibrium condition will be destroyed, and we must examine instead the <u>steady state</u> condition $(dN/dt)_{avg} = 0$, or

$$\left[\frac{N_o - N}{\gamma} - \frac{Nf_w(t)}{\xi}\right]_{avg} = 0$$

In order to make something worthwhile out of this expression, we must restrict our attention for the moment to the limiting case wherein both the mean duration of periods of fair weather and the mean duration of periods of precipitation are short compared to the mean life ξ and the mean repair time γ. Under these circumstances neither the total number of operable sets nor the probability that an individual set is in operable condition undergoes any great excursion with changes in the weather, so that we may replace N/N_o by $(N/N_o)_{avg}$, and $(N/N_o)\ f_w(t)$ by $(N/N_o)_{avg}\ F_w$. Then we find

$$\left(\frac{N}{N_o}\right)_{avg} F_w = P_{ew}\ F_w, \quad \text{where } P_{ew} = \frac{\xi}{\xi + F_w\gamma}$$

Thus the interaction effect of this limiting-case kind of weather can be introduced simply by replacing γ by γF_w in the expression for P_e.

Let us now consider the opposite extreme: mean duration of both fair weather and precipitation periods very long compared to the mean life and mean repair time. Here the probability of an individual set being operable undergoes great excursions with changes in the weather. At the end of a long period of precipitation, failures which may have occurred earlier will almost surely have been repaired. When operation is resumed, the probability of being operable is therefore nearly one initially and begins to decay thereafter toward the equilibrium value P_e, where it remains until the next occurrence of precipitation. During the period of unfavorable weather the probability builds up again toward unity.

Now since the time between weather changes is assumed to be very long, the set's probability of being operable remains equal to P_e throughout all but a negligibly small part of each period of fair weather. Under these circumstances the fraction of total time during which the weather is fair and the set is operable is just $P_e \cdot F_w$. In this limit, there is no significant weather-reliability interaction.

We now have two limiting-case expressions, $P_e \cdot F_w$ and $P_{ew} \cdot F_w$, which establish bounds on the weather and reliability influences upon the set's "readiness probability" F. The weather-reliability interaction, which tends to make F larger for a fixed F_w, increases with increasing frequency of weather changes. Fortunately, for practical values of F_w and ξ/γ, the spread between these bounds is not very great.

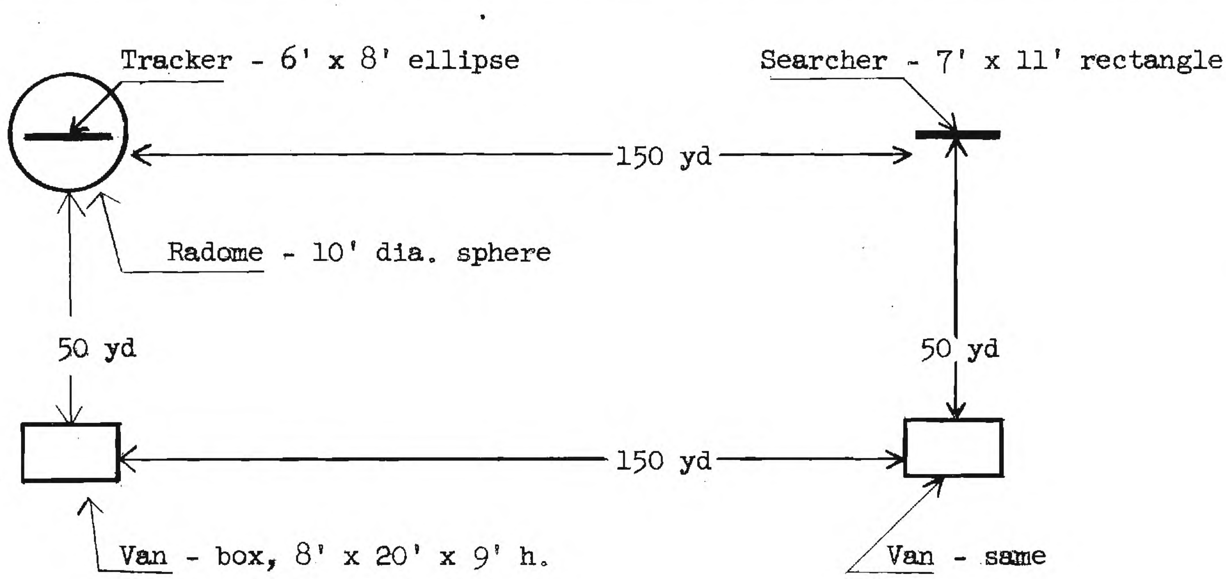
ANNEX E. VULNERABILITY ESTIMATES

If a CBR is to be a feasible device, it must have a reasonable chance of survival in a battlefield environment. Good camouflage can do much to lessen the probability of identification by air and ground observers, and frequent movement can reduce the effectiveness of photointerpretation for detection and fire direction. Nevertheless, such evasive measures are never infallible, and location by RDF techniques cannot be discounted. Inevitably, the system will at some time be brought under fire. It seems essential to make some estimate of the vulnerability of CBR equipment to artillery attack. In making efforts in this direction, EES was fortunate to obtain the cooperation of the Combat Development Department (CDD), TAGMS, Fort Sill.

Vulnerability estimates are customarily made by calculating and tabulating effective "lethal areas" for specific shells against specific types of targets such as personnel or trucks; manipulation of these tables gives the probability of obtaining one or more hits in a critical spot. However, since it is not known at present just what kinds of damage might disable a CBR nor where critical components will be physically situated, a different approach is necessary. For an approximate analysis, the component units of the radar can be represented by simple geometric shapes: vertical planes for the antenna reflectors, a sphere for the radome, and "boxes" for the operations vans. Vulnerability can be expressed in terms of a measure such as the expected number of fragment hits through any surface resulting from a concentration of given shell density.

Such was the problem suggested to Lt. Col. Otis Spears and his associates, a CDD group currently engaged in advanced studies of artillery effects and target vulnerabilities. Preliminary calculations have been completed and made available for presentation here. A more detailed paper will be published by CDD in about two months.

The assumed target model is sketched below. It will be noted that for the antenna units only the surface area of the reflector itself is considered; the trailers and electronics units thereon are disregarded. Some degree of protection could be given these parts by partially digging-in the trailers.



Sketch of Target Area

Calculations were made for two classes of weapons: heavy and light. The 105mm Howitzer was chosen as representative of light artillery, and the 8" Howitzer was chosen as the heavy weapon.

It was assumed that the fire of a single battery firing open sheaf was directed at the installation. For the 105mm Howitzer, intended CI's were placed 30 yards apart on a line bisecting the target in range. The 8" Howitzer intended CI's were placed 50 yards apart on the same line.

The table below gives the expected number of fragments penetrating each unit for one battery volley. The figures apply for superquick bursts or low air bursts. It should be noted that the expected number of penetrations is directly proportional to the number of battery volleys. Also, if the batteries in a battalion are not widely dispersed laterally, figures for battalion N volleys may be obtained as follows: Expected penetrations for battalion N volleys = 3Nn, where n is the tabulated figure for a single battery volley.

EXPECTED NUMBER OF PENETRATIONS FOR ONE BATTERY VOLLEY

	Tracker	Searcher	Radome	Each Van†	Each Van†† (Sandbagged)
105mm How	.156	.320	1.75	1.047	.695
8" How	.596	1.217	4.96	3.442	2.295

†Partially dug-in; roof 6' above ground surface.

††Partially dug-in; roof 6' above ground surface; sandbagged around sides to a level 3' below roof.

NOTE: Fragmentation data is not available for distances less than 20 feet from a burst. Therefore, there is an area surrounding each target, with its boundaries at least 20 feet from the target, which was not included in the area over which integrations were taken.

ANNEX F. THE BATTERY ACQUISITION PROBLEM

It is of interest to consider how many shells a CBR must acquire in order to locate a certain fraction of the batteries whose shells it can see. Once the CBR locks on to a shell, the shell may prove to be visible for too short a time for successful extrapolation, the extrapolation time may be excessive, or the shell may turn out to be from a battery already located. Thus there will be a certain amount of time-consuming "waste motion", and by assuming a possible artillery situation one can get an idea of how serious the problem is likely to be. Work along these lines is being carried out in a related study, Project A-190. Some preliminary results are cited here.

The artillery situation assumed is that of a 10,000 yard corps front, with weapon disposition according to the artillery model discussed in Annex A. A CBR with a 30° search sector is assumed to be situated 4000 yards behind the Zone of Contact (Z/C). Under these circumstances there would be a total of about 40 batteries within the radar's search sector, distributed as follows: light artillery, 26 batteries, 2000 to 5000 yards behind Z/C; medium artillery, 10 batteries, 5000 to 8000 yards; heavy artillery, 4 batteries, 8000 to 11,000 yards. This distribution of artillery is more dense than one would normally expect where threat of atomic attack is imminent, but it is somewhat less dense than the extreme maximum concentration anticipated at Ft. Sill (which implies a 6000 yard corps front).

The fire from these batteries is assumed to follow the classification given in Table A-6 and Table A-7 of Annex A. The four cases presented in these tables will be referred to here as Cases I through IV:

Case I - 50 mil mask, best case (minimum charges)
Case II - 50 mil mask, worst case (maximum charges)
Case III - 100 mil mask, best case (minimum charges)
Case IV - 100 mil mask, worst case (maximum charges)

Now in order to estimate the probability of obtaining a usable track from any one specific battery, one must know something about how mission assignments are distributed among the several batteries of a given class. It is conceivable, for example, that in the course of an engagement each individual battery might be called upon to carry out all of the types of fire missions typically assigned to artillery of its class, so that a usable trajectory might come from any battery of a given type with equal likelihood. An alternative and probably more realistic assumption is that the usable trajectories come only from certain batteries, while the fires of other batteries of the same class are never seen or are always unsuitable for extrapolation. Both situations are considered here. In the latter case, the usable fire from a given class of artillery is taken to be distributed equally among a number of batteries determined from the assumption:

$$\frac{\text{(Number of batteries of a given class firing usable trajectories)}}{\text{(Total number of batteries of the class)}} = \frac{\text{(Amount of usable fire from batteries of the class)}}{\text{(Total amount of fire from batteries of the class)}}$$

The approximate numbers of "accessible" batteries given by this expression are shown in the following table.

ZONE Kiloyards from Z/C	NUMBER OF BATTERIES FROM WHICH USABLE FIRE IS SEEN			
	Case I	Case II	Case III	Case IV
2 to 5 light	13	4	4	0
5 to 8 medium	10	7	6	3
8 to 11 heavy	4	2	2	2

The results of random sampling experiments carried out for both of these extreme situations are presented in Figures F-1 through F-4. The curves show the average number of different batteries located for a given number of projectiles acquired. Situations where mission assignments are varied over all batteries are indicated by the letter "a" following the case number; those where mission assignments are not varied are indicated by the letter "b".

The low efficiency of the location process is evident from inspection of the graphs. It is due partially to repetitive location of the same batteries and partially, in some cases, to the fact that not all visible trajectories are suitable for extrapolation. In the "a" cases one could, as expected, eventually locate all 40 batteries (except in case IVa, where of the many light artillery trajectories seen, none is usable). However, even in Case Ia, where all visible trajectories are usable, the CBR would have to acquire nearly 100 shells to locate an average of 90 per cent of the batteries within its sector. In the "b" cases only a fraction of the batteries in the sector could be located. Again in Case Ib all visible trajectories are usable, but to locate 24 out of the 27 accessible batteries would acquire around 90 acquisitions. In the less favorable situations, not only does the number of accessible batteries fall off, but the efficiency with which even these are located decreases as many of the visible trajectories become unusable.

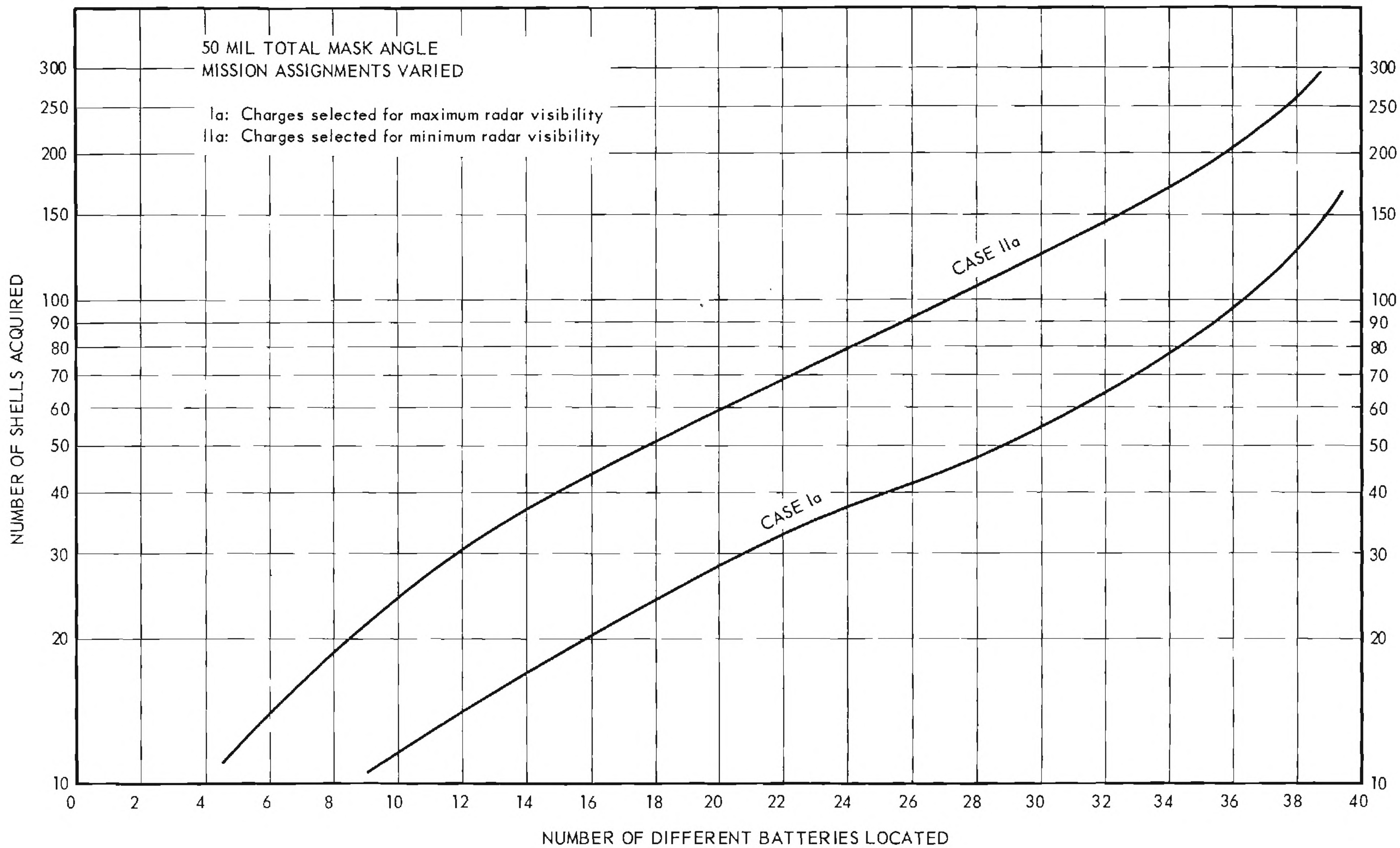


Figure F-1. Average Number of Different Batteries Located as a Function of the Number of Shells Acquired; Cases Ia and IIa.

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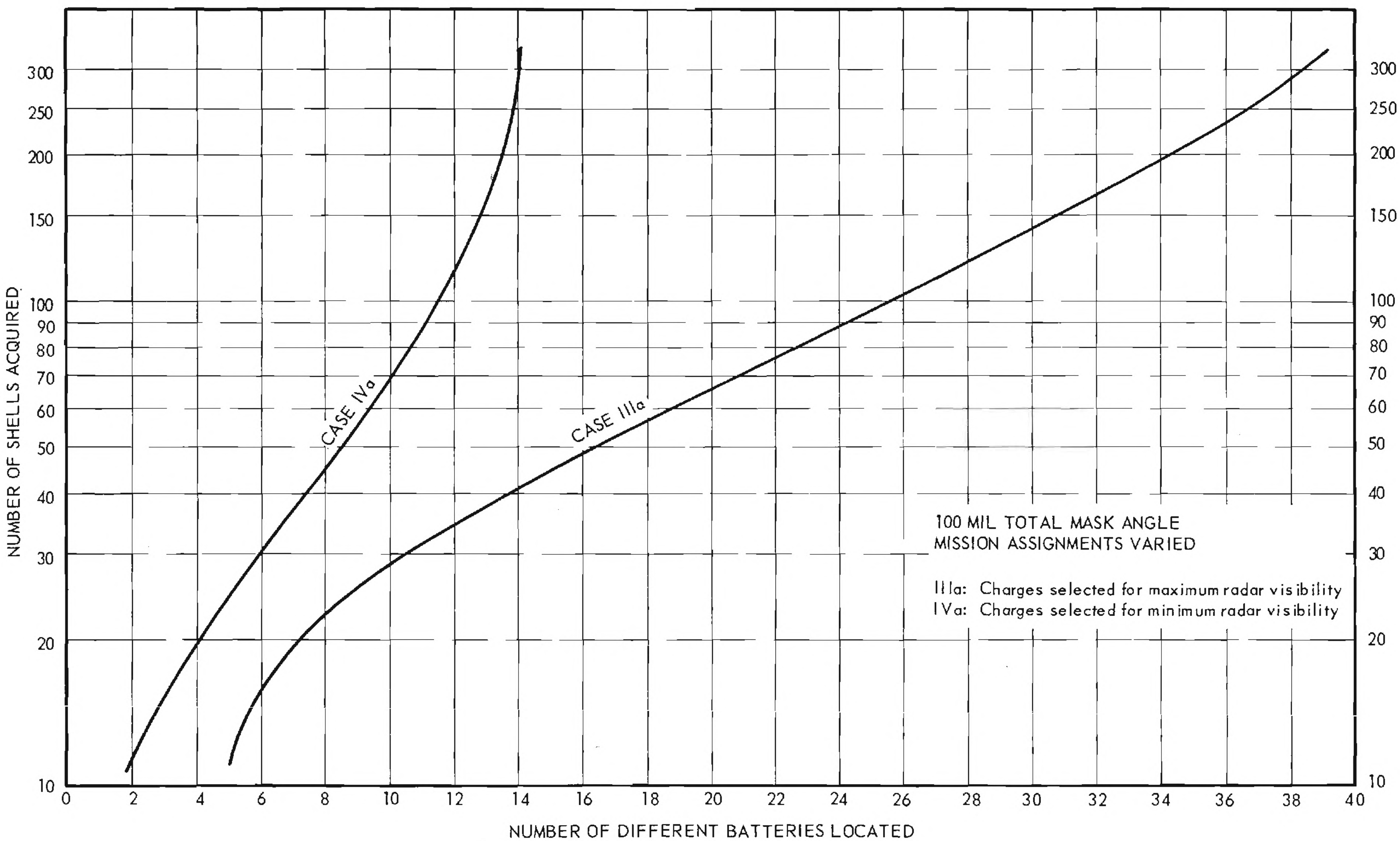

Figure F-2. Average Number of Different Batteries Located as a Function of the Number of Shells Acquired; Cases IIIa and IVa.

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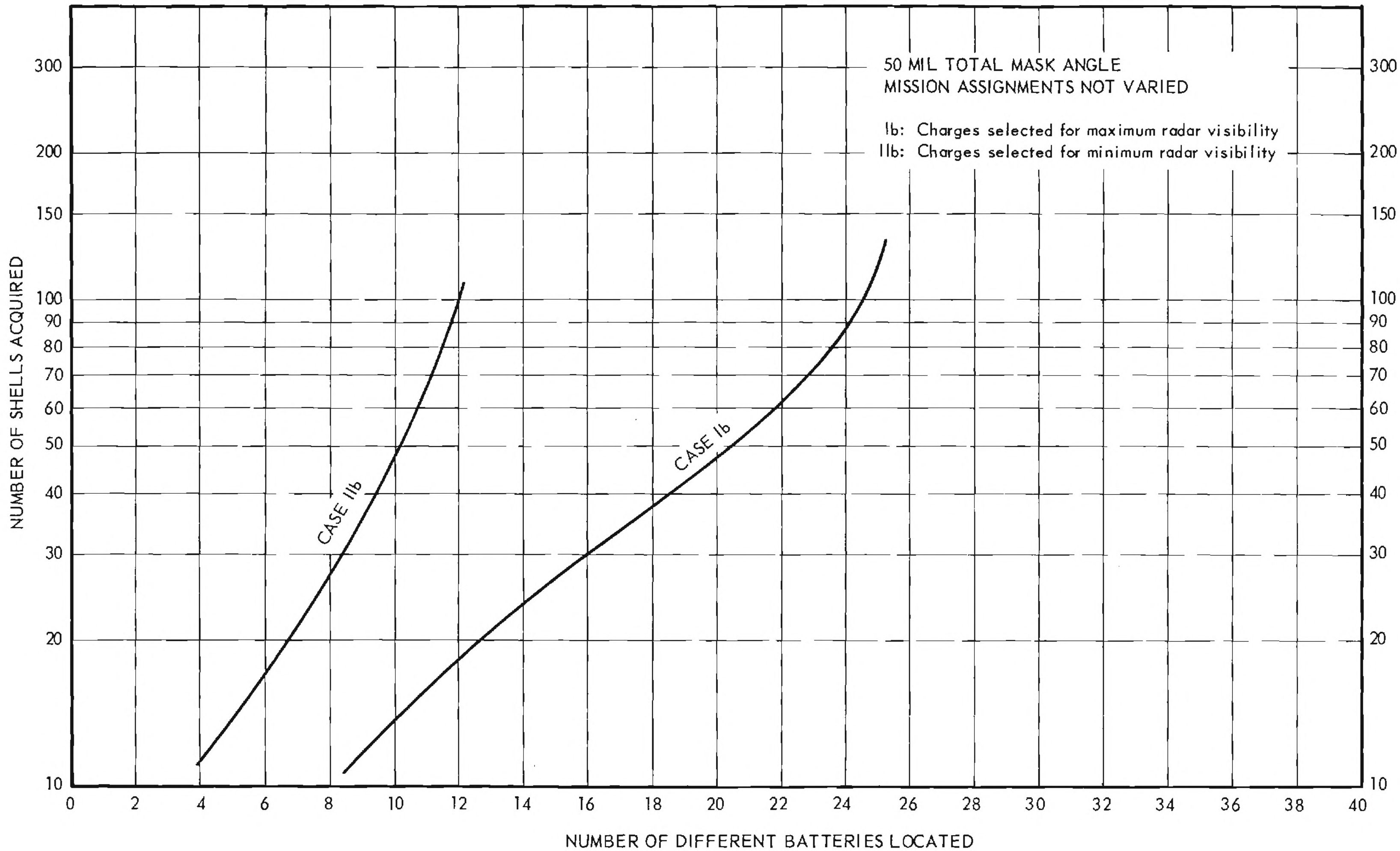

Figure F-3. Average Number of Different Batteries Located as a Function of the Number of Shells Acquired; Cases Ib and IIb.

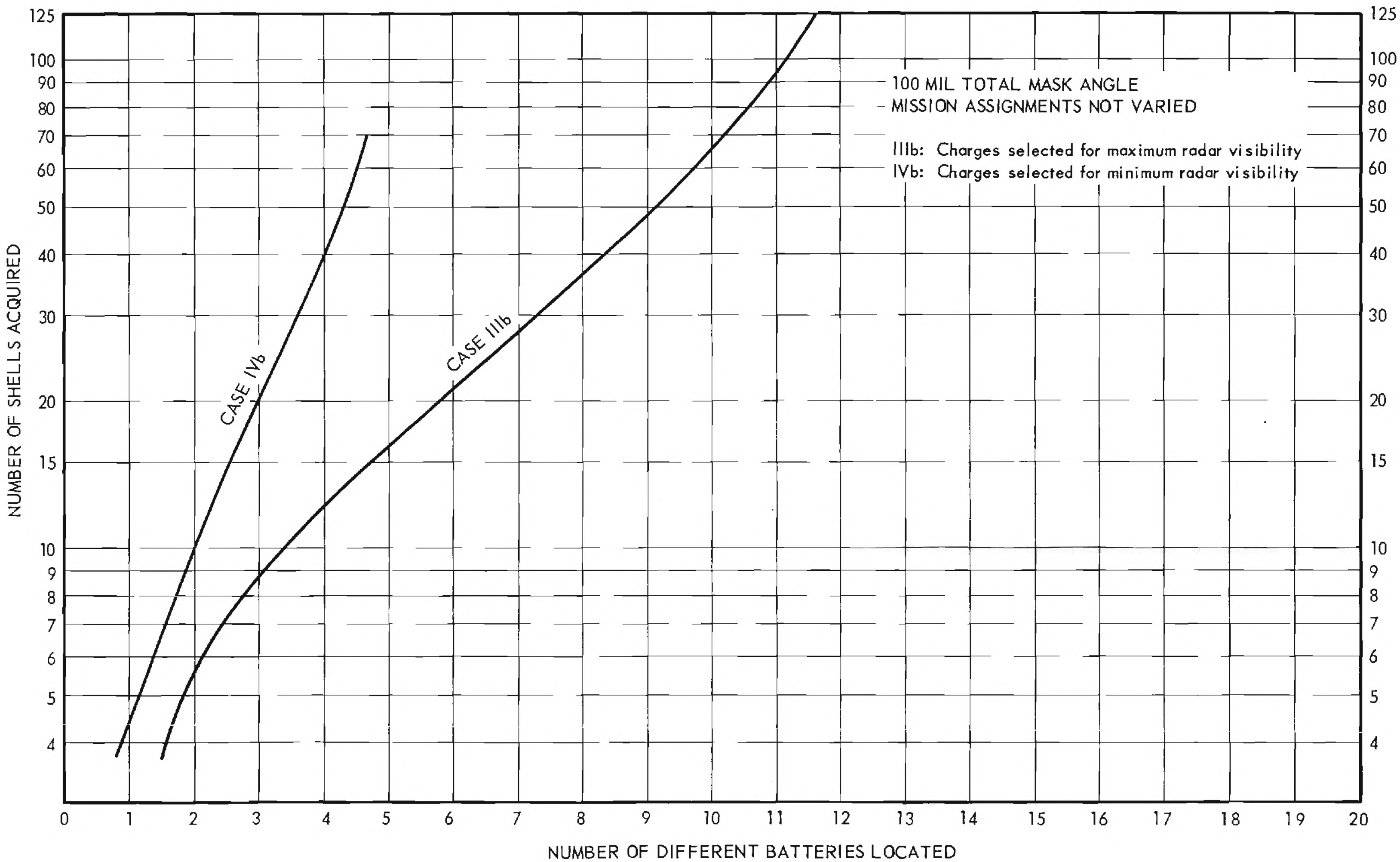

Figure F-4. Average Number of Different Batteries Located as a Function of the Number of Shells Acquired; Cases IIIb and IVb.

The questions now arise of how long it might take the radar to locate an appreciable percentage of the batteries accessible to it and how much damage the enemy artillery might inflict in the meantime.

It can be shown that if visible trajectories appear randomly at an average rate ρ, and if k is the probability of the tracker locking-on to a trajectory seen by the search set, then the rate at which acquisitions are made is

$$R = A\rho \quad \text{where } A = \frac{k}{1 + k\rho\tau}$$

Here τ is the "solution time", or time required to return to search after a shell is acquired. It will be assumed to be the same whether or not the extrapolation is successful, although in practice one would expect a shorter delay in those instances where the visible time turns out to be too short for extrapolation. Neglected, however, is the time spent in returning to search after acquisition has been attempted but lock-on has failed. The effects of these simplifying assumptions tend to balance each other. Actually, the lock-on probability will depend upon where the shell appears in the search sector, but here the average value k is assumed to apply to all visible shells.

The factor A gives the fraction of visible rounds which are acquired. It is plotted in Figure F-5 as a function of k and $\rho\tau$. It will be seen that at very low rates of fire, k has a dominant influence upon A; while when several shells can appear in the time interval required for problem solution, A approaches $1/\rho\tau$.

Reference to the artillery model gives an idea of the rates that might be expected. If all weapons fire at their maximum sustained rates, then about 200 rounds per minute are fired within the radar's search sector, and visible and usable trajectories appear at the following rates:

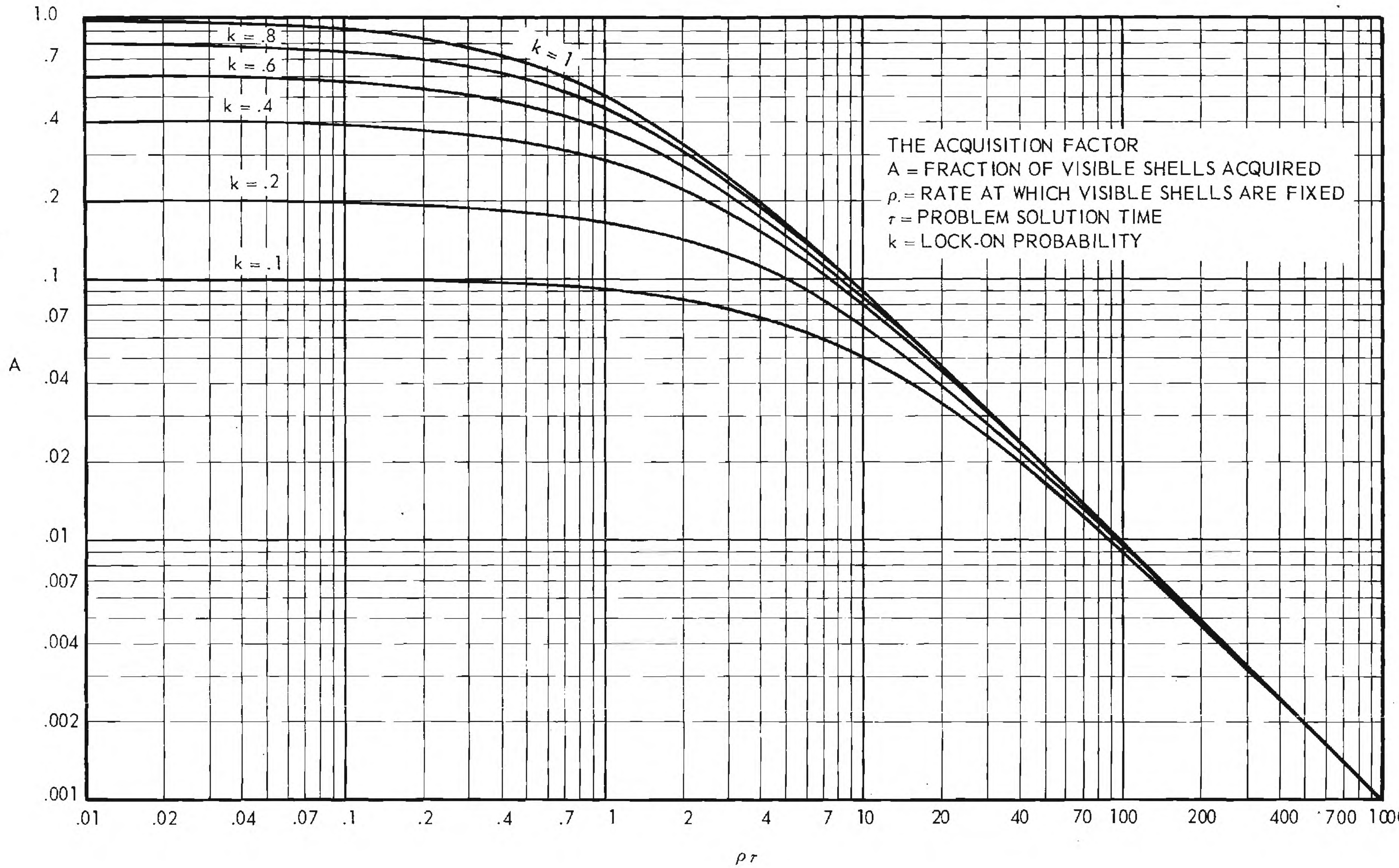

Figure F-5. The Acquisition Factor A Versus $\rho\tau$.

CASE	VISIBLE FIRE ROUNDS/MIN.	USABLE FIRE ROUNDS/MIN.
I	115	115
II	94	46
III	97	42
IV	46	11

For Cases I, II, and III visible trajectories appear at a rate of about 100 per minute; for Case IV, at about 50 per minute. From Figure F-5 one can obtain the acquisition rate figures given in Table F-1 for the situations where all weapons fire at 100, 10 or 1 per cent of their sustained rates. A problem solution time of one minute, as anticipated for the service test model CBR, was used in making the tabulation.

When the weapons fire at their sustained rates the acquisition rate is substantially that at which problems can be solved. Even at one per cent of the sustained rate, loss of efficiency from saturation effects is pronounced when the lock-on probability is high. Saturation can therefore be expected to be a problem for more widely dispersed weapon distributions as well. More serious at the lower rates, however, is the drop in acquisition rate with decreasing lock-on probability.

Consideration of these acquisition rates in conjunction with Figures F-1 through F-4 shows that even when the enemy fire is sufficiently rapid to maintain radar saturation, location of most of the accessible batteries may take one to four hours of radar operation time, exclusive of time spent registering friendly artillery. Furthermore, the number of batteries accessible may be only a small fraction of the total number within the sector. While location is being attempted, the enemy has the capability of delivering thousands of rounds.

TABLE F-1. ACQUISITION RATES FOR MODEL ARTILLERY SITUATION.

Problem Solution Time = 1 minute.

Artillery Rate of Fire; Per Cent of Sustained Rates	Rounds Fired per Hour	Rounds Visible per Hour	Rounds Acquired per Hour k = .2	k = .8	k = 1.0
		Cases I, II, III			
100	12,000	6,000	57	59	59
10	1,200	600	40	53	55
1	120	60	10	27	30
		Case IV			
100	12,000	3,000	55	59	59
10	1,200	300	30	48	50
1	120	30	5.4	17	20

Even this distressing picture may be somewhat optimistic. The loss of efficiency from acquiring unusable trajectories can become worse if the multiple target problem discussed in the A-108 report materializes or if many artillery trajectories first become visible at ranges where extraneous mortar and rocket fires are encountered. Moreover, the assumption that shells are fired randomly can be a poor approximation for periods of low activity. Projectiles are customarily fired in battery volleys, each volley representing one "opportunity" for acquisition, and it is the "opportunity rate" which must be used in the expression for the acquisition rate R when activity is low. This modification can reduce R by as much as a factor of four. Furthermore, even when the average rate of fire is low, volleys may come in "bursts" of high activity interspersed among periods of relative quiet. In this event the volley rate during a burst determines A and the average rate of volley delivery is multiplied by A to determine the average acquisition rate R. The rate of fire over a short interval can be several times the maximum sustained rate. Consequently, saturation can be serious even in periods of very low average activity.

It must be borne in mind that many of the considerations which contribute to the discouraging outlook presented here apply equally well to other battery location schemes, including those such as sound and flash ranging that have been used successfully enough to be considered worthwhile. While the prospective efficiency of the presently envisioned CBR seems clearly low, the need for even low effectiveness may justify the costs of obtaining it. The intent here is simply to point out, first, that in its proposed form a CBR should not be expected to have a revolutionary influence upon artillery warfare; and second, that superb performance already recognized as desirable does indeed appear to be urgently needed in the following respects:

(1) Ability to acquire targets close to the terrain mask.

(2) Ability to perform extrapolations from shorter tracks.

(3) Ability to extrapolate accurately over longer times of flight.

(4) Ability to perform extrapolations more rapidly.

(5) Achievement of high lock-on probability.

(6) Achievement of smooth tracking in the presence of multiple targets.

(7) Ability to recognize and discard quickly unusable tracks.

It might also be remarked that development of a unified fire direction system capable of silencing a battery soon after its location could alleviate the problem of redundant locations.