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Use of Weather-Information in Determining Cost/Performance and Force-Mix Tradeoffs: Weather and Warplanes I

R. E. Huschke

A Report prepared for

UNITED STATES AIR FORCE PROJECT RAND

Rand
SANTA MONICA, CA. 90406

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PREFACE

This is the first of an intended, nonperiodic, series of Reports identified by the common subtitle *Weather and Warplanes*. "Warplanes" is shorthand for "weather-sensitive military systems and operations," as the content of this introductory Report reveals.

The thesis of this line of work is that the atmosphere *does* interfere with military operations in a variety of ways, that to place reliance on "all-weather" systems is an expensive approach with complex consequences, and that the essentials of a more effective approach are at hand. Furthermore, given a quantification of weather effects in ultimate operations, predictions of these effects *should* influence decisions on performance specifications, mixed-force acquisition, and theater deployment, as well as tactical employment.

This Report is addressed primarily to Air Force systems analysts, who, we feel, should be aware of recent progress and trends in the application of weather information in military studies. In part, this Report is a selective overview of weather-effects studies since the mid 1950s. It discusses problems and proposes solutions. Most of all, it expresses and supports the opinion that the costs of the suggested analyses are small compared to the benefits that the Air Force would reap if weather and climatic factors became an important part of the force-planning process.

SUMMARY

Since airborne weapon systems that perform well under adverse weather conditions are technologically complex, they cost considerably more to procure, maintain, and operate than "fair-weather" systems. We suggest that, whenever a military theater is to be supplied with a mix of simple and complex systems, analysis can estimate the appropriate mix as a function of, among other factors, probabilities of pertinent weather conditions.

Methodologies that have been used in studying the effects of weather and weather information on military operations are briefly reviewed and brought up to date, concluding with recent attempts to include weather information directly in system tradeoff studies.

CONTENTS

I. INTRODUCTION

A recent Rand study of the effectiveness of acquisition procedures for major weapon systems[1] established clearly that, of the two principal unknowns -- cost and performance -- performance exceeds specifications as often as it falls short, whereas cost usually overruns. This implies that contractors attempt to meet performance specifications at the frequent, unpredicted expense of time and money. If so, then the initial judgment of performance requirements is the tail that wags the entire system-acquisition dog.

The performance specifications for a weapon system reflect the total environment projected to be that system's future operational milieu. In addition to target characteristics, which certainly have a major impact on weapon-system design, the milieu consists of the enemy's defense environment and the natural environment -- the essentials of the latter, for airborne weapon systems, being day vs. night and adverse vs. "fair" weather conditions. These three factors -- targets, defenses, and nature -- impose problems whose solutions may often overlap. For example, if enemy defenses deny aircraft penetration to a target, the required standoff weapon may well have characteristics that allow its use under conditions of poor visibility in the target vicinity. However, if the target is such that it requires identification via a link from missile sensor to remote controller, then target-area weather conditions remain a critical factor. If a target is available mainly at night, the required night-capable system will probably have characteristics that mitigate some effects of enemy defenses and adverse weather -- and so on.

Targets that are difficult to acquire, and defenses and weather conditions that add to that difficulty, force an increasing demand for complex avionics: to the old requirement for an "all-weather" capability is now added a requirement for a "standoff" capability. On top of inherent expensiveness, experience has shown that complex avionics mean

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[1] R. L. Perry, et al., *System Acquisition Experience*, RM-6072-PR, The Rand Corporation, November 1969.

added troubles: cost and schedule overruns, reduction of total system reliability, and greatly increased maintenance problems. Hence, an "all-weather" and/or "standoff" system is a mixed blessing, and the operational value of the performance gained should be weighed carefully against the appreciable direct and indirect penalties.

In the main discussion of this Report we shall narrow our sights to the "all-weather" problem only, without explicit consideration of the "standoff" problem posed by the enemy's defense environment. The two have much in common, however, and ultimately need to enter the analysis together.

The evaluation of performance gained by anti-weather engineering is a far from simple problem. What is the "all-weatherness" of an "all-weather" system? One misleading implication of the phrase is that an "all-weather" system permits a job to be done as effectively in "bad weather" as in "good weather." Obviously this is not always true. An instrument landing system, for example, permits aircraft to land under instrument flight rules, but at a higher risk and a much slower rate (hence causing higher fuel consumption) than under visual flight rules. Another connotation of "all-weather" is that such systems are always useful, and are therefore used under *all* weather conditions, fair and foul. In reality, however, whenever a simpler, cheaper, fair-weather alternative is available, an "all-weather" system tends to become a "bad-weather" system. Consequently, the usefulness of an "all-weather" system becomes a rather direct function of the frequency of weather conditions that would prevent using the fair-weather alternative. Finally, it must be recognized that *degrees* of "badness" will also affect performance and that there is an estimable fraction of time when the weather will be too bad for even the best of "bad-weather" systems.

On the basis of development and manufacturing costs, and operational reliability and practicality, the best weapon system is the simplest one that will do the job. (In the context of this Report, a simple system is *avionically* simple.) In the Middle East, for example, the clarity of the atmosphere, per se, allows a simple tactical aircraft weapon system to be very effective most of the time; in Central Europe, the same system would be useless because of weather about one-half the time

(but of course, useful to some degree during the other half). Southeast Asia presents yet another combination of weather problems for weapon systems -- and so on around the world. The weather in any region allows a simple system, with all of its economic and operational advantages, to be useful at least part of the time. But our concern is how much of the remaining time an operational capability is desired, that is, what is the desired "utility level?"[2] And how much avionic complexity is required of a system to meet that utility level, i.e., how much will it cost? The answer to the first question must come from analysis of the *military* environment (target dynamics, enemy defenses, conflict type and level, political constraints, etc.). Since much avionic complexity is necessitated by adverse weather conditions, the second question can be completely answered only by analyzing the *natural* environment. A desirable utility level defines, for a given system and location, the worst set of atmospheric conditions for which avionics must compensate. Conversely, avionics limitations suggest a set of worst operational weather conditions for a given system, and these conditions then define a limiting utility level for a given location.

The pairing of avionics requirements and utility levels provides the basis for incorporating information on the natural environment into studies of cost/effectiveness tradeoffs within aircraft weapon systems and studies aimed at revealing force-mix optima among different systems. It is a simple beginning, but nonetheless valuable. The main constraint on the success of this approach is the generally poor state of knowledge about weather effects on weapon performance. The problem of gaining *more* information about weather effects on weapon systems is discussed in Appendix A.

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[2] "Utility level" is defined here as the fraction of time that weather does not prohibit the effective use of a weapon system.

II. THE PROBLEM AND PROMISE OF RELATING SYSTEM PERFORMANCE TO OPERATIONAL CLIMATE

The relating of system performance to operational climate is a fairly old subject.[3] Until the past year or two, however, work on weather vs. system operations has been sporadic and uncoordinated, and hence not very influential. But there now appears to be an upsurge of interest. It is hoped that the subject will be pursued at least to the point where planners will have at hand some consistent methodologies for incorporating natural environmental factors into system analyses.

The whole problem can be broken down into three strongly interrelated parts:

1. What are the effects of weather on systems and operations?

This is obviously the first question that should be asked, but one that is generally left unanswered until after the prime opportunity (the system test and evaluation program) has been completed. It is indeed rare for weather effects to be *measured* in a rigorous and comprehensive way. Some weather effects are fairly straightforward physically and can be *calculated* with reasonable confidence. This is the least problematic type of weather-effect study, although the calculations can be quite complex, as in the prediction of light transmission through scattering media. By far, most of the interesting weather effects on system performance are still only *estimated* by field experience, by logical guesswork, by extrapolation, etc. A common current example is the question of the "effectiveness" of high-angle, visual, dive bombing under different cloud and visibility conditions. Experience has fairly well established that the weather-caused degradation of accuracy is virtually zero if the cloud ceiling is above 12,000 feet and visibility about 7 miles or more, and that the degradation is close to 100 percent with a ceiling below 3,000 feet or visibility less than 2 miles. In between these extremes, the percent degradation is determined quite

[3] And one on which, incidentally, a comprehensive bibliography would be most valuable. A partial bibliography, of relevant Rand work only, is appended to this Report.

arbitrarily, with the help of experience and logic. This is not to say that subjective estimates of weather effects are not useful, but that one hopes they can be replaced by measurement (systematic observation) or sound, theoretical calculations, especially for future weapon systems.

2. What is the nature of the relevant weather information?

In 1959, J. D. Sartor[4] of Rand wrote: "In general..., the availability of weather information is much greater than that of operational information on the *effect* of the weather. The available weather data can usually be considered adequate...." This statement still holds true. Essentially all weather-effect problems of the kind considered here require probabilistic answers. Therefore, the basic source of weather data has to be *long-term climatological records* to ensure statistical accuracy -- but we are restricted by the limited types of information they contain. The challenge is to *interpret* these data, that only partially describe the atmosphere at a particular set of space/time observation points, in terms of weather effects produced in operational space/time volumes; this procedure requires considerable insight into atmospheric processes.

One approach to bridging the gap between standard weather data and operational weather effects is to engage in *special measurement programs* wherein either the operational effect itself, or a nonstandard atmospheric parameter (that can be directly related to an operational effect) is correlated with standard atmospheric observations. Given adequate correlation, the great volume of world-wide climatological data can then be transformed into estimates, with known error distributions, of the probabilities of encountering specific, weather-caused, military problems as functions of location, season, and hour. Very few special measurement programs of this type have been undertaken and completed. (Thousands of special, visual, clear-line-of-sight observations have been collected by the Air Force Cambridge Research Laboratories, but have not yet been correlated with standard cloud and visibility observations.) Much more should be done, and the weapon system

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[4] See Bibliography [Sartor, 1959].

test and evaluation programs provide an ideal opportunity. (See Appendix A.)

3. Given that system performance can be related to information about weather conditions, how may the Air Force exploit this knowledge?

The ultimate exploitation of information about weather conditions has to be in *tactical decisionmaking.* If the field commander has alternative weapons of differing weather effectiveness, he can use weather information and understanding of weather effects to keep both the effectiveness and efficiency of his total force near a practical maximum. On the premise that this is highly desirable in military operations, it is then clear that a combat command should have a weather-optimized mix of weapon systems deployed in its theater of operations. For any given set of weapon systems in the inventory (for which weather sensitivities are known), the force-mix tradeoffs can be compared as a function of climate. A quantitatively based rationale can be developed for making *force deployment decisions* that will tailor the force for its operational environment. Very likely it will be found that the most effective combinations of systems vary significantly from theater to theater and season to season. If such weather-optimized forces are to become a reality, then the total weapon inventory must have sufficient variety to permit flexible deployment planning. The trend toward increasing cost-consciousness and weapon specialization makes awareness of operational weather sensitivity and its significant effects on both costs and utility levels an increasingly important factor in the *process of system acquisition.* Despite the obvious difficulties in predicting the different potential theaters of combat (and, hence, operational climates) far in advance, representative (perhaps threat-weighted) estimates can be made. The historical weather data for the predicted theaters may then serve as statistically sound predictions of potential combat weather, and these predictions in turn serve as the basic weather factor for looking at cost/performance and force-mix tradeoffs for future systems.

The entire problem is cyclic. It is most important to apply our limited resources to purchase future systems so as to optimize military effectiveness across a spectrum of environments. Therefore, some key

decisions have to be made before actual weather effects can be measured, although a "fly-before-buy" procurement policy could reduce this problem somewhat, if competitive "weather testing" were included in the pre-selection program. Experience with current systems will weigh heavily in such decisions; hence, it is important to know what the weather effects on current systems actually are.

III. STUDIES OF WEATHER EFFECTS ON SYSTEM OPERATIONS: A SAMPLE

In the late 1950s, J. D. Sartor developed and applied a general statistical methodology for evaluating operational "effectiveness" and "efficiency"[5] for complex military operations, given that the weather effects on the component parts of the operation ("activities") are quantified [Sartor, 1957, 1959]. His methodology is applicable to various kinds of complex operations wherein the component activities are sequential, parallel, mutually exclusive, or combinations of these. It is a rigorous way of evaluating complex weather effects, per se, on a single, albeit complicated, operation. It allows the direct comparison of the effectiveness of mutually exclusive operations or systems (e.g., either photo reconnaissance *or* radar reconnaissance), but the effectiveness of various mixes of operations or systems can be compared only by inference. Therefore, for this reason and the additional reason that forecast-based tactical decisions (go or no-go; use system A or system B) cannot enter into the calculations, Sartor's technique as it now stands does not lend itself to the study of cost tradeoffs. His basic definitions and statistical approach, however, are completely sound and have influenced other work that has followed. Figure 1 is an example of results of the Sartor technique applied to a reconnaissance problem [Sartor, 1957].

A major difficulty confronted by Sartor and all others in this business is the paucity of hard data on degrees of operational degradation due to weather. One way to partially ameliorate this difficulty is to concede uncertainty, and to make calculations based on a variety of estimates of weather effects. This technique greatly reduces the value of pre-summarized published climatological statistics, for flexibility is needed in choosing the weather variables for which statistics are calculated. Access to a computer file of basic data is almost a

[5]He defines "effectiveness" as the rate or amount of accomplishment, and "efficiency" as the ratio of the effectiveness under given (weather) conditions to the effectiveness under optimum conditions.

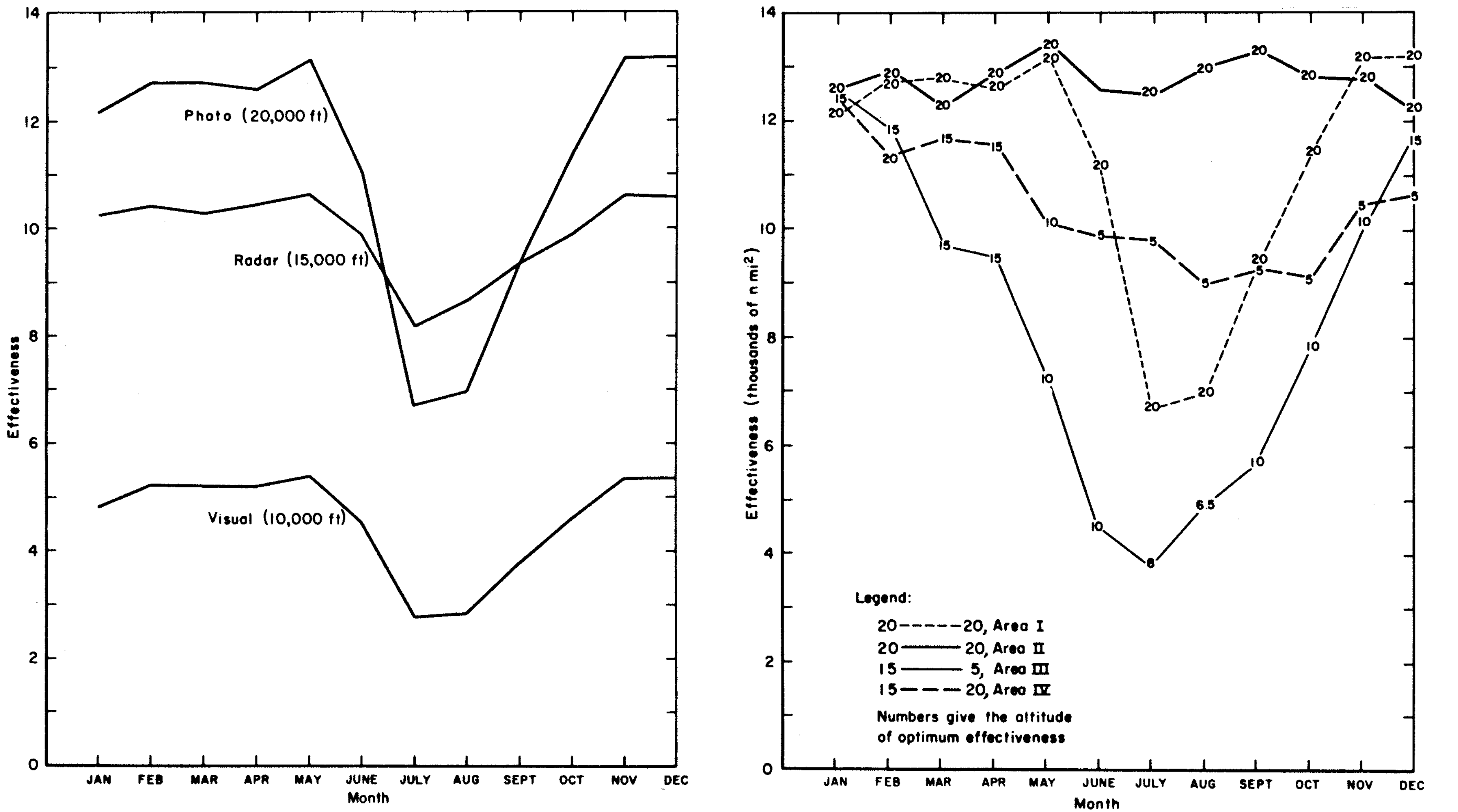

Fig. 1 -- Example of Sartor's technique applied to the effectiveness of reconnaissance systems. (a) Comparison of the effectiveness of three reconnaissance systems over one target area. (b) The effectiveness of photo reconnaissance over 4 target areas in the same region of the world. (From Sartor, 1957, pp. 13 and 17.)

necessity. At Rand, we are developing such a file for selected areas of the world -- the Rand Weather Data Bank (RAWDAB) -- and have used it with gratifying results. Thus far, its principal application to tactical studies has been for calculating joint ceiling and visibility probabilities as a function of location, month, and hour of the day, using different ceiling and visibility values that can be subjectively related to bombing efficiencies. Examples are shown in Fig. 2. Also, a demonstration case was run to calculate the probabilities that 0, 1, 2, or 3 targets of a three-target system would simultaneously have adequate weather to permit nondegraded accuracy in dive bombing (see Fig. 3). These are not novel or sophisticated calculations, but they are a type basic to weather-effect studies, and the capability to perform them with speed and efficiency is extremely valuable.

The Southeast Asian (SEA) conflict generated some practical interest in weather-effect studies, particularly concerning the problem of visual dive bombing. One Rand study [Rapp and Schutz, 1966] calculated the "efficiency" (Sartor's definition) of dive bombing for two locations and two times of day (Fig. 4). They quantified the degrading effect of clouds and visibility on accuracy based on several interviews with pilots experienced in that theater. A more comprehensive and more recent set of SEA dive-bombing data was analyzed by the Aerospace Corporation as part of their contribution to an Air Weather Service (AWS) Mission Analysis under contract to AFSC (SAMSO).[6] A basic conclusion of theirs was that, given good-quality weather forecasts, a tactical decisionmaker could significantly reduce the deleterious effects of the weather on bombing effectiveness *if* he had short-term flexibility in sortie scheduling and targeting. Figure 5 illustrates the nature of their results.

Since the ultimate utility level of a weapon system does (or should) depend in part on the quality of the weather forecasts used in deciding when and what kind of system should be employed, this aspect of the problem has been modeled by Huschke and Rapp [1970] as one of Rand's contributions to the Air Weather Service Mission Analysis. The basic

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[6] Air Force Systems Command, Space and Missile System Organization; see *The Effects of Weather on Tactical Weapon Delivery*, Aerospace Report No. TOR-0066 (5520-05)-8, prepared by General Purpose Systems Directorate, Aerospace Corp., Contract No. F04701-69-C0066, March 1970.

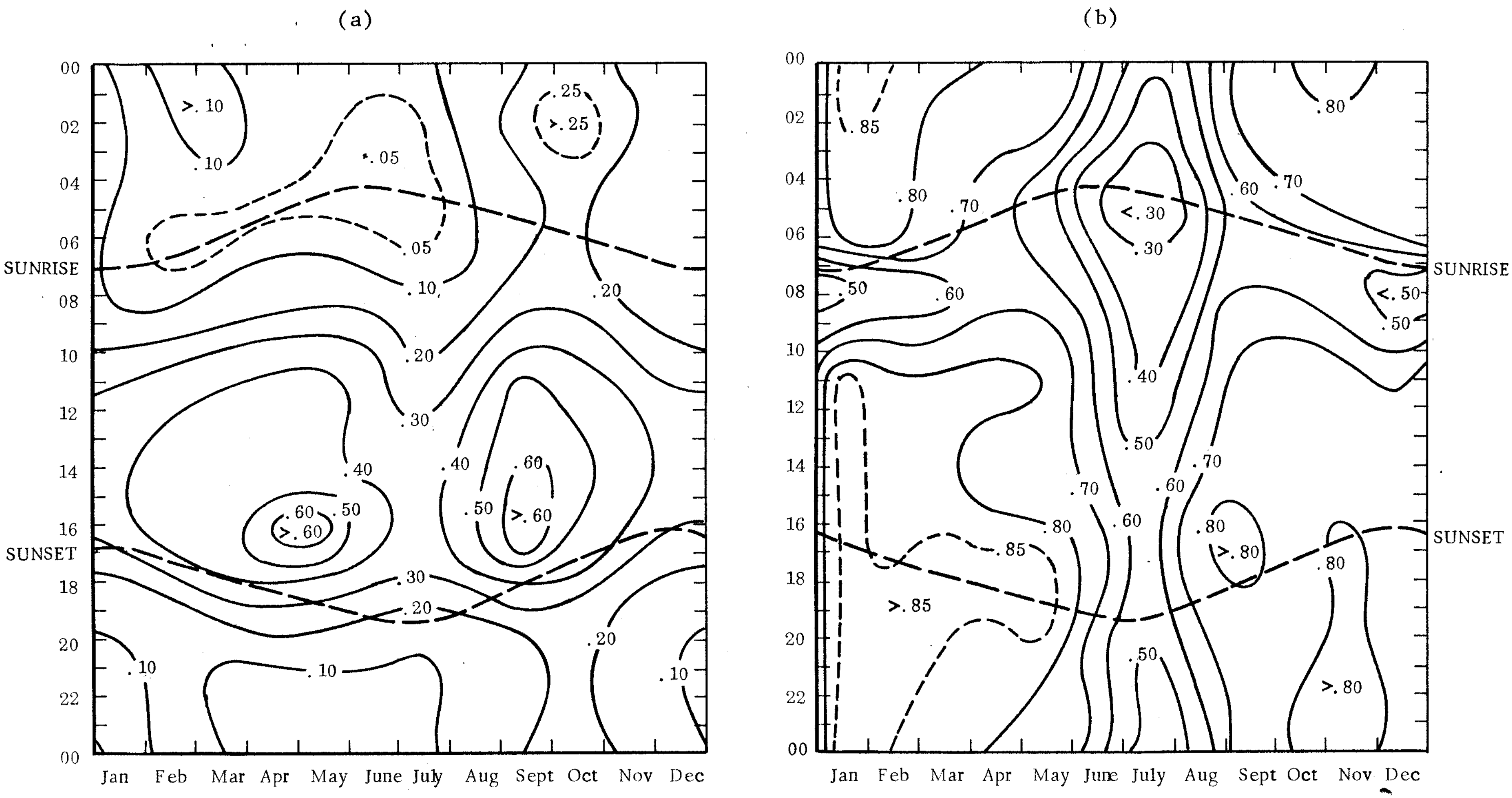

Fig. 2 -- Joint ceiling and visibility probabilities for Sinuiju, North Korea, calculated as a function of month and hour (smooth dashed curves show times of sunrise and sunset). (a) Ceiling ≥ 10,000 ft and visibility ≥ 7 mi. (b) Ceiling ≥ 3,500 ft and visibility ≥ 5 mi.

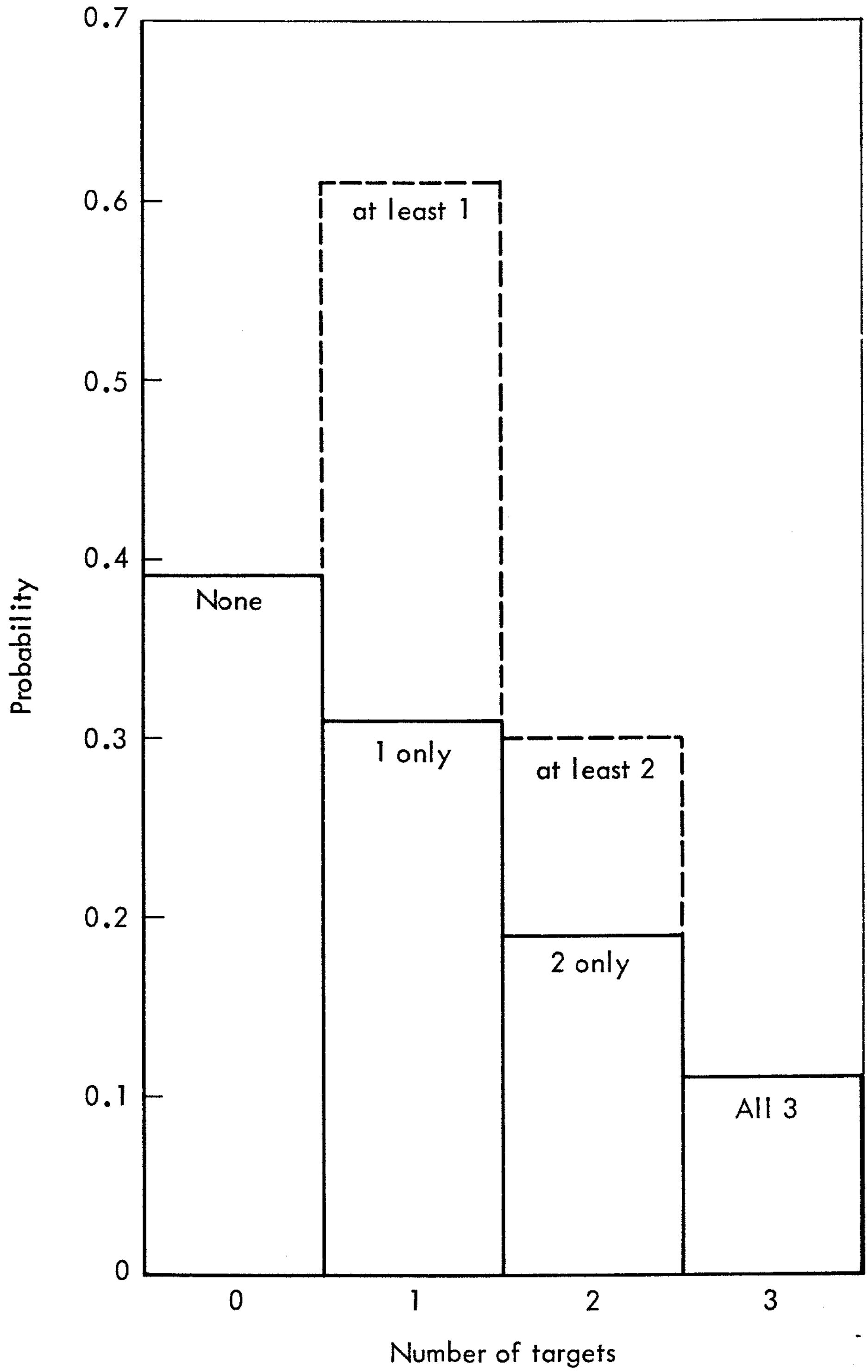

Fig. 3 -- Probability that 0, 1, 2, or 3 targets of a 3-target system simultaneously have adequate weather conditions to permit non-degraded dive bombing. (Example from Western Europe.)

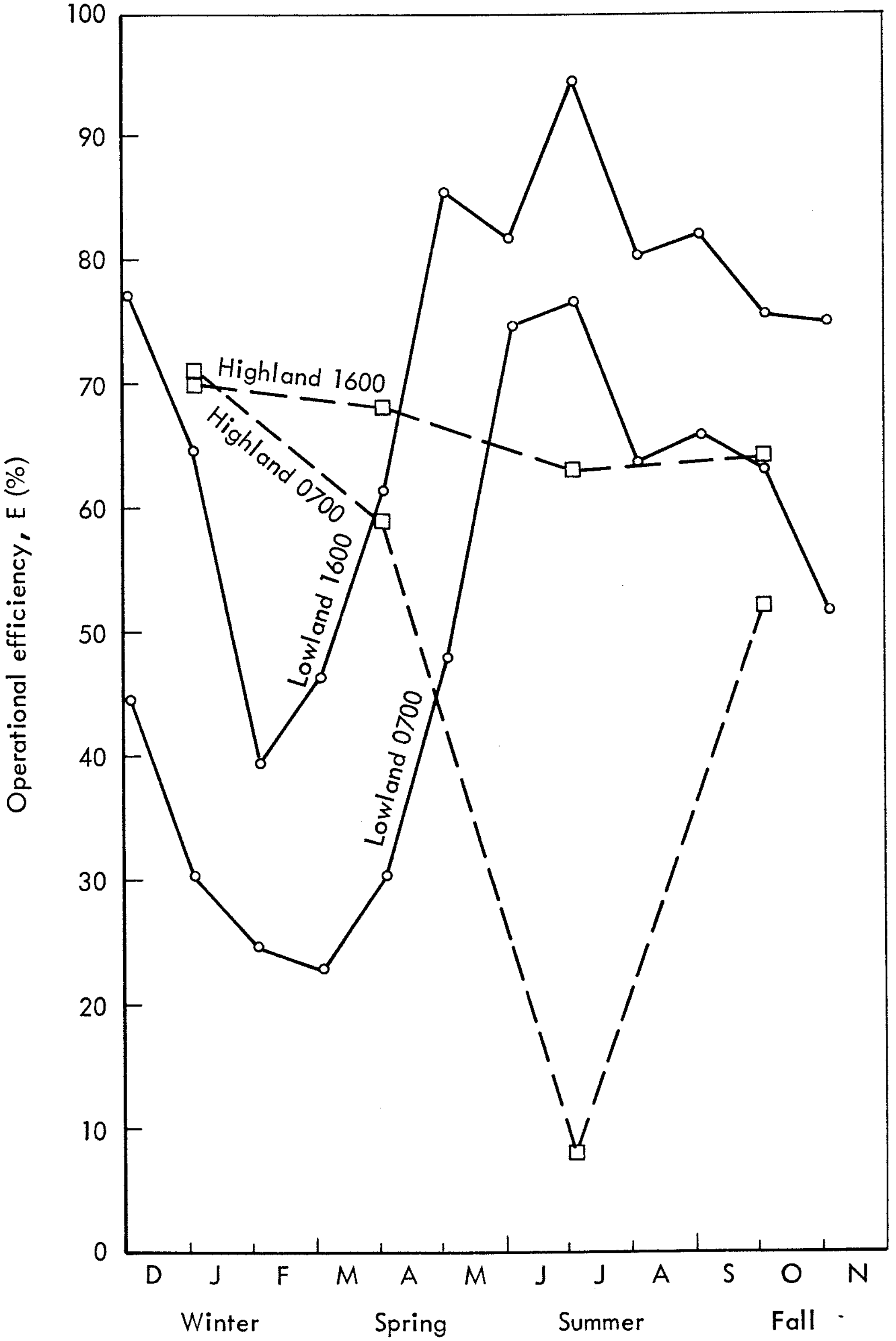

Fig. 4 -- Dive-bombing efficiencies as a function of season and time of day for a highland and lowland location in Southeast Asia (adapted from Rapp and Schutz, 1966).

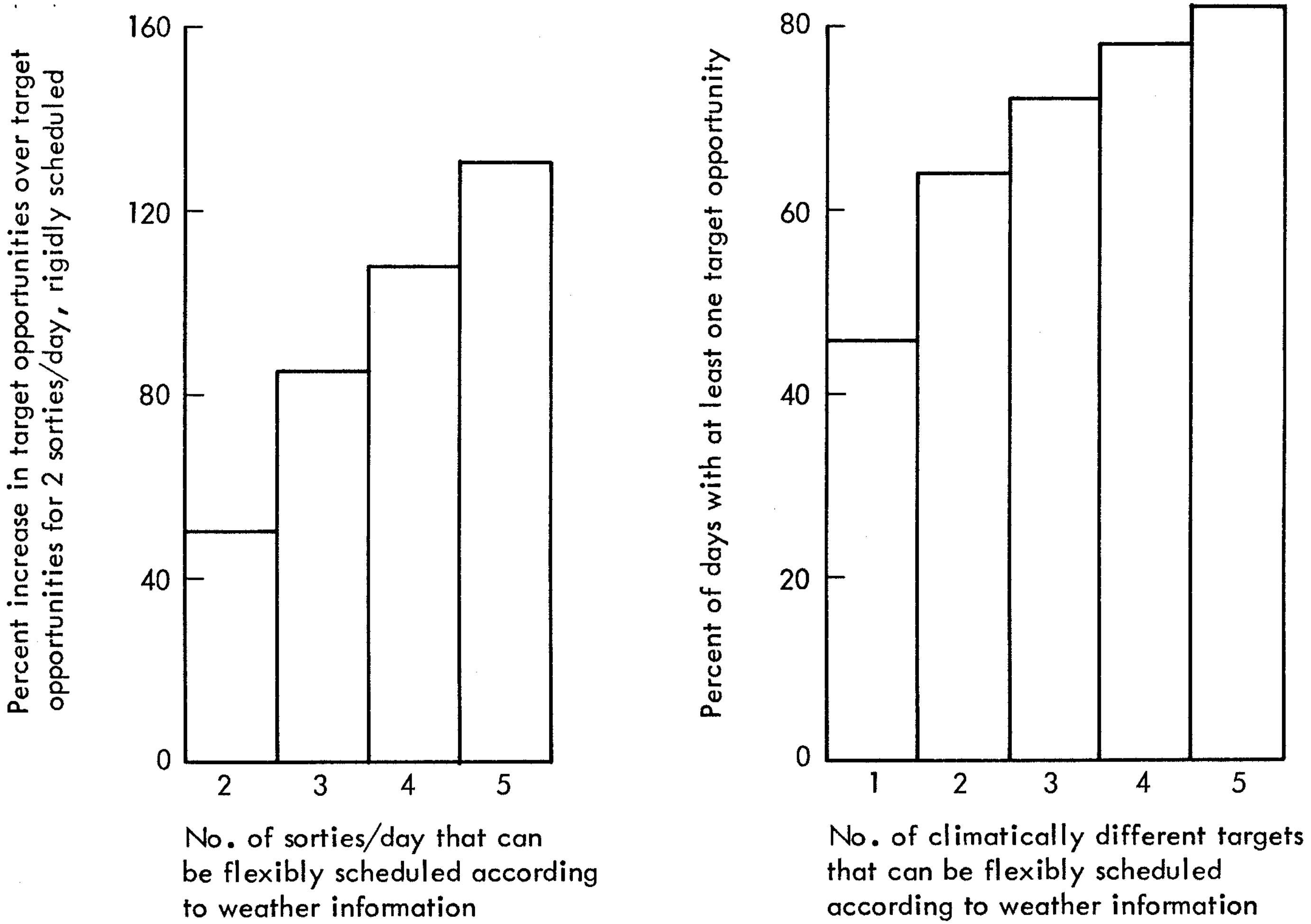

Fig. 5 -- Illustration of the way that weather forecasts in conjunction with tactical flexibility can increase the target opportunities in a tactical bombing campaign. Perfect forecasts are assumed in this illustration. (Adapted from Aerospace Corp.; see footnote, p. 10.)

manner in which forecasts contribute to operational effectiveness is schematically illustrated in Fig. 6, which permits a look at the tradeoffs between expected time and number (hence costs) of sorties required, for a successful attack as a function of the forecast/decision strategy employed. The study for the AWS Mission Analysis modeled a STRICOM (Strike Command) Joint Task Force Commander's go-or-delay decision based on forecast capabilities that were calculated from actual records of forecast verifications; results were couched in terms of the probability of a successful strike assault for different forecast capabilities as a function of the number of days of allowable delay (allotted time). The figure selected to illustrate this work (Fig. 7) also indicates a difference in the expected outcome of a total operation when different bombing systems are used for close air support. In a very rough way, these results could be viewed in terms of cost/performance tradeoffs between dive bombing and low-level bombing as employed in *this particular* situation.

A more direct approach to including the weather factor in cost/performance and force-mix tradeoffs has just recently begun. In November 1969, Lulejian and Associates, Inc., published the results of an excellent exploratory study into the force-mix tradeoffs between fair-weather and all-weather bombing systems in which the major cost/performance factors are varied parametrically.[7] One strong implication of their findings is that there exists a major difference in the optimally effective force mix depending on whether the budgeting is based on force-acquisition costs or sortie costs. Specifically, it appears that, considering force-acquisition budgeting only, a much higher fraction of resources should go into all-weather systems than if the only consideration were sortie-cost budgeting. Figure 8, sketched from the Lulejian results, shows this dependency on the basis for budgeting. In general, taking all their parameter variations into account and assuming a mixed budgeting philosophy, Lulejian and Associates contend that their results

[7]G. P. Gould and W. E. Dreiss, Jr., *The Utility of All-Weather Attack Aircraft (An Exploratory Study)*, TAC-Air Analytical Studies, Contract F-18600-69-C-0029, Final Report, Vol. III, Prepared for Hq. AFSC, Lulejian and Associates, Inc., November 1969.

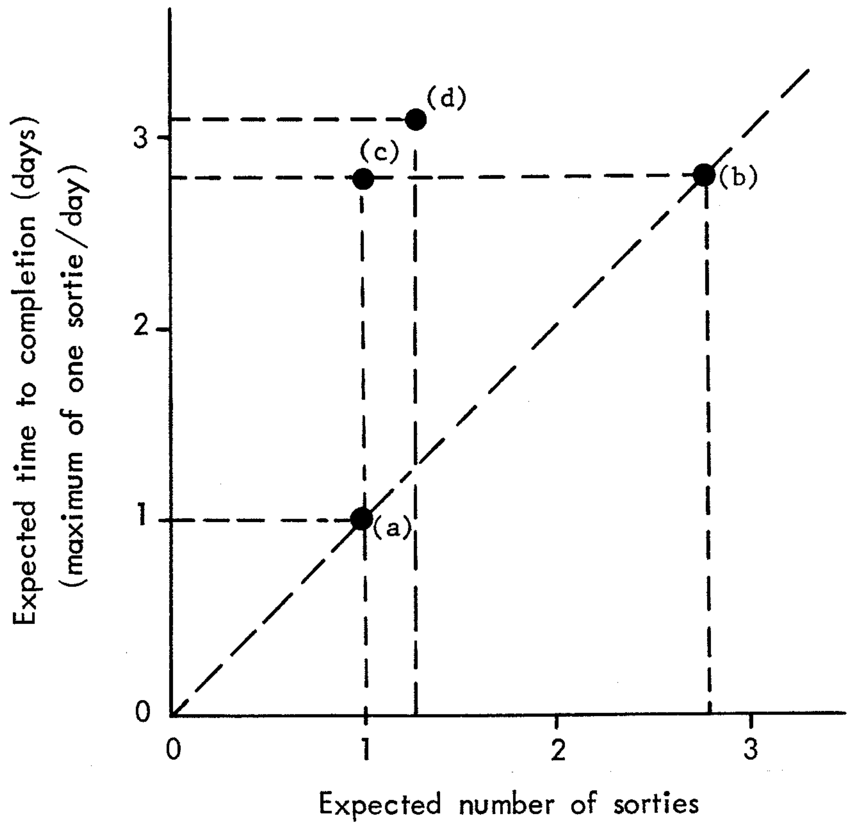

Fig. 6 -- Illustration of time-per-kill vs. sorties-per-kill tradeoffs for various weather assumptions and weather/decision options. Point (a) = perfect weather, try at every opportunity; point (b) = imperfect weather, try at every opportunity; point (c) = imperfect weather, perfect forecasts, try when forecast is favorable; point (d) = imperfect weather, imperfect forecasts, try when forecast is favorable.

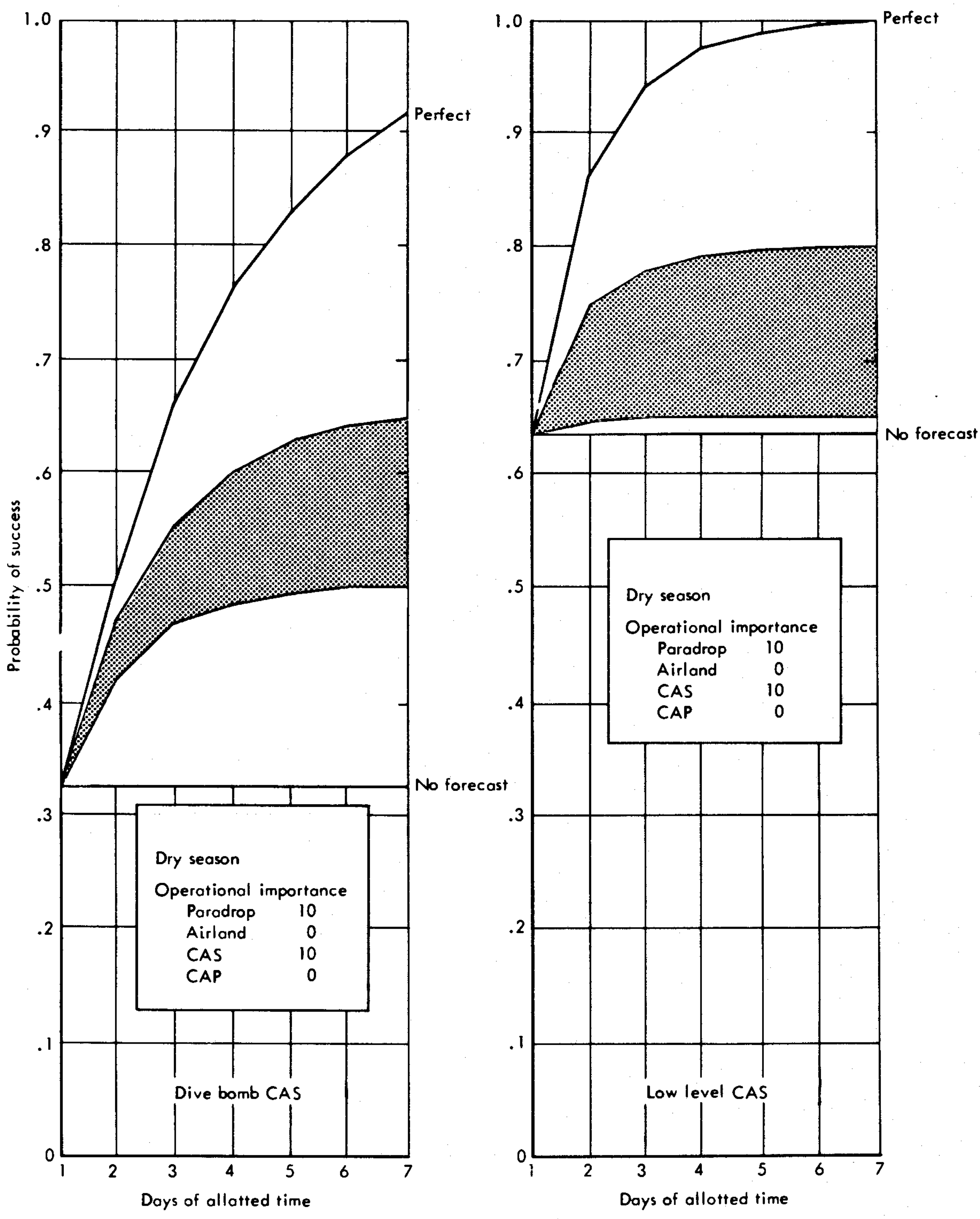

Fig. 7 -- Sample of results from the STRICOM weather/decision model (Huschke and Rapp, 1970, p. 47). For a given location, season, and scenario, it shows the effect on probability of mission success of employing close-air-support systems of differing weather sensitivities. The distance between the lower (no forecast) and upper (perfect forecast) curves represents the theoretical maximum contribution of weather forecasts. The shaded area denotes a range of realistically imperfect forecasts.

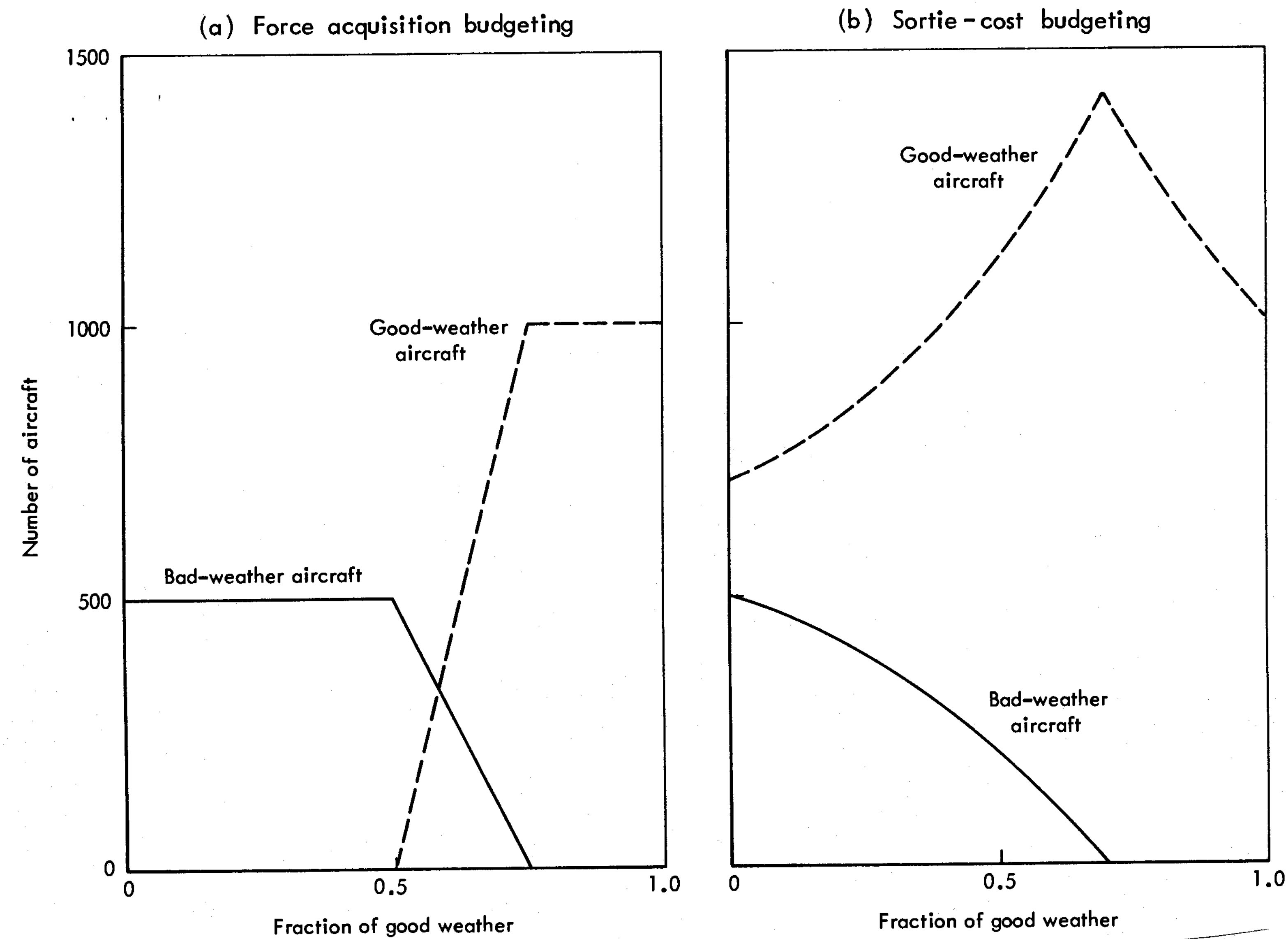

Fig. 8 -- Optimal number of bad-weather and good-weather aircraft as a function of weather conditions for two methods of budgeting. Budget limitations are (a) purchase cost of 1000 good-weather aircraft and (b) sortie cost of 1000 good-weather aircraft operating in 100 percent good weather; bad-weather aircraft costs are twice those of the good-weather aircraft. (Suggested by the analysis of Lulejian and Associates, Inc.; see footnote, p. 15.)

point to an optimal, overall, force mix in which about 0.3 to 0.5 of the systems are all-weather systems.

At Rand, Rapp and Huschke are suggesting an approach (see Appendix B) that is similar to Lulejian's. Here are the main differences in the Rand formulation: (1) there is as yet no explicit target value or target-value decay function; (2) a mixed budgeting philosophy is implicit; (3) the ratio of all- to good-weather systems is inferred as the quantities necessary to maintain given sortie rates under the variable conditions; (4) support costs do accrue to unflown sorties; and (5) the effects of imperfect weather forecasting on force employment can be considered. Two imaginary systems are compared; the results in terms of expected costs per target kill and time per kill are shown in Figs. 9 and 10. The numbers chosen for this comparison represent effective ordnance operating in a very hostile defense environment, with an all-weather system that is about twice as expensive to buy and operate as the good-weather system.

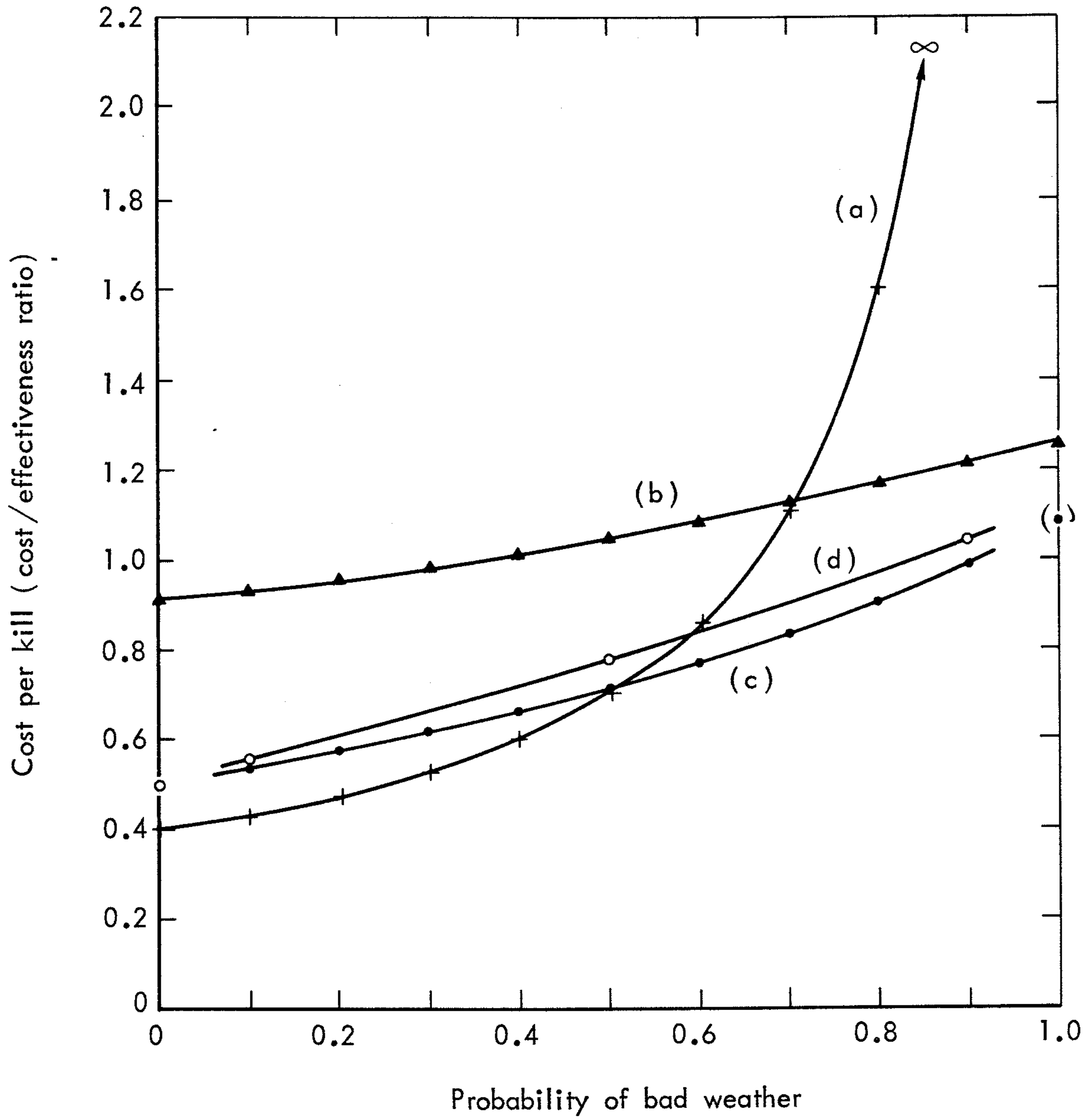

Fig. 9 -- Comparison of cost per kill as a function of weather probability for (a) good-weather system only, (b) all-weather system only, (c) mixed system using perfect weather forecasts, and (d) mixed system using forecasts of current accuracy.

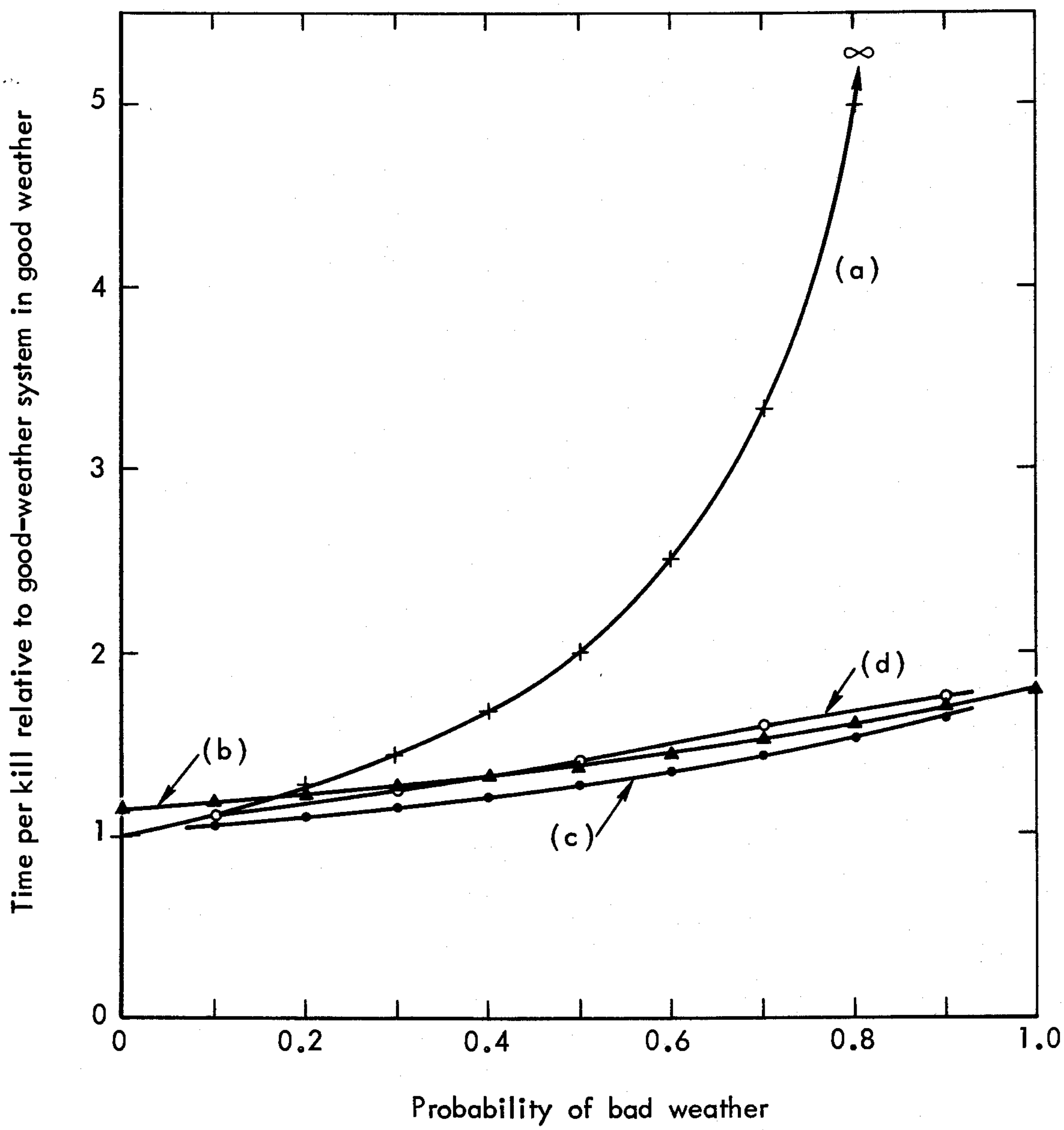

Fig. 10 -- Comparison of time required per kill as a function of weather probability for (a) good-weather system only, (b) all-weather system only, (c) mixed system using perfect weather forecasts, and (d) mixed system using forecasts of current accuracy.

IV. SUGGESTIONS FOR FUTURE WORK

The basic problem of making quantitative determinations of weather effects on systems and operations should be pursued on several fronts. Some suggestions for planning programs to make pertinent measurements in the course of system test and evaluation (R&D Categories I, II, and III tests, and operational test and evaluation) are put forth in Appendix A. Probably the most effective way to start the programs would be to select two or three developmental systems of differing weather sensitivities and specifically design weather-effect phases into their test programs. In those cases where physical theory should be able to provide reasonable predictions of system performance under variable atmospheric conditions (such as target acquisition systems using various portions of the electromagnetic spectrum), increased effort should be devoted to interpreting standard meteorological data in terms of the physical parameters of the theory. For example, the practical application of the visual target-acquisition model proposed by Bailey [1970] must await the day when historical records of observed visibility and cloud conditions can be transformed into the physically defined "meteorological range" employed in the theory that undergirds the model.

Detailed analyses of many specific systems may have to wait for the kind of hard data and secure physical understanding discussed in the previous paragraph. However, generalized and parametric studies of cost/performance and force-mix tradeoffs can and should be made now. The work of Gould and Dreiss at Lulejian and Associates and of Rapp and Huschke at The Rand Corporation provides a good starting basis. It is our intention at Rand to pursue the use and improvement of our model of weather-influenced force-mix tradeoffs, removing some of the over-simplifications that appear in the preliminary version (see Appendix B), and employing relative cost and performance figures that correspond to real (or more realistic) systems. The primary objective of the next phase of this work should be to refine the methodology so that a wide variety of systems and operations, potentially employed at a variety of locations, can be analyzed in a consistent manner.

Finally, attention should be focused on the problem of multiple environments alluded to in the Introduction. Nature is but one principal variable, as are enemy defenses and target characteristics; others may also exist. Ultimately, the kind of statistic that will be sought is, for example, the joint probability that target type X (requiring system package A), protected by enemy defense type Y (requiring system package B), will have to be attacked in weather type Z (requiring system package C). Interrelationships among many combinations of requirements (targets, defenses, and weather) and solutions (system packages) will be extremely complex; but one of the greatest values of this kind of analysis would be in bringing these interrelationships into sharper focus than they now are.

Appendix A

THE NEED FOR TESTS TO QUANTIFY WEATHER EFFECTS ON WEAPON SYSTEMS

C. Schutz and R. E. Huschke

INTRODUCTION

The purpose of this Appendix is to indicate how and why weather should be considered in the preliminary planning stages for the testing of Air Force systems. Weather can degrade the operational performance of many systems and subsystems, but this problem is seldom directly confronted until the systems are operationally deployed. Opportunities for objective testing to quantify weather effects in the course of test and evaluation programs are, it appears, largely ignored.

Air Force research and development (R&D) testing is intended to single out high-quality systems, subsystems, and equipment for use by operational commands. Its documented objectives require that testing be done in as realistic an operational environment as practicable, even suggesting that severe and abnormal environments be used to evaluate safety and reliability. These mandates within the Air Force regulations are therefore directed in part toward determining the weather sensitivity of systems and subsystems during the development (Category II) and operational (Category III) test stages. Within this context falls the Air Force weapon effectiveness testing (AFWET) which is applicable to both R&D and operational objectives. AFWET is specialized to produce, in a realistic environment, quantitative data that can be used as a scientific basis for these objectives:

1. Determining the *effectiveness* of weapon systems and support systems;
2. Obtaining improved *design* parameters and engineering data for developing new systems;
3. Establishing new *tactics and techniques* leading to improved combat effectiveness; and

4. Supporting studies and analyses leading to *new requirements*, operational decisions, and force-structure decisions.

It is well known that these basic engineering, operational, and planning factors change as the weather changes; i.e., a system that works well at established USAF test sites may not perform as well or consistently in Southeast Asia or throughout Western Europe. Yet we know that most weather conditions experienced elsewhere in the world also occur somewhere within the continental United States. This knowledge should be useful in planning more meaningful weather-sensitivity tests and evaluations, as conducted by the Air Force under Category II and Category III, and in the continuing program of operational tests and evaluations. Beyond the tests of actual hardware in each designated category lies the determination of performance, reliability, and integrity of support equipment and personnel, and each of these is weather sensitive. As early as Category I (manufacturer's testing), information gathered for personnel skill identification, for the development of manning documents (handbooks, technical manuals, etc.), for training, and for training-equipment requirements should be based on actual experiences at Air Force bases with conditions representative of the world's climatic regimes.

The substantial need for quantitative data on the degradation of individual weapon systems from the effects of weather is manifest across the Air Force spectrum, from the establishment of performance standards and optimal force mixes to the ultimate tactical employment decisions. A part of every test and evaluation program of a weather-sensitive weapon should be dedicated to acquiring the needed data.

A SUGGESTED APPROACH TO WEATHER TESTING

Although current systems could benefit from some rigorous weather-effect testing under the operational test and evaluation program, our main concern now is with the new generation of aircraft, such as the F-15, the A-X, and the B-1, which are expected to fill the inventory during the 1970s. Because of the new "fly-before-you-buy" policy, we suggest that serious thought be given to weather sensitivity, es-

pecially during the development and operational testing phases, for these new aircraft and their subsystems.

The tests that could be made, without compromise, within specific natural environments are too numerous to list here, but probably the most important would be those involving the effectiveness of sensors and target designators employed in the delivery of air-to-ground ordnance.

The weather parameters that degrade some typical sensors' performance are outlined in Table A-1. Generally, precipitation, visibility restrictions, and cloud cover are the nemeses of light-sensitive seekers, but radar, too, is degraded by precipitation and some clouds. This suggests that testing entirely in the tropical-maritime climate of Eglin AFB, Florida, where high cloud bases and good visibilities prevail, or in the arid climate of Nellis AFB, Nevada, where it is difficult to find "bad" weather at any time, will *not* answer most of the very important questions related to weather sensitivity. On the contrary, it would seem more logical for this purpose to seek test sites where the pertinent weather parameters are highly variable.

The primary purpose of subjecting systems to weather tests is to relate various performance characteristics to standard, "gross," atmospheric parameters. The reason for this is simple: Since the main use of the test data would be to predict and compare the effectiveness of systems in different parts of the world, then the atmospheric descriptors employed in the tests should be the same as those found in the voluminous files of observations that describe the world's weather. It is almost useless to know, for example, that a laser device becomes inoperative at a certain turbulence intensity if that critical intensity cannot be related to such gross variables as wind speed, sun angle, cloudiness, and surface roughness and albedo (all of which can be obtained from climatic, astronomical, and geographical records and can be predicted operationally).

Two types of weather tests are indicated: (1) a series of baseline tests in which a sensor or target designator of each basic type is selected as a "standard" and is evaluated under a relevant variety of weather conditions; and (2) the purposeful inclusion of some weather

Table A-1

A SAMPLE OF SENSORS AND WEATHER PARAMETERS THAT DEGRADE PERFORMANCE

Factor Causing Degradation		Sensor					
		LLLTV	IR	TV-Guidance	Laser	Eye	Radar
1. Precipitation		*	*	*	*	*	*
2. Visibility	haze	*	*	*	*	*	
	fog	*	*	*	*	*	
	smoke	*	*	*	*	*	
3. Clouds		*	*	*	*	*	*
4. Humidity			*				
5. Temperature			*				
6. Wind			*				
7. Ice		*	*	*	*		
8. Turbulence					*		
9. Sun angle		*	*	*	*	*	

variability in Category II and III weapon-system tests.

The first type of test would enable analysts to make reasonable quantitative estimates of the utility of different devices in different atmospheric environments. A current need for this type of testing is implied in Table A-2, which summarizes factors that affect the utility of two specialized, somewhat competitive, target acquisition concepts, LLLTV (low-light-level TV) and FLIR (forward-looking infrared). One or more "standard" devices of each kind would be selected for the test program. Targets, backgrounds, and perhaps countermeasures (rows 1, 2, and 4 of Table A-2) would be controlled and systematically varied. Test locations would be selected to maximize the probability of encountering that range of environmental and atmospheric conditions (rows 3 and 5) within which system degradations are expected. The basic datum of the test program would be some measure of the devices' information output as a function of the variable weather conditions observed by standard (e.g., field weather station) methods. Specialized aerophysical or micrometeorological measurements might be very valuable for deeper physical understanding of the problems, *but the standard observations must also be made.*

The second type of weather test, in the Category II and III and subsequent operational test programs, would be designed to measure weather effects, *in operational terms,* on complete weapon systems. These test results should assist analysts confidently to assume degraded values for CEP or P_k under a spectrum of atmospheric conditions that are less than optimum for a given system. We feel, for example, that every test program requiring visual target acquisition, whether in the air or on the ground, should include at least surface visibility, cloud conditions, and illumination as explicit test variables. Further, at least some of those programs should purposely include tests conducted in the "marginal" range of weather conditions.

A-

Table A-2

FACTORS AFFECTING ELECTRO-OPTICAL SENSOR PERFORMANCE

Factor	Low-Light-Level Television	Forward-looking Infrared
Target	Reflectance and projected area of each exposed surface component. (Reflectance changes with surface condition--dusty, rusty, wet, etc.) Target velocity	Temperature, emissivity, and projected area of each exposed surface component. (Emissivity changes with surface condition) Target velocity
Background	Optical "clutter"--Reflectance distribution of background elements (trees, bushes, grass patches, etc.)	Thermal "clutter"--temperature and emissivity distribution of background elements. (Water puddles, treetops, patches of bare dirt all sometimes appear hot)
Environment	Ambient Illumination (directional or diffused)	Weather and weather history (hours of sunshine previous day, hours since precipitation, wind velocity, percent overcast, time of day, of year, temperature, etc.)
Countermeasures	Ease of shielding or decoying	Ease of shielding or decoying
Atmosphere	Signal attenuation by haze, fog, or clouds. Contrast degradation due to path luminance	Signal attenuation by molecular absorption and scattering from haze, fog, or clouds

Appendix B

A PRELIMINARY MODEL FOR COMPARING THE EFFECTIVENESS OF HOMOGENEOUS VS. MIXED FORCES AS A FUNCTION OF THEIR WEATHER SENSITIVITIES

R. R. Rapp and R. E. Huschke

Consider two systems for attacking targets. One is designed to operate on the basis of visual acquisition, and to attack with a minimum of complex avionics. The other is designed to carry out attacks with a minimum reliance on the pilot's vision. We will call the first system the "good-weather system" and the second, the "all-weather system." Because of the added complexity of the all-weather system, it will, in general, be more expensive to procure, more difficult and more expensive to maintain, and somewhat less effective in bad weather than the good-weather system is in good weather. What we propose is a mix of the two systems, and the following analysis is presented as a possible methodology for determining the proper mix of the two systems. The parameters we have used are ball-park estimates, and we have not yet tried any systematic variation-of-parameter studies to investigate the effect of such changes on the outcome of the analysis.

First, consider the case of an omniscient Air Weather Service that can predict the weather over the target with perfect accuracy. Let p be the probability of good weather (weather in which the good-weather system is effective) and 1 - p be the probability of bad weather. The parameters of the problem are defined with the subscript i for the system and the subscript j for the weather, where i,j = 1 refers to the good-weather system and good weather, while i,j = 2 refers to the all-weather system and bad weather. As a measure of utility, we chose a rather simple cost/effectiveness ratio. Effectiveness is measured by the kill rate of the combined systems and cost is a combination of operating costs, attrition, and basic maintenance of the force.

Let:

r_{ij} = sortie rate of the ith system in the jth weather (sorties/unit time)

ℓ_{ij} = attrition rate of the ith system in the jth weather (planes lost/sortie)

k_{ij} = kill probability with the ith system in the jth weather (kills/sortie)

u_i = unit cost of the ith system (dollars/plane)

n_i = operating cost per sortie of the ith system (dollars/sortie)

M_{ii} = support costs of the mixed system (dollars)

The effectiveness or kill rate is simply defined as

$$E_{ij} = k_{ij} r_{ij}.$$

The costs, which are a function of sortie rate, are dependent on both the operating costs per sortie and the attrition:

$$C_{ij} = r_{ij}(n_i + \ell_{ij} u_i).$$

Attrition enters only as a cost; it does not affect subsequent sortie rates. Support costs, M_{ii}, are not proportional to sortie rates but simply to the complexity of the two systems. They *should* be proportional to the mix of systems, but we will, for now, simply assume a single number for each system separately and another number for a mix of any proportion.

For the proposed perfect-forecast case the pertinent factors can be summarized in the following matrix:

	Good-weather System (1)	All-weather System (2)	Weather Probability
Good Weather (1)	E_{11} C_{11}	E_{21} C_{21}	p
Bad Weather (2)	E_{12} C_{12}	E_{22} C_{22}	1 - p
Support Costs	M_{11}	M_{22}	
	M_{12}		

From these data it is possible to determine the cost/effectiveness ratio for using either good-weather system (1) or all-weather system (2) exclusively, as well as the ratio for a mixed system if it is assumed that the proper mix is always available for the given climatology. This cost/

effectiveness ratio is represented by R_{ii}, where ii = 11 represents a purely good-weather system, ii = 12 represents a mix, and ii = 22 represents a purely all-weather system. From this we obtain

$$R_{11} = \frac{pC_{11} + (1 - p)C_{12} + M_{11}}{pE_{11} + (1 - p)E_{12}} , \tag{1}$$

$$R_{22} = \frac{pC_{21} + (1 - p)C_{22} + M_{22}}{pE_{21} + (1 - p)E_{22}} , \tag{2}$$

and

$$R_{12} = \frac{pC_{11} + (1 - p)C_{22} + M_{12}}{pE_{11} + (1 - p)E_{22}} . \tag{3}$$

For convenience assume that the ratio of sortie costs to unit costs (n_i to u_i) is a definable function of the system. Let $f_i = n_i/u_i$; then

$$C_{ij} = r_{ij}u_i(f_i + \ell_{ij}) ,$$

$$E_{ij} = k_{ij}r_{ij} .$$

If we eliminate dimensions by the ratios $r'_{ij} = r_{ij}/r_{11}$, $U'_i = u_i/u_1$, $k'_{ij} = k_{ij}/k_{11}$ (i.e., by normalizing these quantities to their value for the good-weather system in good weather), then

$$C_{ij} = (r_{11}u_1)r'_{ij}u'_i(f_i + \ell_{ij}) ,$$

$$E_{ij} = (k_{11}r_{11})k'_{ij}r'_{ij} .$$

In order to compare the two individual systems with the mixed system, we estimate the following factors:

$r_{11} = 1$	$r'_{12} = 1$	$r'_{21} = 0.8$	$r'_{22} = 0.8$
$k_{11} = 0.5$	$k'_{12} = 0$	$k'_{21} = 1.1$	$k'_{22} = 0.7$
$\ell_{11} = 0.05$	$\ell_{12} = 0$	$\ell_{21} = 0.055$	$\ell_{22} = 0.025$
$u_1 = 1$	$u_2 = 2$		
$f_1 = 0.05$	$f_2 = 0.07$		
$M_{11} = 0.1$	$M_{22} = 0.2$	$M_{12} = 0.15$	

Hence:

$C_{11} = 0.10$	$C_{22} = 0.152$
$C_{12} = 0.05$	$C_{21} = 0.20$
$E_{11} = 0.5$	$E_{22} = 0.28$
$E_{12} = 0$	$E_{21} = 0.44$

Using these values in Eqs. (1) to (3), we obtain cost/effectiveness ratios as a function of p:

$$R_{11} = \frac{0.05p + 0.15}{0.5p} = \frac{0.1p + 0.3}{p} \tag{4}$$

$$R_{22} = \frac{0.048p + 0.352}{0.16p + 0.28} \tag{5}$$

$$R_{12} = \frac{-0.052p + 0.302}{0.22p + 0.28} \tag{6}$$

Figure 9 (p. 20 in the body of the Report) shows the cost/effectiveness ratio for these three cases as a function of the probability of bad weather. The mixed system shows a clear advantage over the purely all-weather system, although, with very high frequencies of either good or bad weather, our assumption of a fixed-support cost causes an unrealistic departure of the mixed-system curve from the purely good-weather-system curve at the left and the purely all-weather-system

curve at the right. The purely good-weather system shows an advantage over the mix when the probability of bad weather is low, $(1 - p) < 0.4$, but the advantage is small and could be exploited in areas only where there was a high assurance of good weather conditions.

The possibility of having perfect knowledge of the weather conditions is remote, but a positive and increasing skill in weather prediction does exist. Assume, therefore, that the choice of system for a given sortie is dependent solely on the weather forecast and that the categorical forecast is always believed. The frequencies (α_{jk}) of correct ($j = k$) and incorrect ($j \neq k$) forecasts can be displayed in the matrix below. Here j refers to the observed weather and k to the forecast.

j ↓ Obs \ Fcst (k →)	1	2	
1	α_{11}	α_{12}	p
2	α_{21}	α_{22}	1 - p

Assuming a mixed force, with system (1) used when the weather is forecast to be good and system (2) when the weather is forecast to be bad, the C/E ratio becomes:

$$R_{12}(F) = \frac{\alpha_{11}C_{11} + \alpha_{12}C_{21} + \alpha_{21}C_{12} + \alpha_{22}C_{22} + M_{12}}{\alpha_{11}E_{11} + \alpha_{12}E_{21} + \alpha_{21}E_{12} + \alpha_{22}E_{22}} \qquad (7)$$

The verification studies of Wayne Hering, AFCRL,[8] provide a means of expressing the values of the α_{jk} in terms of p. From Hering's graphs a series of 3 matrices have been prepared (Table B-1) for values of $p = 0.1$, 0.5, and 0.9, which give the values of α_{jk} for current operational forecasts in the United States. Using these values in

[8] Letter dated 29 October 1969 from Mr. Wayne S. Hering to Captain Vaughn McDonald, SAMSO.

Table B-1

FREQUENCIES OF CORRECT AND INCORRECT FORECASTS (α_{jk})
FOR THREE FREQUENCIES OF WEATHER-EVENT OCCURRENCE (p).

p = 0.1

k →

Obs \ Fcst	1	2	
j 1	.04	.06	.10
↓ 2	.05	.85	.90
			1.0

p = 0.5

k →

Obs \ Fcst	1	2	
j 1	.40	.10	.50
↓ 2	.10	.40	.50
			1.0

p = 0.9

k →

Obs \ Fcst	1	2	
j 1	.85	.05	.90
↓ 2	.06	.04	.10
			1.0

Eq. (7), the cost/effectiveness for these values of p are:

p	$R_{12}(F)$
0.1	1.034
0.5	0.775
0.9	0.555

As plotted in Fig. 9 (p. 20), these data indicate only a slight increase in the cost/effectiveness ratio as the result of using realistically imperfect forecasts in lieu of perfect forecasts.

Because time may be more important than cost/effectiveness in some military operations, it is useful to estimate an expected time (number of potential flying periods) needed to kill a specified number of targets. The time required will be simply the inverse of the weighted effectiveness figures. If this inverse is multiplied by the kill probability for the good-weather system in good weather (in this example, 0.5), the time for the good-weather system in a climate with 100 percent good weather will be unity. The time-to-completion equations are:

$$T_{11} = \frac{0.5}{pE_{11} + (1 - p)E_{12}}$$

$$T_{22} = \frac{0.5}{pE_{21} + (1 - p)E_{22}}$$

$$T_{12} = \frac{0.5}{pE_{11} + (1 - p)E_{22}}$$

$$T_{12}(F) = \frac{0.5}{\alpha_{11}E_{11} + \alpha_{12}E_{21} + \alpha_{21}E_{12} + \alpha_{22}E_{22}}$$

The results of these calculations are plotted in Fig. 10 (p. 21 of the body of the Report). They show that the time penalty associated with a purely good-weather system increases rapidly as the probability of bad weather exceeds about 0.3, and that there is very little difference between the time penalties associated with a purely all-weather system and a mixed system.

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