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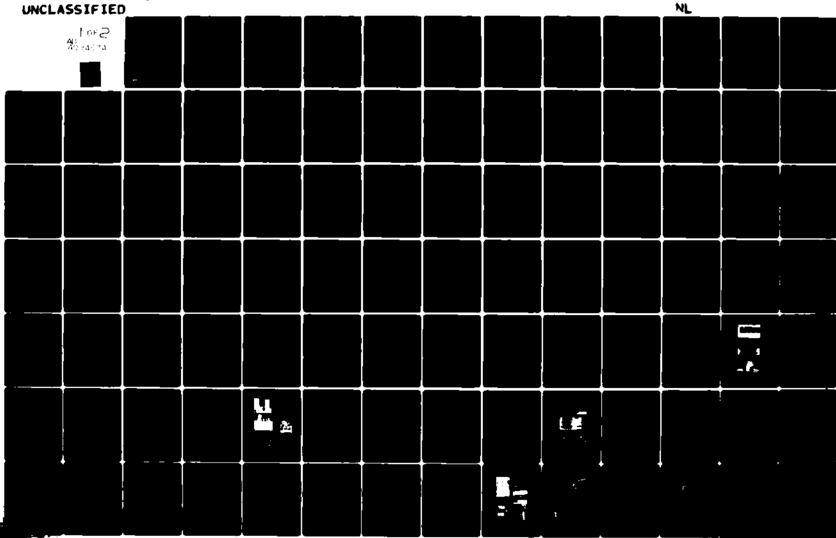

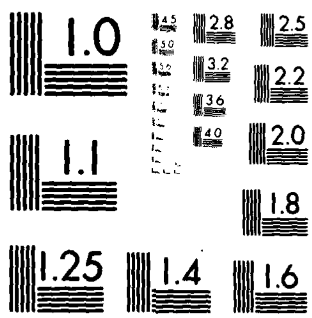


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# BLAST/FIRE INTERACTIONS:

## Analysis of Parametric Sensitivity and Large-Scale Experimental Determination of Ignition Thresholds

BLAST/FIRE INTERACTIONS FEMA WORK UNIT 2563F



October 1980

Annual Report
For the Period 1 October 1978 to 31 March 1980

By: Stanley B. Martin
Raymond S. Alger
John R. Rempel
Peter S. Hughes (Los Alamos Technical Associates, Inc.)

Prepared for:

FEDERAL EMERGENCY MANAGEMENT AGENCY
Office of Mitigation and Research
Washington, D.C. 20472

Attention: Dr. David W. Bensen, COTR

Contract No. DCPA01-78-C-0279
FEMA Work Unit 2563F
SRI Project PYU 7814





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This annual report of progress describes activities in three areas of technical services in the research field of blast/fire interactions. Two are concerned with parametric sensitivity in predictive modeling, the third with verification of laboratory ignition thresholds using a large field-test source of intense thermal radiation.

Airblast effects are shown to be a major source of uncertainty in assessment of fire effects of a nuclear explosion. Blast caused fires may be


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more important than primary fires in the regions experiencing lower over-pressures, but current inadequacies in secondary fire modeling severely limit the comparisons. Moreover, airblast extinction introduces very large uncertainties in estimates of initial fire incidence, and blast damage to structures introduces similarly large uncertainties in ~~the~~ evaluation of the further destruction from fire spread and possible mass fire development.

The large scale ignition experiments generally confirmed laboratory-based predictions. Mixed fuel results were inconclusive.

Further investigation of several aspects of this problem area are continuing and will be updated in a subsequent report.

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## SUMMARY

This report describes research activities conducted by SRI International for the Federal Emergency Management Agency in three areas of technical services in blast/fire interaction during the period 1 October 1978 to 31 March 1980. Two of the three areas involve predictions of fire damage and evaluation of the effectiveness of mitigating actions. Requirements for analytical models are reviewed, the sensitivity of their predictive outputs to assumptions, uncertain data, incompletely understood phenomena and parametric dependencies, and possibly erroneous algorithms invented to cover the lack of factual information are investigated, and the net practical effect of these uncertainties on utility and reliability appraised. The third area of technical service entails identifying and planning for field test opportunities. Reported here are the results of an experiment conducted by Los Alamos Technical Associates (with assistance from SRI) using a large, intense thermal radiation source to simulate the thermal pulse of a nuclear explosion in air. Predicted ignition thresholds, based principally on laboratory exposures of small, simple targets, were verified in the field with targets of practical size and complexity. Char depths were also determined and compared with both laboratory and nuclear test data to verify the appropriateness of the simulation technique.

### Formal Analysis of Sensitivity

A first-pass analysis has been completed. Fire effects in urban areas resulting from a 5-MT air burst and surface burst were modeled using the SRI Blast/Fire Model. We did not model fire effects beyond the initial distribution because of the inadequacy of state-of-the-art analytical methodology to deal with the dynamics of fire growth and spread in blast-damaged urban tracts. Initial fire distributions are described in terms of frequency of significant building fires as functions of the independent variable (distance from ground zero or the

corresponding free-field overpressure) for specified values of a variety of parameters. Three categories of parameters are recognized: attack parameters, target parameters, and response parameters. The first two include scenario variations, some of which are inherently unpredictable to the defense planner. Others, however, such as the state of preparedness, at least in principle subject to his control, or weather variables, which are subject to statistically describable periodic and/or seasonal fluctuations, do warrant inclusion in a study of parametric sensitivity. Response parameters are those associated with the physical and chemical processes that govern fire behavior. Their uncertainties are due to technological limitations; these parameters constitute the principal group subject to refinement through research.

In the evaluation of primary fires prior to blast arrival, the current model, while notably broad brushed, is thought to be adequate for many present purposes and reasonably reliable to the extent that interior fires alone determine the fire threat. Prediction are particularly sensitive to atmospheric transport of thermal radiation, but given a specified visibility (in a cloudless atmosphere) the model provides estimates of the free-field flux and fluence that are certainly adequate in relation to field-of-view uncertainties. Clouded atmospheres are another matter, especially when a broken deck above the burst point extends the thermal radiation field (as it presumably did at Nagasaki in 1945) in an unsymmetric pattern around ground zero. The primary-fire reach of surface bursts is further complicated by variations in the artificial horizon (due to both terrain and buildings) to which the thermal radiation field is quite sensitive.

Airblast effects are the major source of the lack of confidence in any current predictions of fire consequences of nuclear attack, although the model's failure to include other potentially important primary fire-start mechanisms (e.g., exterior ignitions and ignition of debris after blast) may rise to dominate at the higher overpressures. In the 2- to 5-psi region, secondary fires can rival primaries in importance, depending especially on airblast extinction of the incipient primary fires and whether the atmosphere or artificial horizon limits the frequency and range of primary fire starts; however, current inadequacies in secondary fire modeling severely limit the comparisons. Airblast extinction introduces a very large uncertainty in estimates of the initial fire distribution. Blast damage introduces similarly large uncertainties in the evaluation of the further destruction due to fire spread and mass fire development.

## Supplemental Evaluation of Sensitivity

This study focused on machine tools and their fire survivability as a gauge of the practical requirement for fire damage modeling in a context of threat to critical resources and industries. Records of World War II and a peacetime fire disaster are supplemented by data on blast effects in nuclear tests to show the relative importance of fire as an effect. We developed and advanced a prediction procedure for machine tool survival to accomplish two functions:

1. Provide a general estimate of the national machine tool losses under a given attack scenario.
2. Give specific guidance for local action to minimize machine tool damage.

The order in which the procedural steps are taken minimizes the number of cases that need to be carried through to the more difficult and unreliable fire modeling steps.

## Large Thermal Source Experiment

Three aspects of the fuel and its environment were of particular concern:

- Target size, particularly the potential for thermal reinforcement in tall targets.
- Geometry, especially the possible reinforcement in cracks, folds, and reentrant corners.
- Combinations, notably the possible synergistic effects of mixed fine and coarse fuels.

Two tests were run during July 1979 at Kirtland AFB. In general, the results were as predicted and reinforcing effects of size and geometry were minor. Mixed fuel results were somewhat inconclusive because differences in sample packing of simulated debris appeared to have a large, inadequately controlled effect in these experiments.

# 1. INTRODUCTION

Fire from nuclear weapon attack is a direct threat to the population of the United States and an indirect, long-term threat to national survival because fire can destroy the shelter, sustaining resources, and industrial machinery essential to economic recovery. Unresolved questions about interactions between blast effects and fire effects preclude any reliable estimates of the incendiary outcome of a nuclear attack on the United States. As such, these uncertainties are a major obstacle to defense planning and interfere with national security policymaking at the highest levels.

To rectify the technical deficiencies underlying the lack of predictability of the incendiary outcome of nuclear attack on the United States and to formulate a well-directed program of research, the Defense Civil Preparedness Agency (DCPA) contracted with SRI International (SRI) in early 1978 to convene a conference of authorities on fire, air blast, structural response, and other related technologies. The report of the conference* identifies the technical deficiencies that prevent or inhibit the development of a theoretical or analytical basis for predicting fire effects under the uncertainties introduced by interaction with air blast waves and blast effects. It provides a logical, analytical framework for structuring and performing a research program to either eliminate technical deficiencies or reduce to an acceptable level the contribution these deficiencies add to the uncertainties in damage prediction. Recommendations are made for early attention to key issues that prevent the development of credible blast/fire models. Analytical modeling of blast/fire interactions is not only a goal of the program, but a necessary adjunct, through sensitivity analysis, of program planning and review.

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*"Blast/Fire Interactions: Program Formulation," Final Report of SRI Project PYU 7432, DCPA Work Unit 2563D (October 1978).

A technical problem of this magnitude and complexity requires a program of at least five years duration and involves a wide range of interdisciplinary research activity conducted by government-agency laboratories and private research institutes, with appropriate assistance from industrial contractors. A program of this scope requires strong, consistently applied monitoring and coordination to (1) ensure that the obtainable goals are significant, (2) maintain a level of performance that is consistent with need, and (3) synchronize complementary or dependent elements. Accordingly, the Blast/Fire Conferees urged DCPA to designate a lead laboratory to research key across-the-board elements of the program and to assist in coordinating the variety of tasks performed by contractors and other contributors. SRI began fulfilling some of the functions of a lead laboratory under contract to DCPA.

Program implementation began in 1978, and a second conference was held in 1979. In July 1979, by executive order of the President, the Federal Emergency Management Agency (FEMA) was created and emergency functions, including DCPA research activities, were transferred to FEMA's Director. Under contract to the new Federal Emergency Management Agency's Office of Mitigation and Research, SRI is continuing to provide the services initiated in 1978 and extended in 1979.

This report covers activities for the period 1 October 1978 to 31 March 1980. An appreciable part of the effort was given to the program planning service functions, including the arranging and hosting of the second conference. The proceedings of the conference and the research guidance it generated are documented in a separate report.* The other major effort was devoted to the analysis of parametric sensitivity and conceptualization of damage-assessment and mitigation-effectiveness models for use in both planning and operational applications. Chapters 2 and 3 describe progress to date in those subject areas. Finally, field test opportunities were investigated. We assisted the FEMA Office of Mitigation and Research in planning blast/fire experiments for MILL RACE (not

*"Blast/Fire Interactions: Asilomar Conference, March 1979," Proceedings of the Conference (SRI Project PYU 7814, DCPA Work Unit 2653F (1979).

reported here) and participated in some large-area, complex fuel ignition experiments conducted at Kirtland AFB by Los Alamos Technical Associates using the large aluminum/oxygen thermal sources developed by Science Applications, Inc. This experiment and its results are described in Chapter 4.

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## 2. SENSITIVITY ANALYSIS OF BLAST/FIRE PREDICTIONS

Fire effects of a nuclear explosion are inseparably interrelated to the effects of airblast. From a single explosion, the area subjected to intense thermal radiation sufficient to light fires in either urban or wildland environments is roughly the same as the area suffering significant mechanical damage caused by the airblast, and since this is also the area where any secondary (i.e., blast-caused) fires will occur, the initial fires are largely confined to the area of significant blast damage. Multiple bursts may increase the fire vulnerability of a target, but initial fire effects will rarely extend much beyond the regions of blast damage.

Unlike blast effects, fire spreads, continuing to cause damage and threaten survivors for considerable periods of time after the initiating event. Appreciable additional destruction can result. Resources such as machine tools that are notably resistant to blast damage may suffer from fire exposure; personnel shelter space that may provide a measure of safety from airblast, prompt radiation, and fallout may become intolerable in a fire; and, under some conditions, fire may spread well outside of the area initially affected by the explosion adding unexpected collateral damage. Fire effects are also susceptible to mitigating actions and a variety of credible countermeasures.

The combined blast and fire effects of nuclear explosions in urban environments are recognized and documented as operationally significant and important to strategic planning and civil preparedness. Fire effects are notoriously difficult to predict, because they depend on such a variety of target, weather, and scenario variables, but they are made all the more uncertain by incompletely understood interactions with airblast, interactions that include both dynamic and residual effects. The dynamic interactions include such effects of the passing air shock on ignited materials as fire enhancement or extinguishment. The residual effects include changes in fire growth and spread by blast-caused fires, structural damage, and blast-induced disarray of combustibles (debris production). Nevertheless, fire-damage and fire-threat prediction models must be developed, despite the technical difficulties, and regularly upgraded to reflect the improved state of the art. Obviously, they can be used to evaluate fire countermeasures and mitigating actions, both relative cost-effectiveness and return on investment, but they have a potentially bigger contribution to make in strategic planning, in deciding when and how to relocate the population, in the selection and upgrading of high-risk area shelters, in the deployment of emergency services, and in the stockpiling of fire-vulnerable resources.

## 2.1 Technical Background

Because of the complexities and inherent uncertainties in predictive fire modeling, it is neither practical nor desirable to attempt a detailed, chronological analysis of an entire urban target. One must continually ask: How much detail is really needed? Which are the crucial consequences of the fire and which effects can be neglected or roughly approximated? To some extent, the limitations are determined by such practical matters as lack of knowledge about the physical processes, insufficiently detailed description of the target, or computer size. But even if these were not present, we would still have imperfect informat. n about the future which renders any prediction more or less uncertain. Fortunately, we have very little experience with the unique effects of nuclear explosions. However, fires and their threats are more commonly experienced, and lessons learned during World War II are to some extent applicable to the nuclear catastrophe. Fires of catastrophic proportions resulted from aerial attack on urban centers years before the advent of the nuclear bomb. This experience may help us to determine the key practical issues.

### 2.1.1 Fire Experience in World War II

The intense, large-scale aerial bombardments of German and Japanese cities during the period 1943 to 1945 clearly demonstrated several facts that are in all likelihood directly applicable to any future nuclear counterpart.[1,2]

- The fire outcomes could be readily identified with two broad categories: area fires and mass fires
- A disproportionate increase in damage and casualty rates was associated with mass fires due to their unusually hostile environment and the futility of attempts to control them.
- Mass fires were of two distinct types: (i) the ones called firestorms, which were generally associated with low natural (i.e., preattack) wind speeds, and (ii) those called conflagrations whose destructiveness was due, at least in part, to spread under the influence of high natural winds. In both cases, characteristics of the urban area are believed to be important and the density (and perhaps extent) of fire starts are probably critical factors.

In view of the high damage potential and extreme life hazard of mass fires, it is certainly reasonable to focus on the conditions necessary for mass production. Studies based on the experiences of World War II have produced some rules of thumb. High building density is a common factor in developing large mass fires. Twenty-five percent of the land area covered by buildings has been proposed as a criterion of mass fire production. This is met only by the central city areas of most U.S. cities, especially the older parts adjacent to (or including) the central business district (CBD). Additionally, a firestorm may require an initial fire start of roughly one out of two buildings in a roughly square mile area, and a wind speed of less than about 10 mph. More likely, the important factor is the power density of heat released by the fire and the size of the area is probably of significance mainly in relation to the height of the convection column required to overcome the stabilizing effect of the atmosphere (e.g., its fluid inertia tending to oppose the development of large-scale circulation). Conflagrations may not have such demanding power density and size restrictions. In principle, a conflagration can result from a single start, but high natural winds and low humidity clearly favor their development. Gage-Babcock developed a set of "conflagration potential" criteria for U.S. cities.[3]

### 2.1.2 Past Modeling Efforts--The Five-City Study

Several competitively developed models for the initiation and spread of fires reached a stage of utility during the Five-City Study.[4,5,6] To compare the results, these models were applied independently to evaluate fire effects in San Jose, California. The scenario was specified in advance, and a common data base was provided. Blast effects were intentionally ignored except for secondary fire. The damage contribution due to secondary fire was derived from the earlier risk assessment of McAuliffe and Moll,[7] which in turn had been developed from historical information. Each participant was encouraged to conduct on-site surveys and to acquire data for his fire model, but little constraint was applied to the method of data acquisition or its level of detail.

The results by the participants were substantially different, enough so that DCPA employed SRI and Dikewood Corp. to review independently the models and recommend a course of action. The conclusions of these reviews are nearly as valid today as when they were published in 1970, and they are of fundamental importance to future research plans.

The SRI review[8] was limited to the fire-spread aspects of fire modeling and commented on the lack of:

- Mass-fire model development
- Treatment of spread mechanisms besides radiation
- Consideration of effects of fire control countermeasures
- Development of a spread model for blast-damaged configurations.

The SRI authors were unwilling to select any candidate model to meet future civil defense needs, and suggested the independent formulation of and alternative model.

The Dikewood review[9] concentrated on fire initiation and early fire development; accordingly, they included the Naval Applied Science Laboratory (NASL) Fire-Start Model[10] along with the broader context models of URS,[4] IIT Research Institute (IITRI),[4] and Systems Sciences, Inc. (SSI).[6] The Dikewood study showed that, even without introducing the uncertainties of blast perturbation, simplifications introduced into the models led to quite different estimates of the probable severity of the initial fire threat. The Dikewood authors were less sweeping in their criticism of the fire-initiation models than the SRI reviewers had been of the fire-spread models. In fact, they made specific suggestions as to which model might be used in different applications and how each might be used to provide a framework for specifying needed additional research. They stressed the importance of developing a "good scientific model" before trying to arrive at a simpler operational model.

The Dikewood authors, pointing to the omission of blast interaction in the Five-City Study, commented: "The nuclear attack fire problem is radically different where overpressures cause essentially complete collapse of structures," but they acknowledged that the interactions of blast and fire were not well enough known to permit systematic treatment in any fire model.

In seeking a model amenable to modification that would qualify it as the basic framework for a civil defense fire model, the Dikewood study concluded that both the NASL and IITRI models were strong candidates. In NASL's favor were the following factors:

- Treatment of actual street patterns
- Use of much more use-class-dependent data
- Inclusion of distributions of attenuators at window openings
- Ability of model to summarize results for an entire city
- More accurate treatment of effects of window shades.

Against the use of the NASL model were the following factors:

- Inability to relate the predicted ignitions to building fires or even to room flashover
- Inability to obtain the data required for application to numerous cities

- Inferior modeling of the fireball-shielding and building-window-room interior geometry compared to SSI or IITRI
- Uncertainty concerning validity of the "ignition volume" concept.

Arguments in favor of adopting the basic structure of the IITRI model were:

- Excellent geometrical analysis, resulting in the intensity of received thermal radiation at every point on the ignition plane
- Careful treatment of the "seen" area of the fireball
- Relative ease of applying model to a "new" city
- Compatibility with existing fire-spread models.

Against the adoption of the IITRI model were the following points:

- Application to other use-classes of data specific to residential occupancy
- Lack of treatment of nonnormal azimuthal angles
- Use of precalculated distributions of separation distances and room contents and room sizes
- Assumption that a room flashover implies building burnout.

The Dikewood study found little difference in the adaptability of the two models; thus, major changes would be required if either model were adopted. In their view, the decision depended on such factors as:

- The long- and short-range goals of a national program using the results of any urban nuclear fire study and the the relationship between these goals
- Likelihood of funding levels sufficient for continued research and data-gathering
- Urgency associated with developing a working "scientific" model.

Considerations such as these led Miller and his coauthors to make several recommendations contingent on program goals and the urgency to implement such models. They recommended the IITRI model for either immediate use, given no time or funds available for model modification, or short-term development, given moderate funding support and the time necessary to do a major rewrite of such of the model's algorithmic logic. For long-term development, given adequate developmental funding, they recommended the NASL model. They noted, however, that significant improvements in any of the modeling approaches are stymied by lack of understanding of basic phenomena, especially the interacting effects of blast and fire.

### 2.1.3 The SRI Blast/Fire Model

At present, only one analytical model purports to treat the interactions of blast and fire. Reference 11 describes the SRI blast/fire model modified to account for the results of shock tunnel experiments on interactions of shockwaves with incipient fires. Reference 12 describes a more recent modification of the model in which it was used to estimate possible collateral-damage impact of tactical nuclear weapons on a German village. An early form of this probabilitistic model (as used by URS[4] in the Five-City Study) estimates:

(1) The density distribution of significant, primary structural fires resulting from the ignition of interior fuels by thermal radiation from the nuclear fireball.

(2) The growth of fire in structures as a measure of "time to total involvement," the "duration of a fire-spread generation," and "time to structural burnout."

(3) The rate and extent of fire spread by short-range mechanisms.

(4) The density distribution of actively burning and burned-out structures as a function of time following attack.

There are also provisions to include secondary fire starts and fire spread by long-range mechanisms such as fire brands; however, the basis for these effects is more tenuous than the other parameters.

The primary fire initiation model deals with events in rooms: exposure of its contents through windows, ignition of some, and growth of the incipient fires to flashover. The basic premise is that ignition of exterior materials rarely leads to structurally damaging fires. Implicitly, it is assumed that the room geometry remains intact long enough for the incipient fires to develop to a point of full-room involvement or, failing to grow, to subside and go out. Accordingly, this is a no-blast-damage or at best a low-overpressure model for any buildings other than strong-walled (and reasonably fire-resistive) structures.

Based on the recognition that ignition of fine fuels by thermal radiation is of practical consequence only when these ignited kindlings can, in turn, ignite more substantial items, the model estimates the likelihood of full room involvement from the estimate of number and kinds of primary ignitions in that room by classifying the room contents into categories of potential to cause flashover given ignition. In the Five City Study, expert judgment was used to accomplish this classifying process. Specially trained firemen, who performed the building surveys, tallied the ignitable contents of "exposed" rooms into the following categories:

- Single item which, when ignited, can by its act of burning alone cause flashover of the room containing it; i.e., a "critical fuel unit" (CFU $\geq$ 1).
- Array of items in contact for which CFU $\geq$ 1.
- Item or array representing an appreciable fraction of a CFU but less than one (e.g., 1 > CFU $\geq \frac{1}{2}$, $\frac{1}{2}$ > CFU $\geq \frac{1}{4}$, CFU < $\frac{1}{4}$).

The model allows for three ignition mechanisms:

- Direct exposure of the item to a thermal fluence exceeding its ignition threshold.
- Indirect ignition by the piloting action of a lighter, more ignitable item with which it is in contact during the thermal exposure. In the Five City Study it was assumed that the ignition threshold for the combination was just the average of their individual values.
- Indirect ignition by a burning item (or fragment thereof) not initially in contact. This could include both dropping of brands due to the fire and transport of brands by the blast wave.

With inadequate knowledge of blast effects, the model is deficient in at least two respects: (a) it deals with the room's contents and their arrangements as they exist normally, not as they would exist following blast impact, and (b) it cannot anticipate what fraction of the primary fire starts will survive the potential suppression mechanisms accompanying blast impact. Therefore, while the model's estimates of primary ignitions may be good, prior to arrival of the airblast wave, its translation of these estimates into significant (i.e., damaging and spreading) room fires may be quite erroneous.

Conservative estimates of initial fire densities (such as were made by URS in the Five City Study and by the SRI/SAI team in Reference 12) both (1) neglect primary ignitions in all CPU $<$ 1 items, except window coverings, and (2) drastically reduce the primary ignition frequency in regions where free-field peak overpressures exceed 2 to $2\frac{1}{2}$ psi. Moreover, since the model has no provision whatsoever for treating fire incidence from exterior ignitions, it may seriously underestimate fire incidence, especially at close-in locations. On the other hand, arguments can be made, based in part on the bombing survey data from Hiroshima and Nagaski, to imply serious overestimates.

The time taken for flashover to occur following primary (or secondary) ignition is based on the IITRI experiments in model (but full-scale) rooms.[13] The results are expressed as the probability that the room has (or has not) flashed over as a function of time after ignition. Since these experiments did not include blast-effects simulations, the probability-versus-time algorithms are apt to be erroneous, but we are so uncertain of what the effect might be that we have no basis for evaluating it. Not just magnitude of effect is in doubt, but even whether there is an effect and, if so, whether it increases or decreases the rate of buildup. In fact, it conceivably could do both, increasing rates in one range of airblast overpressures and decreasing them in another.

Subsequently, blast effects may change the rate and manner of room-to-room fire spread (assuming of course that identifiable rooms still exist). The uncertainties here are no less serious than in the estimates of times to flashover.

In the original model, the fire buildup followed the exponential growth of flashover volume as described in the work at IITRI[13] and subsequently amplified by SRI.[11] To account for effects of blast damage and structural collapse, Martin et al.[12] modified the build-up times to agree with the results of damaged-structure fires reported in Reference 11.

Finally, blast-damaged structures will exhibit a different rate and extent of fire spread by short-range mechanisms than their relatively undamaged counterparts modeled in Reference 11. Clearly, a substantial increase in fire buildup to full involvement, or in fire spread, could counteract a reduction in primary ignitions. In the study reported here, the relative sensitivity of estimates of the fire intensity and its final extent to these three points of blast intervention have been explored analytically over a range of parameters, using the best estimate of blast effects from experts in the field of blast-fire and blast/structure effects.

## 2.2 Current Study Method

The research plan incorporates two complementary approaches. One exercises the existing SRI Blast/Fire Model to determine the sensitivity of the initial fire distribution to the influence of the key variables and simplifying assumptions. The other examines the required levels of fire intensity-time conditions to threaten shelterees and irreparably damage machinery protected against blast effects; this establishes how well (i.e., how confidently and in what detail) the fire consequences must be forecast. The mathematical definition of sensitivity, given in Appendix A, provides an unambiguous formalism for purposes of this study; however, a practical view of sensitivity will often as not entail questions on the confidence with which one can make and rely on operational decisions. A case in point is the predictability of mass fires, their effects, and the countermeasure effectiveness needed to ensure, to some specified level of reliability, the protection of lives or resources from their effects. At today's state of the art, this latter evaluation of "operational sensitivity" is, of necessity, in part judgmental. In any case, the evaluation process, even with its concessions to subjectivity, can be immensely aided by structuring it with a physically based, mathematical model.

### 2.2.1 Basic Approach--Exercise the Model

Chronologically, this analysis commences with the nuclear detonation and follows events until the number of primary and secondary fires have been established in essentially undamaged structures. This task entails the following four steps:

Step 1--Review the 1970 Dikewood Analysis of the Models used in the Five-City Study to identify: (1) the key variables and their plausible value ranges as perceived by the authors of that previous study, and (2) the differences between modeling approaches that they determined to be responsible for the major differences in prediction results.

Step 2--Use the most recent applicable version of the SRI Blast/Fire Model to estimate initial-fire frequency functions (i.e., probabilities of fire starts as functions of distance from ground zero) for:

- Two or more weapon sizes in the strategic-yield range
- A surface-burst and a low air burst
- Two or more land-use categories including areas representative of residential and industrial (manufacturing) occupancies
- Several atmospheric conditions covering the practical range of thermal transmission factors

and test the sensitivity of the results to: (1) the basic assumptions used in developing the model, (2) the algorithms invented to cover the lack of factual data, and (3) the variability (natural dispersion) in weather conditions, target changes resulting from population response to warning, and other scenario-related variables.

Step 3--Compare the inherent uncertainties due to scenario variables with the potentially correctable uncertainties due to technical deficiencies. This will guide the establishment of practical goals for predictive modeling and the associated requirements for resolution of technical uncertainties.

Step 4--Rank the factors, contributing significantly to uncertain predictions, according to sensitivity and amenability to resolution through research. This will be expressed in matrix form for ready guidance to deciding how to assign priorities for research attention, in allowing for scheduling in logical sequence, and for making cost-effective trade-offs in choice of alternative funding programs.

To date, Steps 3 and 4 have been tentative.

### 2.2.2 Supplemental Approach--Blast/Fire Effects Modeling Requirements

Because existing fire models do not deal with sustained fires and fire spread in severely blast-damaged regions of an urban target, they provide no evidence regarding the dependence of fire development on structural collapse and makeup of the resultant debris field. Therefore, this second approach examines the requirements for modeling of blast effects and debris-field descriptions in the context of fire intensities and durations that clearly threaten people in sheltered locations and industrial machinery and equipment expediently protected from blast damage. Attention is focused on the question of how the fire's intensity and time vary with fuel characteristics whose changes are identifiable with blast effects on target elements. This supplemental approach entails the following three steps:

> Step 1--Estimate the critical fire intensity levels required to destroy major machinery on the basis of historical records, particularly war-damage records. Part of this task will entail identifying critical* types of equipment and seeking statistical data on structures housing these.
>
> Step 2--Estimate effects of structural damage on the fire time-intensity levels both for spreading fires and fires where all the structures ignite simultaneously. These estimates will involve tenuous extrapolations from meager data and expert opinions.
>
> Step 3--Estimate significant differences in the damage levels required for descriptions of extent of structural collapse and the debris field.

## 2.3 Status

The planned efforts of the supplemental approach are completed and are reported in Chapter 3 of this report. The basic approach is also completed as a first pass to determine the feasibility and practical utility of this method. Specifically, Step 1 is finished, Step 2 had been completed for a single weapon yield (5 MT), Step 3 has been completed for the cases analyzed in Step 2, but difficulties encountered which will be discussed below) have raised doubts about the advisability

*i.e., critical to war fighting and postwar recovery.

of proceeding as originally planned, and Step 4 was deferred pending resolution of the questions raised in Step 3.

### 2.3.1 Results to Date

Table 2-1 lists some parameters of the SRI model divided into three categories: attack parameters, target parameters, and response parameters. The attack parameters include many if not most of the factors that are inherently uncertain to the recipient of the attack because he cannot tell when, where, and with what he will be attacked. Only good military intelligence can reduce these uncertainties appreciably. In the current exercise, as in the Five City Study, specific values with no uncertainties were arbitrarily assigned. These are also given in Table 2-1.

To a lesser degree, target parameters also are subject to scenario uncertainties. They include uncertainties in thermal radiation transport and loss and in weather variations beyond the control (often even the predictability) of the defense planner. No amount of research and its application will reduce these uncertainties appreciably; however, the relevant parameters and their effects are measurable and their variations are definable within bounds and subject to describable periodic and seasonal fluctuations from historical records. Thus, the uncertainties are describable in at least a stochastic sense. In our exercise, we found it convenient to use annual statistics for Magdeburg, DDR.[15] Such statistics, showing seasonal variability as well, are available for most cities of the United States. Another scenario uncertainty is the state of warning and/or preparedness in the target. This is subject to control by the defense planner.

Target parameters that are not scenario dependent (i.e., parameters that are inherent characteristics of the target), can in principle be described with any desired degree of accuracy. In practice, however, the cost and effort preclude detailed description; moreover, many of these characteristics (e.g., the distribution of ignitable room contents and their view of the sky wherein the fireball, or a portion of it, may appear) are in a constant state of flux making any one-time attempt at a detailed survey quite unrewarding. Consequently, in practice class-average values are assigned based on survey statistics. We used data

Table 2-1

SENSITIVITY ANALYSIS

| Parameters | Current Study Values |
|---|---|
| **Attack** | |
| Weapon yield | 5 MT (±0) |
| Thermal partition | 1/3 (±0) |
| Ground zerio location | Unspecified |
| Height of burst | Surface and 500 scaled ft (±0) |
| Time of day, year, etc. | Unspecified |
| **Target** | |
| Land use and occupancy | Residential, commercial industrial (see the Five City Study) |
| Construction type/density | Same as San Jose in Five-City Study |
| Distribution of ignitables | Same as San Jose in Five-City Study |
| Weather (present and recent past) | Same as San Jose in Five-City Study |
| Atmospheric transmission ($\bar{T}$) | Mean value based on 10.5 km (6.5 mi) visual range ($\bar{T} \pm 0.3\bar{T}$). |
| Cloud cover | None (but see text) |
| State of warning/preparedness | Minimal, windows covered/ uncovered |
| Previous damage | None |
| **Response** | |
| Ignition thresholds, primary | Correlation per NRDL* |
| Secondary fire initiation | Algorithms (see Reference 7) |
| Airblast extinction thresholds | Algorithms (see Refernce 14) |
| Structural damage | Minimal or none |
| Fuel redistribution | None |
| Fire growth/spread | Not treated |
| Extent of fire damage | Algorithms (see Reference 4) |

*Naval Radiological Defense Laboratory

from the Five-City Study. The uncertainties can be deduced from the variance of the survey statistics or plausible ranges can be arbitrarily assigned. We did some of both, using whatever statistical measures we could find.

By and large, the response parameters are those associated with the physical and chemical processes governing fire initiations and subsequent behavior. The uncertainties, therefore, are due largely to limitations in the state of the technology and are potentially correctible through research to any desired accuracy and precision. The SRI model employs various algorithms to bridge these deficiencies, and the validity of the assumptions range from fair where there is some experimental justification to poor when based on a dignified guess. Additional knowledge should materially reduce the uncertainties in the descriptions of the mechanisms, and indeed the lion's share of the current FEMA program is devoted to improving estimates of fires that survive the effects of airblast. In the meantime, however, we are forced to resort to several poorly established or largely unfounded and speculative algorithms to acquire quantitative relationships for use in the model. Most of the remaining discussion in this chapter deals with the efforts to make these relationships as credible as the state of the technology permits.

#### 2.3.1.1 Primary Fires Prior to Blast Arrival

Results of the model computations are illustrated in Appendix B. For each parameter evaluated, we determined the effect of variation in magnitude of values assumed for the parameter on the calculated frequency of fires expressed as a function of distance from ground zero and the free-field peak overpressure associated with that distance. This result was expressed in three different ways: (1) the fire frequency (or probability) itself, (2) rate of change of the probability with respect to change in the parameters (not illustrated), and (3) a dimensionless measure of sensitivity, which is analogous to relative error, as described in Appendix A. These illustrations represent only a small sample of the total run in the study to date. Only two parameters are included:

the ratio of window areas to wall areas for an airburst and the elevation of the artificial horizon for a surface burst. However, several other factors can be gauged from these. For example, the results show effects of variation in atmospheric transmission (FAC: .7, 1.0, 1.3), differences due to occupancy variations and between air bursts and surface bursts can be seen, and the effects of covering windows or leaving them uncovered are shown. Most parameters analyzed in this way are target parameters. Because of the still vague state of blast/fire interactions, these effects cannot now be modeled adequately to permit useful calculational evaluation of the response variables. Therefore, we have attempted to estimate their sensitivity in other ways.

#### 2.3.1.2 Interactions of Airblast and its Effects

As noted previously, the uncertain extent of extinction by airblast, and the conditions under which it will or will not occur, is of enormous potential impact on the reliability of fire damage assessment. The algorithms used in the SRI model are based on the studies of Goodale[14,16,17] and others[18] in the URS-operated airblast simulation facility at Ft. Cronkite, California. The general applicability of their results is questionable, and seemingly contradictory evidence exists. It is such an important question that we felt compelled to review the subject and to take another look at some of the older data, notably the records[19] from Nagasaki and Hiroshima, the test reports[20,21,22] of the atmospheric nuclear test events, and the earlier studies of airblast extinction conducted at UCLA.[23]

The reconstructed fire effects in the two A-bombed Japanese cities provide some benchmarks and bounding values based on actual experience. Figures 2-1 and 2-2 compare the bombing survey data with the calculated initial fire distribution based on the latest modification of the SRI model; blast effects algorithms are thus included. These algorithms prescribe the following rules:

(1) Below 2-psi peak overpressure, the blast wave has no effect

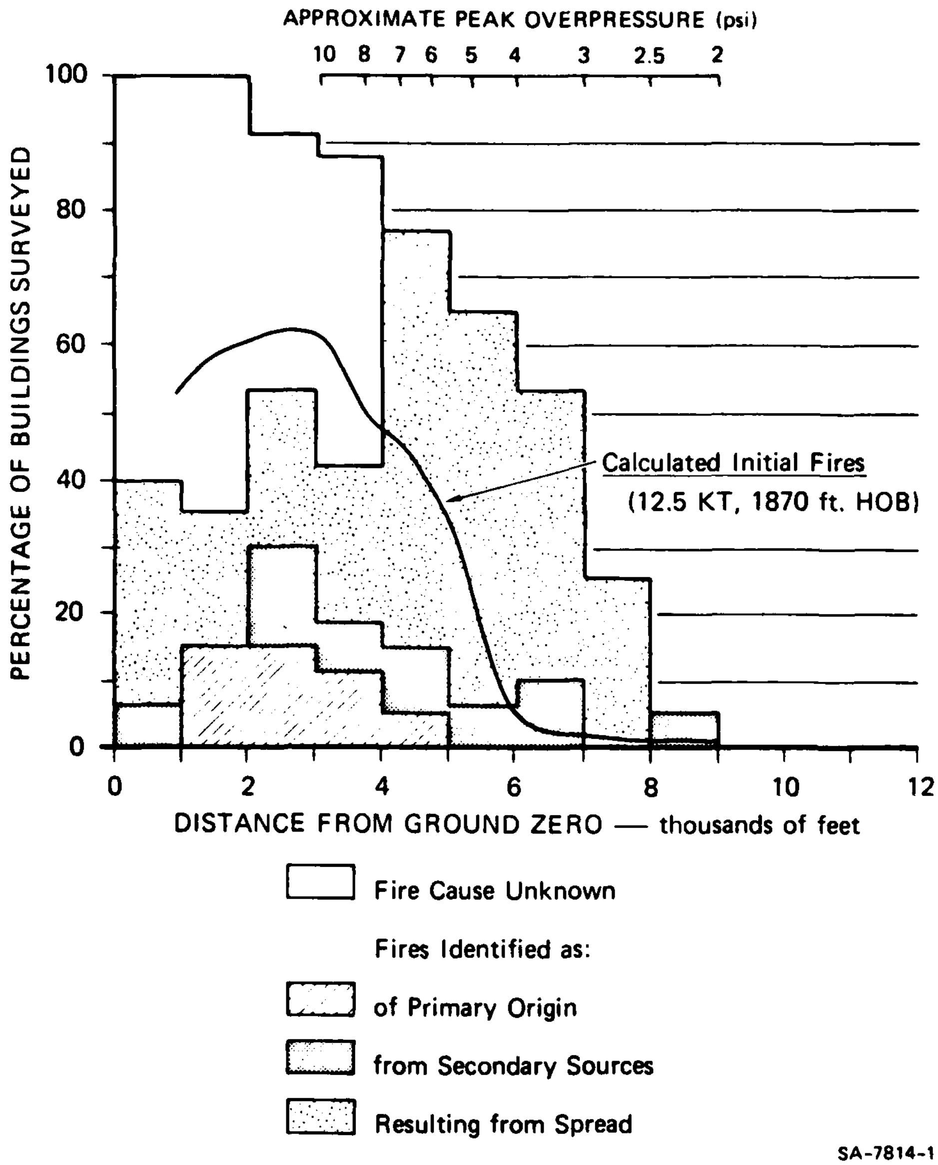


FIGURE 2-1 FIRES IN NONRESIDENTIAL STRUCTURES RESULTING FROM NUCLEAR EXPLOSION OVER HIROSHIMA

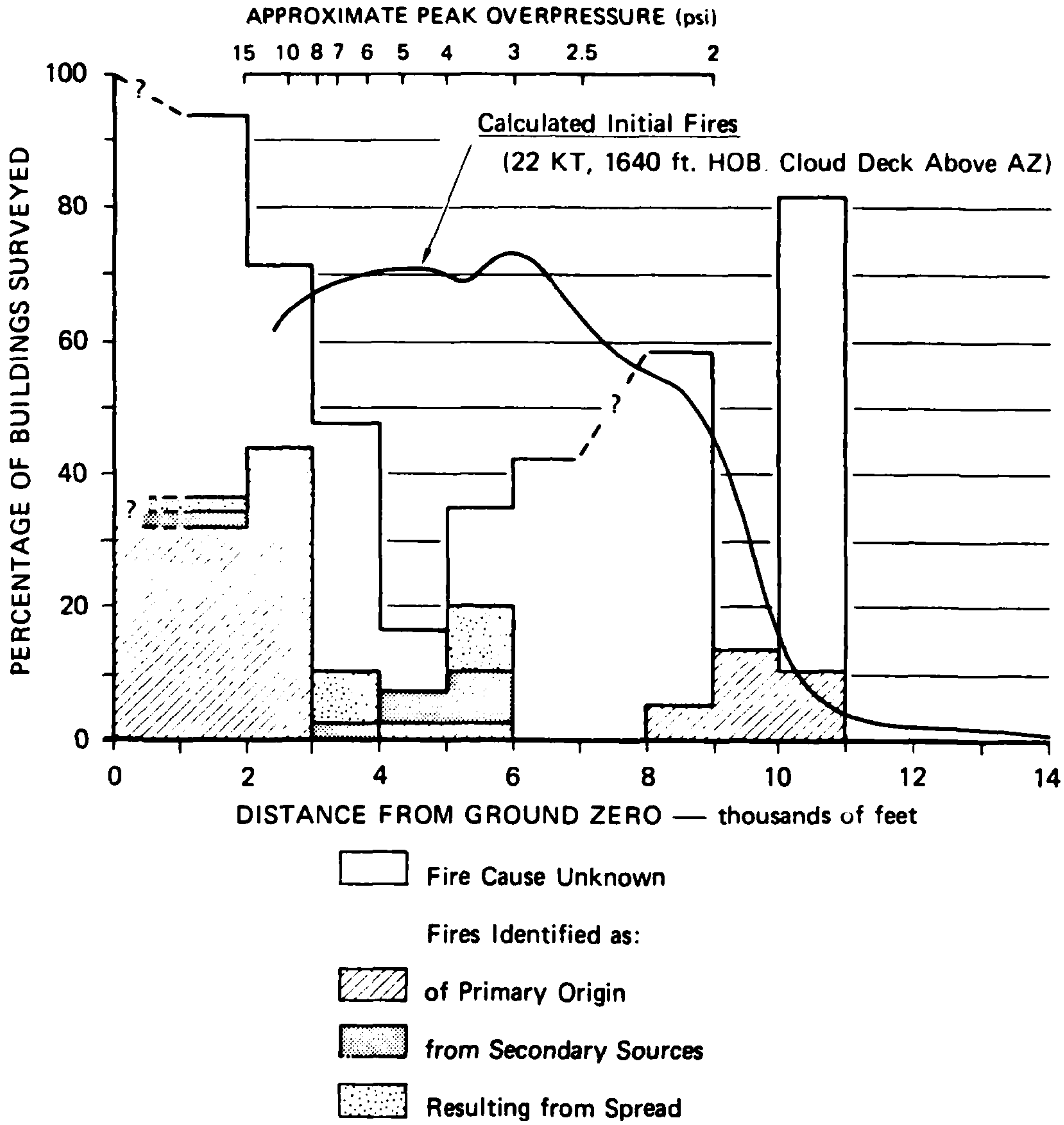


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FIGURE 2-2 FIRES IN NONRESIDENTIAL STRUCTURES RESULTING FROM NUCLEAR EXPLOSION OVER NAGASAKI

(2) Above 2-psi (a) a fraction of room fires, equal to the quantity (8-P)/6,* where P is the peak overpressure in psi, survive the airblast blowout to grow to the flash-over stage, and (b) an additional 1% of the buildings suffer secondary fire starts.

The model succeeds fairly well in estimating the ranges of incendiary effects, but appears to overestimate fire frequency in the intermediate overpressure range, perhaps because more primary fires are blown out than the algorithm prescribes, and appears to underestimate fire frequency at the high overpressures, perhaps because of initiating mechanisms that are not modeled.

The UCLA data suggest that the airblast extinction thresholds, which depend on both intensity and duration of air flow, are sensitive to the duration of preburn. In terms of a single nuclear explosion, this translates into the time between the thermal pulse and the arrival of the blast wave. Figure 2-3 shows some of the UCLA results with airblast characteristics of nuclear airbursts superimposed. To make this comparison possible, we transformed the extinction velocities in which the UCLA results were expressed to corresponding overpressures, it being assumed that (for low overpressures) the velocity of air flow immediately behind the shock is proportional to the peak overpressure, and that duration of flow is equatable to positive-phase duration. A surprising result of this exercise is that over a wide range of weapon yields, from 1 KT to 1 MT, extinction occurs for overpressures of about $2\frac{1}{2}$ psi and greater, irrespective of yield. It will be interesting to see if this result holds up in the shocktube studies and at MILL RACE.

### 2.3.2 Discussion of Results

Not surprisingly, the poorly understood interactions of airblast and its effects with fire are responsible for most of the uncertainty in fire-damage predictions (for cases of specified scenarios of attack). The uncertainties in blast-caused (i.e., secondary) fires are especially important in regions of low overpressure. At somewhat higher overpressures, the uncertain conditions for fire extinction by airblast

*This expression is applicable only in the range of 2 to 5 psi. Above 5 psi, it is assumed that half of the initial fires survive.

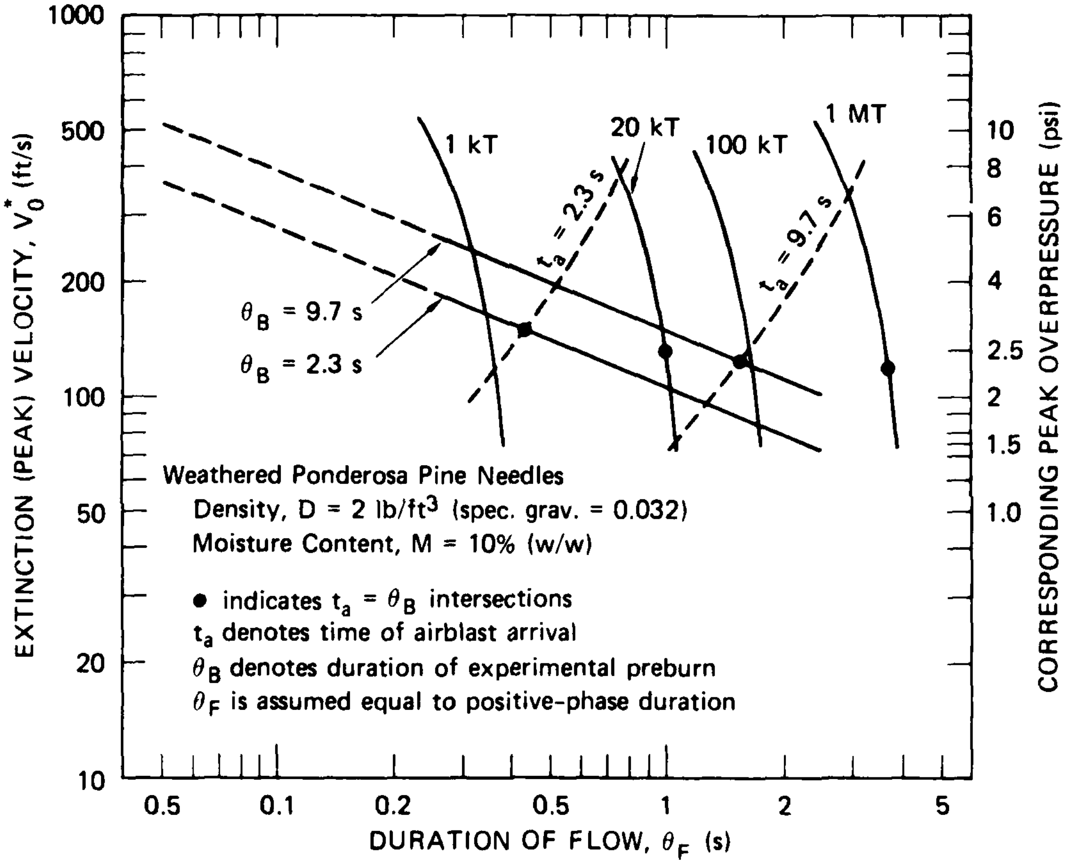


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FIGURE 2-3 RESULTS OF UCLA STUDY COMPARED WITH AIRBLAST CHARACTERISTICS OF NUCLEAR AIR BURST (500 FT SCALED HOB) become more important, and the uncertainties get larger with increasing overpressures because the current model is inapplicable here. A similar comment applies to the model's inability to deal with fire growth and spread in heavily blast-damaged targets.

Atmospheric transmission through unclouded atmospheres can be handled with sufficient accuracy and reliability, whenever the application permits the meteorological (visual) range to be specified. The presence of clouds, however, even when their altitudes and structure are specified, can introduce large uncertainties in the reach of primary fires. This factor was not included in our analyses, but a practical demonstration of its importance is inferred from the long-range primary fires identified by the bombing surveys of Nagasaki in 1945. The only plausible explanation based on present information is that cloud cover nearly doubled the transmitted levels of thermal radiation and greatly increased the distances to which ignition thresholds for kindlings extended. This explanation is in accord with our treatment of cloud effects within the present atmospheric transmission model. (See Figure 2-4)

Although not explicitly evaluated in this study, inherent uncertainties due mainly to the unpredictability of an attack scenario are certain to dominate uncertainties in many cases and, in fact, they will compel the choice of a predictive model appropriate to how vital scenario concerns may be in the application of such models. Technical deficiencies (the potentially correctible uncertainties) are totally outweighed by the effects of plausible scenario variations. This raises again the question of relevance and practicality of weapon-effects modeling of whole urban areas as predictive tools in civil defense planning and preparedness exercises. These questions of practicality and relevance are further addressed in the next chapter.

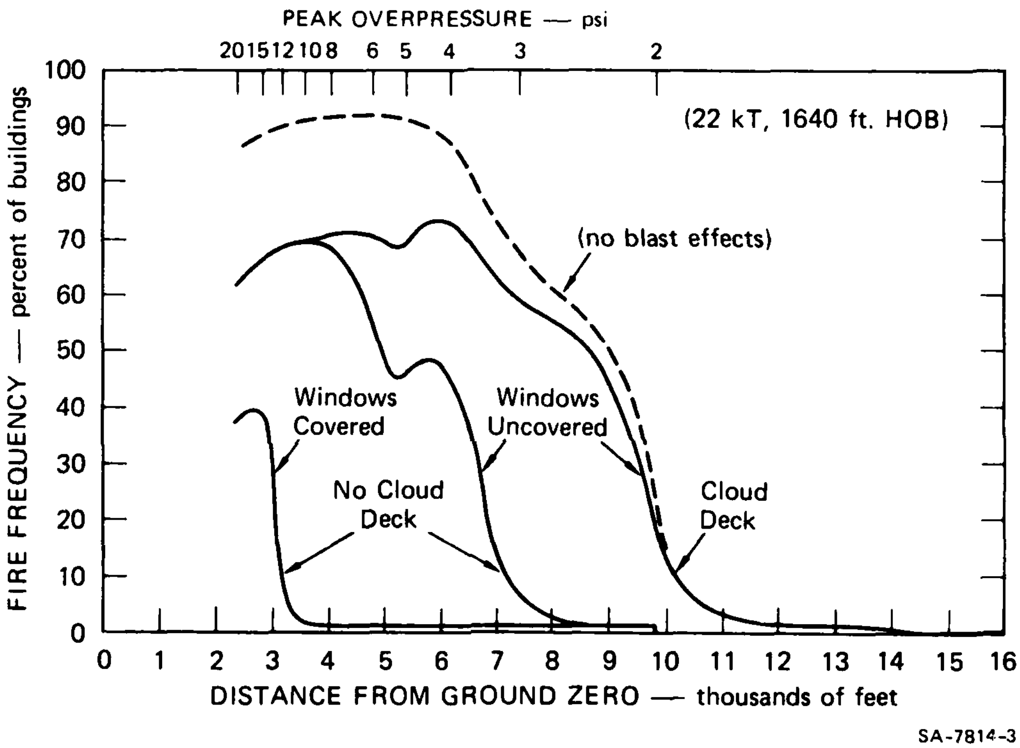


FIGURE 2-4 EXAMPLES OF SENSITIVE SCENARIO VARIATIONS

2.4 References


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# 3. SUPPLEMENTAL APPROACH TO EVALUATION OF SENSITIVITY

## 3.1 Machine Tool Survival in the Fires from a Nuclear Attack

The United States is highly dependent on machine tools for survival in times of peace and for victory in the event of war. Consequently, a serious issue in civil preparedness concerns the survival of critical machine tools in a nuclear attack. Plans for recovery following such an attack depend strongly on estimates of the machinery available to rebuild our industry. Experience during World War II and subsequent nuclear tests in Nevada indicates that heavy duty machines can survive substantial blast overpressures but not necessarily the accompanying fires. Considerable uncertainty persists about the potential for fire damage; therefore, this review examines the information available about machine tools, their location, and the fire potential. The goal is to identify the areas of ignorance that should be addressed in the blast/fire prediction program. Specific concerns include the definition of critical tools, the nature of fire damage, historical evidence from World War II records and peacetime fire reports, procedures for dealing with the damage question in the fire models, and countermeasure options.

## 3.2 Tools Critical to Post-Attack Recovery

### 3.2.1 What Tools are of Concern?

Several groups within the Federal Government are concerned with the role of machine tools in emergency situations, and include:

- The Industrial Preparedness Agency, DOD
- The Defense Industrial Production Equipment Center (DIPEC), DOD
- Industrial Defense and Production Security, DOD
- The Office of Industrial Mobilization (OIM), Department of Commerce.

We will concentrate on the types of machine tools these agencies consider to be important for postattack recovery, as well as for mobilization and defense. Some factors involved in selecting a machine for the critical list are:

- Availability, the lead time required to procure or replace a machine under normal circumstances. Some large or complex machines have lead times of 2 or 3 years.
- General utility. This emphasis is on basic machines that can be used to make a variety of items including other machines. Specialty machines that make only one item are usually of secondary concern.
- Major production machines (SIC* 3541, metal cutting types, and 3542, metal forming types) usually costing more than $25,000.
- Tools used in finishing operations, such as turning, boring, or milling tools, versus saws or cut-off tools used in the first step to obtain the rough material.
- Numerically controlled (N/C) or other forms of automatic machinery. OIM is particularly interested in N/C machines because one of these devices can replace three shifts of skilled machinists on manual machines. Also, one semiskilled caretaker machinist can keep several N/C machines operating. The availability of skilled labor would be of concern in the recovery from a nuclear incident.

These factors also influence the routine selection and utilization of machine tools; consequently, the current demand for and inventory of these tools provide additional guidance for incorporation in the critical list. For example, DIPEC does not select tools to be procured for the DOD inventory but determines which tools obtained on government contract should be retained. Under the defense mobilization requirements, DIPEC compares current machine tool usage to the peak requirements during the Southeast Asia episode and tries to stock the difference. This inventory includes three groups of machine tools:

---

*SIC = Standard Industrial Classification, Office of Statistical Standards, U.S. Bureau of the Budget

- Plant equipment packages (PEP), which include everything required to produce a particular weapon system.
- Industrial plant equipment
- Unused or underused government owned equipment in contractor plants.

### 3.2.2 How Many Tools are Involved?

The American Machinist Inventory of Metalworking Equipment published by McGraw-Hill Inc. provides the most comprehensive accounting of tools according to SIC categories, industry, and geographical location. According to the 12th inventory, the U.S. machine-tool population reached a peak of 3,810,000 in 1973 and has decreased 14% to 3,365,700 in 1978. Despite this reduction, the replacement of older tools with N/C and other automatic machines has permitted a substantial growth in the production index during this same 5-year period. About 76% of these tools are in the metal cutting category (SIC 3541) and 24.4% are metal forming tools (SIC 3542). Tools owned by the DOD total 104,107 or about 3% of the country's total. About 82% of the DOD-owned machines are of the metal cutting variety.

Many of these 3.4 million machines do not meet the criteria for critical machines, but the specific number is not available from the census. Recently, the survey began including information on machine size. For example, the 12th survey records lathes according to size, and about 30% of these are bench lathes or have swings of less than 8 inches. If a similar fraction of other tools miss the critical list because of size, age, or degree of specialization, about 40 to 50% or 1.5 million machines might be considered as vital.

### 3.2.3 Where are the Machines Located?

Determining the location of critical machines subject to fire damage requires certain information: (1) the geographical location particularly, with respect to potential nuclear targets and (2) the industry's size and products, i.e., factors that signal some information about the combustibility of the tool's environment. Figure 3-1 shows the location

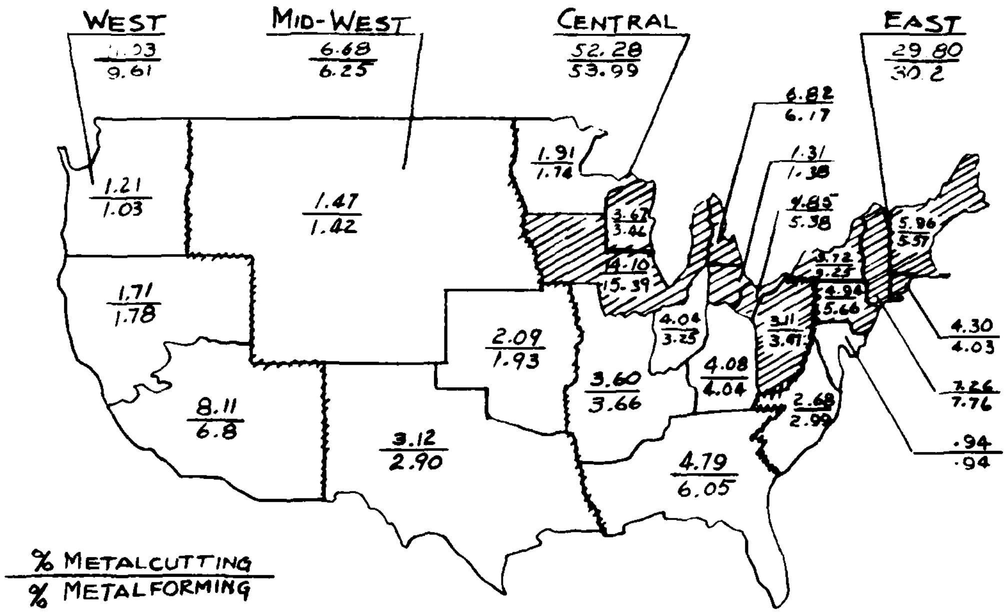


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FIGURE 3-1 LOCATION OF METAL CUTTING AND METAL FORMING MACHINES of metal cutting and metal forming machines as given in the 12th American Machinist Inventory. More than 80% of the machines are in the central and eastern part of the country and 60% are located in the small shaded area that includes New England and the states bordering the Great Lakes. The area dominated by Chicago contributes the largest fraction, namely about 15%. Thus, the design and construction of industrial buildings in the Northeast part of the country are most pertinent to estimates of potential machine losses due to fire.

Information about plant size and the combustibility of their products is even more indirect. The 12th American Machinist Inventory lists the number of plants in the various industrial categories as shown in Table 3-1. An indication of average plant size and machinery count can be estimated from the average number of employees per plant. Table 3-1 also shows the percentage of plants and employees in each category. Presumably, the major machines will be used in SIC categories 33 through 37, which contain about 89% of the industrial plants and employees.

Table 3-1

NUMBER OF PLANTS AND PLANT SIZE FOR VARIOUS INDUSTRIES

| SIC | Industry | Ave. No of Employees Per Plant | Plant % of Total Industry | Employee % of Total Industry |
|---|---|---|---|---|
| 25 | Metal furniture and fixtures | 185 | 1.8 | 1.3 |
| 33 | Primary Metals industry | 312 | 10.2 | 12.8 |
| 34 | Fabricated metal products | 153 | 26.4 | 16.3 |
| 35 | Machinery except electrical | 178 | 31.7 | 22.8 |
| 36 | Electrical machinery & equipment | 358 | 13.2 | 19.1 |
| 37 | Transportation equipment | 283 | 6.5 | 19.3 |
| 38 | Misc. manufacturing industries | 154 | 4.2 | 2.6 |

### 3.3 Nature of Fire Damage

Fire damage to machines can be divided into four categories:

- Destruction or combustion
- Heat distortion of the main framework
- Mechanical damage from falling building components
- Corrosion of metal surfaces from exposure to the weather or from fire fighting agents.

Peripheral damage such as the loss of electrical motors, hydraulic lines, gauges, and control handles usually can be repaired locally and in the past has not caused vital machines to be removed from production for long periods. However, the steady increase in the number of N/C machines has increased the potential for and seriousness of peripheral damage. As the guiding computers and the associated interfacing controls become more complex, longer times will be required to recover from this peripheral damage, although the main body of the machine may still be usable. When intense heat persists for long times, such as when red hot coals bury the main framework, annealing and creep can destroy the alignment and thereby much if not all the utility of the main structure. Traditionally, the massive structural members have been cast from gray iron or steel. A modern trend in machine design employs more structures welded together from constructional steels. These welded structures achieve higher strength-to-weight ratios than similar cast structures, but the reduced mass reduces the heat capacity and the thermal insult that can be tolerated before destruction temperatures are reached. Normally, a thermal insult is described by the temporal and spatial history of the incident heat flux; intensity, duration, and distribution all are important facets of the description. The response of a heated piece of iron or steel in terms of creep or deformation also involves three factors, namely, temperature, time, and stress. Time appears in both the insult and the response, and temperature will be related to intensity; therefore, these parameters provide a starting point for estimating the damage potential of a fire.

Fire durations depend on both the fuel loading and the ventilation, the total heat release is fixed by the fuel loading and the intensity will be controlled by the burning rate, which in turn is a complex function of fuel type distribution and ventilation. If the fuel is class B, which includes hydraulic oils and cutting oils, the fire can develop quickly and be very intense as long as the fuel lasts. Normally, however, the limited quantity of oil prevents a long-lasting fire (e.g., small fractions of an hour). On the other hand, class A fuels in the form of building structural members typically burn for the better part of an hour and the coals may remain hot for several hours if properly insulated. Thermal capacity could protect heavy structural members from the short class-B fire, but the time/temperature relationship for annealing and creep will have to be examined in more detail to predict the consequences of exposure to the class-A fire. For example, the creep rate for gray iron at 480°C is sufficient to cause warpage and other dimensional changes in less than 2 hours. Because only a small percentage of castings are stress-relieved before machining, the internal stress can produce distortions even in the absence of substantial external forces. Some gray iron parts are hardened by rapid cooling or quenching. When temperatures of such pieces reach the range of 600 to 760°C, permanent softening occurs and the temper is lost. Whereas gray iron is commonly used in metal cutting machines, cast steel is more apt to appear in metal forming machines where strength and dimensional stability are very important. Consequently, such steel parts are usually annealed and dimensional changes in a fire are minimal until temperatures are high enough e.g., around 500°C) to cause creep. With structural steels, the residual stresses are high and annealing temperatures could cause significant distortion as the residual stresses are relieved. In typical steels, the tensile strength is reduced to about half the room temperature value at 566°C; consequently, creep due to both internal and external stress should become a problem in this temperature range for lengthy exposures. An obvious countermeasure--one that was employed during World War II--is to limit the fuel loading so any fire duration cannot maintain the annealing and creep temperatures long enough to seriously damage the machinery.

The third damage category namely, mechanical damage due to fire initiated building collapse involves rather special conditions for a nuclear blast environment. Presumably, such losses could occur only beyond the range of serious blast damage to the structure, for example, beyond the 3 to 5 psi overpressures and inside the range for insignificant ignitions. The potential for this type of damage will be examined next in the Hiroshima and Nagasaki survey reports.

The final category of damage, corrosion from exposure to the elements and fire suppression agents, is a slow acting mechanism that can occur only when no timely postattack recovery occurs to protect the equipment. Obviously, some corrosion can be tolerated before the problem becomes serious.

## 3.4 Japanese World War II Machine Tool Losses

### 3.4.1 Hiroshima

The "U.S. Strategic Bombing Survey" covers the machine tool damage observed in 19 one-story buildings scattered throughout the target area as shown in Figure 3-2. Four buildings were outside the burned-over area indicated by the dotted line. Twelve buildings sustained 100% structural damage and 19 buildings were considered to be combustible. The survey divides the types of building into three categories: (11) wood frame, (5) steel frame and (3) load bearing brick wall structures. This list includes all of the unburned wood-framed machine shops, all steel-framed shops, all load-bearing brick wall shops within the blast-affected area in addition to a few typical wood frame shops that did burn. No multistory or reinforced concrete machine shops were in the area.

Table 3-2 reproduces the machine tool data summary table from the "U.S. Strategic Bombing Survey." A column of overpressures has been added to augment the distances from the burst. In general, most of the initial structural damage was caused by blast while fires caused most of the machinery damage. When buildings destroyed by blast subsequently burned, they were listed in the blast category. All the serious damage to machines attributed to blast was caused by debris and this was a small percentage of the total damage. For example, in the 19 buildings

*See Reference 19, Chapter 2.

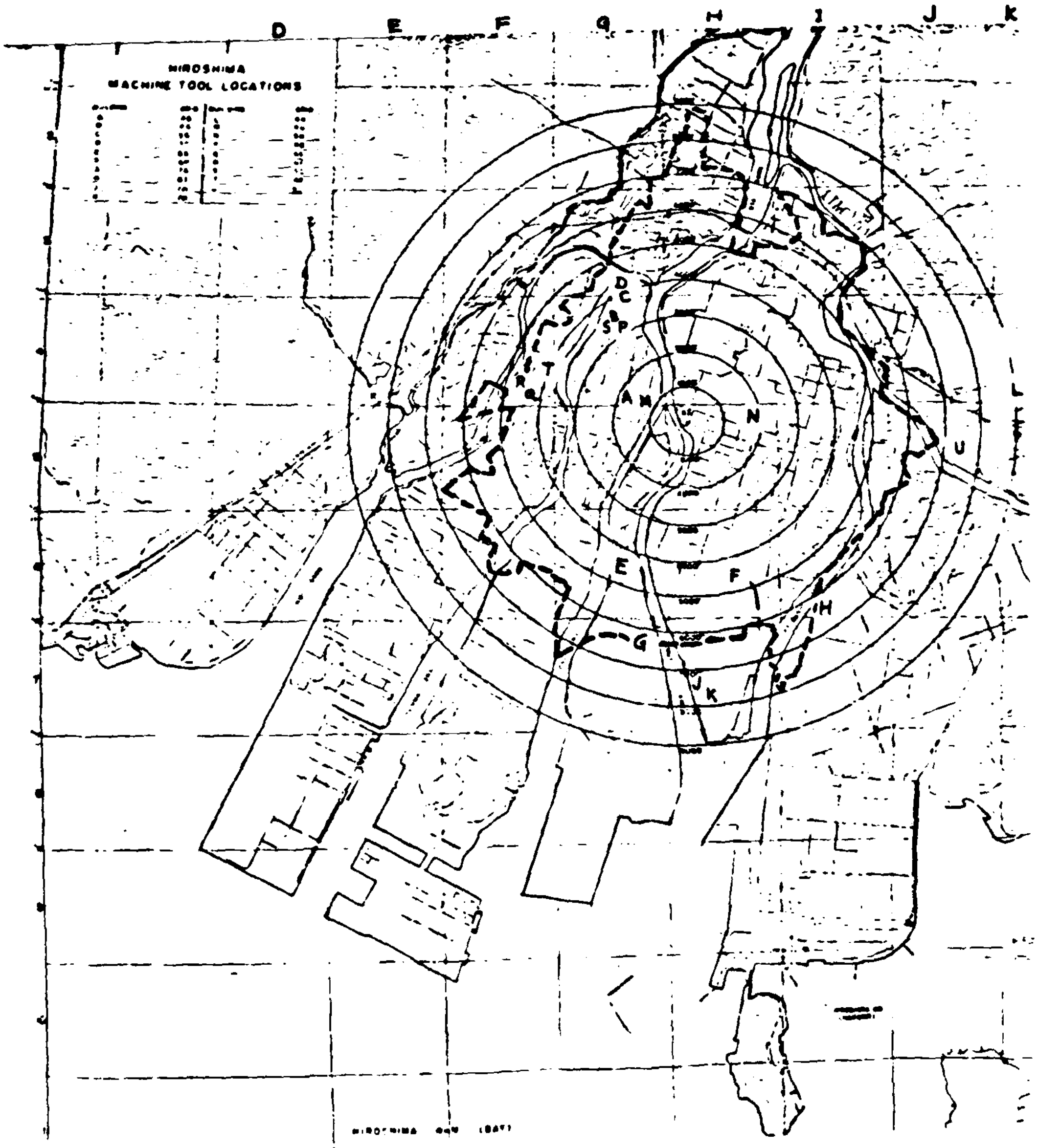


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FIGURE 3-2 MACHINE TOOL LOCATIONS IN HIROSHIMA SHOWING PERIMETER OF FIRE AREA

Table 3-2

CAUSES OF INDUSTRIAL DAMAGE IN HIROSHIMA

| Building Designation | Distance from Gz (ft) | Estimated Overpressure (psi) | Class of Structure | Building Damage (%) Due to Blast | Building Damage (%) Due to Fire | Machine Tool Damage (%) Due to Debris TD | Due to Debris HD | Due to Debris SD | Due to Fire* TD | Due to Fire* HD | Due to Weather# SD | All Causes TD + HD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 1,600 | ∿ 13 | Wood | 100 | 0 | 15 | 0 | 10 | 70 | 15 | 0 | 100 |
| B | 3,400 | 10 | Wood | 100 | 0 | 0 | 10 | 5 | 60 | 30 | 0 | 100 |
| C | 4,000 | 7 | Wood | 77 | NF | 0 | 0 | 20 | - | - | 80 | 0 |
| D | 4,400 | 6 | Wood | 100 | 0 | 0 | 5 | 5 | 90 | 5 | 0 | 100 |
| E | 4,700 | 6 | Wood | 100 | 0 | 0 | 0 | 15 | 65 | 35 | 0 | 100 |
| F | 4,900 | 6 | Wood | 100 | 0 | 0 | 0 | 10 | 80 | 20 | 0 | 100 |
| G | 6,000 | 4 | Wood | 100 | NF | 0 | 0 | 10 | - | | 10 | 0 |
| H | 6,500 | 4 | Wood | 100 | 0 | 0 | 15 | 5 | 65 | 20 | 0 | 100 |
| J | 7,500 | 3 | Wood | 0 | NF | 0 | 0 | 0 | | - | 25 | 0 |
| K | 7,600 | 3 | Wood | 0 | NF | 0 | 0 | 0 | | | 0 | 0 |
| L | 9,000 | 2 | Wood | 0 | 100 | 0 | 0 | 0 | 75 | 25 | 0 | 100 |
| M | 1,500 | ∿ 14 | Steel frame | 100 | 0 | 0 | 0 | 20 | 80 | 20 | 0 | 100 |
| N‡ | 1,800 | ∿ 12 | Steel frame | 100 | 0 | 0 | 0 | 0 | 0 | 100 | 0 | 100 |
| P | 3,300 | 11 | Steel frame | 0 | 0 | 0 | 0 | 0 | 40 | 60 | 0 | 100 |
| Q | 4,700 | 6 | Steel frame | 18 | NF | 0 | 0 | 0 | | | 100 | 0 |
| R | 4,700 | 6 | Steel frame | 47 | NF | 0 | 0 | 0 | | | 100 | 0 |
| S | 3,300 | 11 | Brick, load-bearing steel truss | 100 | 0 | 0 | 0 | 15 | 50 | 50 | 0 | 100 |
| T | 4,000 | 7 | Brick, load-bearing steel truss | 100 | NF | 50 | 25 | 0 | | | 25 | 75 |
| U+ | 7,500 | 3 | Brick, load-bearing steel truss | 0 | NF | 0 | 0 | 0 | | | 20 | 0 |

TD denotes such severe damage that machines were scrapped.
HD denotes sufficient damage that machines could not be repaired by normal maintenance squad.
SD denotes light enough damage that machines could be repaired by normal maintenance squad.
NF denotes no fire.

*No cases of SD
#No cases of either TD or HD
+Noncombustible structure
‡Outside the fire area.

surveyed, only 3% of the machine tools sustained serious damage from blast and debris. This small effect was attributed to the nature of the structural damage, which did not generate heavy projectiles.

Most of the wood-frame buildings had combustible roofs, floors, and walls; consequently, their collapse placed considerable debris close to the machines. Estimates of damage in the wood-frame buildings were

- 64% of total floor area of buildings was damaged by blast
- 41% of the machine tools suffered serious damage of which 3% was attributed to blast.
- Seven of the 11 buildings studied burned completely and all of their machine tools were seriously damaged

In addition to the combustible buildings and their contents, the surrounding buildings in this congested area were also burning and contributing to the general high temperature.

The text of the bombing report is not always in consonance with the numbers in Table 3-2 but such discrepancies do not alter the conclusions. In the steel-framed buildings, "Fire caused all serious damage to machine tools in the five buildings. Three of these buildings including the noncombustible one were completely burned out." Serious fire damage occurred because the floors, walls and roof sheathing, and some contents were combustible. About 28% of the machine tools were seriously damaged and a similar fraction of the total floor area was involved in the fire. Apparently, blast damage was not serious because "the blast caused mass distortion of the steel frame without tearing loose heavy structural members." Debris from the walls and roofs was light and caused only slight damage.

Table 3-2 shows that of the three load-bearing, brick-walled buildings, only the one closest to ground zero experienced a fire and it was burned out completely. Building U was outside of the fire area as shown on Figure 3-2. Again, the fire damage resulted from combustible roof sheathing and contents in the vicinity of the machine tools.

In assessing the machine tool damage in Hiroshima, several features of the city and the attack deserve notice:

- Hiroshima was a poor example to evaluate atomic bomb damage to machine tools because of the low concentration of such tools in the direct effects area. The bomb was detonated near the center of the city and all large industrial plants were located on the outskirts beyond the range of either blast or fire damage. No sizable industries were within 1½ miles of ground zero. Several conditions combined to favor a mass fire in Hiroshima. There were many combustible buildings crowded close together. The weather had been dry, precautionary measures such as fire shutters and doors were destroyed by the blast, and the public fire department was decimated by the blast.

- The fire behavior as reported by eyewitnesses was as follows:
  - Hundreds of fires started almost simultaneously within 10 minutes of the detonation.
  - Numerous fires were a direct consequence of radiant heat from the bomb, but the majority of the ignitions were from secondary sources (e.g., industrial processes, electrical shorts, kitchen charcoal).
  - A large proportion of the burned-out area resulted from the merging and spreading of fires.
  - About 20 to 30 minutes after the explosion, a noticeable "fire wind" developed in the direction toward ground zero during this time, individual fires apparently spread in all directions.
  - The fire wind reached its maximum about 2 to 3 hours after the explosion, suggesting that the maximum burning rate had been reached. After about 6 hours, the wind had decreased to light or moderate and variable in all directions, indicating the fire had died down.
  - Fire spread to industrial buildings appeared to be only about 60% of the spread to domestic buildings; however, this difference is not statistically established since less than one third of the burned area was industrial.

### 3.4.2 Nagasaki

"Nagasaki offered an excellent opportunity to study the atomic bomb effects on machine tools, equipment and plant utilities." Within the damage range, which was 6,500 ft from ground zero, 1,830 machines and approximately 450 pieces of equipment were contained in 16 buildings grouped as follows:

| Type of Building Construction | Percent of Machines |
|---|---|
| Heavy and light-steel frame | 50 |
| Reinforced concrete | 22 |
| Wood frame | 27 |

In the steel buildings only about 3% of the machines and equipment were damaged by fire; 97% of the damage was due to blast and weather. The 22 reinforced concrete buildings less than 4,700 ft from ground zero sustained 75% structural damage by blast and 80% interior damage by fire but only 9% of the machine tools were damaged by the fires. Fourteen of the wood buildings surveyed were destroyed by blast and fire within 6,500 ft of ground zero. These structures were used for temporary auxiliary machine shops; consequently, their importance to production was relatively small. Although 95% of the machines were damaged only 10% of this damage resulted from the fires and these machines were characterized as lightweight. Altogether only 26% of the machine tools in the industrial plants were damaged by the Nagasaki atomic bombing and most of these were only slightly damaged.

### 3.4.3 General Conclusions and Recommendations of the Strategic Bombing Survey

- Atomic bomb damage to machine tools, equipment, and utilities will depend on the type of building involved and the protective measures. Almost all damage was caused by debris or heat from the burning buildings.
- Steel-frame buildings are as suitable or better than reinforced-concrete buildings for industrial purposes, provided they are of heavy column construction and the roofs and sidings are light-weight.
- Reinforced-concrete buildings should have adequate strength to withstand the blast pressures.

Furthermore, the Nagasaki results support the comment at the end of the Hiroshima study that it is doubtful that fire would have caused serious damage generally to machine tools in modern, noncombustible or fire-resistive machine shops. Therefore, the fire hazard to machine tools can be most effectively limited by installing them in fire-resistive or noncombustible buildings containing a minimum of combustible contents.

## 3.5 German World War II Losses

### 3.5.1 German Machine Tool Industry

Germany entered the war with an abundance of machine tools and the bombing of machine tool plants did not seriously affect the flow of war material. Several factors contributed to this result. First, in 1940, the German machine tool inventory exceeded that of the United States by a factor of $1\frac{1}{4}$ and the United States did not achieve equality until 1944. Second, the German preference for general purpose machines provided a flexibility that could maintain production even though some machines were damaged. This preference differed from the United States emphasis on special purpose machines designed for mass production with less skilled workmen. The loss of a few special purpose machines can readily stymie production whereas one general purpose machine can be substituted for another provided sufficient highly skilled labor is available. Third, before the war, the Germans enjoyed a large export trade in machine tools. When this trade stopped, this reserve capacity was available for internal use; consequently, the machine tool industry remained on a single shift operation throughout the war and some of the highly skilled workmen were diverted into the armed forces or other types of production. Fourth, the machine tool industry was not particularly vulnerable to bombing attack because:

- The natural dispersion or decentralization of the industry would require a great many attacks to significantly damage the overall capacity.
- Individual plants were arranged so that important machines of the same kind were scattered to prevent destruction of all machines of a particular type.
- Machine tools are very hard to destroy, particularly when protected with blast walls. Their destruction required virtually a direct hit by a 500-lb bomb.
- The high rate of recuperability of the industry would have necessitated almost constant repetition of raids.

Finally, the machine tool plants were never a specific target system; damage resulted from either area attacks or spillover from tactical attacks on other targets.

### 3.5.2 Relation of Structural Damage to Machine Damage

The damage to structures and plant facilities was generally much greater than to the contents. For example, in 17 plants investigated, plant damage averaged 30% compared to 15% for machinery damage. Only 4% of the machines were destroyed beyond practical repair. Even in cases of severe structural damage, the fraction of tools lost remained small, for example, 80% of the Collet and Engelhard buildings were damaged but only 2% of the tools. In another case, 63% of the Wanderer Werke was damaged but only 1% of the machines were destroyed. These figures include all forms of damage, namely, blast, fire, water, falling debris, and weathering.

### 3.5.3 Fire Damage

Generally, incendiary weapons were more effective than high explosive attacks on the German machine tool plants. Such features as large unpartitioned areas, high ceilings, large area windows and skylights weakened the blast effects. For example, 65 500-lb high explosive bombs dropped on the Gustloff Werke damaged 15.7% of the total inventory but only seriously damaged 7% of the machine tools. Features that made the plants vulnerable to incendiary attack were large area skylights, wood roofs, wooden flooring, and single story construction. Usually, the wood floors had absorbed inflammable oil and lubricants so that in combination with the wood roof, there was ample fuel available for fire spread. Various modes of fire damage were:

- Burned off lubricants and frozen movable parts
- Corroded and damaged accurate surfaces
- Destroyed electric motors and controls
- Warped structural members
- Loss of temper in heat-treated and hardened parts

- Melting of some nonferrous parts
- Weathering after the attack.

The Collet and Engelhard factory in Offenbach is a good example of a company whose production was practically stopped due to damage caused by area bombing. Wooden roofs and floors made the buildings very vulnerable to the 500 incendiaries dropped during the second raid. An estimated 75% of the buildings were destroyed, 50% from fire and 25% from high explosives. However, only 12% of the machine tools were destroyed or severely damaged. Complete destruction of the plant's foundry ultimately terminated machine tool production when the castings on hand were used up, but other machinery operations continued. One of the Naxos-Union plants at Frankfurt am Main demonstrated the effectiveness of fire-proof construction against incendiary attacks. Several of the wood-framed structures were completely gutted by fires that also destroyed everything inside; however, the incendiary bombs that penetrated the fire-proof building burned themselves without damaging the machines.

Generally, the German experience agrees with the observations in Japan and elsewhere; namely, that in the absence of a fire, it is very difficult to damage machine tools severely by blast, although severe fires can bring operations to a halt.

### 3.6 The Great Livonia Fire, A Peacetime Example

One of the greatest industrial fires of all times occurred on August 12, 1953 when the $35 million General Motor's transmission factory burned. At 3:50 PM, sparks from an oxy-acetylene cutting torch ignited flammable liquid in a 120 ft long drip pan. Despite immediate action by the fire watch and welding crew, the flames spread to the tar and gravel roof and to the wood block floor. All efforts by the plant and professional firemen failed to stem the fire spread, and about 12 hours later, the fire burned itself out leaving the 34.5-acre "noncombustible" factory a twisted mess of collapsed girders, roofing panels, and walls.

Several fuels contributed to the fire. After burning for about 5 minutes, the fire warped the drip pan allowing flaming oil to drop to the creosoted, oil-soaked wood block floor, which ignited immediately. As heat built up under the roof, the condensed oil on the steel trusses and roof ignited, adding additional heat. Shortly, the roof sheathing began to warp allowing molten tar and asphalt to drip through the cracks. Altogether the roof contributed about 2,000 tons of tar and asphalt to the fire. When the fire reached the 450-gallon dip tank of rust inhibiting liquid, the plant firefighters gave up their efforts to control the flames with $CO_2$ extinguishers and evacuated the building. Other tanks and barrels contributed several thousand gallons of flammable liquids to the fire.

About 6 minutes into the fire, major electrical circuits were interrupted, lights went out, the exhaust fans stopped and smoke particles from the burning floor began to fill the building. In retrospect, it appears that the Livonia plant was lost from this time on. When the professional firemen arrived 10 minutes after ignition, the dense smoke and heat kept the firemen from entering the building although less than 1% of the floor area was actively involved in flames. External suppression efforts were relatively ineffective because the dimensions of the building far exceeded the reach of hose streams. By the time the fire reached the shipping department and storage areas protected by 3,740 automatic sprinklers, the intensity overwhelmed the sprinklers and those parts of the building were also destroyed. Fire spread was not particularly rapid but the trapped heat and interaction between the burning roof and floor kept the flames moving from the point of ignition until the entire structure was involved. Essentially, all of the roof collapsed but it did not always reach the floor and the burn pattern of the wood block floor was not uniform. There were many burned spots but the entire floor was not consumed.

When the fire started, the plant contained about 11,000 employees, 3,310 machines, 25,000 motors to power the machines, and numerous Defense Department machines. All but three of the employees escaped. In a massive effort employing the considerable resources of GM and their suppliers, 73% of the machines were salvaged, 27% were replaced, the plant was moved to Willow Run, and transmissions were in production within about 4 months from the fire. Percentagewise the 900 machines junked is comparable to the Nagasaki losses to the atomic bomb, but considerably more than the German factory losses due to conventional bombing raids in World War II.

As a result of the Livonia fire, plant designs and building codes were examined in efforts to prevent such fire damage in the future. Improvements have been made, but many of these earlier factories still exist, with a potential for comparable losses in the event of uncontrolled fires. Consequently, estimates of 25 to 30% machine losses in fallen burned out factories are not unreasonable for such serious cases. A few simple precautions could substantially reduce these losses.

### 3.7 Nuclear Tests of Blast Effects on Industrial Buildings and Machinery

During the Nevada and Pacific tests of 1953, 1955, and 1956, various industrial type buildings and machine tools were exposed to peak overpressures in the range from 1.1 to 10 psi. Fires were avoided by limiting the industrial structures to the noncombustible types, such as steel-framed buildings sheathed with sheet metal or asbestos cement panels and self-framing steel structures. The damage observed was less than the Japanese experience because there were no fires and the total amount of debris was probably less than in an operating factory. Also, there was no weather exposure damage. Some pertinent observations are as follows:

- Effect of overpressures from 16- and 26-KT weapons on damage to various structure types
  - Rigid steel frame, with an aluminum sheet roof and wall panels, are repairable for pressures up to about 1 psi. At 3.1 psi, many aluminum panels were blown away and the steel frame was severely distorted
  - Self-framing buildings with light channel-shaped steel panels were repairable for exposures to 3/4 to 1 psi At 3.1 psi, the roof collapsed onto the machinery located inside the building. The structure was completely collapsed and destroyed.

- Self framing with 16 gauge-corrugated steel panels were repairable for pressures below about 3 psi. Some buckling occurred but the building was usable, and the contents were not damaged.

- Effect of positive-phase duration on structural damage. Several identical steel frame buildings were exposed to similar overpressures but different phase durations at Nevada and Eniwetok tests:

| Test Site | Yield | Overpressure (psi) | Pressure Duration | Construction Type |
|---|---|---|---|---|
| Nevada | KT | 6.5 | .9 sec | Frangible roof and siding |
| Nevada | KT | 3.5 | 1 sec | Concrete siding |
| Eniwetok | MT | 6.1 | Several seconds | Frangible roof and siding |
| Eniwetok | MT | 5 | Several seconds | Concrete siding |

In the Nevada tests the frangible roof and walls were completely blown away but the framework remained standing though substantially damaged and the concrete siding building suffered little damage. At the longer phase durations both structures suffered complete collapse.

- Damage to machines versus machine size and blast overpressure. Heavy duty machines can survive overpressures up to 10 psi without substantial damage, although debris and missiles can destroy the delicate mechanisms and appendages. For example, in a Nevada test lathes weighing 12,000 and 7,000 lb and milling machines weighing 10,000 and 7,000 lb were mounted in typical shop fashion on a concrete slab behind a concrete block wall at the 10-ssi overpressure station. The large lathe survived with only superficial damage but the three smaller machines were overturned and seriously damaged. A vertical mill weighing about 3,000 lb and an oven survived the collapse of the self-framed corrugated steel building with only minor damage from a 3-psi overpressure. Finally, a hydraulic press weighing 49,000 lb was located at the 5 psi position behind a brick house. This unit received only minor debris damage from the totally demolished house.

Such results suggest that the doughnut shaped area of concern for machine tool survival extends from the 1-psi isobaric line in toward ground zero to at least the 10 psi region. Beyond the 1 psi region, the buildings should survive structurally and the potential for fires is small. The 10-psi limit is more a limit to observations rather than a survival limit.

### 3.8 Prediction Procedure (Model) for Machine Tool Survival

The procedure set forth below is designed to accomplish two functions:

- Provide a general estimate of the national machine tool losses under a given attack scenario.
- Give specific guidance for local action to minimize the mach'ne tool damage.

Two approaches--one specific and the other general--can be used to estimate machine tool survivability. The specific approach would be similar to the Five City Study in that specific cities would be examined to determine (1) the number of industrial buildings of various types, (2) their locations and (3) their immediate environment. Attention would be limited to the classes of industries that employ the machine tools of interest; therefore, the fraction of a city's structures involved would probably be less than 1%. Total losses would be obtained by extrapolating from the population of machine tools in the study to the total machine tool inventory in the country.

In the second approach, a hypothetical city would be derived containing industrial buildings and machines in proportion to the population of each particular type in the country. After exercising the attack scenario on this average hypothetical city, the model would extrapolate the damage nationwide again on the basis of population.

Figure 3-3 outlines the procedure, which is independent of the approach ultimately selected. The first step is to determine the fire hazard of the machine's environment, i.e., the fuel loading. For situations where the fuel loading is too light to create a serious threat, the analysis can stop and only the moderate and severe cases would be continued to the next step. $P_1$ is defined as the probability of continuing on to step 2. The second step is also concerned with the fire threat but this time the question is whether the fuel is located where

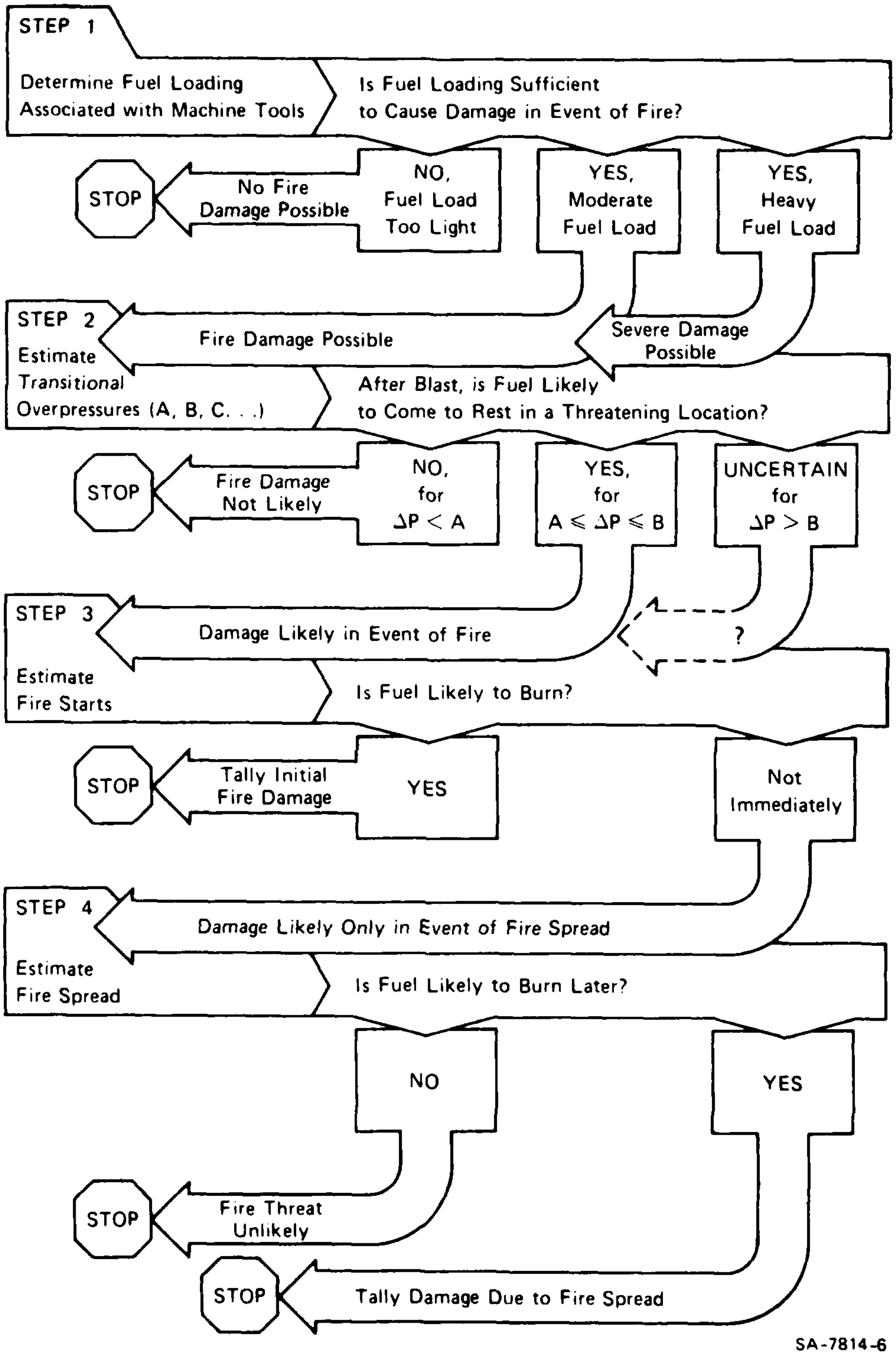


FIGURE 3-3 POTENTIAL FOR MACHINE TOOL DAMAGE — LOGIC FLOW CHART

a fire could damage the machines. For example, if the fuel were primarily in the roof structure and the roof remained in position after the blast, most of the heat would be liberated before the roof collapsed and brought the fire to the machines. Based on a blast analysis, the probability, ($P_2$), of going to step 3 is evaluated.

Step 3 evaluates the probability of ignition $P_3$ by any of the alternate paths--primary, secondary, or fire spread. Since the question of ignition is probably the most difficult to answer reliably, the order of progression through the steps has been selected to minimize the number of cases to be treated. Finally, the probability for damage (P) is equal to $P_1P_2P_3$. The following information is required to proceed through the analysis:

1. Typical fuel loadings versus the type of structure and occupancy.
2. Degree of collapse for these industrial type structures versus shock overpressure. Referring to the damage levels in the Asilomar 78 report,* only 4, 5, and 6 are of interest.
3. The inventory of fine fuels required for radiant ignition as function of structural type and occupancy.
4. The presence of secondary ignition sources as function of occupancy.
5. A better determination of the fuel loadings required to damage machine tools.
6. Distance beyond which neighboring buildings can be neglected both from their potential to contribute to the fuel loading and as an ignition source by fire spread.

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*Blast/Fire Interactions, Program Formulation, DCPA Work Unit No. 2563D, October 1978.

# 4. ADVANCED PLANNING FOR LARGE SCALE FIELD TESTS--IGNITION THRESHOLDS OF LARGE AND COMPLEX FUEL ARRAYS DETERMINED WITH LARGE-SCALE THERMAL RADIATION SOURCE AT KIRTLAND AIR FORCE BASE*

## 4.1 Introduction

This task is designed to keep track of field test potentials and how participation in such tests could benefit the FEMA blast/fire program. The programs outlined in References 1 and 2 envision a verification of the theoretical and small-scale experimental results through large-scale field tests; therefore, the program contains a variety of full-scale test options. Dedicated field tests can be very expensive; consequently, the economics of such tests usually dictate a cooperative or piggy back effort. Situations of particular interest include:

- Large area thermal sources suitable for simulating the thermal pulse from a nuclear weapons, e.g., the DNA Thermal Radiation Sources (TRS), using combustion of alumirum powder with oxygen.
- Large explosive tests, such as the Misty Castle series, (e.g., the MILL RACE event scheduled for October 1981) which are suitable for blast/fire interactio observations.
- Large area burns involving structures suitable for fire spread measurements particularly in damaged buildings or debris piles; e.g., the burns in Downtown Burbank, California and the possibilities at Lark, Utah.

The principal FY79 activity involved ignition measurements with the DNA Thermal Radiation Source at Kirtland AFB. This effort was in cooperation with the Los Alamos Technical Associates, Inc. who conducted the field tests. Our participation involved assistance in designing the tests and interpreting the results. This chapter summarizes the objectives and accomplishments of the ignition tests conducted on 11 and 13 July 1979.

*Substantial portions of this chapter were provided by Peter Hughes of Los Alamos Technical Associates (LATA) who was responsible for the conduct of the tests.

### 4.2 Background

During the March 79 Asilomar Conference on blast/fire interactions, Workshop 1 suggested a program "Ignition Thresholds of Fuel Arrays of Practical Size and Complexity." "The objective is to determine the thresholds for sustained ignition due to exposure of modern furnishings, in their in-use configurations, and similar large-area fuel arrays to the thermal radiation from nuclear detonations." Three aspects of the fuel and its environment were of particular concern:

1) Fuel size effects, particularly the potential for thermal reinforcement with tall specimens.
2) Geometrical factors that provide thermal reinforcement; e.g., cracks and interior corners.
3) Combination fuel effects, i.e., situations where the transient ignition of heavy fuels may be converted to sustained combustion by the thermal contribution from readily ignited fine fuels.

In the recommended program this effort was suggested for initiation in FY81 when the procurement of a suitable large area thermal source would become one of the first orders of business. When access to an 800 $ft^2$ source with fluence levels up to 25 cal $cm^{-2}$ became available through some DNA FY79 tests at Kirtland AFB, it appeared desirable to participate with some preliminary ignition tests. The goals were to:

- Gain experience and data with the DNA ALOX/TRES which (1) is one of the chief contenders among the large area sources and (2) will probably be used in some of the MILL RACE experiments.
- Evaluate the suitability of the TRES source for ignition tests.
- Test our ability to predict ignition thresholds.

### 4.3 Description of the TRS

The Thermal Radiation Source (TRS) at Kirtland AFB provides the facilities for testing materials at macroscopic levels. Specimen sizes may be very large; for example, 60 ft long and 30 ft high with a "depth of field" of more than a foot. Figure 4-1 shows a plan view calibration

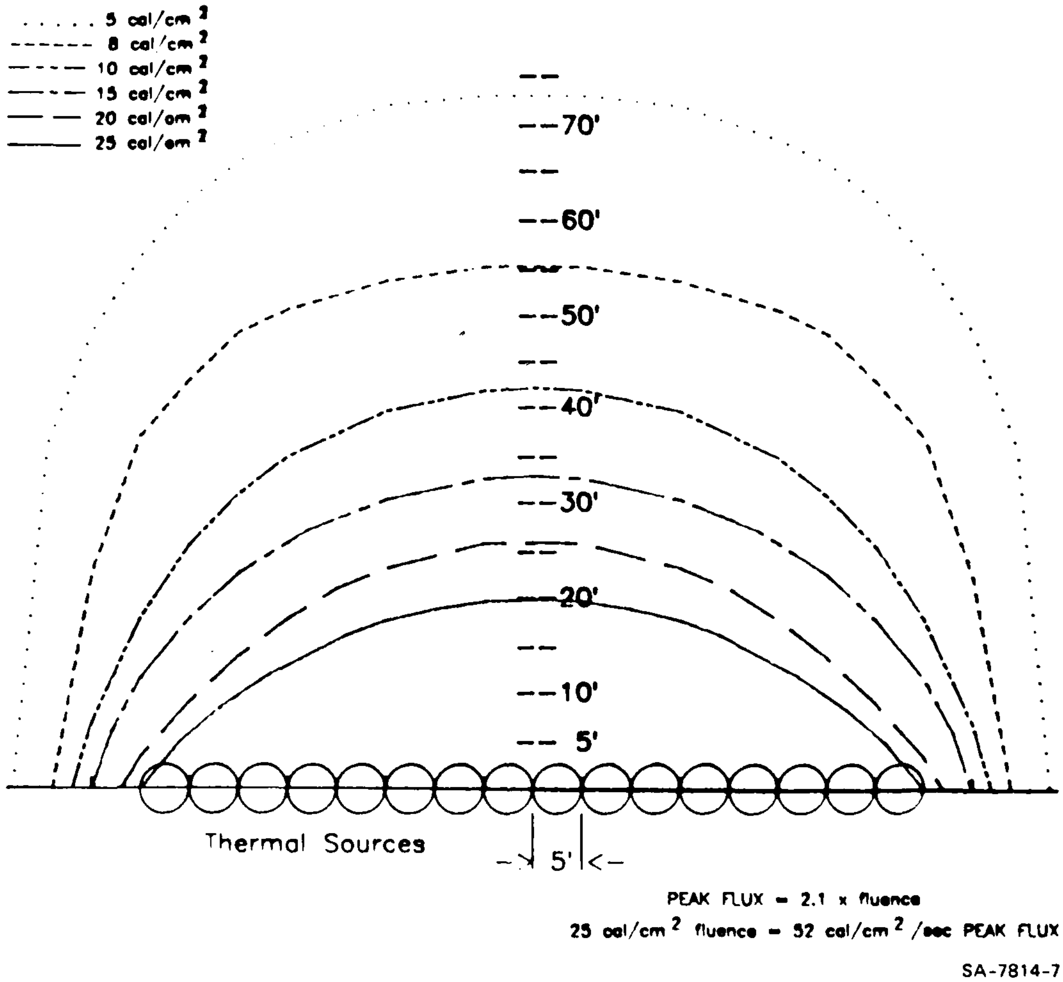



FIGURE 4-1 TRS SITE CALIBRATION

for one side of the TRS. The test bed is symmetrical with the iso-fluence contours identical to that shown in Figure 4-1 for specimens located on both sides of the thermal sources.

The thermal sources are 20-ft-high plastic bags inflated with oxygen. At shot time, aluminum is sprayed into the bags and the mixture is ignited. The resulting flash is a few seconds in duration with a maximum temperature of about 3,300°K. Figure 4-2 shows photos of a flash sequence.

The facility itself is in an arid region with favorable wind conditions. It is bordered on three sides by mountains, providing protection from wind, high-frequency electromagnetic noise, and casual observation.

The area immediately surrounding the thermal source is leveled and configured for quick experimental setup, easy data acquisition and about 36-hour turnaround between shots. In addition, the test area is only 10 miles from metropolitan Albuquerque and about 15 miles from the Albuquerque International Airport.

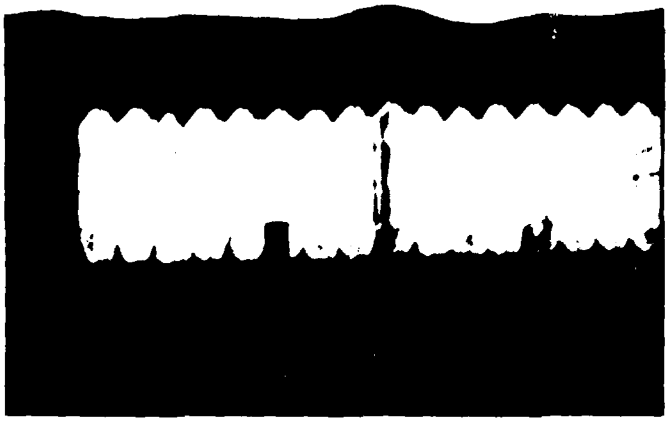
Numerous tests have been conducted at the TRS, resulting in improved simulation methods, improved turnaround, and additional equipment.

## 4.4 Test Approach

Test specimens and exposure conditions were selected on the basis of the following constraints and requirements:

- The maximum anticipated thermal fluence of 25 cal $cm^{-2}$ limited the choice of ignition samples to light weight materials such as fabrics, papers, and sheet plastics.
- For prediction purposes, materials were selected because ignition data had been obtained for them in previous laboratory or field tests.
- The samples should be appropriate for each of the three areas of concern outlined by Workshop 1.
- The costs of the samples and the tests should be appropriate for a "shoe string" operations.

References 3 and 5 provided the ignition data used to select the specimen materials and geometries for the tests. Table 4-1 lists pertinent ignition thresholds obtained from these references.



Ignition

Maximum
Flux

Fireball
Rise

SA-7814-8

FIGURE 4-2 TRS FLASH SEQUENCE

Table 4-1

IGNITION THRESHOLDS

| Material | Ignition-Threshold Fluence Values (in cal cm$^{-2}$) for Various Weapon Yields | | |
|---|---|---|---|
| From Ref. 3 | 35 KT | 1.4 MT | 20 MT |
| Black rayon | 9 | 14 | 21 |
| Black cotton | 10 | 15 | 21 |
| News print (text area) | 6 | 8 | 15 |
| From Ref. 4 | Time to second thermal MAX = 0.3 sec | | |
| 9.5 oz Black cotton sateen | ~ 12 | | |
| 1.8 oz Black cotton sateen | ~ 3.5 | | |
| News print (classified section) single sheet | 9 | | |
| News print (classified section) double sheet | 5.5 | | |
| From Ref. 5 | Peak flux = 2.8 cal cm$^{-2}$ sec$^{-1}$ | | |
| Black rayon on cotton batting | 22.7 | | |

From the values in Table 4-1 a fluence range from 10 to 25 cal $cm^{-2}$ appeared adequate for typical cotton cloth samples; therefore, a supply of nominal 10 and 4 oz black cotton cloth was procured for the tests. Table 4-2 lists the ignition thresholds observed with these materials when exposed at various flux levels to a tungsten iodine quartz lamp bank.

These single sample observations are in general agreement with previous laboratory tests. The measured cloth weights were 310 g $m^{-2}$ and 146 g $m^{-2}$ for the heavy and light cloth, respectively. Test stations were located at 5 cal $cm^{-2}$ intervals, between fluences of 10 to 25 cal $cm^{-2}$ in Test 1 and 5 to 25 cal $cm^{-2}$ in Test 1A.

Figure 4.3 shows the following sample configurations, dimensions, and method of construction:

- (#1) 2 ft x 8 ft long sample to check for thermal reinforcement in the vertical direction. All samples were 10 oz cotton except at the 10 and 15 cal $cm^{-2}$ stations in Test 1 where 4 oz materials were used.
- (#2 ≡ 10 oz and #3 ≡ 4 oz) 6 in. x 6 in. square samples like some used in Reference 4. A light and heavy weight sample was installed at each station.
- (#4 ≡ 10 oz and #5 ≡ 4 oz) right angle samples with a corner crease to enhance thermal reinforcement. A light and heavy weight sample was installed at each station.
- (#6 ≡ Mixed fuels) A combination of newspaper, pine boards, and gypsum board to simulate a debris pile. The arrangement was designed so that papers ignited with a match would not burn all the wood, i.e., some thermal energy had to be applied to the wood for complete combustion.

Figure 4-4 shows the location of the samples on the support framework at each station. All samples were above the 10 ft elevation to avoid casting shadows on the DNA test articles. A completed test stand is shown in the photograph (Figure 4-5).

Table 4-2

IGNITION THRESHOLDS FOR VARIOUS SAMPLES AND EXPOSURE CONDITIONS

| Material | Flux ($cal\ cm^{-2}\ sec^{-1}$) | Time to Ignition (sec) | Fluence at Ignition ($cal\ cm^{-2}$) |
|---|---|---|---|
| 4 oz black cotton over 1" cotton batting | 2.78 | 6.1 | 17 |
| 10 oz black cotton over 1" cotton batting | 2.78 | 10.4 | 29 |
| 4 oz black cotton over 1" cotton batting | 2.28 | 8.7 | 20 |
| 10 oz black cotton over 1" cotton batting | 2.28 | 20 | 46 |
| 4 oz black cotton over 1" cotton batting | 1.96 | No flame--Pyrolysis and Glowing | |
| 10 oz black cotton over 1" cotton batting | 1.63 | No flame--Pyrolysis and Glowing | |
| 4 oz black cotton over 1" cotton batting | 1.63 | No flame--Pyrolysis and Glowing | |
| 4 oz black cotton over 2" cotton batting | 1.63 | No flame--Pyrolysis and Glowing | |
| 4.1 mill back α cellulose #4090 | 1.63 | 3.7 | 6.1 |
| 30 mill black α cellulose #4104 | 1.63 | 11.9 | 19.4 |
| 4.1 mill paper + 1" cotton batting #4090 | 1.63 | 3.6 | 5.9 |
| Newspaper (classified) | 1.63 | 5.5 | 8.9 |

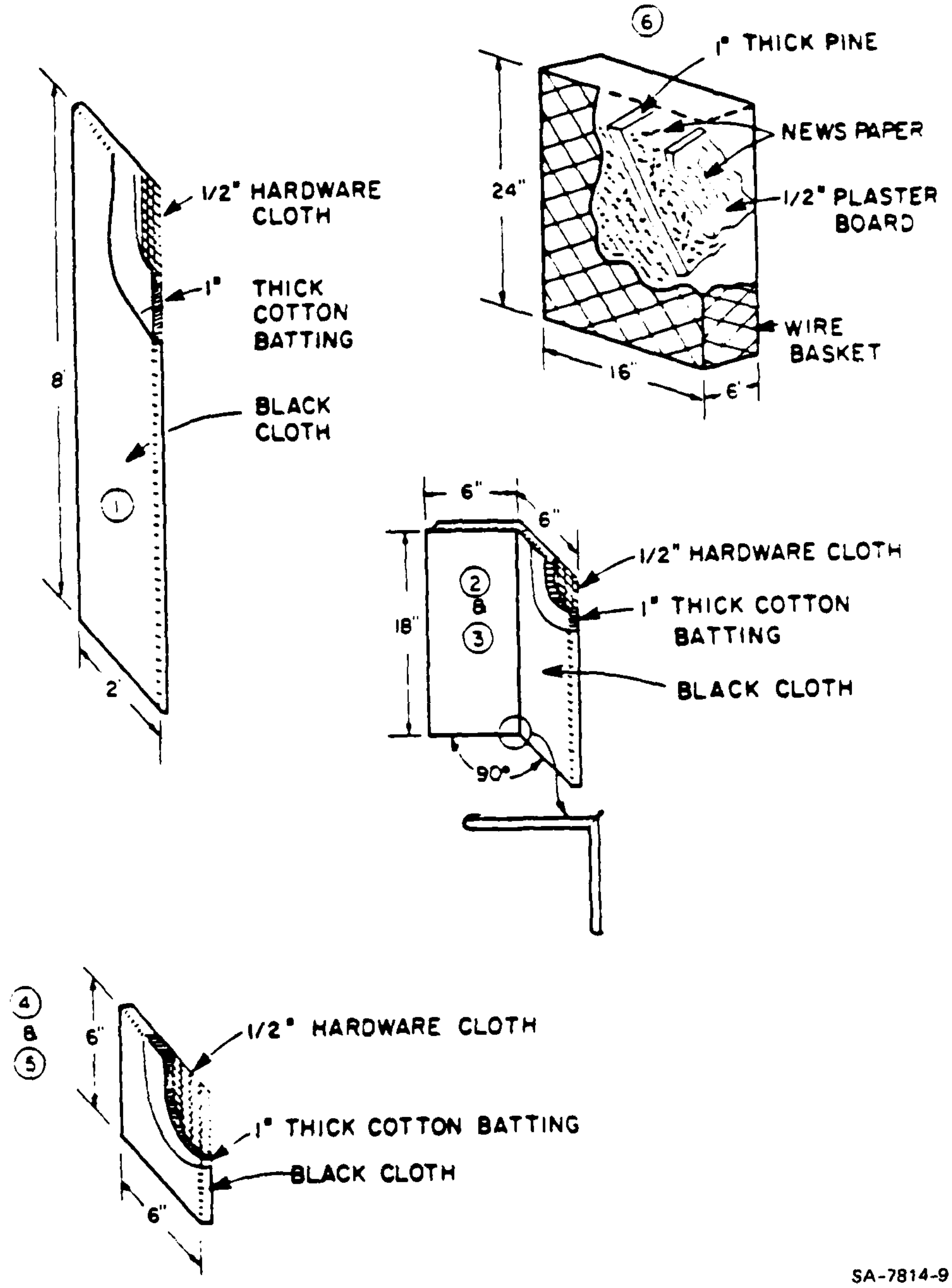
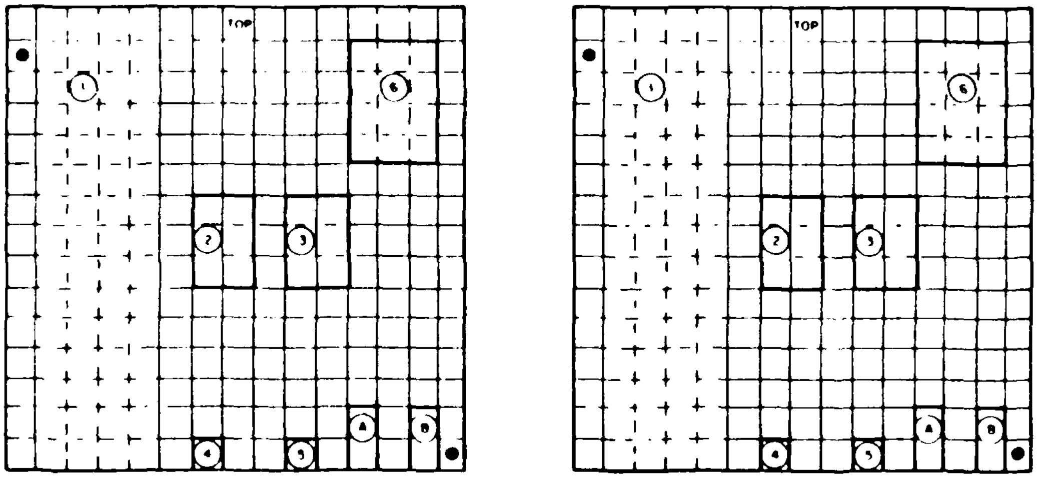



FIGURE 4-3 TEST MATERIALS




Stations 3 and 4 — Scale 6 in. per square — Stations 1 and 2

Stations 3 and 4:

1 Heavy Cloth
2 Heavy Cloth (Corner)
3 Light Cloth (Corner)
4 Heavy Cloth
5 Light Cloth
6 Debris Pile Holder
A Wood - Series A
B Wood - Series B
● Calorimeters

Stations 1 and 2:

1 Light Cloth
2 Heavy Cloth (Corner)
3 Light Cloth (Corner)
4 Heavy Cloth
5 Light Cloth
6 Debris Pile Holder
A Wood - Series A
B Wood - Series B
● Calorimeters

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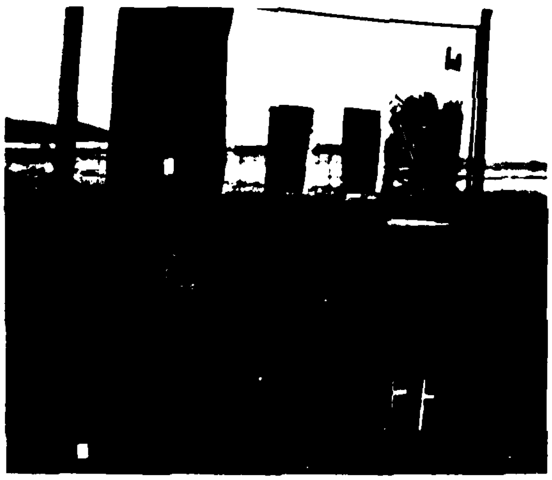
FIGURE 4-4 TEST STAND CONFIGURATION



Clockwise from Top:
Items 2 & 3
Debris Pile
Items A & B
Station Configuration

SA-7814-11

FIGURE 4-5 TEST 1, PRESHOT SAMPLES

Samples A and B are pieces of Spanish Cedar used in char measurements. During the period of atmospheric nuclear weapons tests, similar wood samples (Guatemalan Cedar) were used extensively to establish char depths as a function of the incident thermal fluence. The char samples were included in the current tests to provide another correlation with nuclear tests. Strips of aluminum foil protect portions of the surface and leave an uncharred point for measurements of the original thickness. Two layers of newspaper on the bottom halves of the "B" samples could produce several effects depending on the radiation flux and fluence levels. At low fluences, e.g., near the ignition threshold for paper, the paper could shield the wood and reduce the char thickness. Also, the cloud of pyrolysis particles or smoke could shadow the top half of the sample and reduce the charring. At the fluence levels above the sustained flaming threshold, the rising flames could add to the thermal insult and increase the char depth.

The ritual for removing the char layer and measuring the depths of the pyrolysis zone has been described in Reference 6. A brass wire brush is used to remove the char without damaging the virgin wood. Although char depths reflect some of the grain pattern in the wood, the micrometer measurements are fairly reproducible and average depths are reasonably reproducible from one observer to another.

## 4.5 Test Results

### 4.5.1 Test on July 11, 1980

The firing of the thermal bags for Shot 1, on July 11, 1979, went according to plan. Table 4-3 lists the general environmental conditions the day of the shot. The average wind speed at shot time was less than 3 miles per hour, from the direction of Station 2, but gusted to almost 10 miles per hour a few minutes after the shot.

Figure 4-6 gives the recorded calorie levels at each station on the test bed. Measurements are from LATA-designed plastic passive gauges. The electronic calorimeters on this shot were unreliable due to incorrect calibration. The passive gauge data, however, is reliable and consistent with its calibration. As shown in Figure 4-6, the actual fluence levels are close to the nominal predicted levels.

Table 4-3

TEST 1 ENVIRONMENT

| Time | Measurement | Description |
|---|---|---|
| 0700 | 58°F | Air temperature |
| | 49% | Relative humidity |
| | 90°F | Approx. cloth temperature (facing sunlight) |
| | 70°F | Approx. cloth temperature (shaded) |
| 0900 | 82°F | Air temperature |
| | 32% | Relative humidity |
| | 134°F | Approx. cloth temperature (sunlit) |
| | 94°F | Approx. cloth temperature (shaded) |
| 1030 (Shot Time) | 92°F | Air temperature |
| | 28% | Relative humidity |

Table 4-4 gives visual observations of the test specimens, recorded within the first 30 minutes after flash exposure. One general observation was that due to the slight wind, Station 2 was slightly under its predicted energy level and Station 4 was slightly over its predicted energy level.

Figure 4-7 shows photos of the postshot specimen damage for Shot 1 on July 11, 1979.

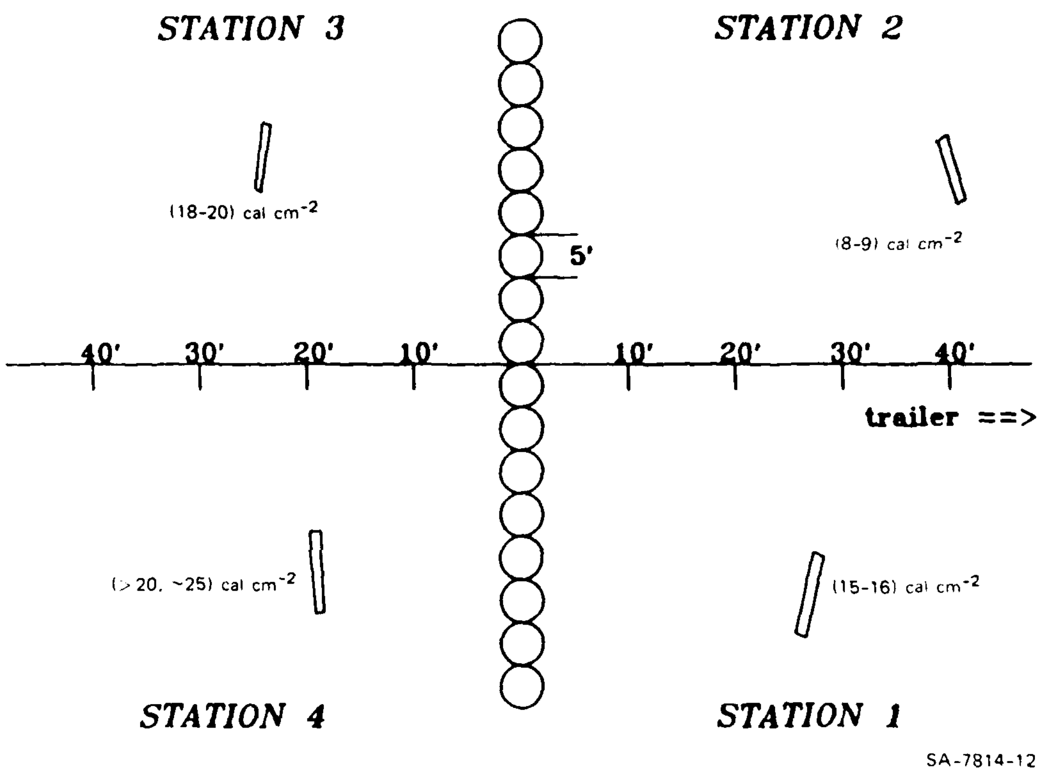



FIGURE 4-6 TEST 1, TEST BED

Table 4.4

TEST 1--POSTTEST
OBSERVATIONS
July 11, 1979

| Time from ignition (minutes) | Station | Event Visual Observation |
| --- | --- | --- |
| T + 5 min | 2 | Still smoking. Extensive damage on all samples |
| | 1 | Debris continues to burn. |
| | 3 | 8 × 2 ft sample burned and batting has fallen out, debris pile burning. |
| T + 12 min | 4 | Wood continues to burn (continuity of burn appears to be a function of packing density producing a "chimney effect") |
| T + 20 min | 1 | Debris still burning vigorously |
| T + 30 min | 2 | 8 × 2 ft sample burns more vigorously with breeze |

TABLE 4.5

TEST 1A--ENVIRONMENT

| Time | Measurement | Description |
| --- | --- | --- |
| 1100 | 24% | Relative humidity |
| | 78°F | Air temperature |
| | 24.87 in. of Hg | Barometric pressure |
| | 15 mi/hr | (E-SE) gusting to 20 mi/hr |
| 1130 (Shot Time) | | Wind velocity < 3 mi/hr from SE |
| 1200 | 22% | Relative Humidity |
| | 77°F | Air Temperature |
| | 24.84 in. of Hg | Barometric Pressure |
| | 13 mi/hr (SE) | Wind |

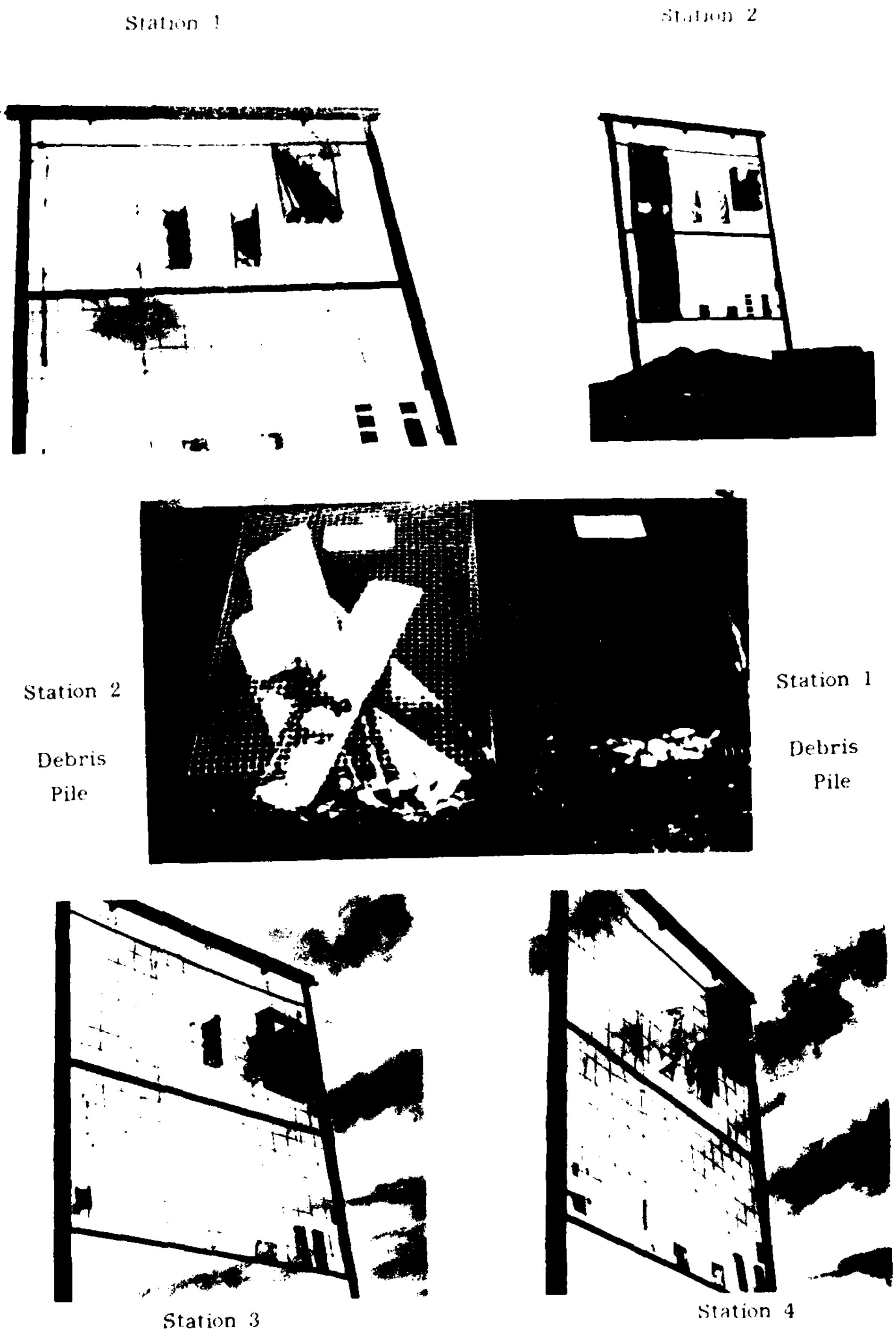



FIGURE 4-7 TEST 1 DAMAGE

### 4.5.2 Test of July 31, 1979

The firing of the thermal bags for Shot 1A provided very reliable data. Table 4-5 lists the general environmental conditions of that day. The wind velocity at shot time was near zero, which shifted the highly buoyant fireball only after it was about 50 ft above the ground.

Figure 4-8 gives the maximum calorie levels recorded at each gauge on each station on the test bed. These measurements are taken from electronic copper slug calorimeters. Passive gauges were used for redundancy.

Figure 4-9 is the flux calorimeter energy pulse shape of this shot. The pulse shape is similar to that of a low-yield nuclear weapon.

Figure 4-10 compares the slug calorimeter recordings at each station. The only malfunction was the lower calorimeter at Station 4.

Table 4-6 provides a chronology of visual events as observed from high-speed color films. These events are, in turn, superimposed on a reproduction of each station's respective slug calorimeter output. Figures 4-11 through 4-14 show these time and event observations traced along a center line at the 10-cal-cm$^{-2}$ level.

The results of the shot on July 31, 1979 were very reliable. Flame indicators, which were strips of aluminum foil, showed that each large vertical sample did indeed ignite. This occurred on all four stations.

The additional samples at the extra test stand at 5 cal-cm$^{-2}$ did not ignite. Thus, the ignition point of the fabrics was likely between 5 cal-cm$^{-2}$ and 10 cal-cm$^{-2}$ for these simulations. The tightly bound debris piles also seemed to have provided better results than in Shot 1.

Figures 4-15 and 4-16 show preshot specimens and postshot results for Shot 1A.

### 4.5.3 Summary of Test Results

Nominal fluence values are employed in the following description of the ignition results. Unfortunately, the motion picture coverage failed to provide sufficient detail to establish a complete temporal descrip-

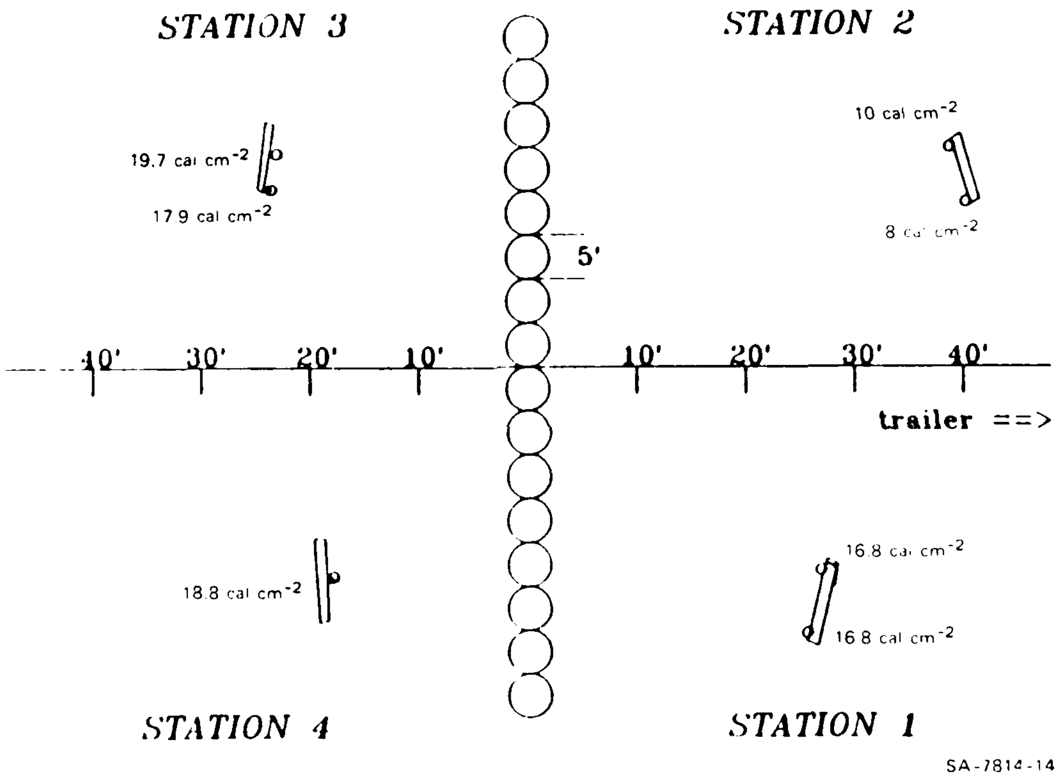



FIGURE 4-8 TEST 1A, TEST BED

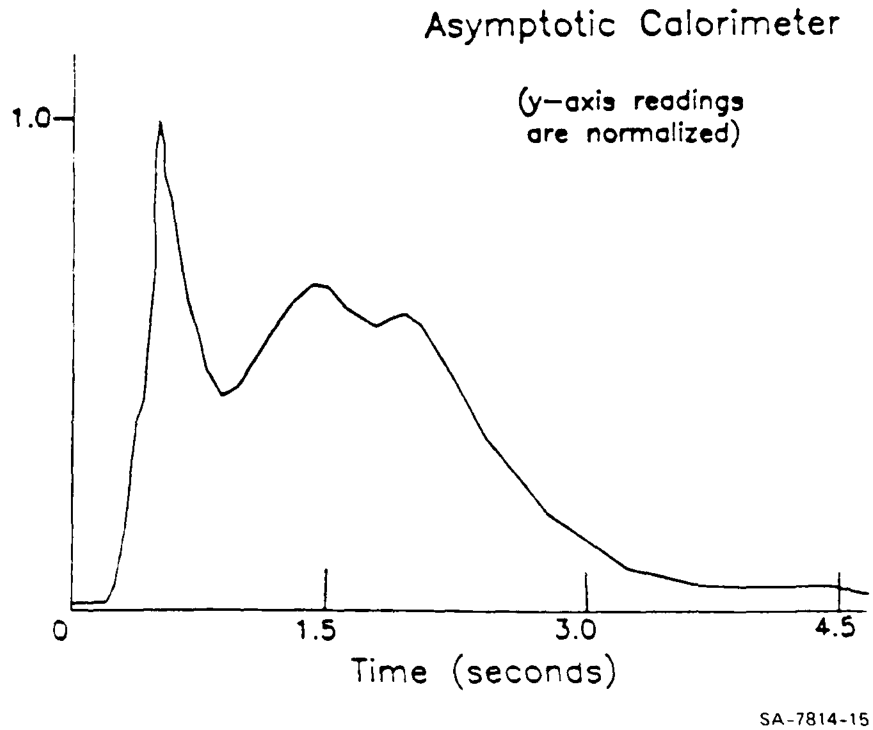



FIGURE 4-9 TEST 1A, PULSE SHAPE

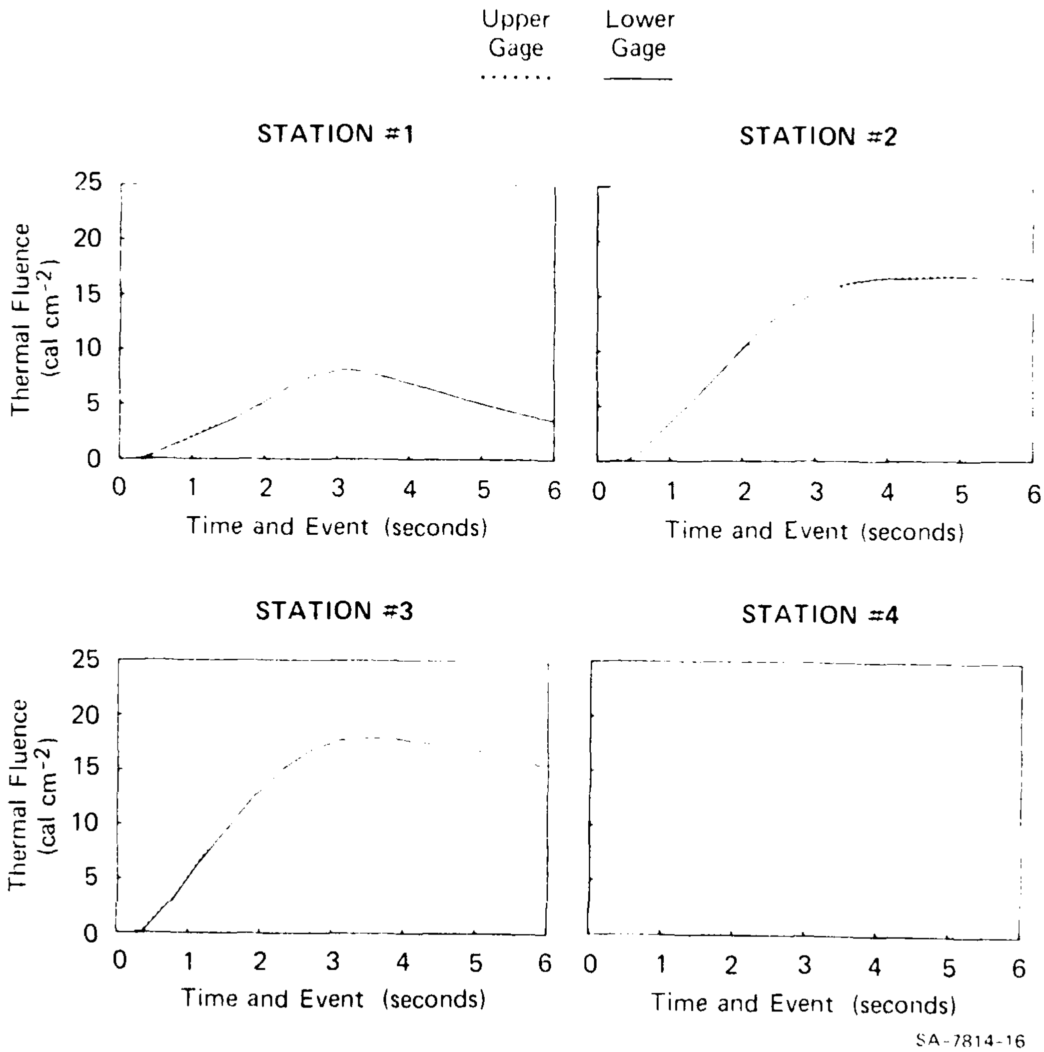



FIGURE 4-10 TEST 1A CALORIMETER COMPARISON

TABLE 4-6

TIME AND EVENT FILM OBSERVATIONS
July 31, 1979

| Time from ignition (seconds) | Station | Event Observation |
|---|---|---|
| 0.25 | 2 | No evidence of smoke. |
| | 1 | No evidence of smoke. |
| | 3 | No evidence of smoke. |
| | 4 | No evidence of smoke. |
| 0.34 | 2 | No change. |
| | 1 | Smoke appears very faintly on backside of fabric. |
| 0.35 | 3 | No change. |
| | 4 | Smoke appears on fabric. |
| 0.40 | 2 | No change. |
| | 1 | Smoke building along backside of fabric panel |
| | 3 | Fabric starts to smoke near bottom. |
| | 4 | Fabric smoking full length. |
| 0.45 | 3 | Fabric continues smoke buildup. |
| | 4 | Debris basket begins to smoke. Fabric continues smoke buildup. |
| 0.50 | 2 | No change. |
| | 1 | Smoke from full length of fabric panel. |
| 0.65 | 2 | No change. |
| | 1 | Smoke evident on front side of fabric panel. Backside smoke is building. |
| 0.70 | 2 | Faint traces of smoke near bottom of third panel. |
| | 1 | Obscured by smoke (front and back). |
| | 3 | Full smoke. |
| | 4 | Full smoke. |
| 0.80 | 2 | More evidence of smoke from fabric panel. |
| | 1 | Smoke continues to build. |
| 0.90 | 2 | Continuation of smoke buildup. Debris basket begins to smoke. |
| | 1 | Debris basket obscurred by smoke from fabric panel. No visible flames. |

TABLE 4-6
(continued)

| Time from ignition (seconds) | Station | Event Observation |
|---|---|---|
| 1.00 | 2 | Clear evidence of smoke coming from fabric and debris basket. |
| | 1 | Smoking heavily. No sign of flame. |
| | 3 | Continued smoke buildup. |
| | 4 | Flames appear on fabric. |
| 1.18 | 3 | Flames appear on fabric. |
| 1.25 | 3 | Fabric in flame on bottom half of panel. Top half in heavy smoke. |
| | 4 | Fabric in full flames. |
| 1.30 | 2 | Debris basket smoking moderately. Full length of fabric panel smoking. |
| | 1 | Continuing buildup of smoke. No visible flames. |
| 1.45 | 2 | Fabric smoking heavier on bottom third of panel. |
| | 1 | Burning particles from ignition appear in vicinity. Flames appear on bottom. |
| 1.50 | 3 | Fabric in full flame. |
| | 4 | Fabric in heavy burn. |
| 1.55 | 2 | Corner of fireball enters picture More burning particles from ignition. |
| 1.60 | 2 | Smoke building. |
| | 1 | Fabric panel in full flame. |
| 1.65 | 3 | Heavy burn through 2.50 seconds. |
| | 4 | Heavy burn through 2.50 seconds. |
| 1.70 | 2 | Fireball very prominent in picture. Smoking moderately. No flames. |
| | 1 | Burning good. |
| 1.90 | 2 | Heavy smoke buildup. No flames. |
| | 1 | Fireball in close proximity. Heavy burn. |
| 2.00 | 2 | Continuous buildup of smoke through 2.3 seconds. |
| | 1 | Flames through 2.30 seconds. |

TABLE 4-6
(continued)

| Time from ignition (seconds) | Station | Event Observation |
|---|---|---|
| 2.40 | 2 | Continuous buildup of smoke through 2.30 seconds. |
| | 1 | Flames through 2.30 seconds. |
| 2.50 | 2 | Flames start on fabric and debris basket. |
| 2.60 | 2 | Good flame. |
| | 1 | Fabric coming apart. |
| 2.70 | 2 | Full flame. |
| 2.75 | 3 | Flames appear to be pulling away. |
| | 4 | Flames appear to be pulling away. |
| 2.90 | 2 | Heavy burn on fabric and debris basket. |
| | 1 | Fireball has moved up and out of picture. Fabric buckling and coming apart. |
| 3.00 | 3 | Fabric nearly burned up. |
| | 4 | Fabric panel appears to be coming apart. |
| 3.30 | 2 | Still heavy burn. |
| | 1 | Flame starts subsiding. |
| 3.35 | 3 | Fabric panels coming apart. |
| | 4 | Fabric panels coming apart. |
| 3.60 | 2 | Flame starts to subside. |
| | 1 | Residual burn. |
| 4.00 | 2 | Residual burn. |
| | 1 | Residual burn. |
| | 3 | Nearly burned up. Coming apart. Flames subsiding. |
| | 4 | Nearly burned up. Coming apart. Flames subsiding. |
| 4.10 | 2 | Residual burn down to no flame, cinders and smoke to 4.70 seconds. |
| | 1 | Residual burn down to no flame, cinders and smoke to 4.70 seconds. |

TABLE 4-6
(concluded)

| Time from ignition (seconds) | Station | Event Observation |
|---|---|---|
| 4.25 | 3 | Fabric panel material breaking off. Debris basket burning heavily. |
| | 4 | Debris basket burning heavily. |
| 4.50 | 3 | Flames subsiding to a residual burn to 5.50 seconds. |
| | 4 | Flames subsiding to a residual burn to 5.50 seconds. |
| 4.70 | 2 | End of sequence. |
| | 1 | End of sequence. |
| 5.50 | 3 | Residual burn to end of sequence. |
| | 4 | Residual burn to end of sequence. |

STATION #1

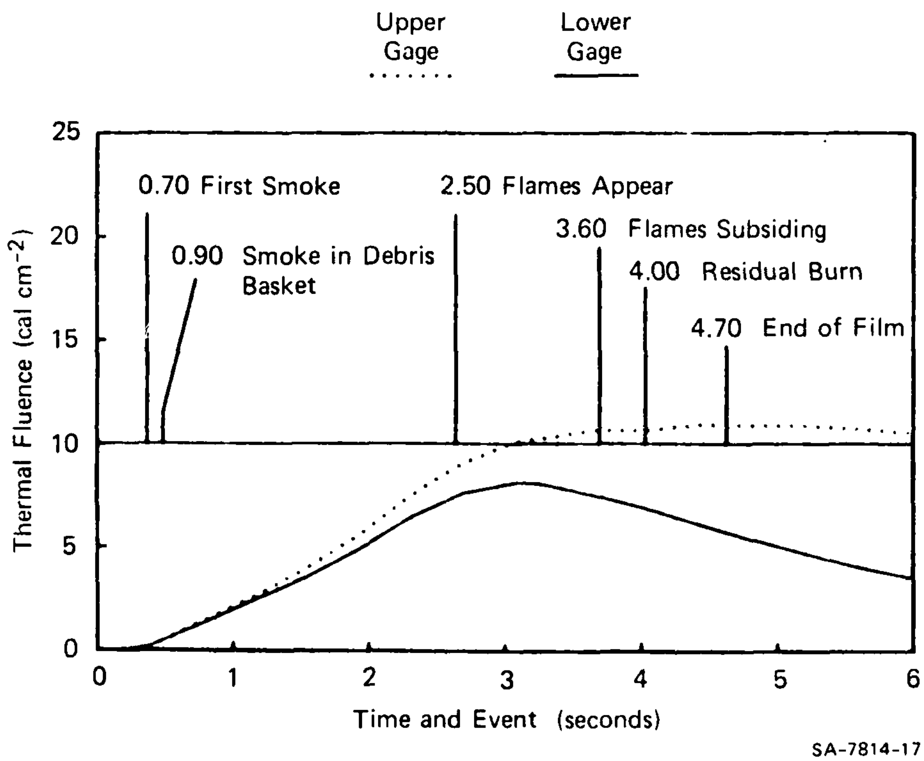



FIGURE 4-11 TEST 1A TIME AND EVENT, STATION 1

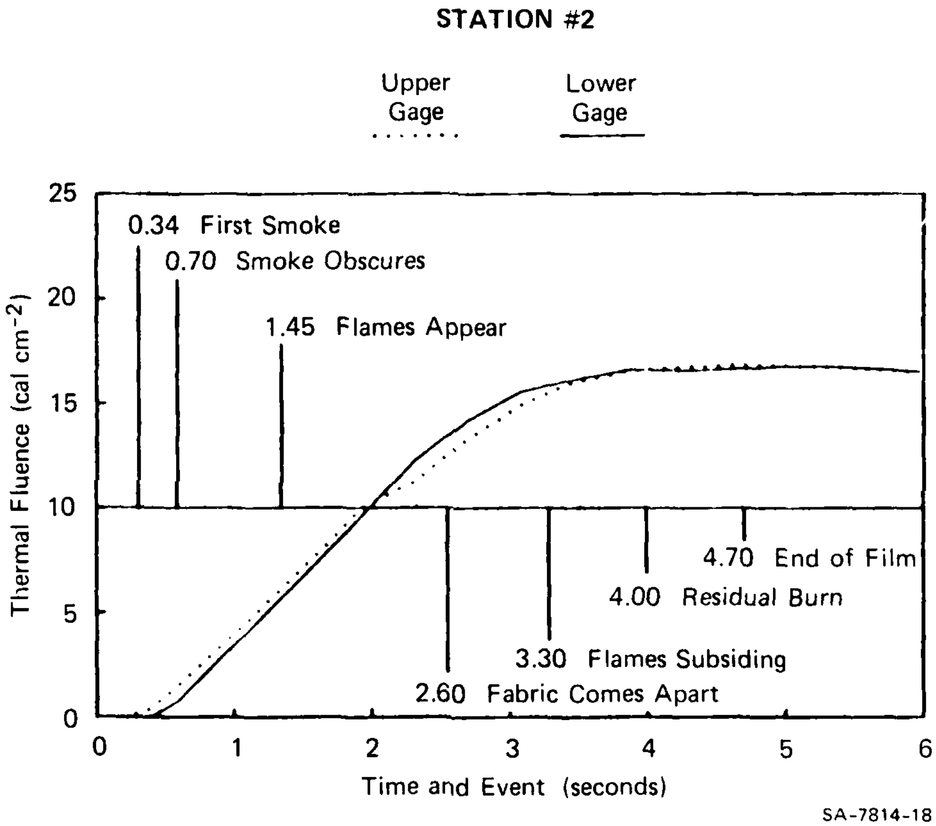



FIGURE 4-12 TEST 1A TIME AND EVENT, STATION 2

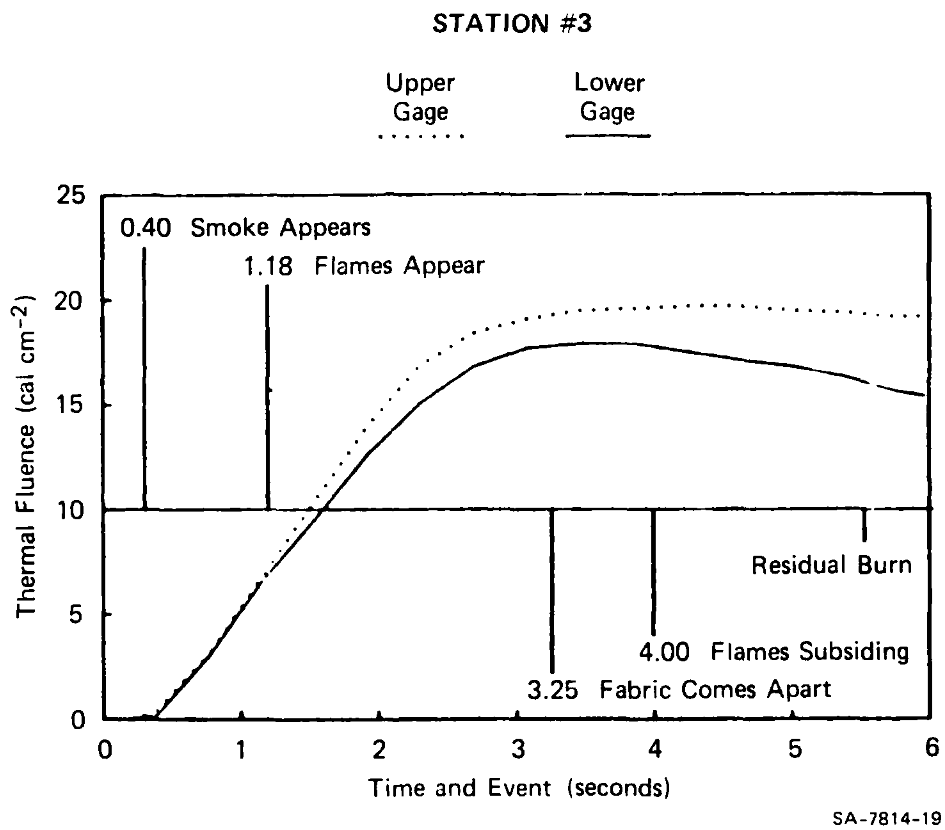



FIGURE 4-13 TEST 1A TIME AND EVENT, STATION 3

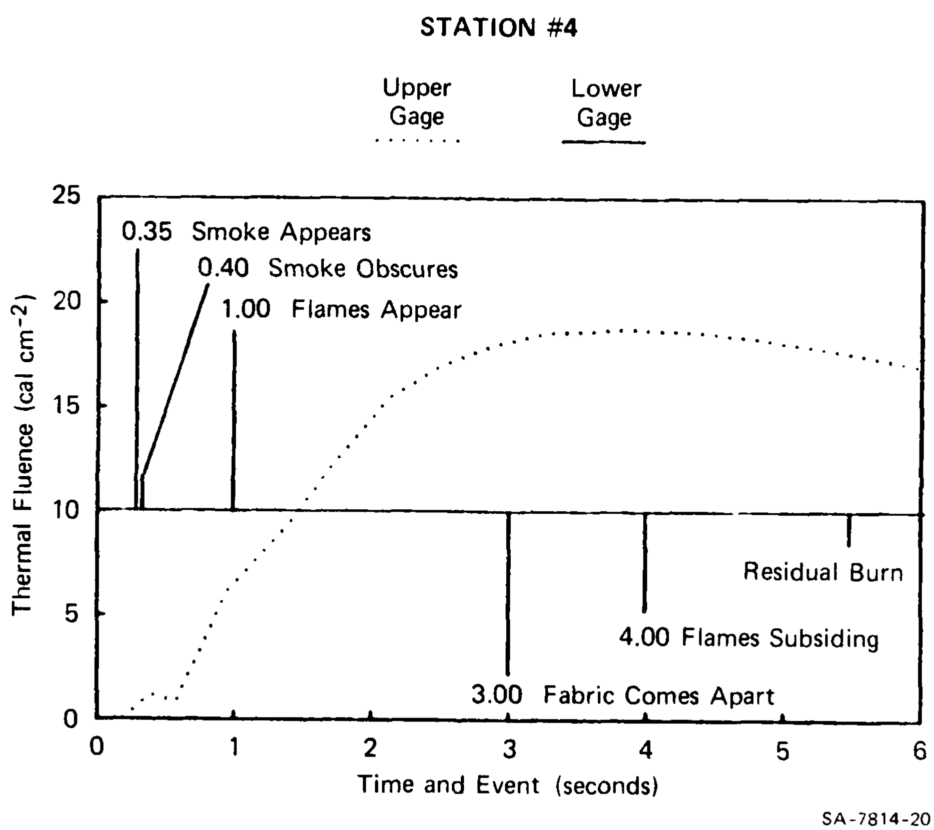
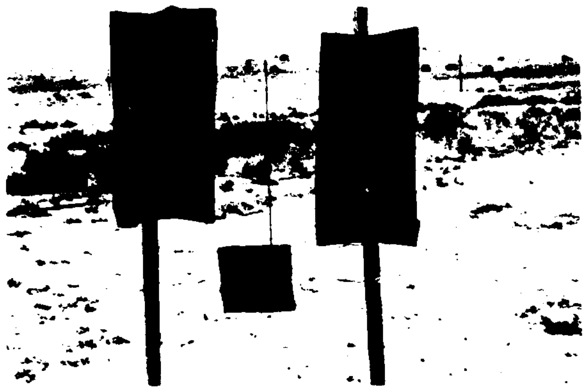
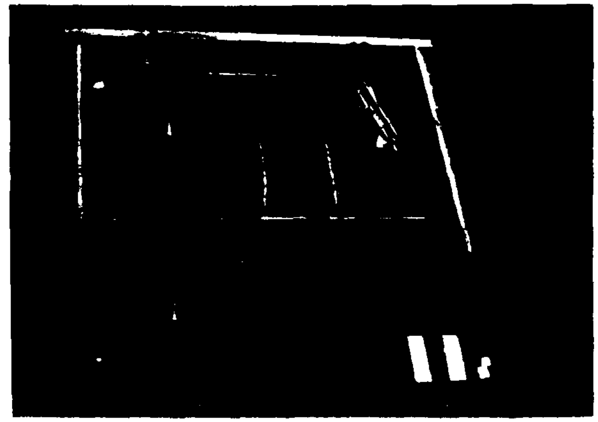



FIGURE 4-14 TEST 1A TIME AND EVENT, STATION 4

5 cal-cm$^{-2}$ Station



Station 1



Station 1 & 2 Debris Pile

Station 3

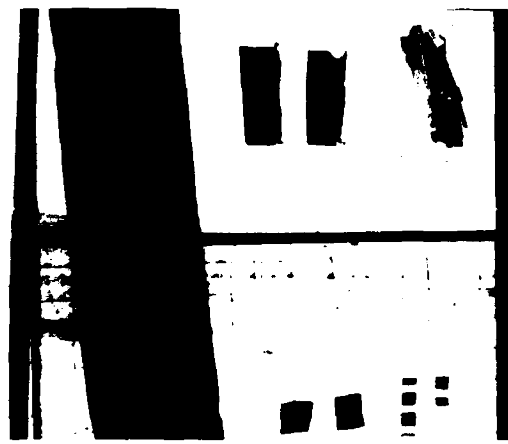


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FIGURE 4-15 TEST 1A PRESHOT SAMPLES

Station 1

Station 2

Station 3

Station 4

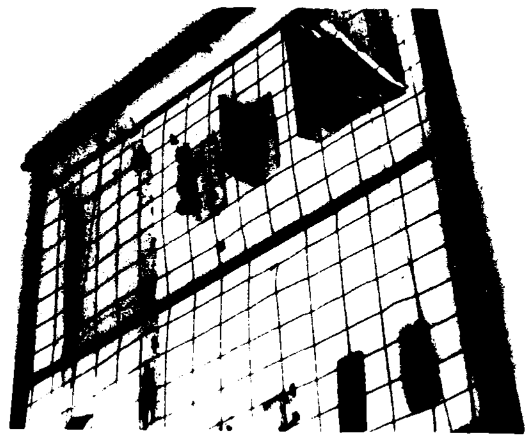

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FIGURE 4-16 TEST 1A, DAMAGE

tion of the ignition and combustion process; consequently, sustained flaming ignition cannot always be differentiated from transient flaming followed by glowing combustion, which in turn may be confused with glowing ignition. The results are listed according to the type of test specimen.

- Type #1 samples (2 feet x 8 feet). In test 1, observers reported that both the 10- and 4-oz fabrics flashed into flame at all stations and only the 10 cal cm$^{-2}$ station samples were not burning vigorously at T+1 min. At the 25- and 20-cal cm$^{-2}$ stations the 10-oz cloth burned promptly (before the recovery team reached that position at T+10 to T+12 min) and permitted the cotton batting to fall to the ground where it was ultimately consumed by glowing combustion. The 4-oz sample at the 15 cal cm$^{-1}$ location suffered a similar fate by T+5 min. Figure 4-17 shows the 10 cal cm$^{-2}$ station at T+5 min. Only a small spot near the middle of the sample #1 is glowing. At T+30 min. Figure 4-18 shows smoldering combustion has consumed approximately ¼ of the sample. In test 1A, 10-oz cloth was tested at all stations and again the samples exposed to 25 and 20 cal cm$^{-2}$ were consumed by flaming ignition. At the 15 and 10 cal cm$^{-2}$ stations the pictures are not as definitive. Figures 4-16 stations 1 and 2, taken at some unknown time after the flash, show some patches that appear to be charred cloth along with patches of batting or white ash, suggestive of flowing combustion. Apparently, the fluence at the 10 cal cm$^{-2}$ station was greater in test 1A than in test 1. It appears that the threshold for sustained flaming ignition in the 10-oz samples was between 15 and 20 cal cm$^{-2}$ and for the 4-oz samples this threshold was between 10 and 15 cal cm$^{-2}$. The glowing ignition threshold for the 4-oz cloth was about 10 cal cm$^{-2}$ based on test 1.
- Type 2 and 3 samples (right angle samples with crack). Figure 4-8 shows that these samples were not mounted quite as initially envisioned; consequently, the two sides of the angle did not receive equal thermal insults; however, such exposures are typical of furniture in anticipated situations. In test 1, both samples 2 and 3 were consumed at the 15, 20, and 25 cal cm$^{-2}$ stations by the time the recovery team arrived at T+5, T+20, and T+12 min, respectively. Presumably, sustained flaming ignition occurred at these stations, although some residual ash or batting at the 15 cal cm$^{-2}$ station

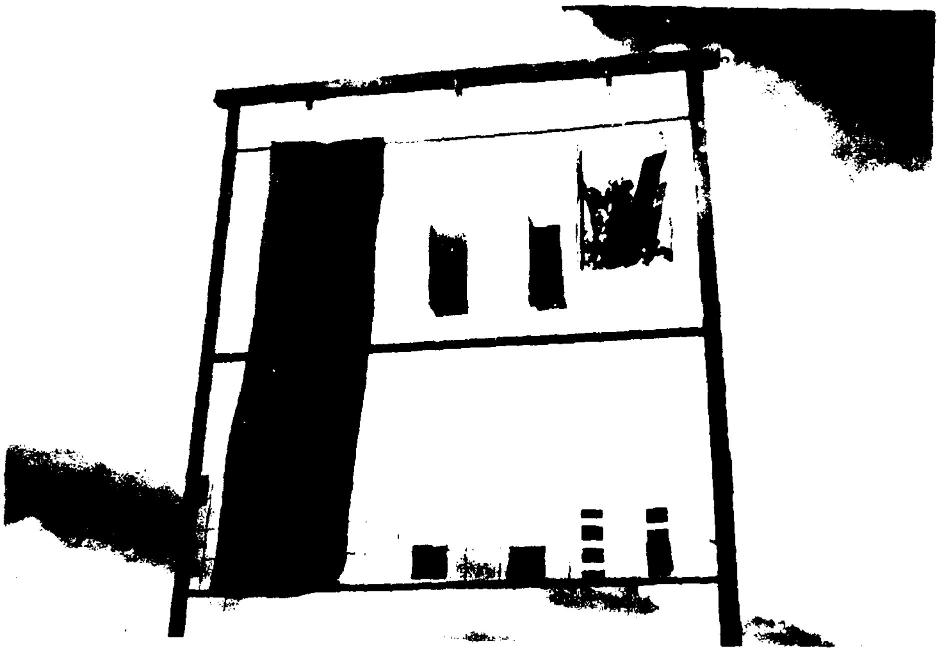

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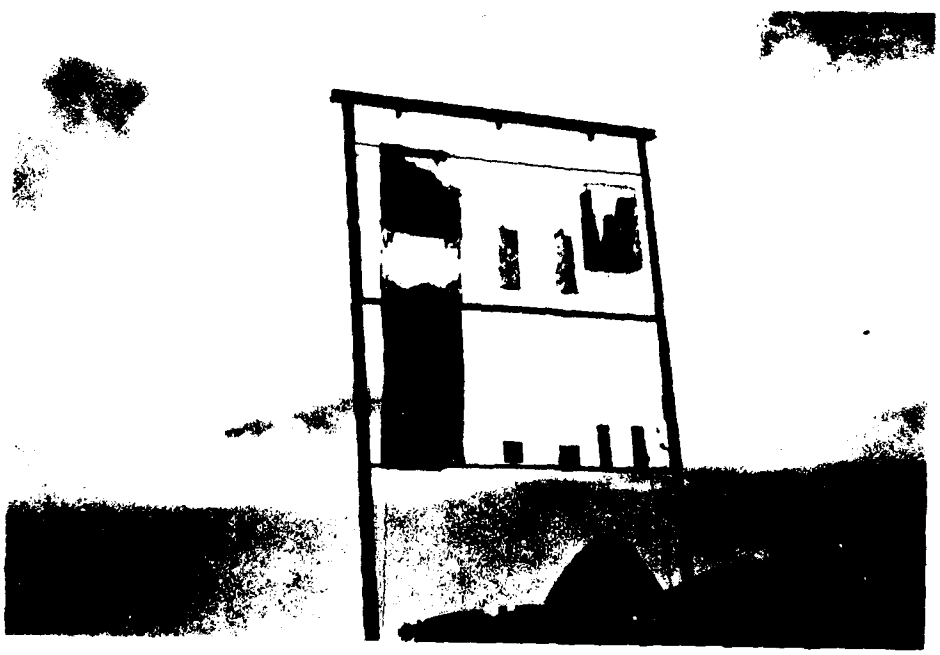
FIGURE 4-17 TEST 1, 10-CAL CM$^{-2}$ STATION AT T + 5 MIN



SA-7814-23

FIGURE 4-18 TEST 1, 10-CAL CM$^{-2}$ STATION AT T + 30 MIN suggests the possibility of glowing combustion (Figure 4-19). At the 10 cal $cm^{-2}$ level, Figure 4-19 shows a smoldering spot or hole in sample 2, and possibly damage at the bottom edge of #3. By T+30 (Figure 4-18), both samples were nearly consumed by glowing combustion. In test 1A the postshot pictures show that samples 2 and 3 were consumed at stations 10, 15, 20, and 25 cal $cm^{-2}$. The samples exposed to 5 cal $cm^{-2}$ survived although there appears to be some discoloration. These results indicate the threshold for glowing ignition is between 5 and 10 cal $cm^{-2}$ but nearer the 10 cal $cm^{-2}$ level for both weights of cloth. The threshold for flaming ignition is not defined by the postshot pictures. Apparently, sustained flaming occurs between 15 and 20 cal $cm^{-2}$ but the threshold is not established. Both weights of cloth gave essentially the same results.

- Type 4 and 5 samples (6 inches x 6 inches squares). In test 1, sample 4 was the only cloth specimen to survive the 10 cal $cm^{-2}$ exposure without burning at least partially. Figure 4-19 shows sample 5 is glowing along the top edge of the sample and by T+10 min the top half of sample 5 is consumed. Both samples were completely consumed at the higher fluence levels. In test 1A, the samples survived at 5 cal $cm^{-2}$ but were consumed at all higher fluence stations. The threshold for glowing ignition is slightly below 10 cal $cm^{-2}$ for the 4-oz samples and slightly higher for the 10-oz materials. Thresholds for sustained flaming ignition are not defined but apparently the value is below 20 cal $cm^{-2}$.

- The debris pile. In test 1 the paper burned at all test locations and the wood burned at the 15, 20, and 25 cal $cm^{-2}$ stations. The wood did not burn at the 10 cal $cm^{-2}$ location. In test 1A the wood in these tightly packed samples survived at all locations. The paper ignited but extinguished itself before generating a sustained ignition of the wood. Obviously, the crucial effects of packing density exceeded the impact of the thermal insult. If the initial premise, i.e., that in the loose-packed samples the paper burning alone could not ignite the wood, the results support the concept of enhanced ignition in mixed-fuel situations; however, the reproducibility of the packing factor leaves room for doubt and indicates an improved experiment is needed.

SA-7814-24

FIGURE 4-19 TEST 1, 15 CAL CM$^{-2}$ STATION AT T + 5 MIN

AD-A094 074 SRI INTERNATIONAL MENLO PARK CA F/G 18/3
BLAST/FIRE INTERACTIONS: ANALYSIS OF PARAMETRIC SENSITIVITY AND--ETC(U)
OCT 80 S B MARTIN, R S ALGER, J R REMPEL DCPA01-78-C-0279

UNCLASSIFIED NL

2 OF 2

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DATE
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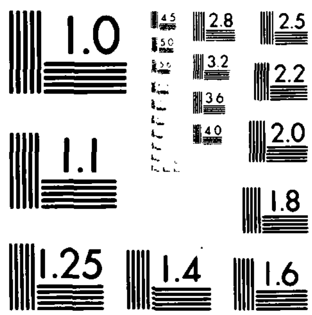


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

- Char depths in Spanish Cedar (samples A and B). Figure 4-20 shows the char patterns formed on all the A and B samples from test 1. Where the newspaper covered the B samples, the char is not as deep as in the unprotected areas, and there is no indication that the paper either enhanced or reduced the char formation in the top half of the B samples. Figure 4-21 summarizes the char measurements for both tests 1 and 1A. For comparison, char depths produced in past laboratory studies and nuclear tests have been included in Figure 4-21. Two observations can be deduced from Figure 4-21. First, the energy absorbed by the wood samples appears to be about 2.5 cal $cm^{-2}$ less than the predicted values assigned to the sample positions. Second, at the low flux stations, i.e., 10 and 15 cal $cm^{-2}$, test 1A exhibited a slightly higher fluence than test 1. While such fine distinctions are stretching the capabilities of char measurements, the second observation is in agreement with the behavior of the cloth samples at the 10 cal $cm^{-2}$ station.

4.6 <u>Test Conclusions</u>

- The tall sample effect: within the precision permitted by the station locations, i.e., 5 cal $cm^{-2}$ increments, there was no difference between the behavior of the 2 feet x 8 feet specimens and the 6 inches x 6 inches samples, i.e., no enhancement was observed.

- Thermal reinforcement due to right angle geometry and crack: At the 10 cal $cm^{-2}$ station in test 1, sample #2 was consumed by glowing combustion while sample #4 survived thereby suggesting a slight reinforcement effect. However, in test 1A both samples burned at the 10 cal $cm^{-2}$ location indicating that any enhancement effect was small.

- Ignition threshold estimates for exposure to the bag source: 10 oz black cotton cloth over 1 inch cotton batting

  - Glowing ignition about 10 cal $cm^{-1}$

  - Sustained flaming ignition probably 15 cal $cm^{-2}$ or greater

  - 4 oz black cotton cloth over 1" cotton batting

  - Glowing ignition between 5 and 10 cal $cm^{-1}$ but closer to the value of 10

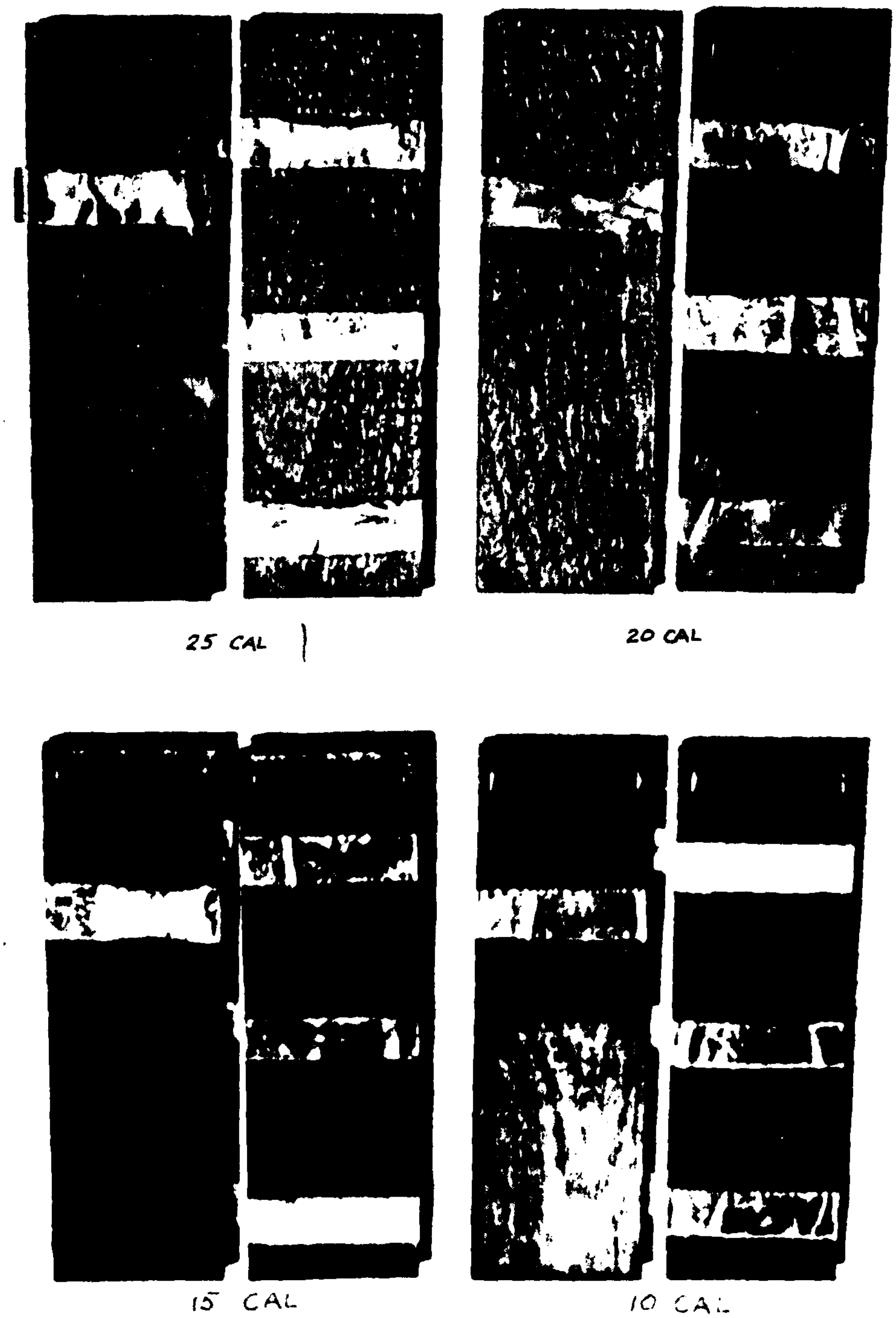


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FIGURE 4-20 CHAR DEPTH SAMPLES AFTER EXPOSURE

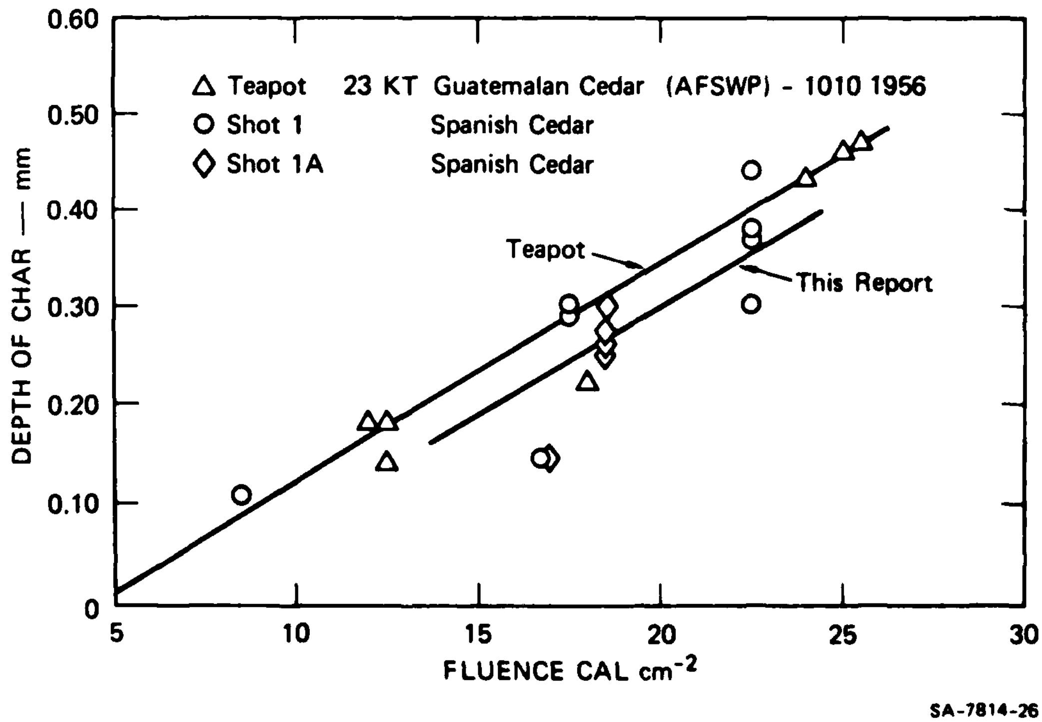


FIGURE 4-21 EMPIRICAL DEPTH-OF-CHAR/FLUENCE RELATIONSHIP

- Sustained flaming ignition between 10 and 15 cal $cm^{-2}$

- Mixed fuel or debris pile effects: Sample packing effects were more pronounced than possible enhancements from the combined convective plus radiative heating.

## 4.7 References

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3. "The Effects of Nuclear Weapons," Ed. by S. Glasstone, and P. J. Dolan, Third Edition 1977, Prepared for DOD and DOE.

4. Martin, S. B. and N. J. Alvares," Ignition Thresholds for Large-Yield Nuclear Weapons," USNRDL TR-1007, Defense Atomic Support Agency NWER Subtask 12.032 (1966).

5. Lee, B. T. and L. L. Wiltshire, "Investigation of Ignition and Fire Spread Characteristics of Cloth Covered Upholstery and Carpeting," NRDL-TR-69-68, Defense Atomic Support Agency NWER Subtask NA005, DASA Information and Analysis Center, G. E. Tempo, Santa Barbara, CA (1969).

6. Butler, C. P., "Notes on Charring Rates in Wood," Fire Research Note #896. Fire Research Station, Borehamwood, Herts, U.K. (1971).

## Appendix A

## DEFINITION OF SENSITIVITY

Mathematically, the sensitivity of a function to uncertainties in its parameters may be defined using the concept of relative error.* Consider the function y(x) to be exactly determined for all values of the independent variable x, subject to the exact specification of a set of parameters p, q, r, ...(etc), which themselves may be functions of x. However, at any specified value of x, the parameters exhibit variability in value (i.e., errors) dp, dq, dr, ..., the magnitude of which may (but often will not) depend on x. Any resultant error, dy, in the function

$$y = y(x;\ p,\ q,\ r,\ \ldots)$$

due to errors in the parameters is functionally described by the expression:

$$y + dy = y(x;\ p + dp,\ q + dq,\ r + dr,\ \ldots)$$

When expanded by Taylor's theorem for a function of several variables, the right-hand member becomes:

$$y(x;\ p,\ q,\ r,\ \ldots) + \frac{\partial y}{\partial p}\,dp + \frac{\partial y}{\partial q}\,dq + \frac{\partial y}{\partial r}\,dr + \ldots$$
$$+ \tfrac{1}{2}\left[\frac{\partial^2 y}{\partial p^2}\,dp^2 + \ldots + 2\frac{\partial^2 y}{\partial p\,\partial q}(dp\,dq) + \ldots\right] + \ldots$$

For as long as the errors dp, dq, dr, ... are relatively small, we are justified in neglecting their squares, products, and higher powers.

---

*Scarborough, J. B., Numerical Mathematical Analysis, (The Johns Hopkins Press, Baltimore, MD 1930).

Then

$$y + dy = y + \frac{\partial y}{\partial p} dp + \frac{\partial y}{\partial q} dq + \frac{\partial y}{\partial r} dr + \ldots$$

or

$$dy = \frac{\partial y}{\partial p} dp + \frac{\partial y}{\partial q} dq + \frac{\partial y}{\partial r} dr + \ldots$$

Relative error is the absolute error divided by the "true" value of the quantity. In dealing with random variables, the mean of the distribution takes on the sense of the true value for purposes of computing errors. Thus, the expression for relative error is

$$\frac{dy}{y} = \frac{\partial y}{\partial p}\frac{dp}{y} + \frac{\partial y}{\partial q}\frac{dq}{y} + \frac{\partial y}{\partial r}\frac{dr}{y} + \ldots$$

The resultant relative error may then be expressed as a linear combination of the relative erros in each parameter; thus,

$$\frac{dy}{y} = A\left(\frac{dp}{p}\right) + B\left(\frac{dq}{q}\right) + C\left(\frac{dr}{r}\right) + \ldots$$

where

$$A = \frac{p}{y}\left(\frac{\partial y}{\partial p}\right), \quad B = \frac{q}{y}\left(\frac{\partial y}{\partial q}\right), \quad \ldots$$

As applied in our study of parametric sensitivity, y is the computed fire frequency distribution and x may be either distance from ground zero or (since yield and burst height are specified) peak overpressure. Each parameter is evaluated separately, holding the others constant (usually at their mean or midrange value).

The coefficient A is a measure of the sensitivity of the resultant fire distribution to variations (uncertainties, errors, or statistical variance) in the parameter p, B measures sensitivity to q, and so on. Since

$$d(\ln u) = \frac{du}{u}$$

the coefficients are readily evaluated using logarithms.

## Appendix B

### SAMPLE CALCULATIONS OF PARAMETRIC SENSITIVITY
Room Fire Probability Distributions Prior to Blast Arrival

The following figures illustrate the output of the model computations for only a few combinations of the many computed. The outputs are presented in two forms:

(1) Room fire probability versus airblast peak overpressures* (POP in units of pounds per square inch).

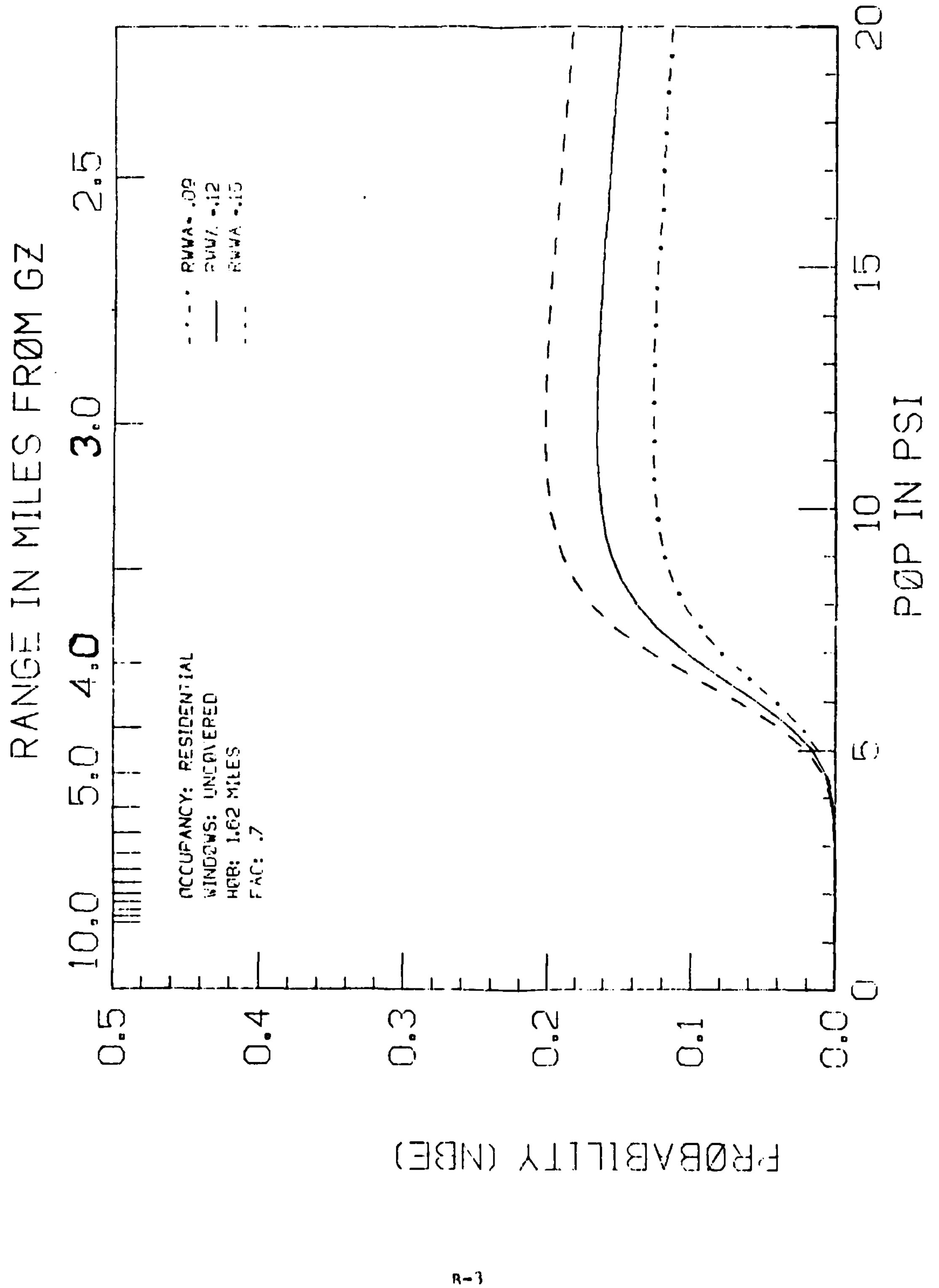
(2) Rates of change of room fire probability with respect to the parameter whose sensitivity is being evaluated versus airblast peak overpressure.*

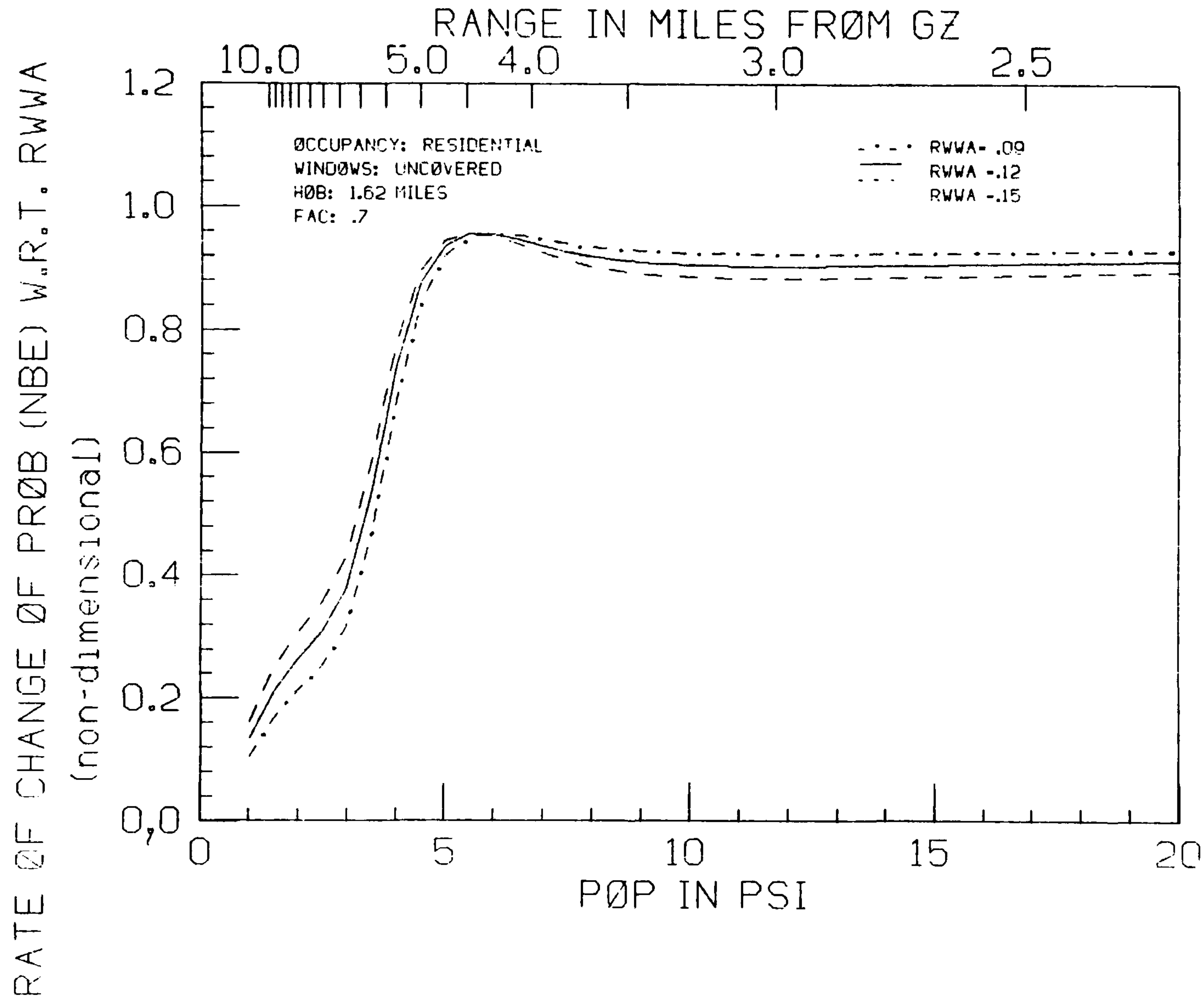
The graphs are in two sets; those representing the evaluation of sensitivity to variation in the parameter, ratio of window area to wall area (RWWA), and those representing the evaluation of sensitivity to variation in the parameter, height of the artificial horizon (BETA, $\beta$, the elevation angle in degrees). Within each set there is a repeating pattern of variation in subordinate parameters; e.g., occupancy (residential, commercial, and industrial), window states (covered or uncovered), heights of burst (surface bursts, HOB = 0, and airbursts, HOB = 1.62 miles), and transmission of the atmosphere relative to the base case (FAC:0.7, 1.0, 1.3).

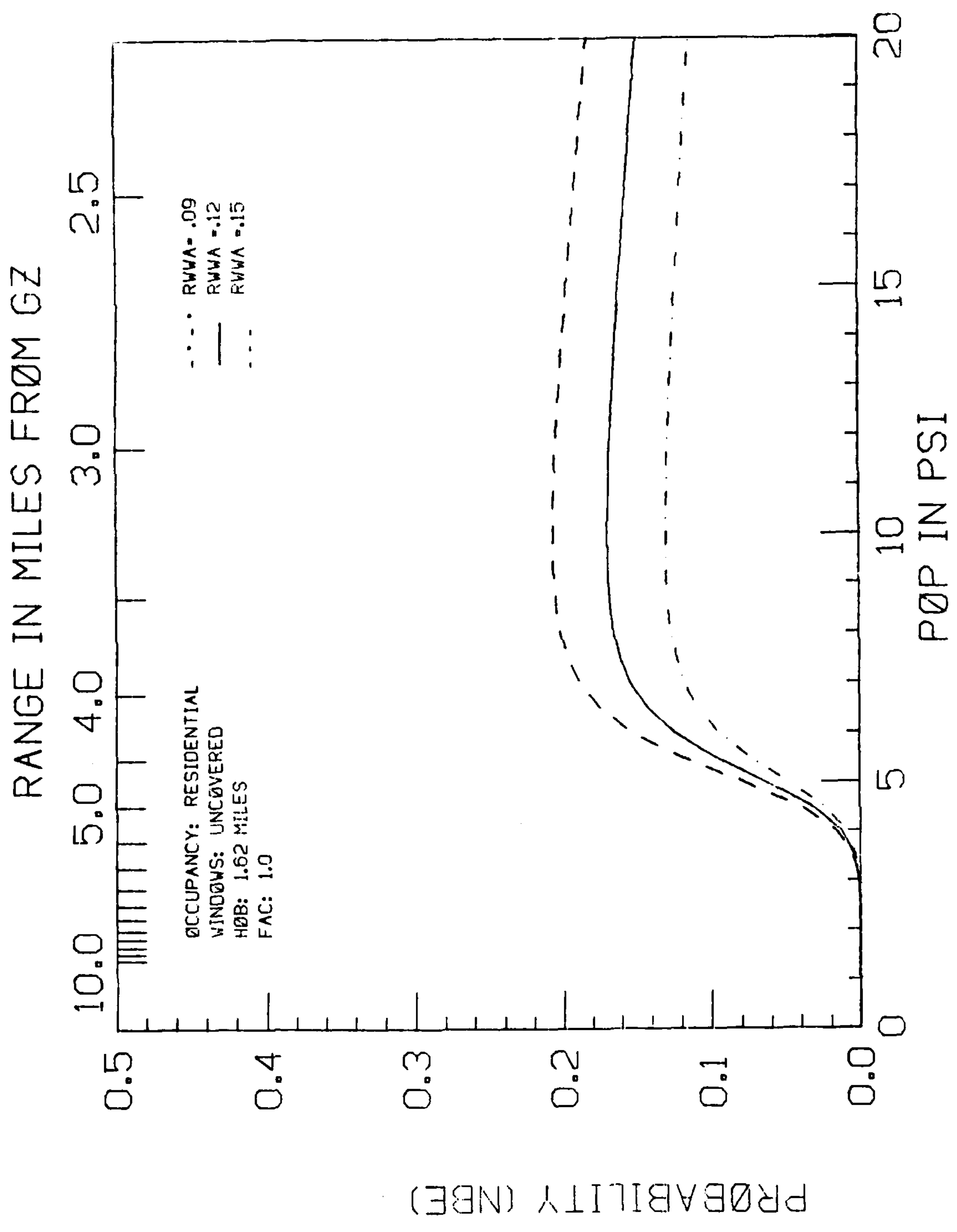
The abbreviation NBE stands for no blast effects, and refers to the lack of attempt to model the interactions of air blast.

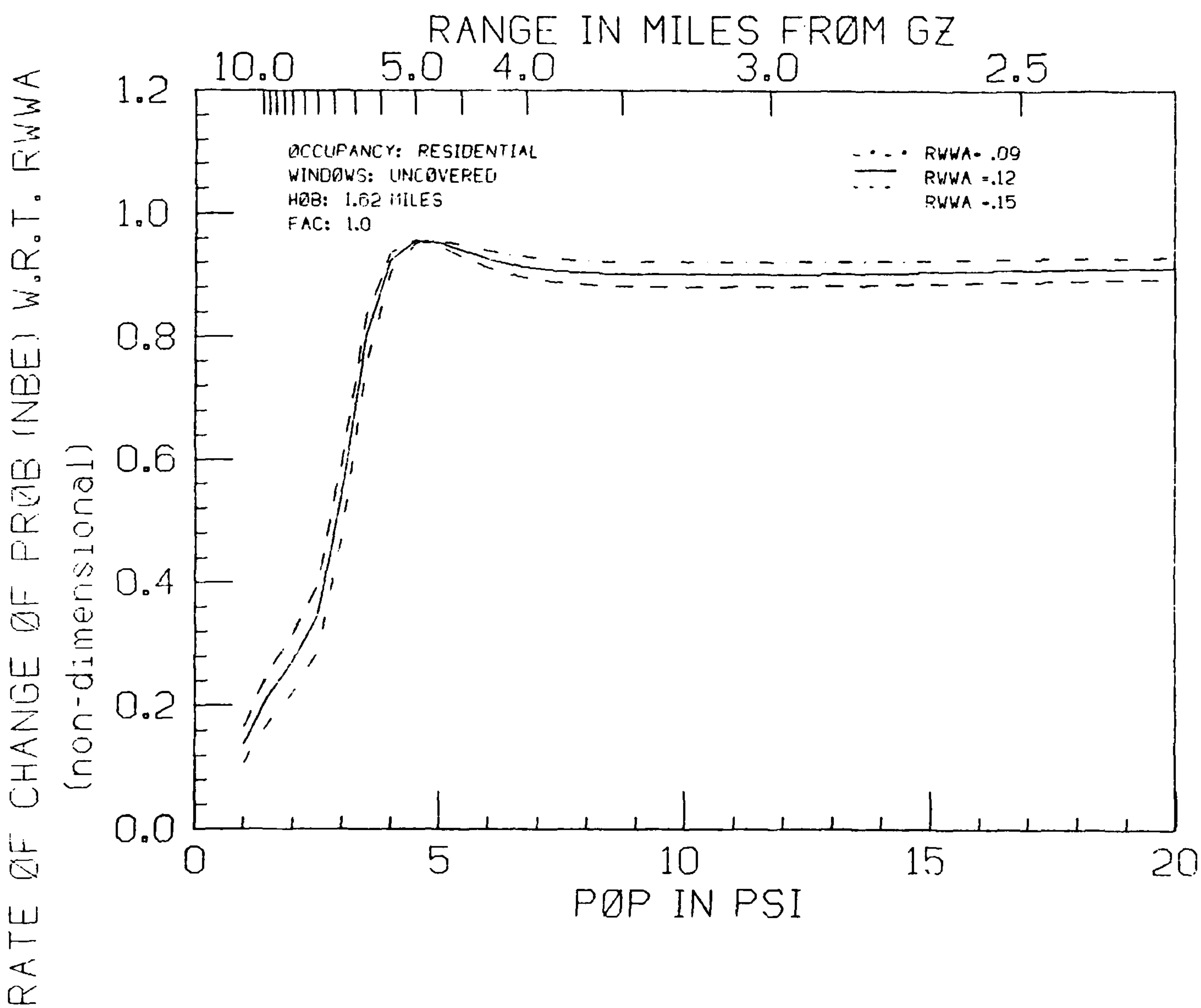
*The corresponding distances from ground zero (GZ) are also shown at the top of each graph.

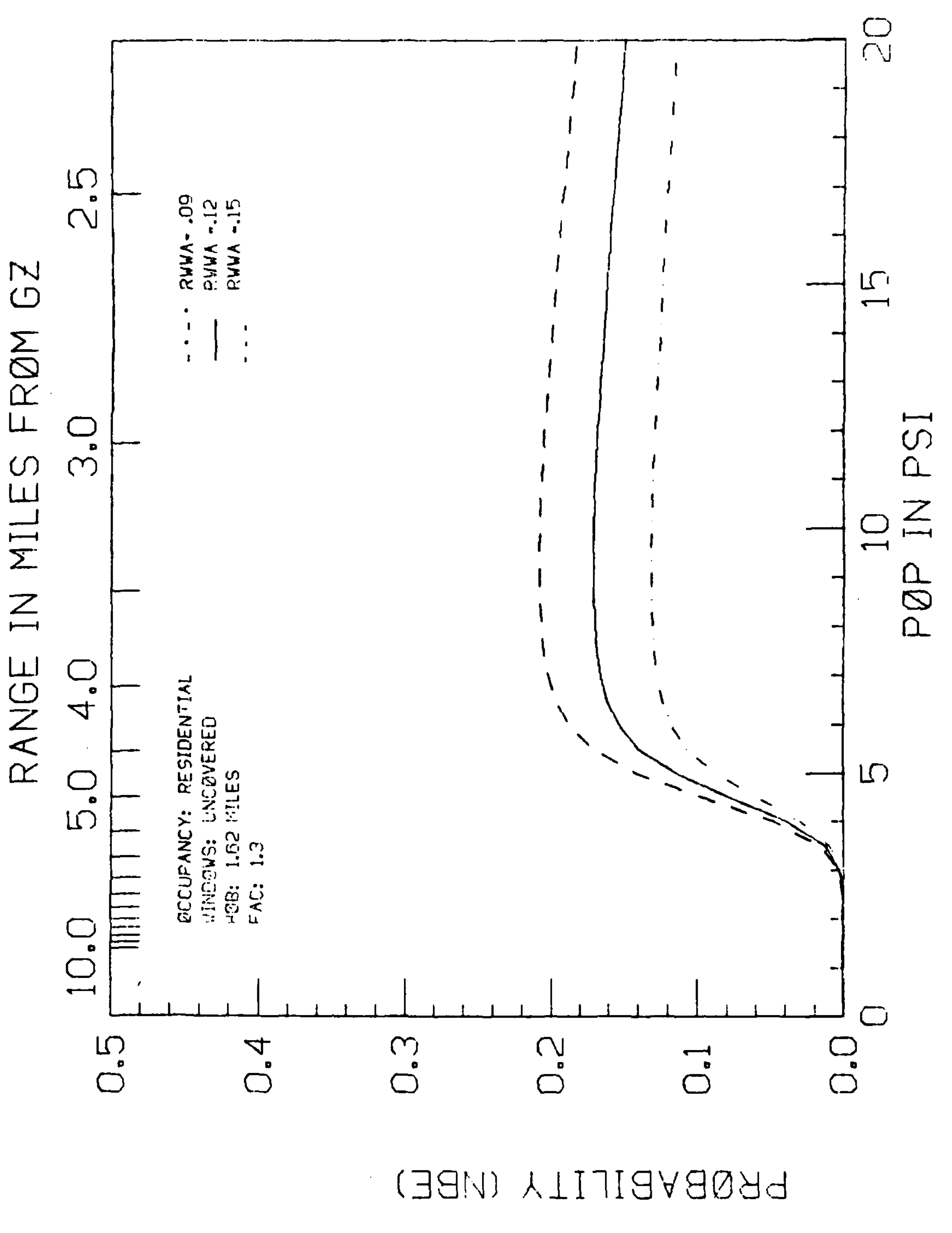
ROOM FIRE PROBABILITY DISTRIBUTION
SHOWING EFFECT OF VARIATIONS IN RATIO
OF WINDOW AREA TO WALL AREA

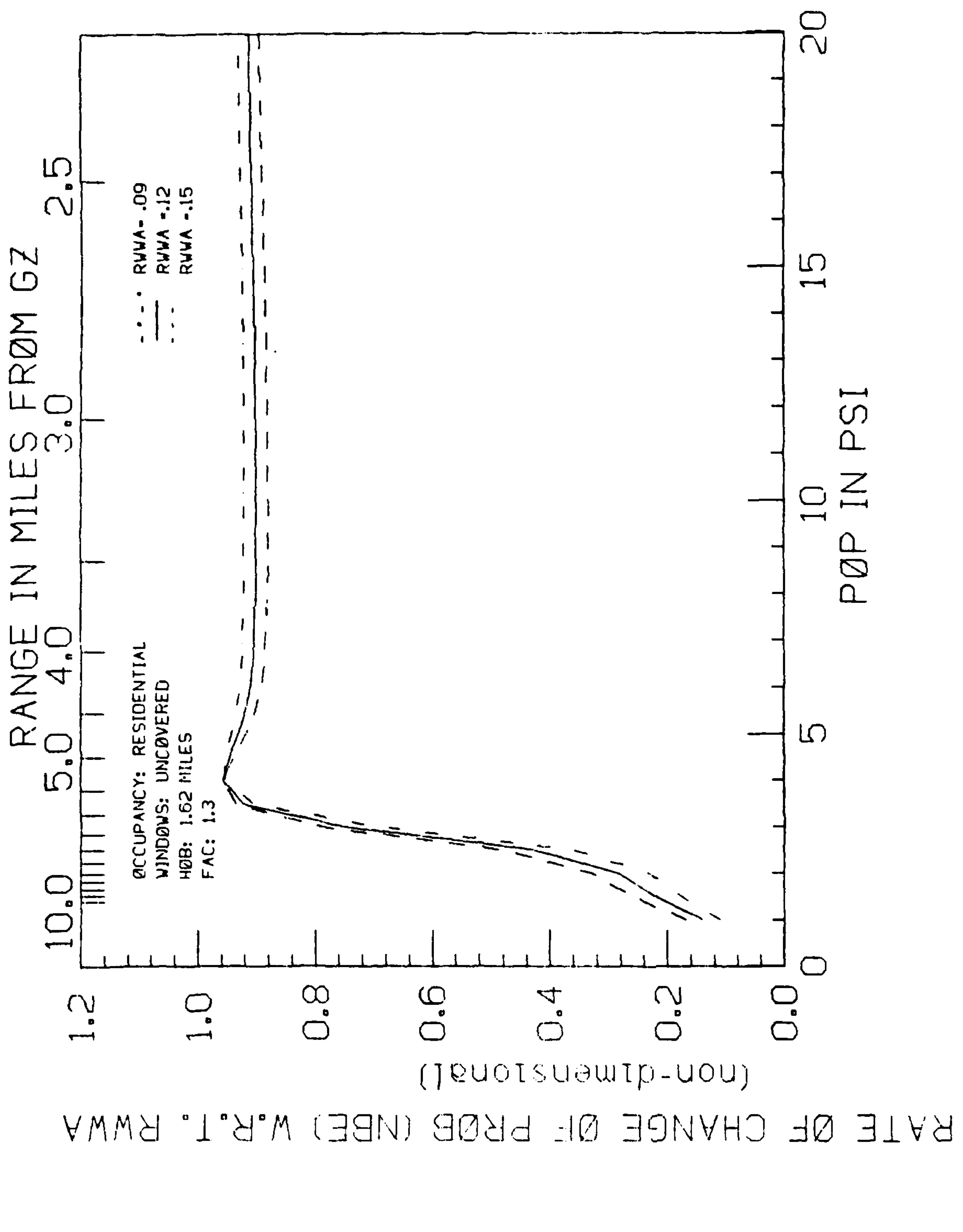

RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
OCCUPANCY: RESIDENTIAL
WINDOWS: UNCOVERED
HOB: 1.62 MILES
FAC: .7
RWWA .09
RWWA .12
RWWA .15
0.5
0.4
0.3
0.2
0.1
0.0
PRØBABILITY (NBE)
0
5
10
15
20
PØP IN PSI


RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
PØP IN PSI
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)
ØCCUPANCY: RESIDENTIAL
WINDØWS: UNCØVERED
HØB: 1.62 MILES
FAC: .7
RWWA- .09
RWWA -.12
RWWA -.15

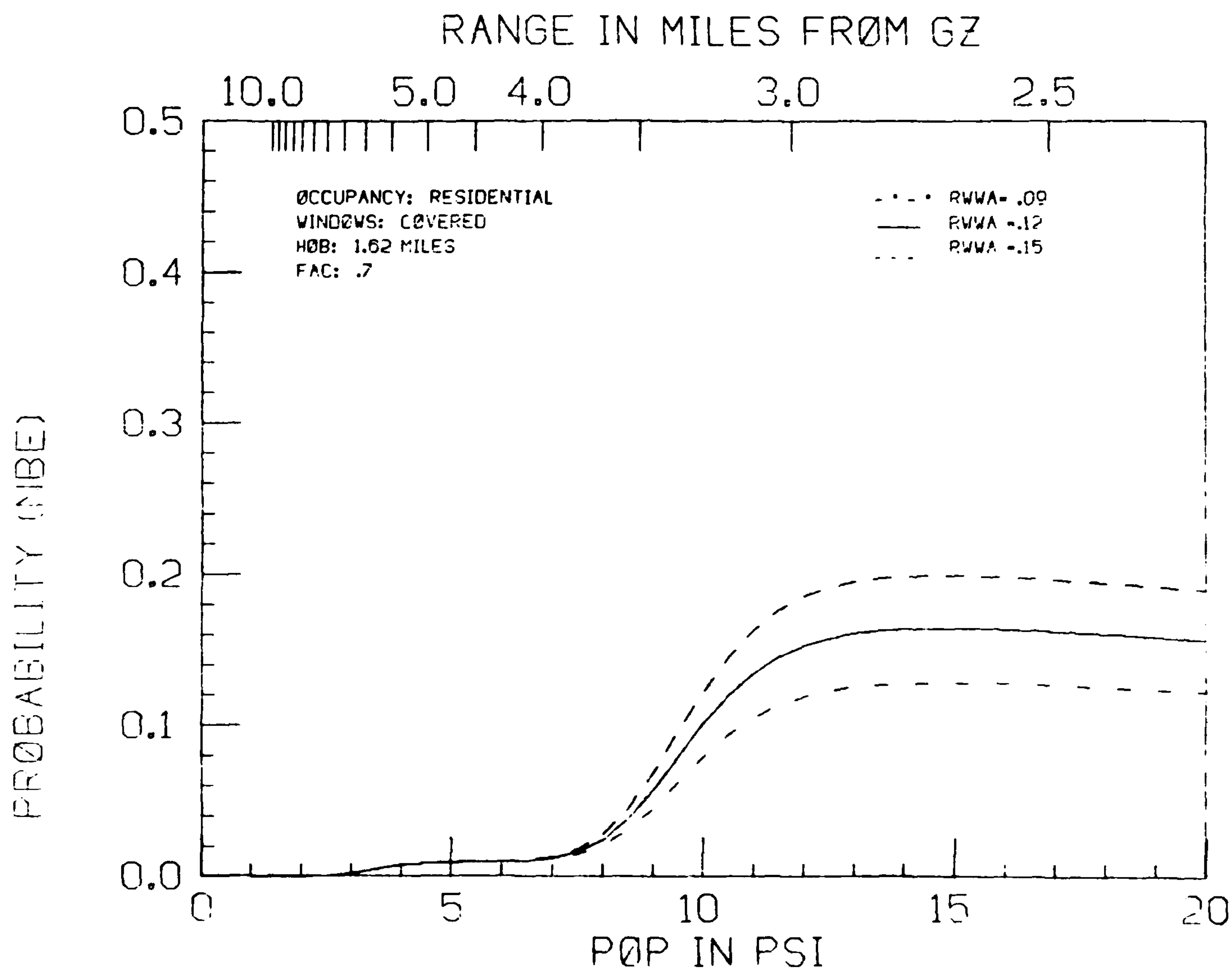

RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: RESIDENTIAL
WINDØWS: UNCØVERED
HØB: 1.62 MILES
FAC: 1.0
RWWA= .09
RWWA =.12
RWWA =.15
PRØBABILITY (NBE)
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
PØP IN PSI

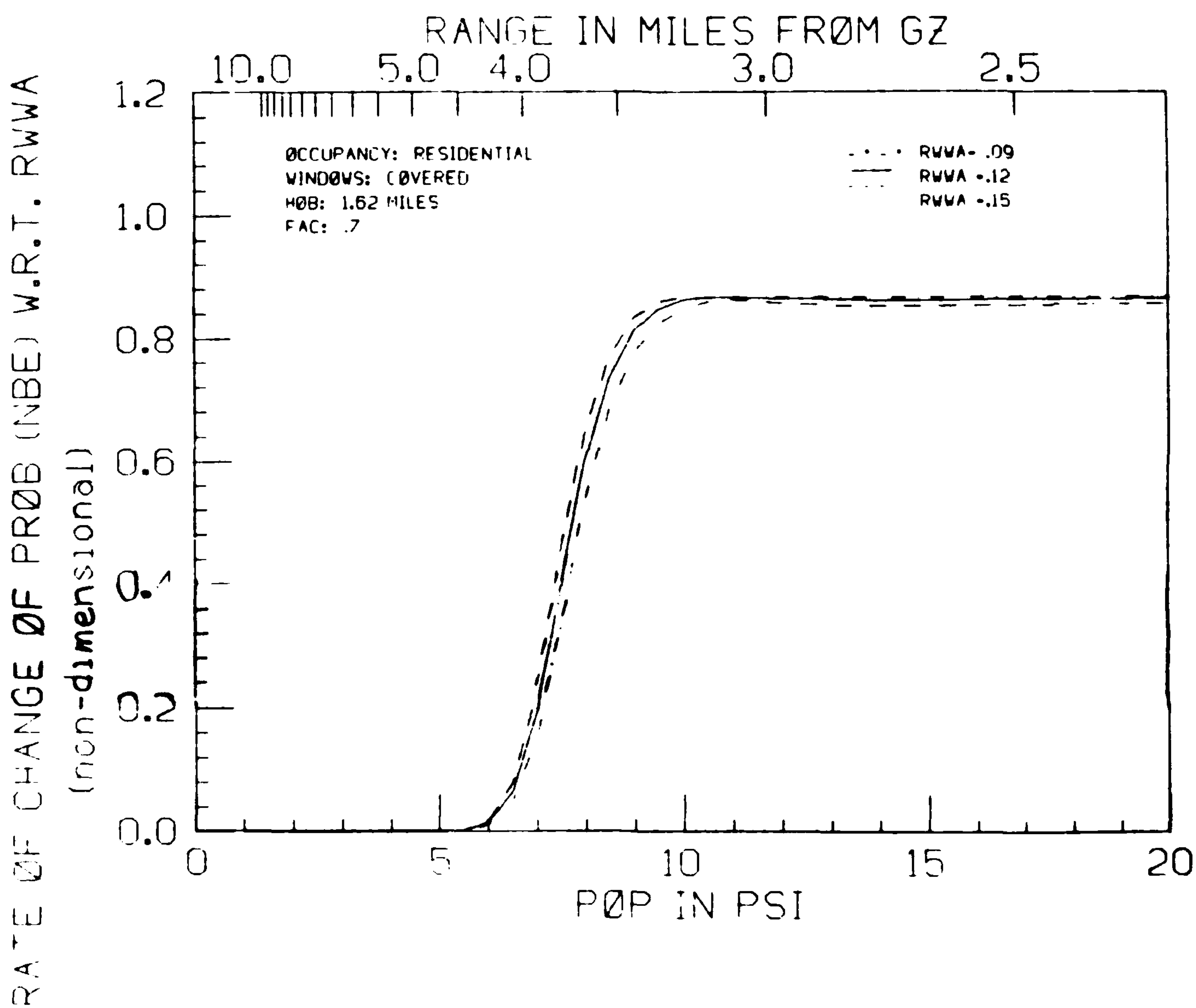

RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
1.2
1.0
0.8
0.6
0.4
0.2
0.0
ØCCUPANCY: RESIDENTIAL
WINDØWS: UNCØVERED
HØB: 1.62 MILES
FAC: 1.0
RWWA= .09
RWWA =.12
RWWA =.15
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)
0
5
10
15
20
PØP IN PSI

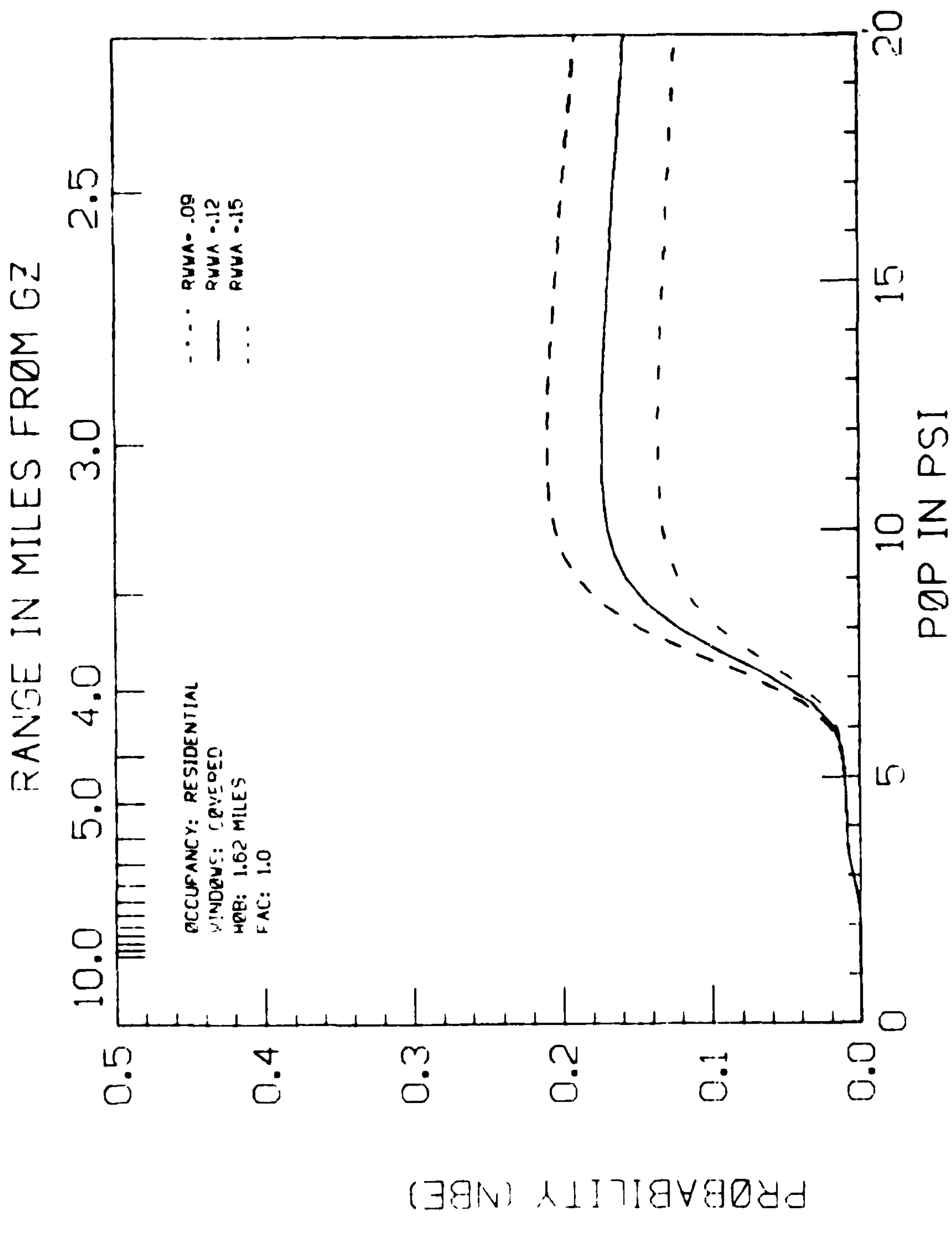

RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: RESIDENTIAL
WINDØWS: UNCØVERED
HØB: 1.62 MILES
FAC: 1.3
RWWA- .09
RWWA -.12
RWWA -.15
PRØBABILITY (NBE)
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
PØP IN PSI



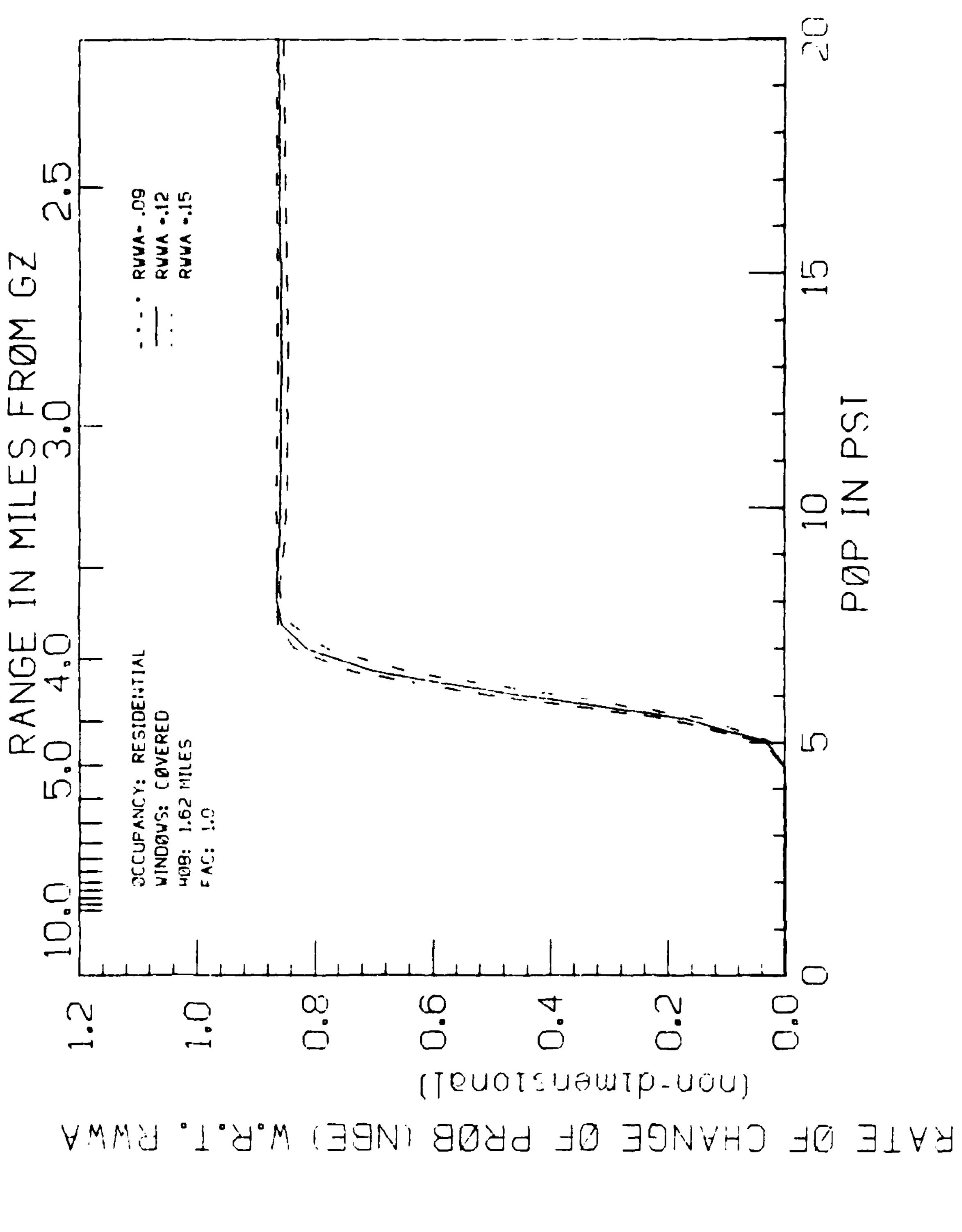
RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: RESIDENTIAL
WINDØWS: UNCØVERED
HØB: 1.62 MILES
FAC: 1.3
RWWA- .09
RWWA -.12
RWWA -.15
0
5
10
15
20
PØP IN PSI
1.2
1.0
0.8
0.6
0.4
0.2
0.0
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)


RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
0.5
0.4
0.3
0.2
0.1
0.0
ØCCUPANCY: RESIDENTIAL
WINDØWS: CØVERED
HØB: 1.62 MILES
FAC: .7
RWWA= .09
RWWA =.12
RWWA =.15
0
5
10
15
20
PØP IN PSI
PRØBABILITY (NIBE)

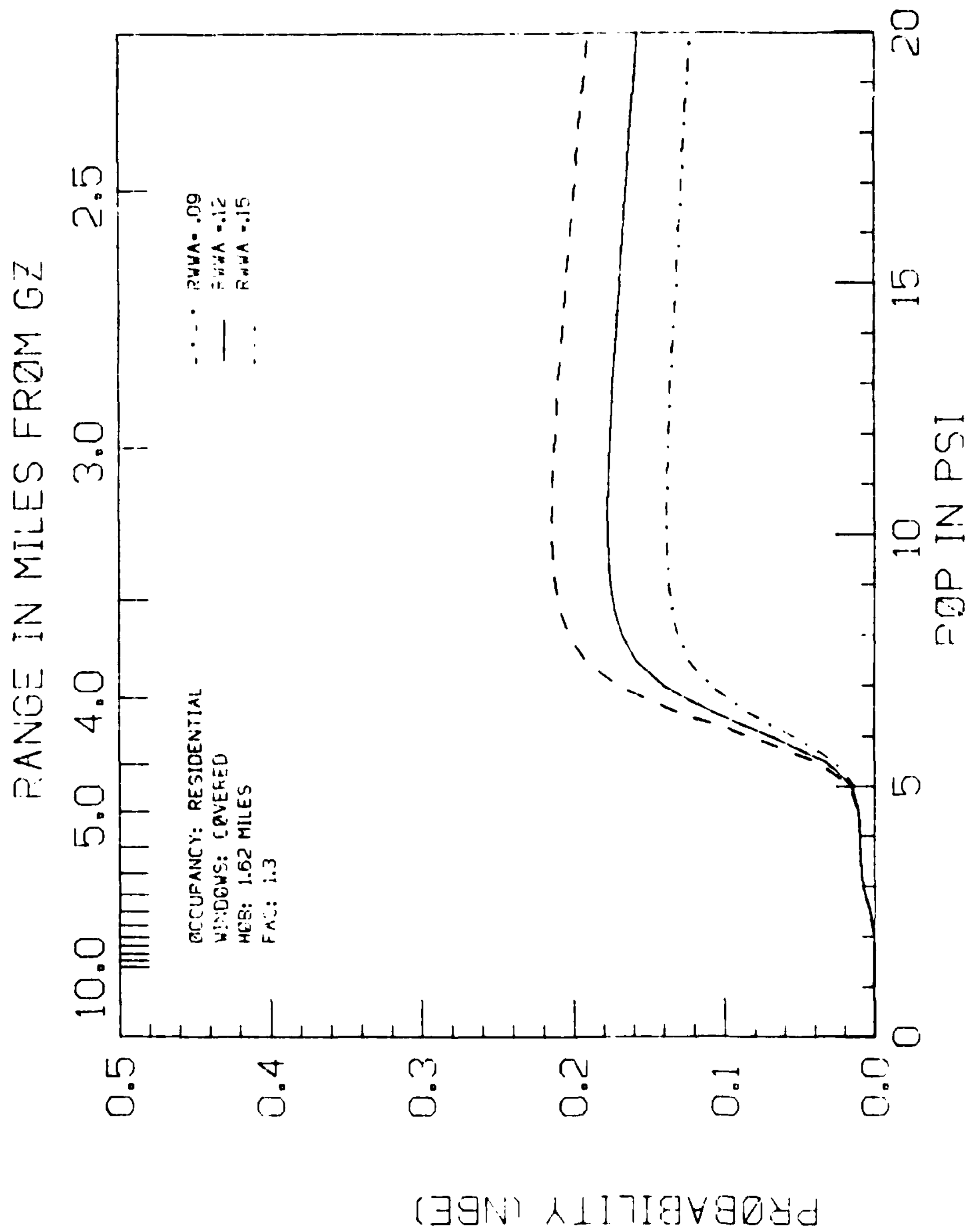

RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: RESIDENTIAL
WINDØWS: CØVERED
HØB: 1.62 MILES
FAC: .7
RWWA- .09
RWWA -.12
RWWA -.15
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)
1.2
1.0
0.8
0.6
0.2
0.0
0
5
10
15
20
PØP IN PSI

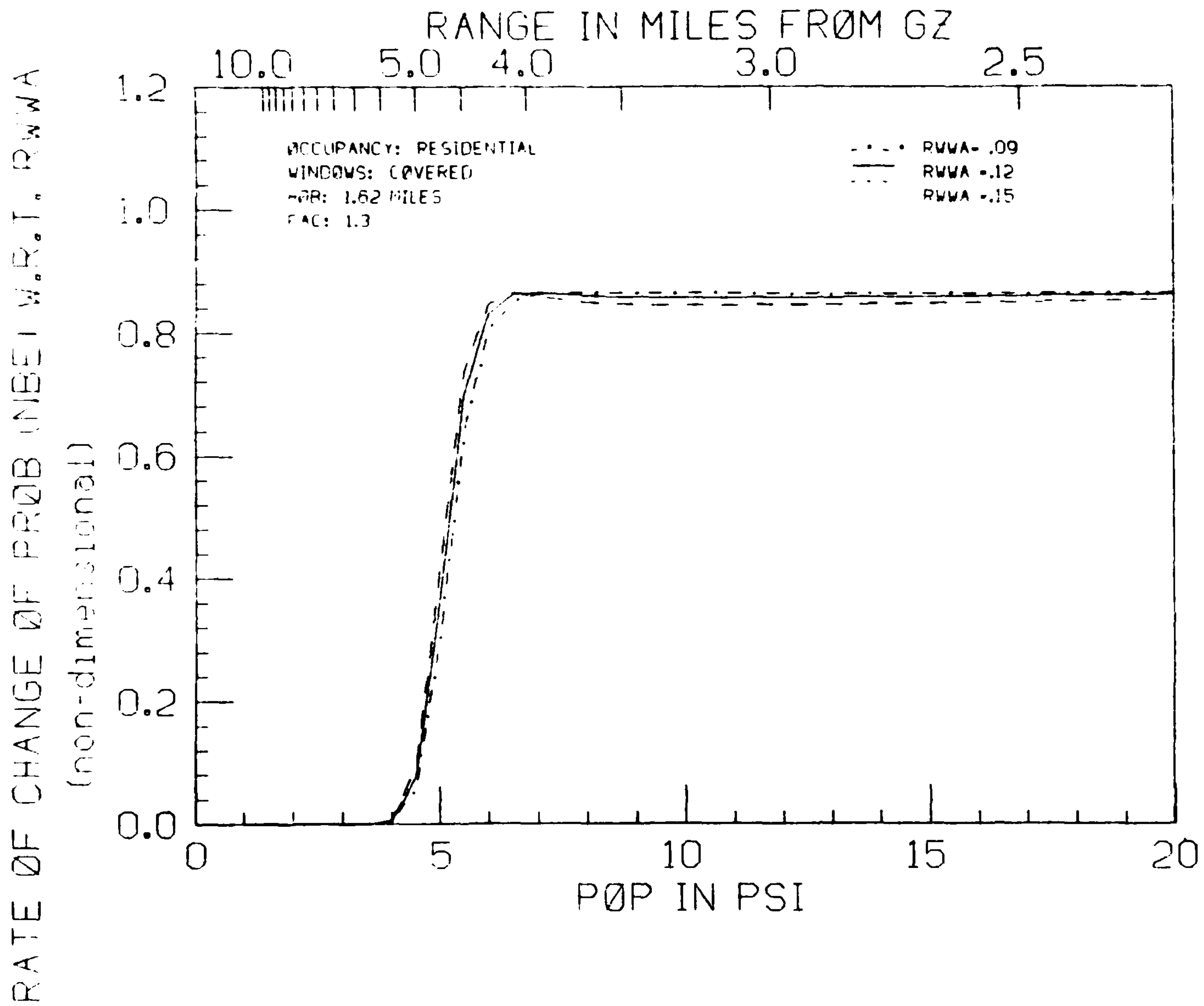


RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: RESIDENTIAL
WINDØWS: CØVERED
HØB: 1.62 MILES
FAC: 1.0
RWWA=.09
RWWA=.12
RWWA=.15
PRØBABILITY (NBE)
0.0
0.1
0.2
0.3
0.4
0.5
0
5
10
15
20
PØP IN PSI

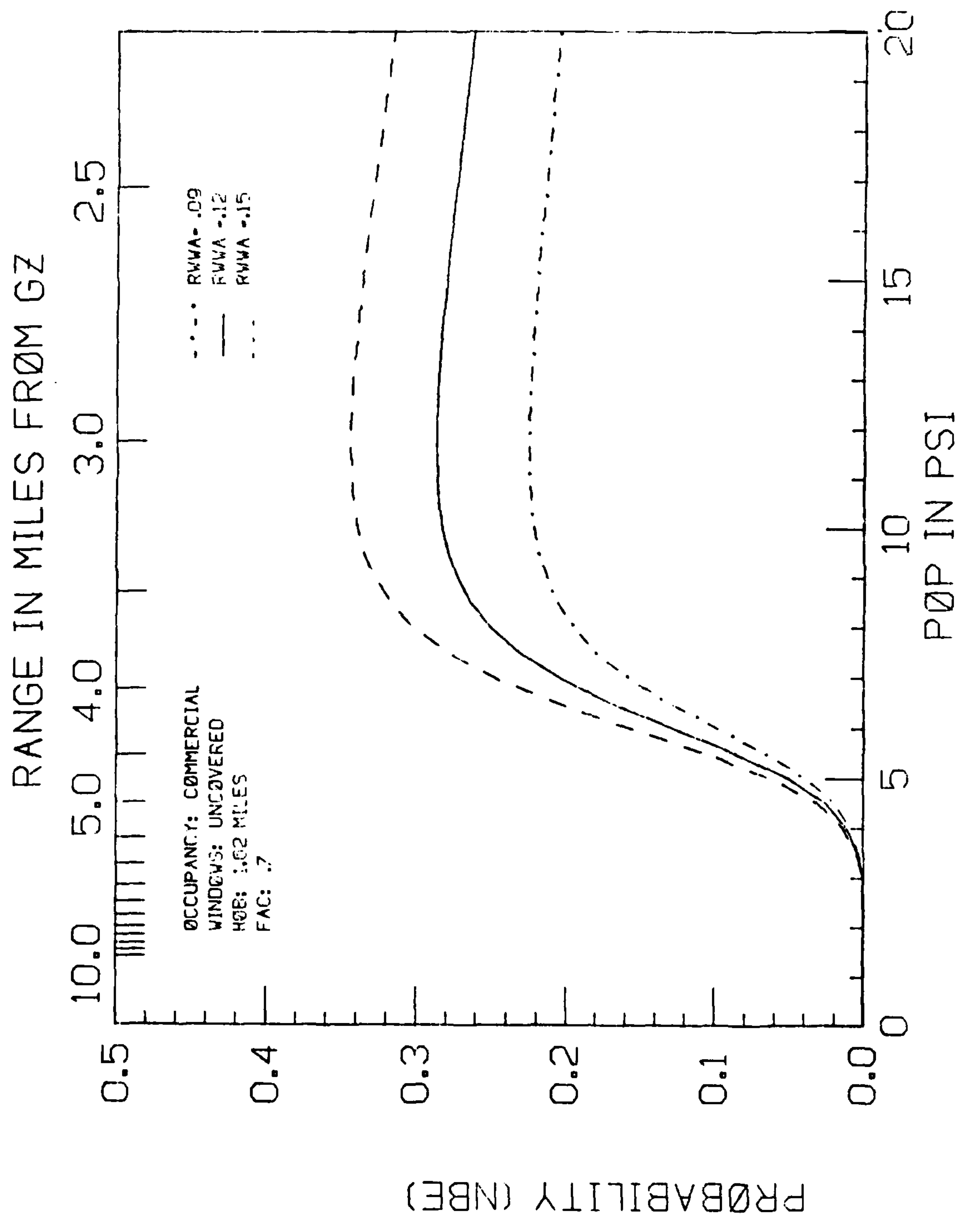


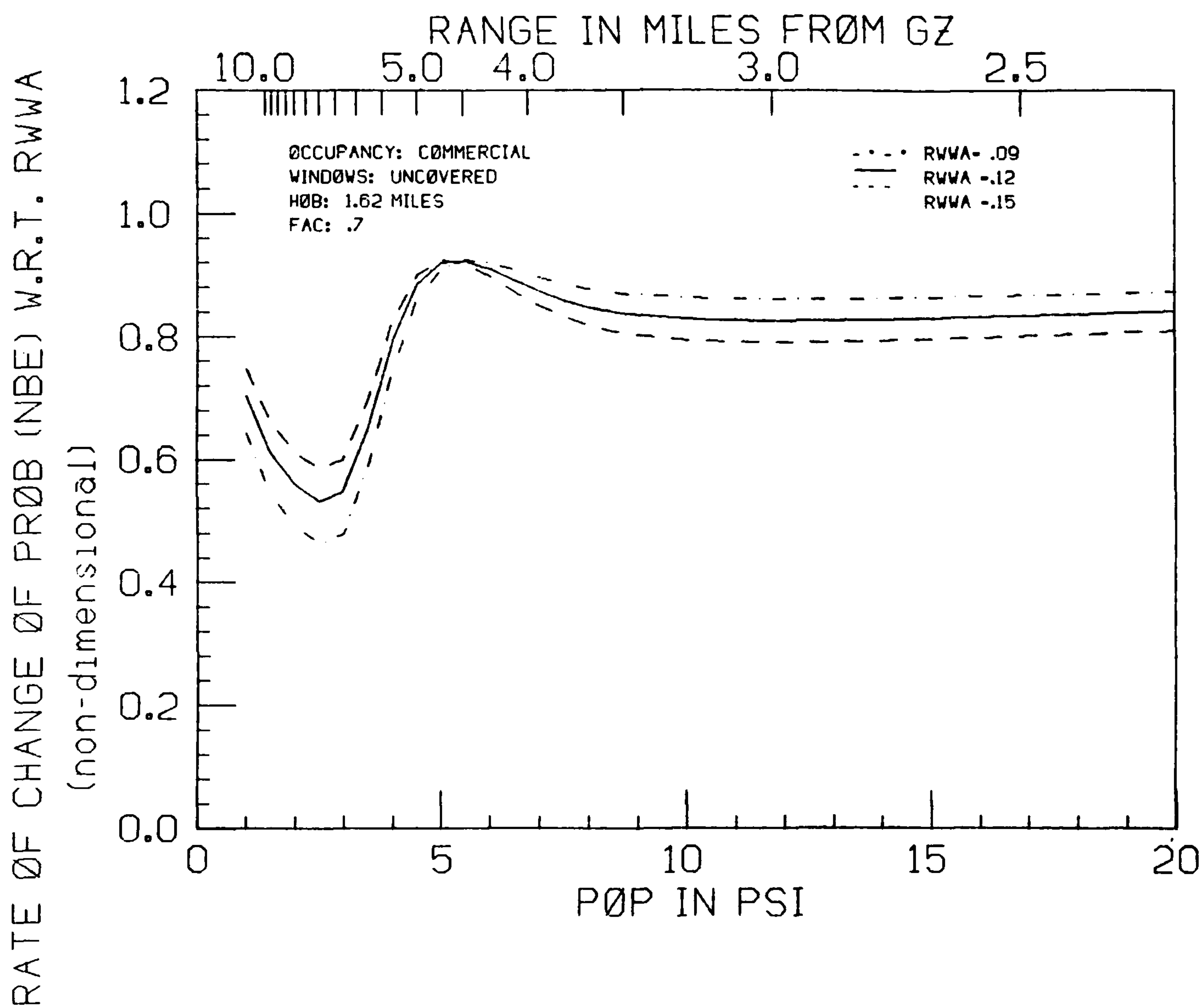
RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
OCCUPANCY: RESIDENTIAL
WINDØWS: CØVERED
HØB: 1.62 MILES
FAC: 1.0
RWWA=.09
RWWA=.12
RWWA=.15
0
5
10
15
20
PØP IN PSI
0.0
0.2
0.4
0.6
0.8
1.0
1.2
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)

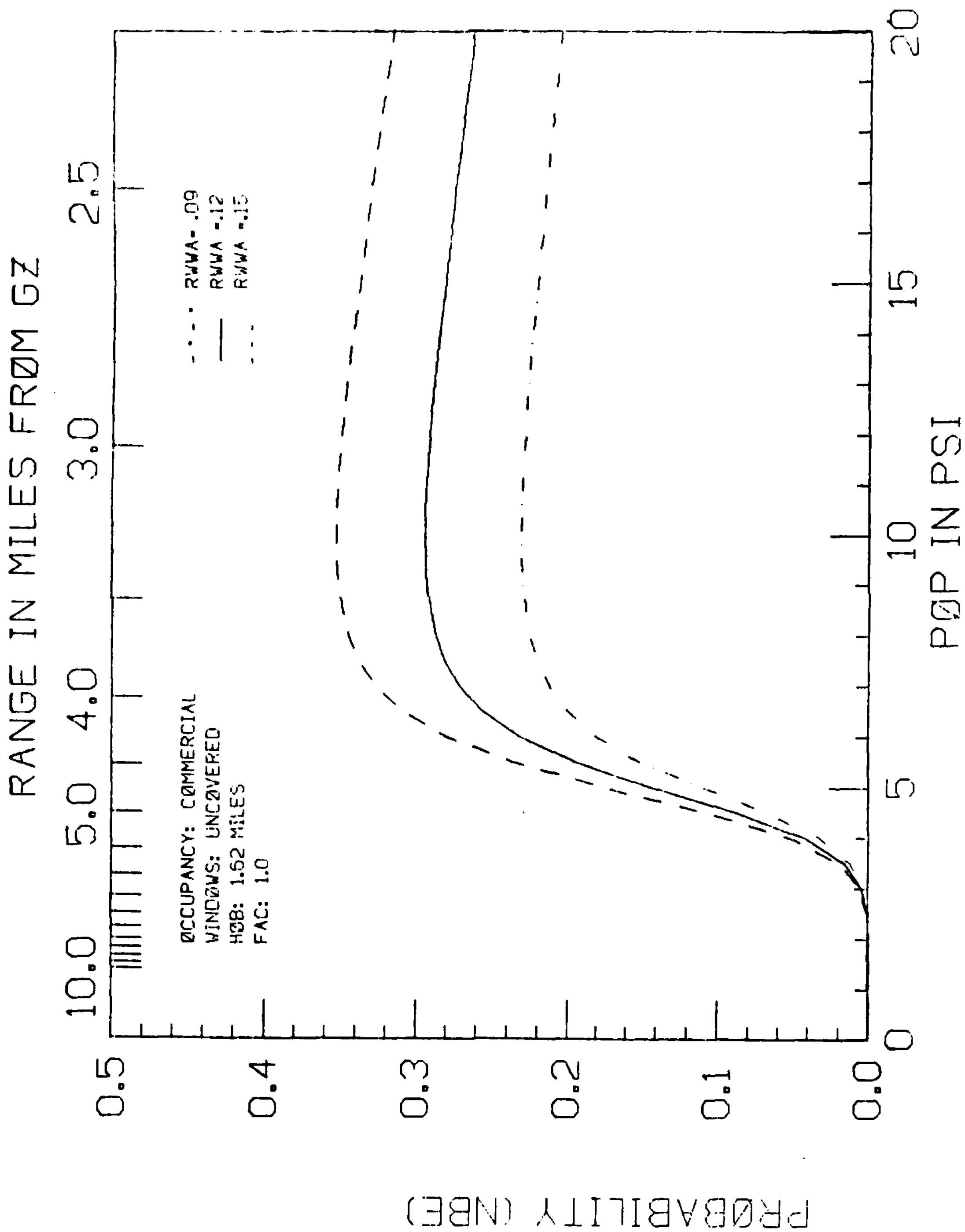

RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: RESIDENTIAL
WINDOWS: CØVERED
HØB: 1.62 MILES
FAC: 1.3
RWWA= .09
RWWA =.12
RWWA =.15
PRØBABILITY (NBE)
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
PØP IN PSI



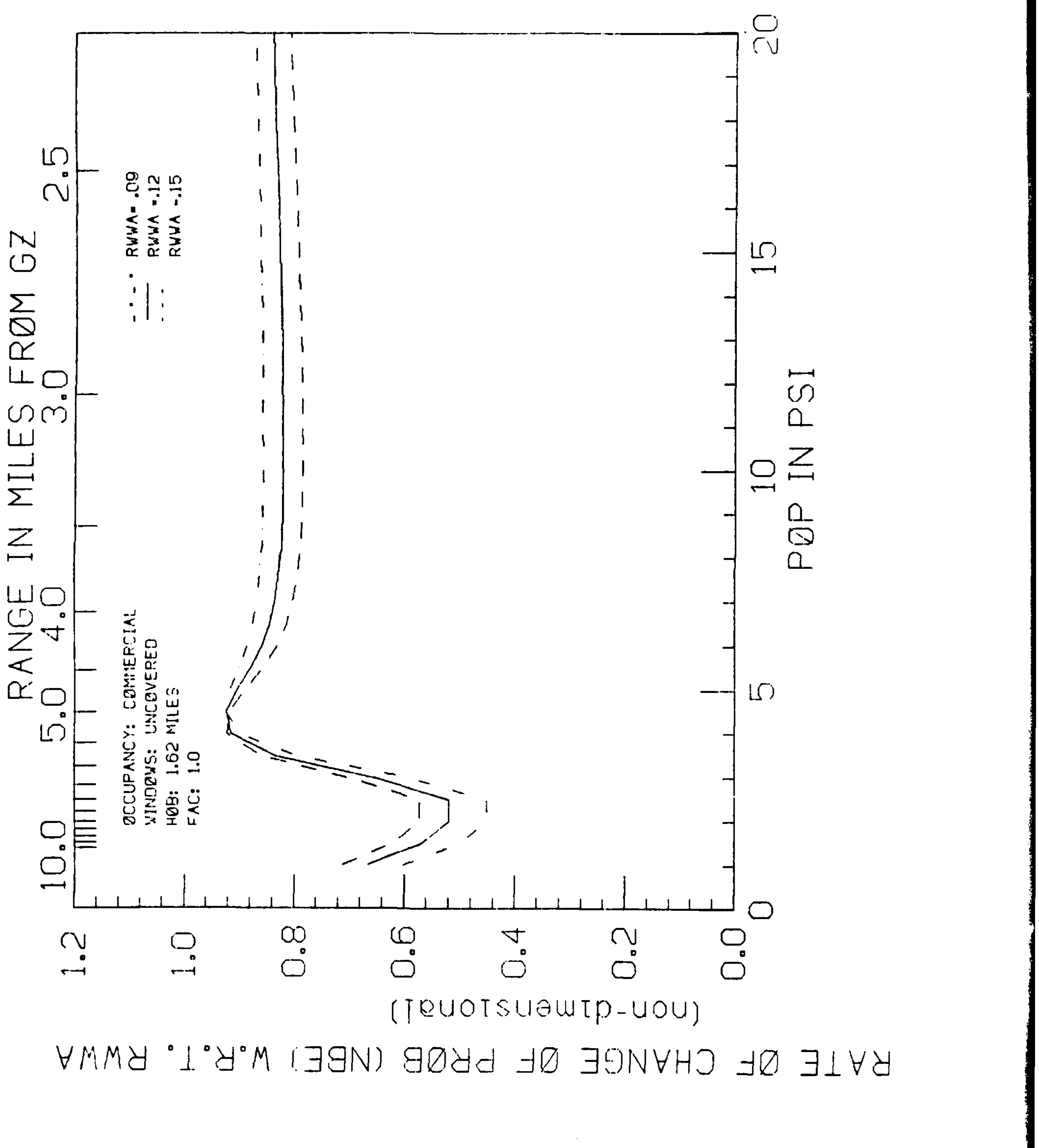
RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
1.2
1.0
0.8
0.6
0.4
0.2
0.0
ØCCUPANCY: RESIDENTIAL
WINDØWS: CØVERED
HØB: 1.62 MILES
FAC: 1.3
RWWA= .09
RWWA =.12
RWWA =.15
0
5
10
15
20
PØP IN PSI
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)

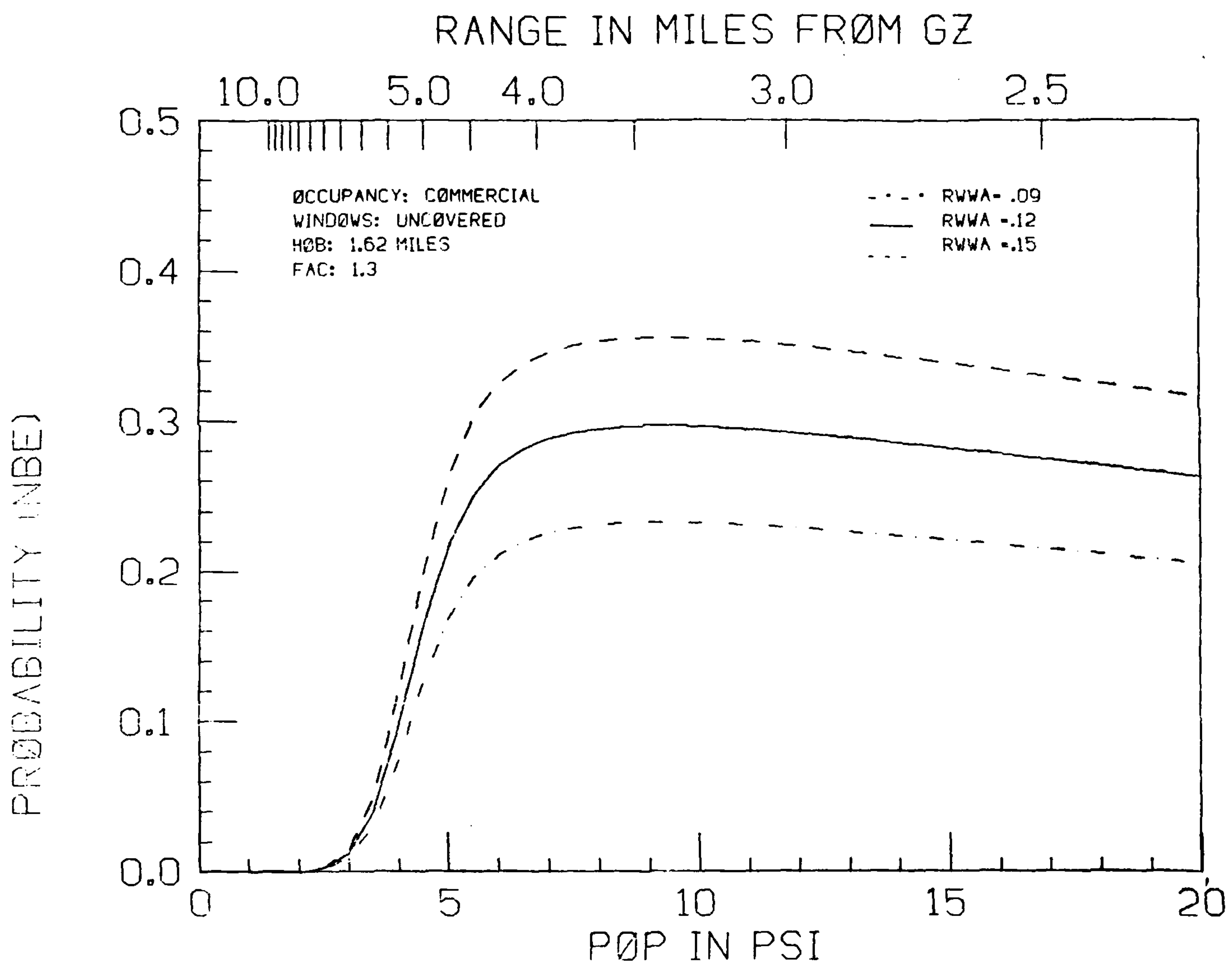

RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
RWWA=.09
RWWA =.12
RWWA =.15
ØCCUPANCY: CØMMERCIAL
WINDØWS: UNCØVERED
FAC: .7
0.5
0.4
0.3
0.2
0.1
0.0
PRØBABILITY (NBE)
0
5
10
15
20
PØP IN PSI

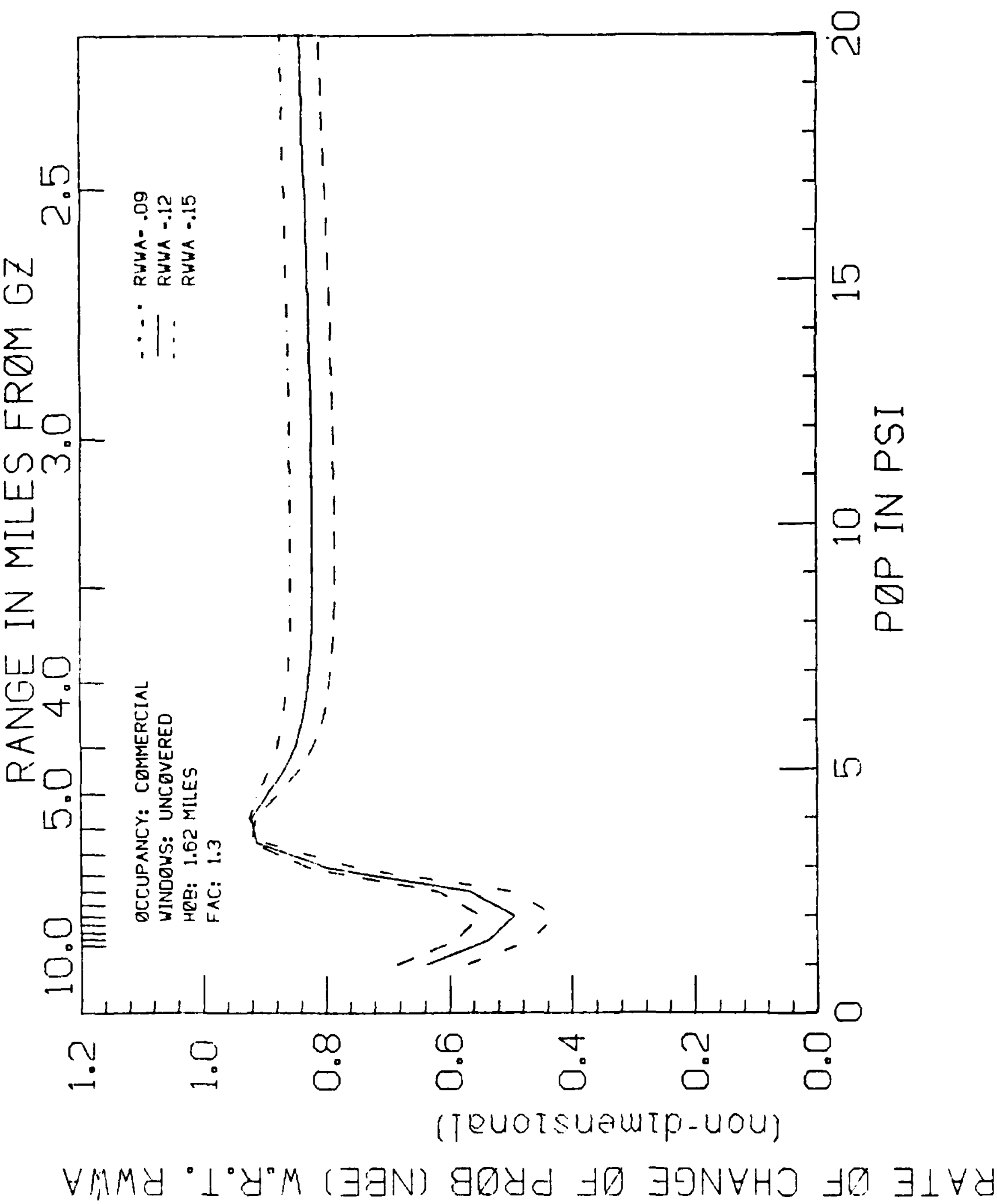

RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
PØP IN PSI
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)
ØCCUPANCY: CØMMERCIAL
WINDØWS: UNCØVERED
HØB: 1.62 MILES
FAC: .7
RWWA- .09
RWWA -.12
RWWA -.15

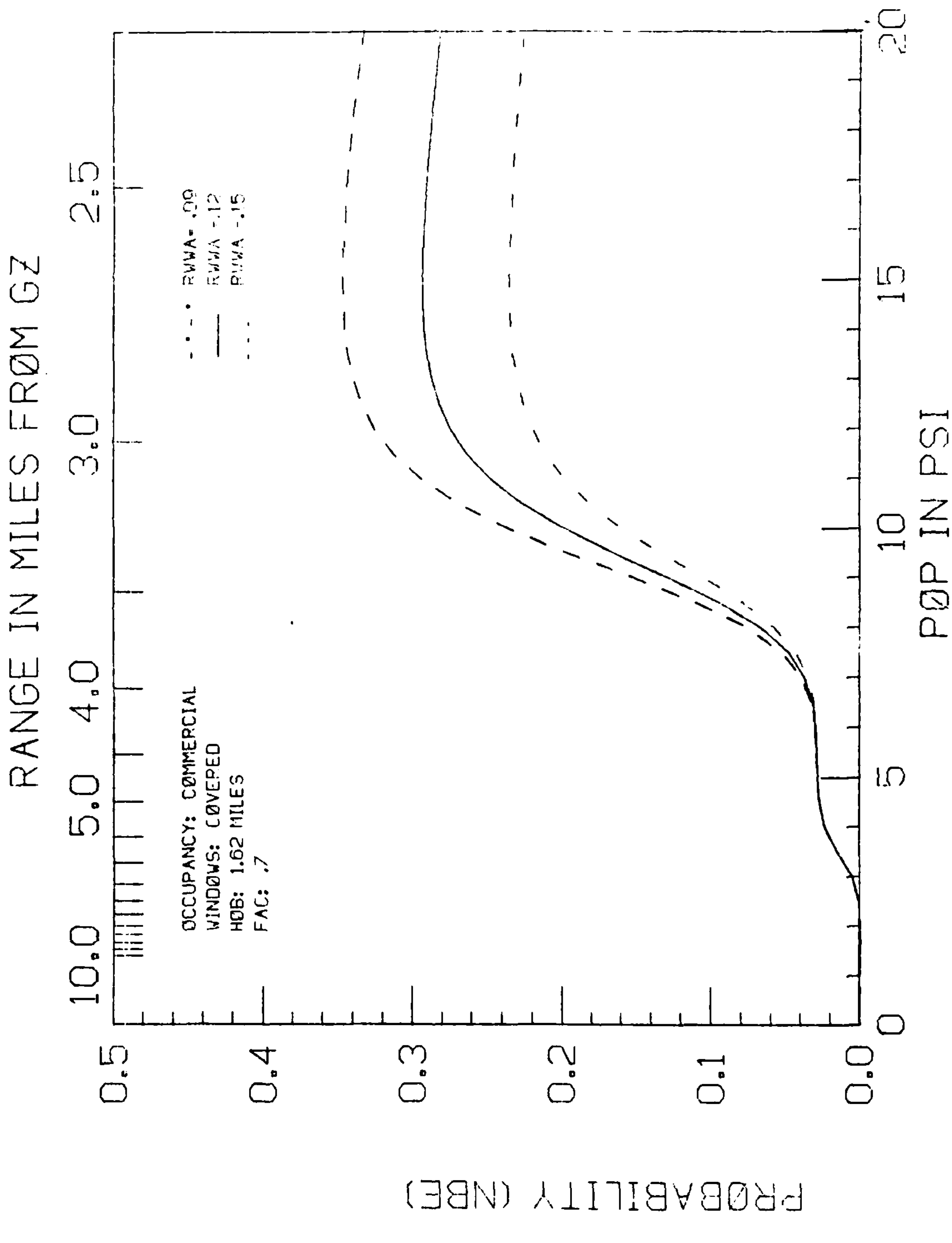


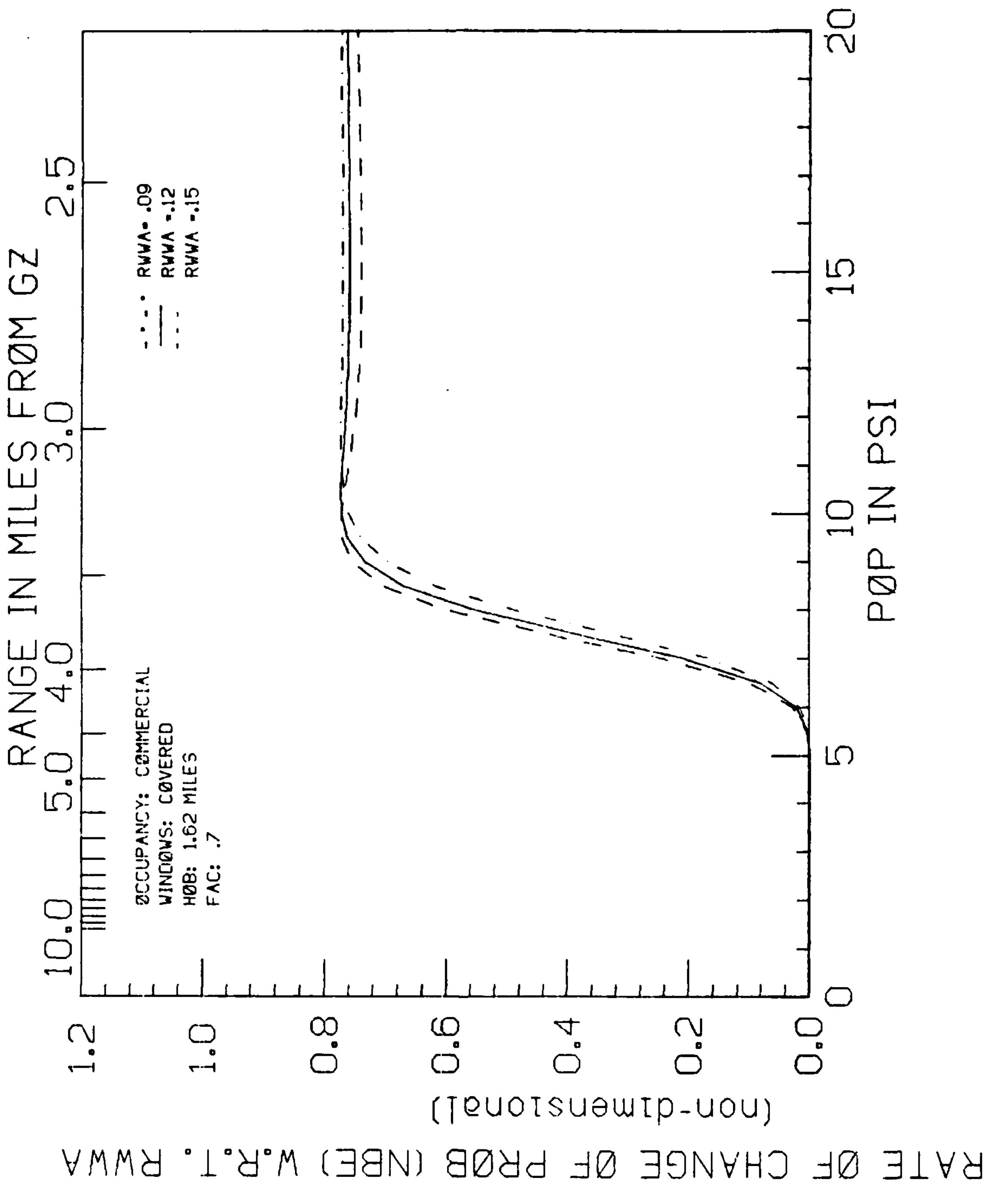
RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: CØMMERCIAL
WINDØWS: UNCØVERED
HØB: 1.52 MILES
FAC: 1.0
RWWA= .09
RWWA =.12
RWWA =.15
0.5
0.4
0.3
0.2
0.1
0.0
PRØBABILITY (NBE)
0
5
10
15
20
PØP IN PSI

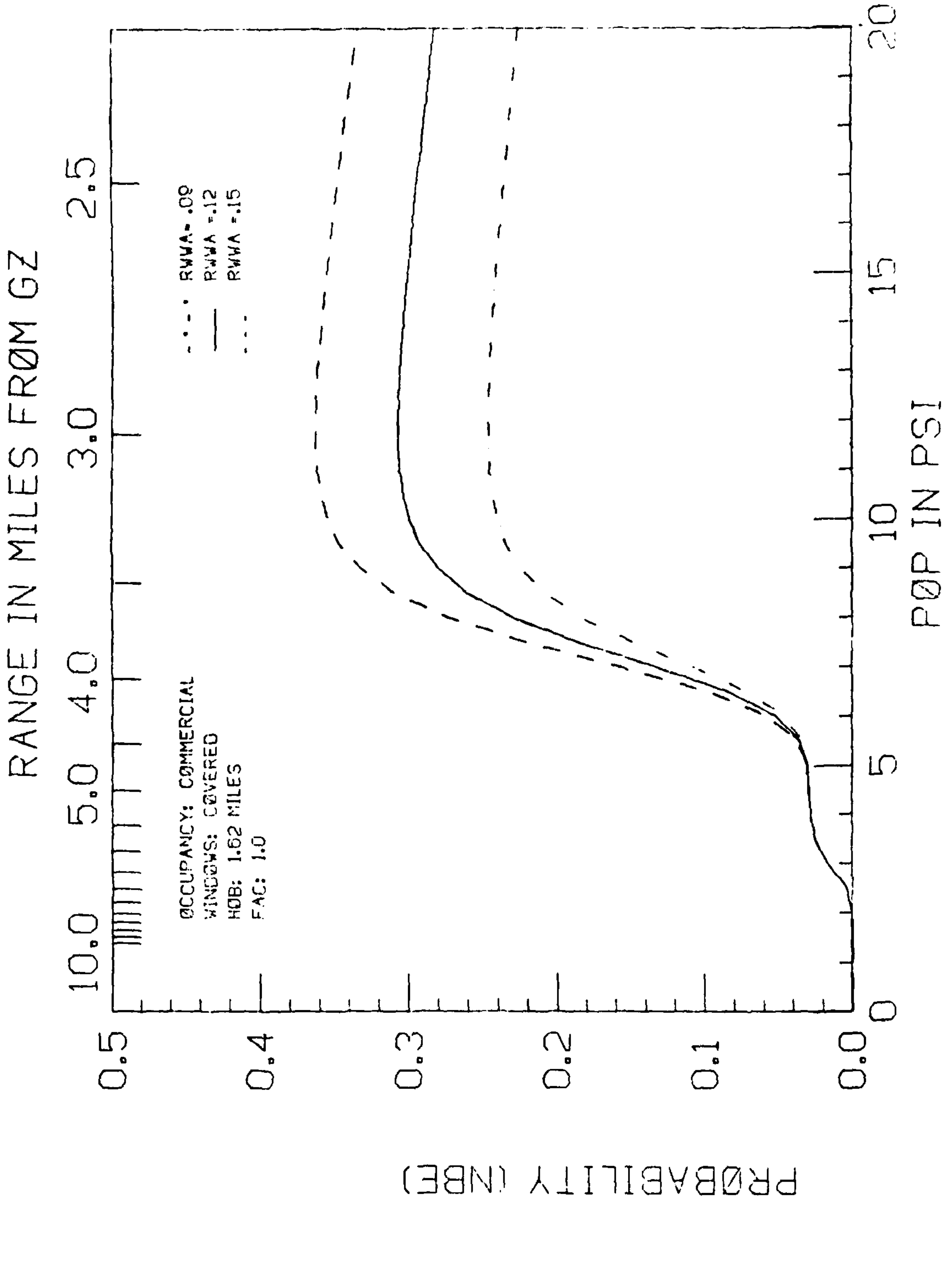

RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: CØMMERCIAL
WINDØWS: UNCØVERED
HØB: 1.62 MILES
FAC: 1.0
RWWA = .09
RWWA = .12
RWWA = .15
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
PØP IN PSI
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)

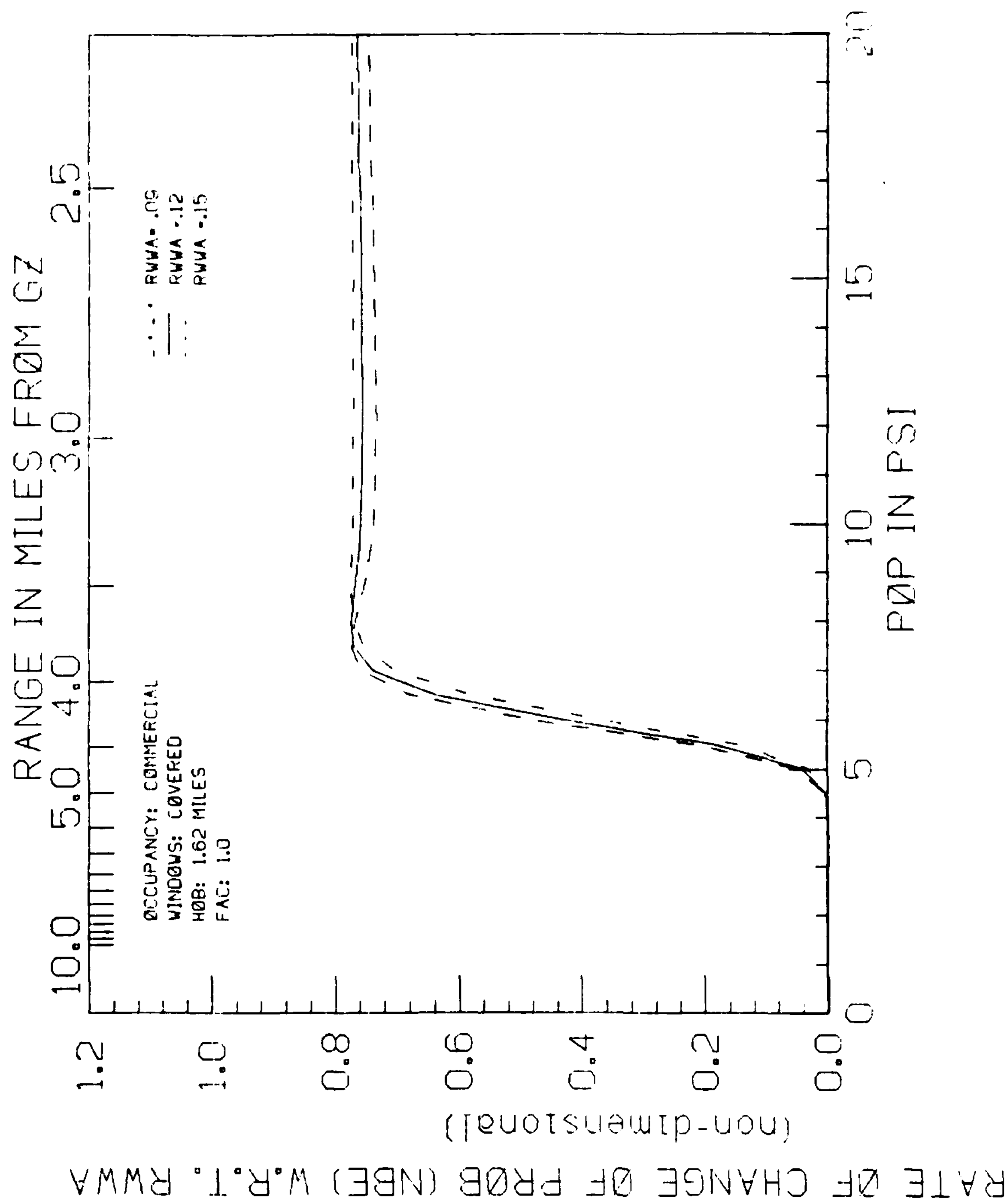

RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: CØMMERCIAL
WINDØWS: UNCØVERED
HØB: 1.62 MILES
FAC: 1.3
RWWA= .09
RWWA =.12
RWWA =.15
PRØBABILITY (NBE)
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
PØP IN PSI

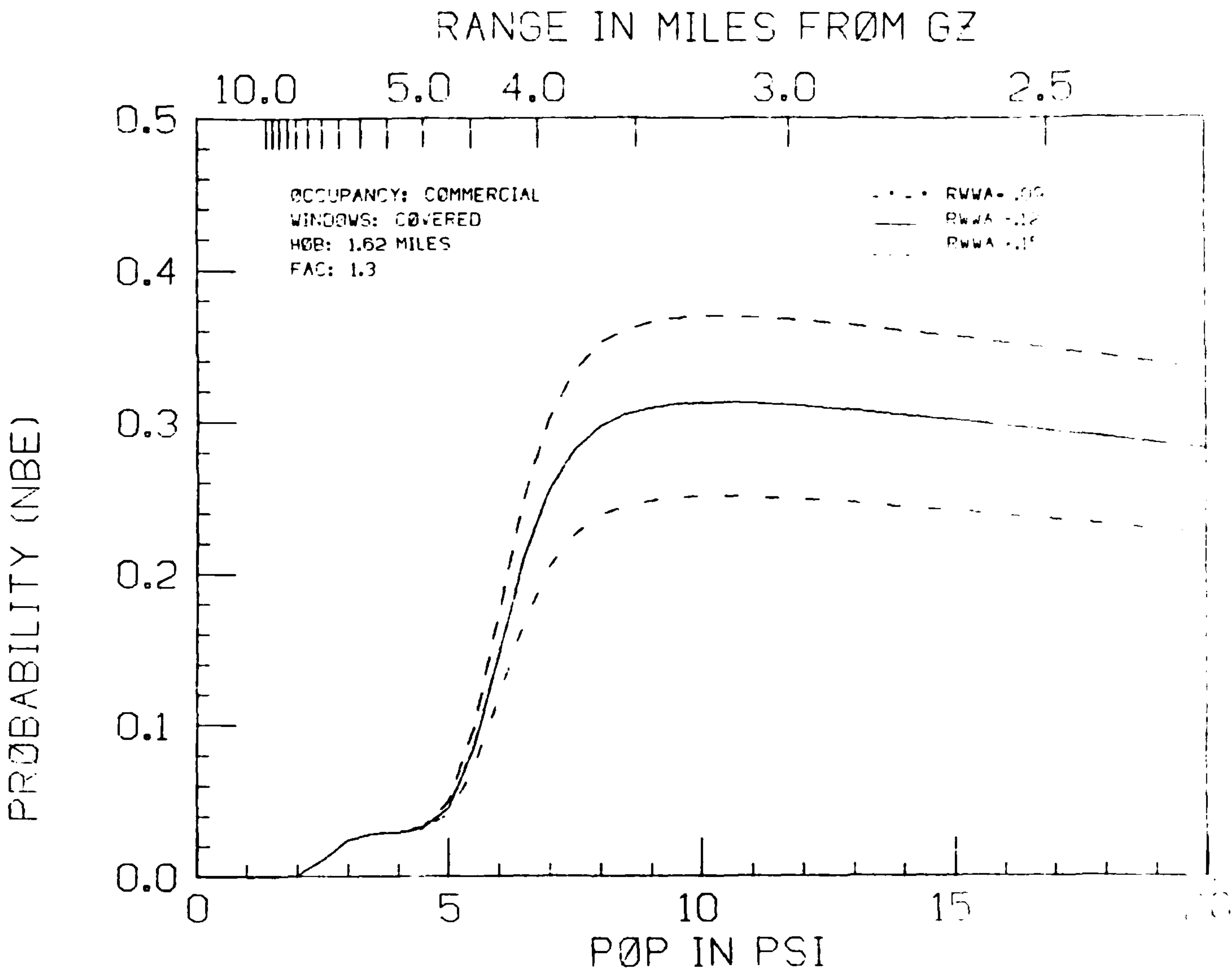

RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: CØMMERCIAL
WINDØWS: UNCØVERED
HØB: 1.62 MILES
FAC: 1.3
RWWA- .09
RWWA -.12
RWWA -.15
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
5
10
15
20
PØP IN PSI

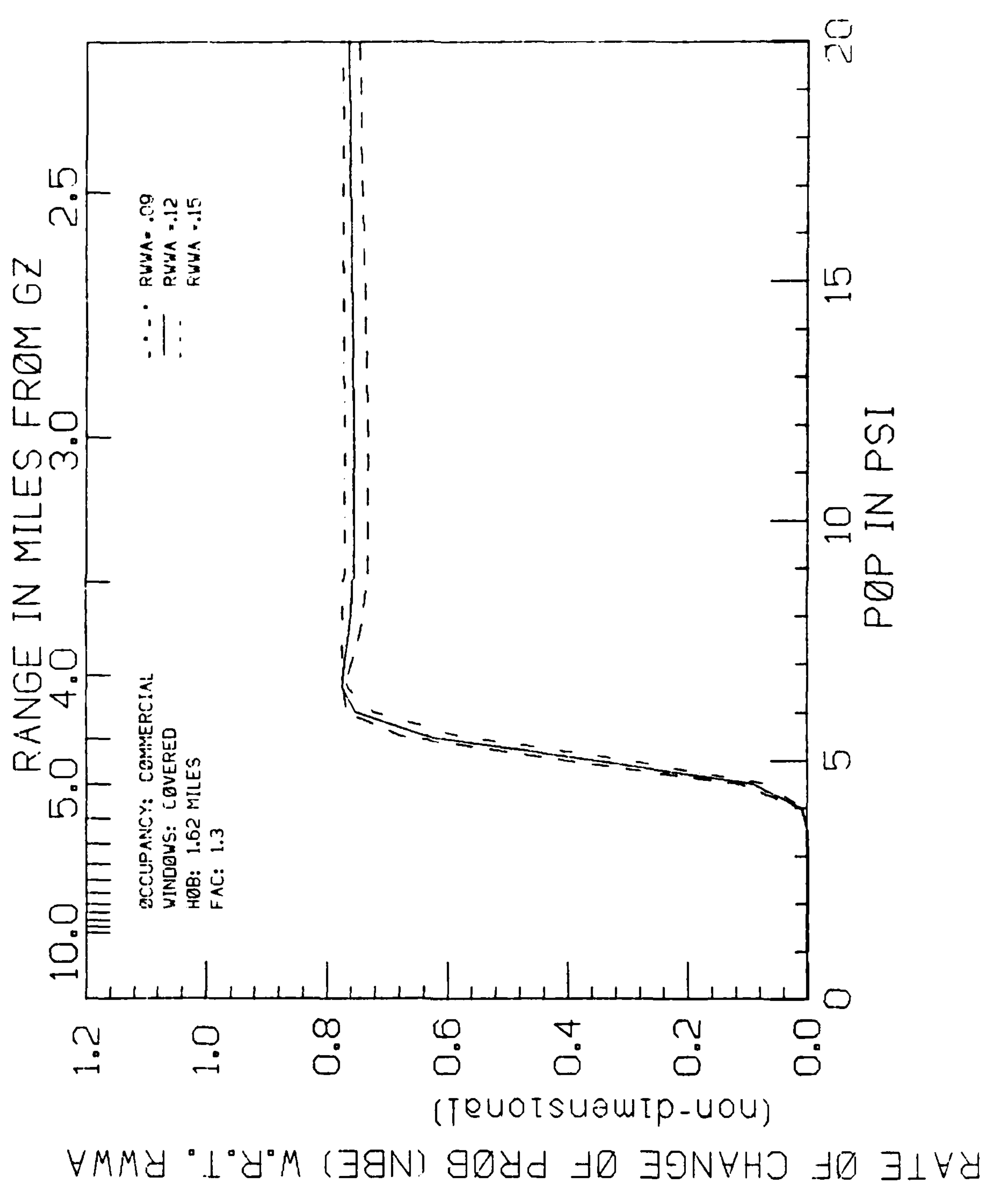

RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: CØMMERCIAL
WINDØWS: CØVERED
HØB: 1.62 MILES
FAC: .7
RWWA- .09
RWWA -.12
RWWA -.15
PRØBABILITY (NBE)
0.0
0.1
0.2
0.3
0.4
0.5
PØP IN PSI
0
5
10
15
20

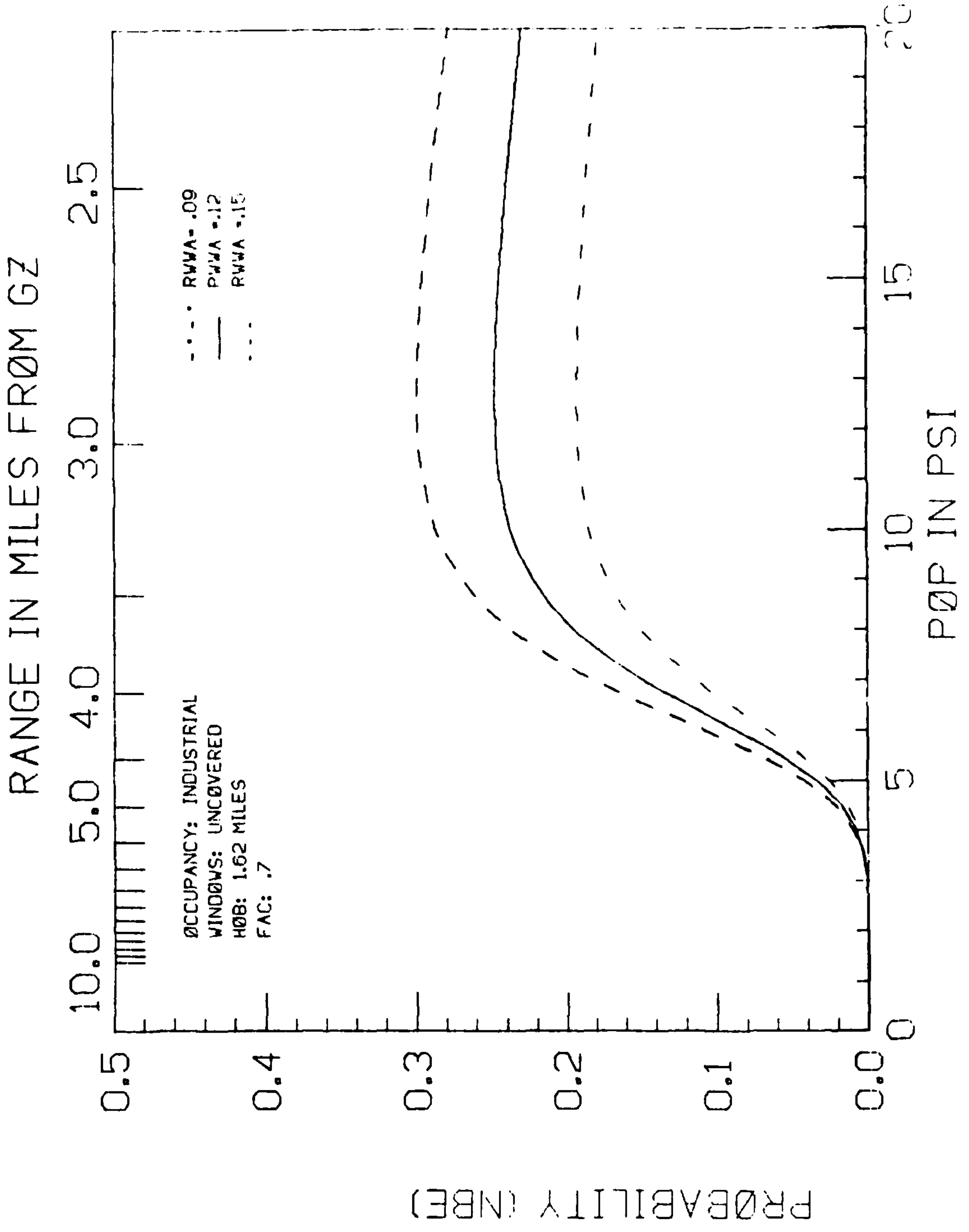

RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: CØMMERCIAL
WINDØWS: CØVERED
HØB: 1.62 MILES
FAC: .7
RWWA= .09
RWWA =.12
RWWA =.15
0
5
10
15
20
PØP IN PSI
0.0
0.2
0.4
0.6
0.8
1.0
1.2
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)

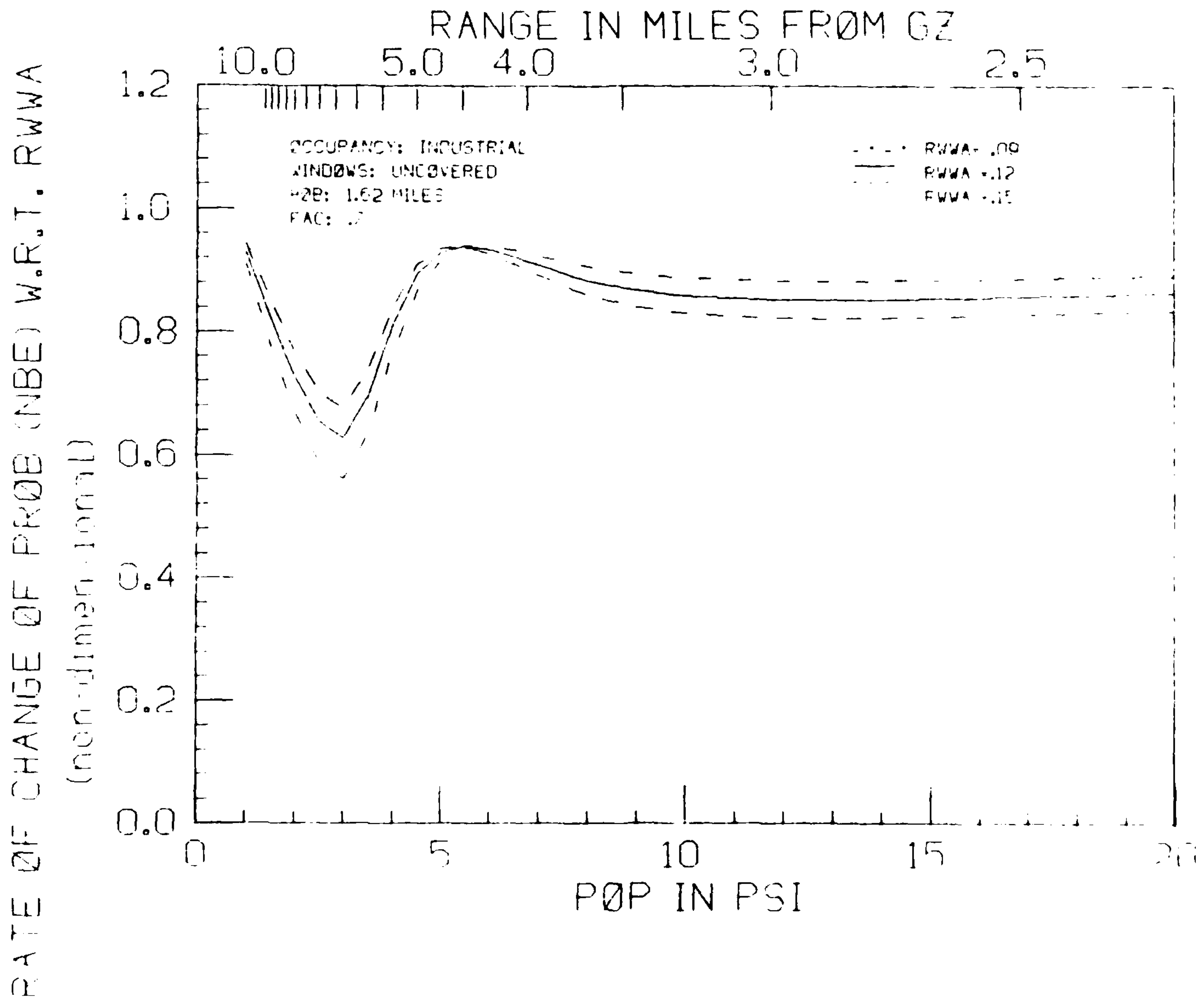

RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: CØMMERCIAL
WINDØWS: CØVERED
HØB: 1.62 MILES
FAC: 1.0
RWWA= .09
RWWA =.12
RWWA =.15
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
PØP IN PSI
PRØBABILITY (NBE)

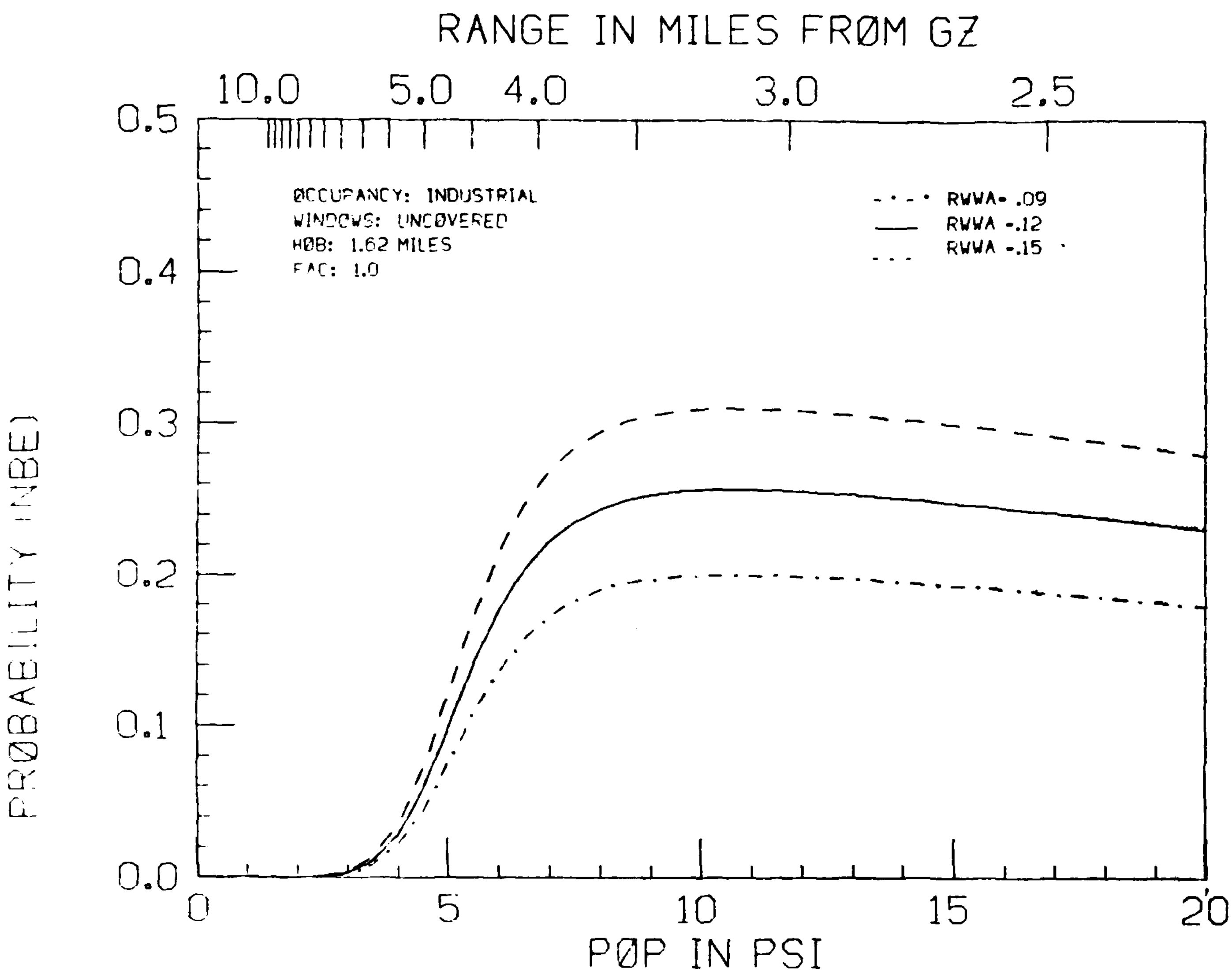

RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: CØMMERCIAL
WINDØWS: CØVERED
HØB: 1.62 MILES
FAC: 1.0
RWWA= .09
RWWA = .12
RWWA = .15
0
5
10
15
20
PØP IN PSI
0.0
0.2
0.4
0.6
0.8
1.0
1.2
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)


RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: CØMMERCIAL
WINDØWS: CØVERED
HØB: 1.62 MILES
FAC: 1.3
RWWA
RWWA
RWWA
PRØBABILITY (NBE)
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
PØP IN PSI


RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: CØMMERCIAL
WINDØWS: CØVERED
HØB: 1.62 MILES
FAC: 1.3
RWWA= .09
RWWA =.12
RWWA =.15
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
PØP IN PSI


RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
PØP IN PSI
0
5
10
15
20
PRØBABILITY (NBE)
0.0
0.1
0.2
0.3
0.4
0.5
ØCCUPANCY: INDUSTRIAL
WINDØWS: UNCØVERED
HØB: 1.62 MILES
FAC: .7
RWWA- .09
RWWA -.12
RWWA -.15


RANGE IN MILES FRØM GZ
10.0
5.0
4.0
3.0
2.5
ØCCUPANCY: INDUSTRIAL
WINDØWS: UNCØVERED
RWWA=.09
RWWA=.12
RWWA=.15
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
PØP IN PSI
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimen-ional)


RANGE IN MILES FRØM GZ
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5.0
4.0
3.0
2.5
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WINDOWS: UNCØVERED
HØB: 1.62 MILES
FAC: 1.0
RWWA- .09
RWWA -.12
RWWA -.15
PRØBABILITY (NBE)
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0.4
0.3
0.2
0.1
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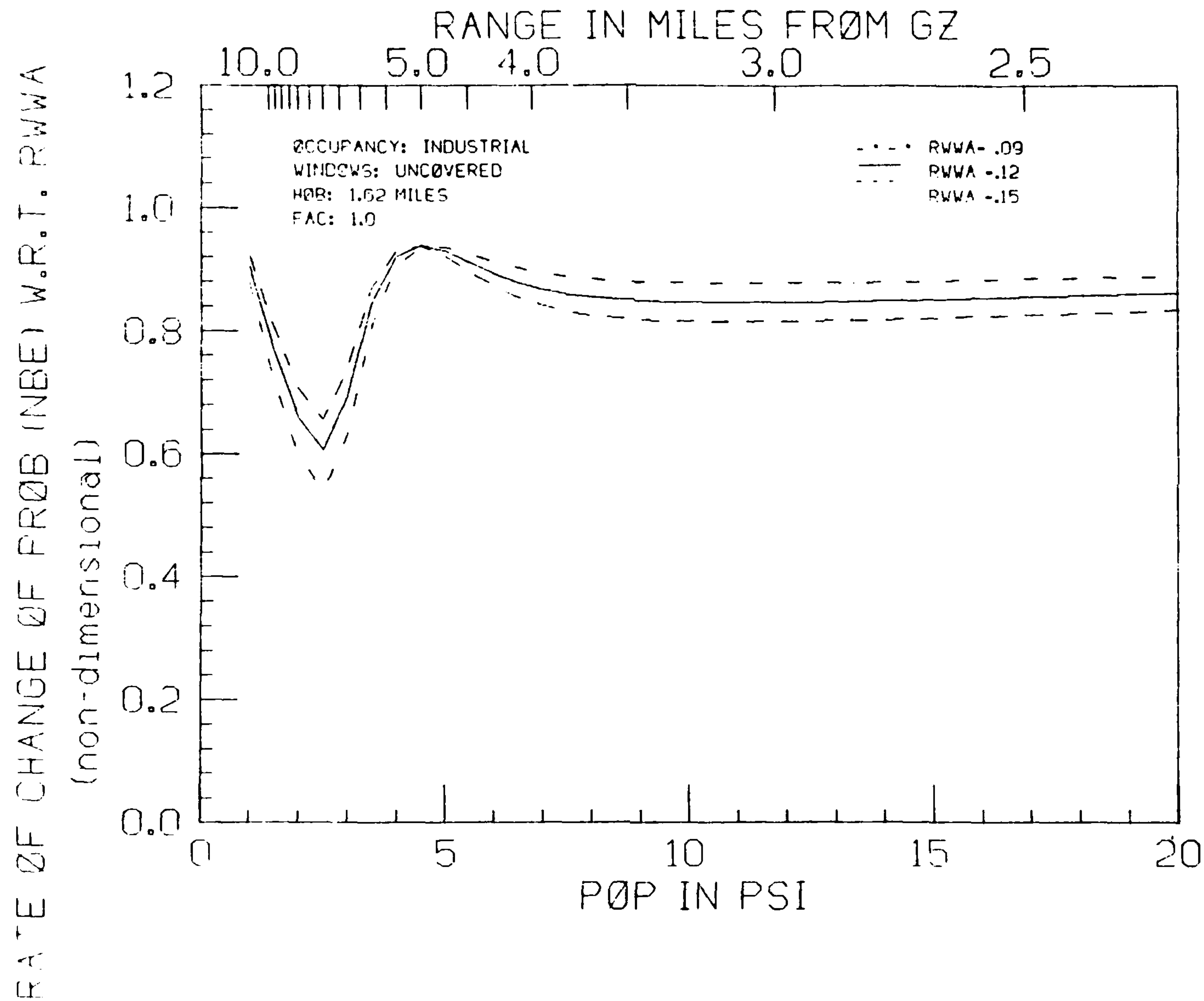
0
5
10
15
20
PØP IN PSI



RANGE IN MILES FRØM GZ
10.0
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3.0
2.5
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WINDØWS: UNCØVERED
HØB: 1.62 MILES
FAC: 1.0
RWWA-.09
RWWA -.12
RWWA -.15
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)
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0.8
0.6
0.4
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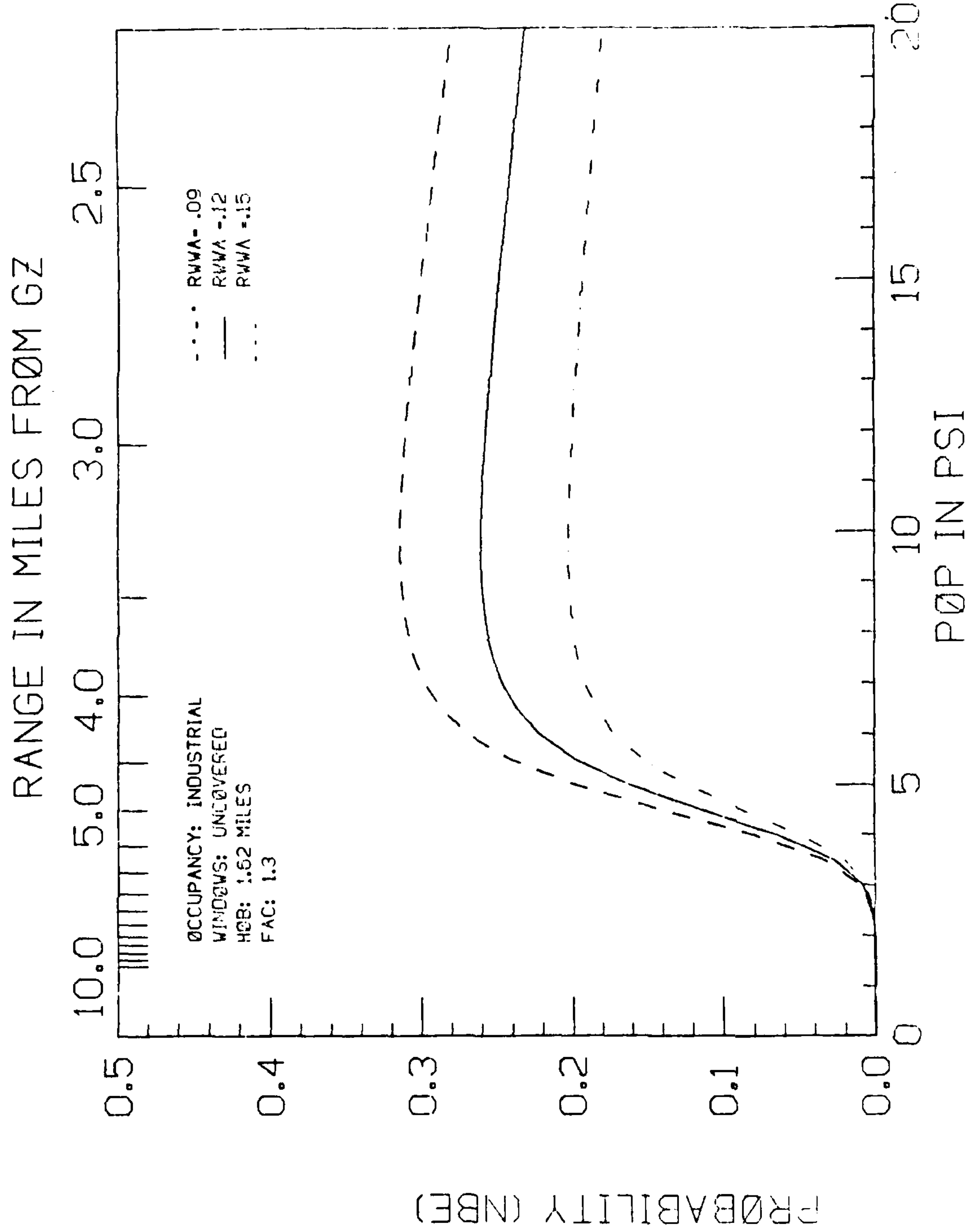
0
5
10
15
20
PØP IN PSI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HØB: 1.62 MILES
FAC: 1.3
RWWA- .09
RWWA -.12
RWWA -.15
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0.4
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0.2
0.1
0.0
0
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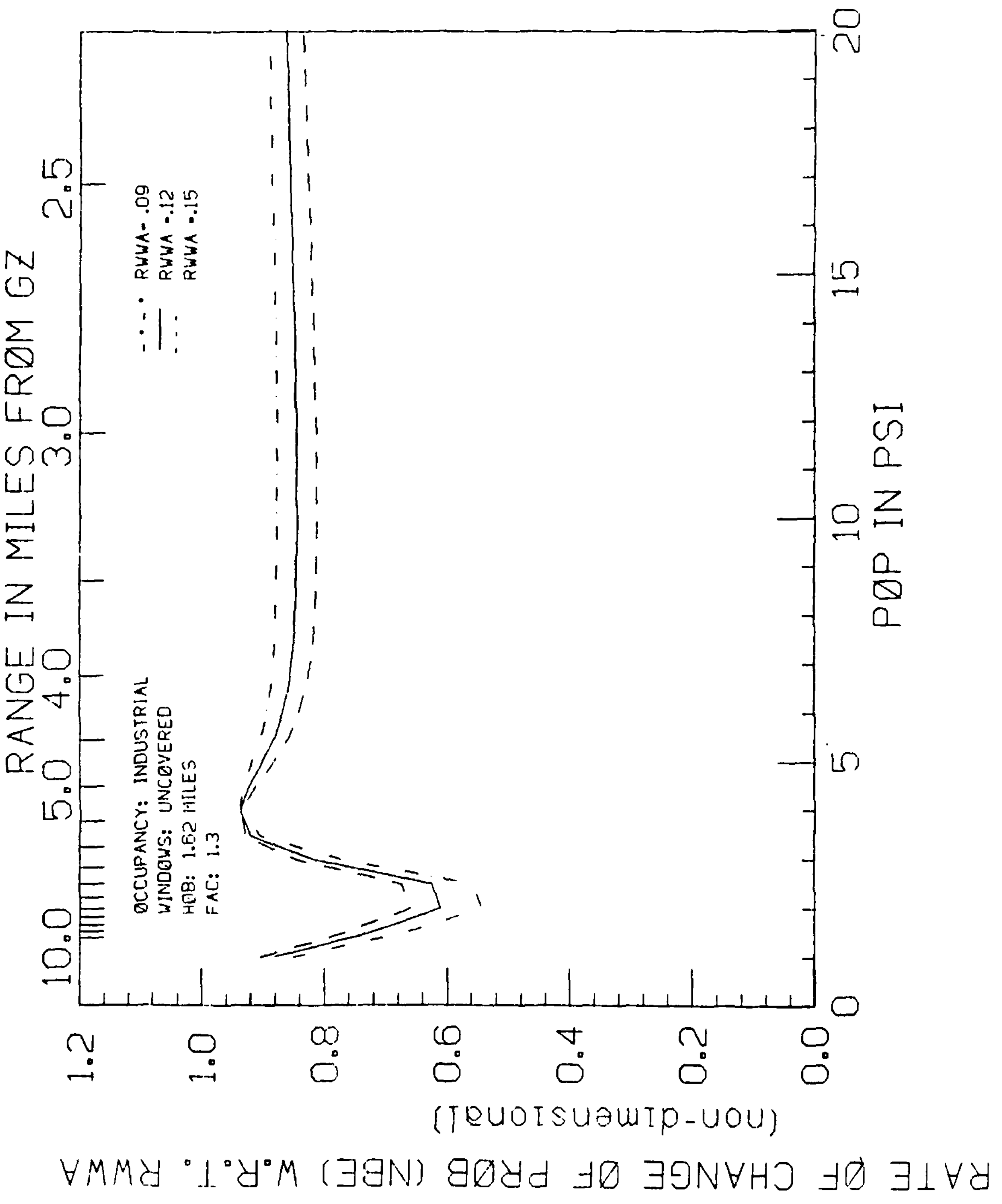
15
20
PØP IN PSI
PRØBABILITY (NBE)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3.0
2.5
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WINDØWS: UNCØVERED
HØB: 1.62 MILES
FAC: 1.3
RWWA=.09
RWWA =.12
RWWA =.15
0
5
10
15
20
PØP IN PSI
0.0
0.2
0.4
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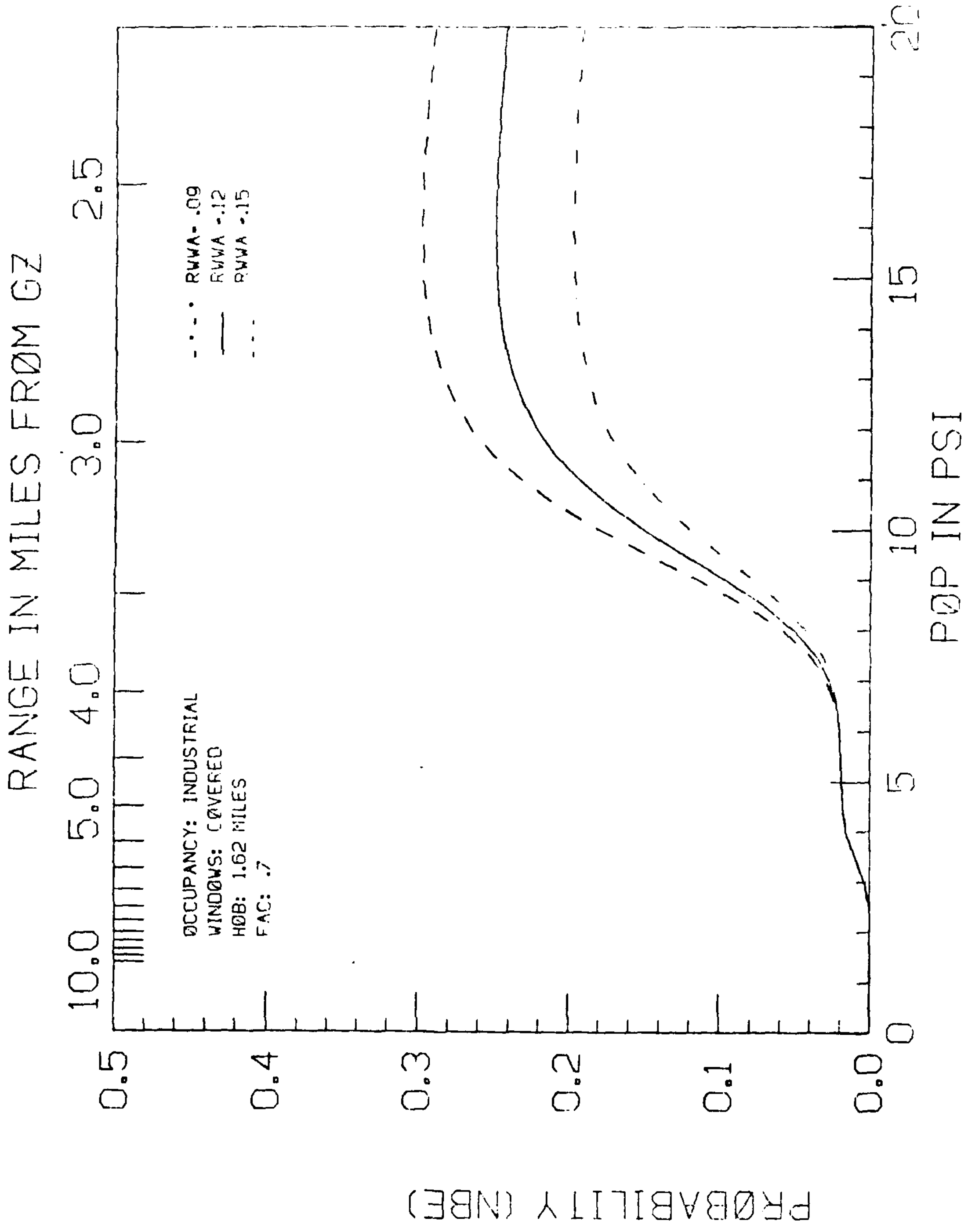
1.2
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)



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WINDØWS: CØVERED
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FAC: .7
RWWA- .09
RWWA -.12
RWWA -.15
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0.2
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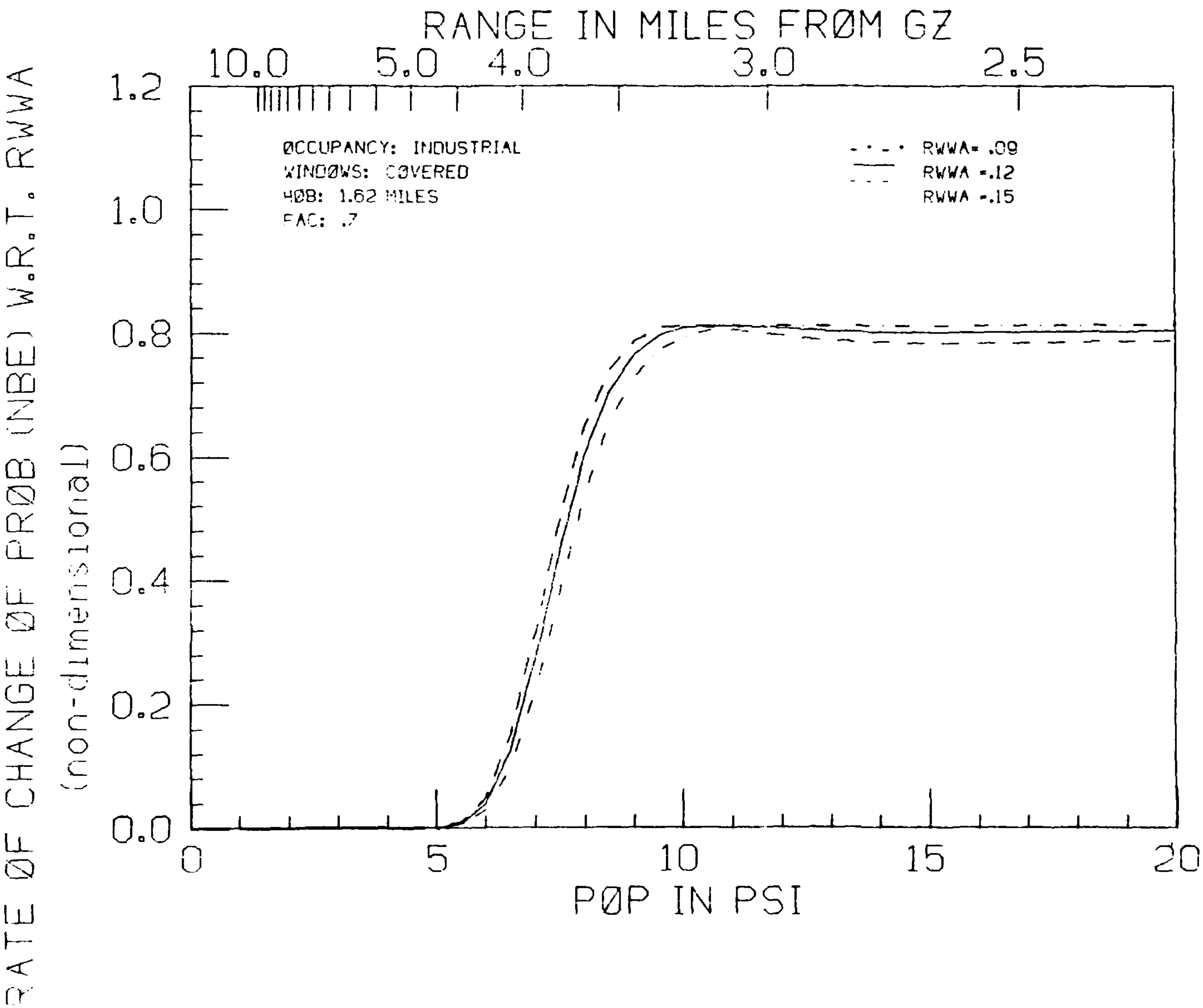
15
20
PØP IN PSI
PRØBABILITY (NBE)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2.5
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WINDØWS: CØVERED
HØB: 1.62 MILES
FAC: .7
RWWA= .09
RWWA =.12
RWWA =.15
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)
1.2
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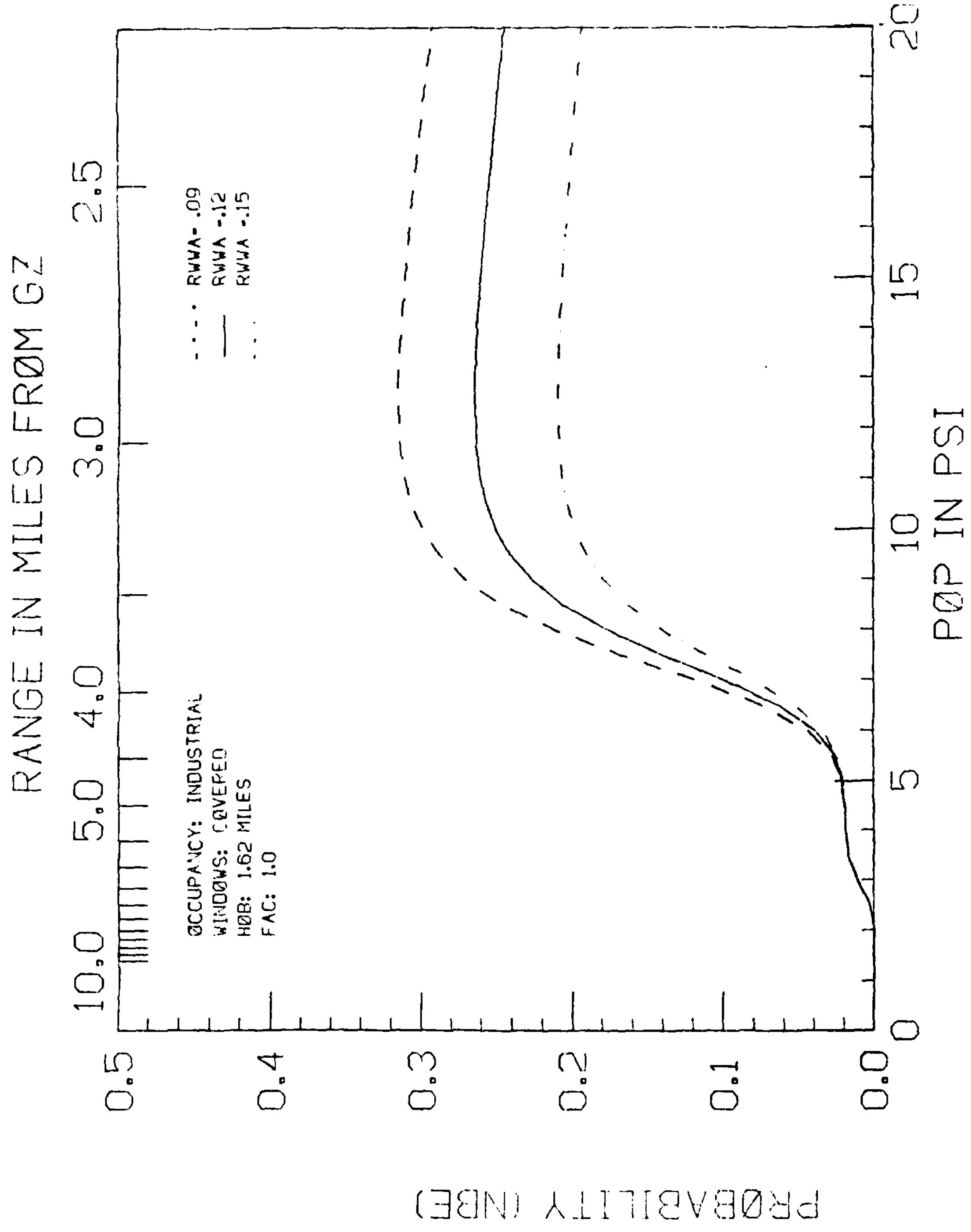
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
PØP IN PSI



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2.5
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WINDØWS: CØVERED
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FAC: 1.0
RWWA- .09
RWWA -.12
RWWA -.15
PRØBABILITY (NBE)
0.0
0.1
0.2
0.3
0.4
0.5
PØP IN PSI
0
5
10
15
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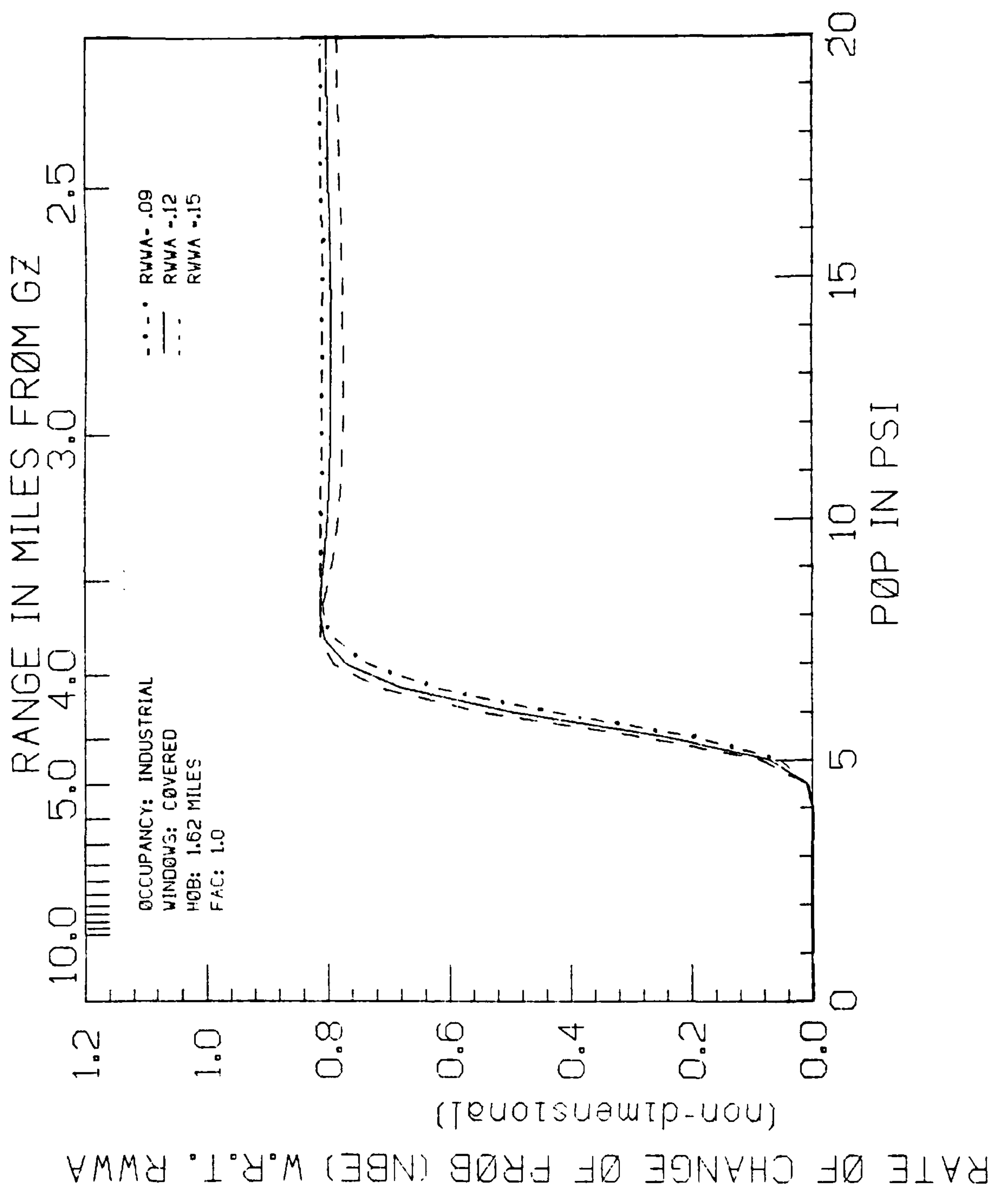
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4.0
3.0
2.5
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WINDØWS: CØVERED
HØB: 1.62 MILES
FAC: 1.0
RWWA- .09
RWWA -.12
RWWA -.15
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
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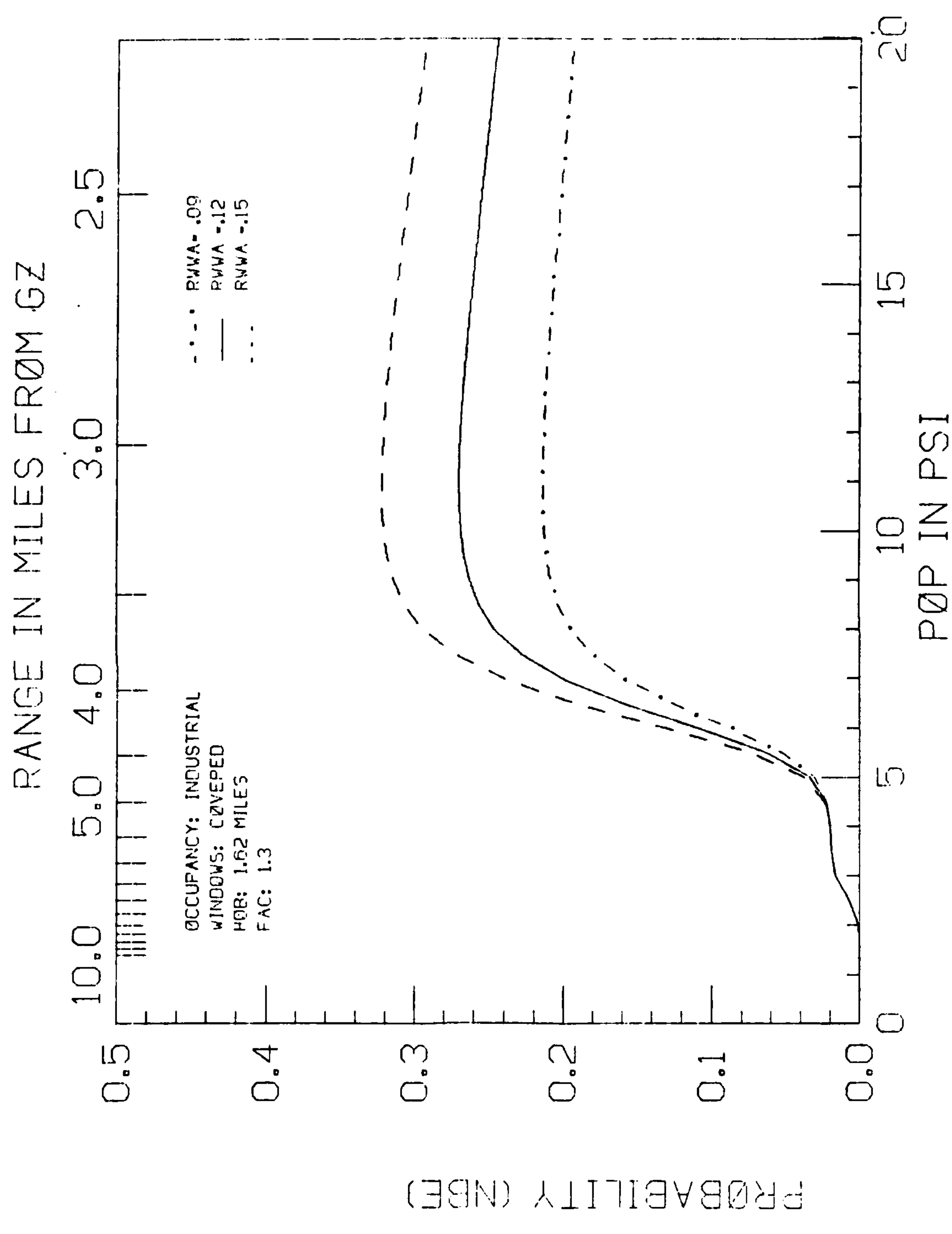
10
15
20
PØP IN PSI
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)


RANGE IN MILES FRØM GZ
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5.0
4.0
3.0
2.5
PØP IN PSI
0
5
10
15
20
PRØBABILITY (NBE)
0.0
0.1
0.2
0.3
0.4
0.5
RWWA-.09
RWWA -.12
RWWA -.15
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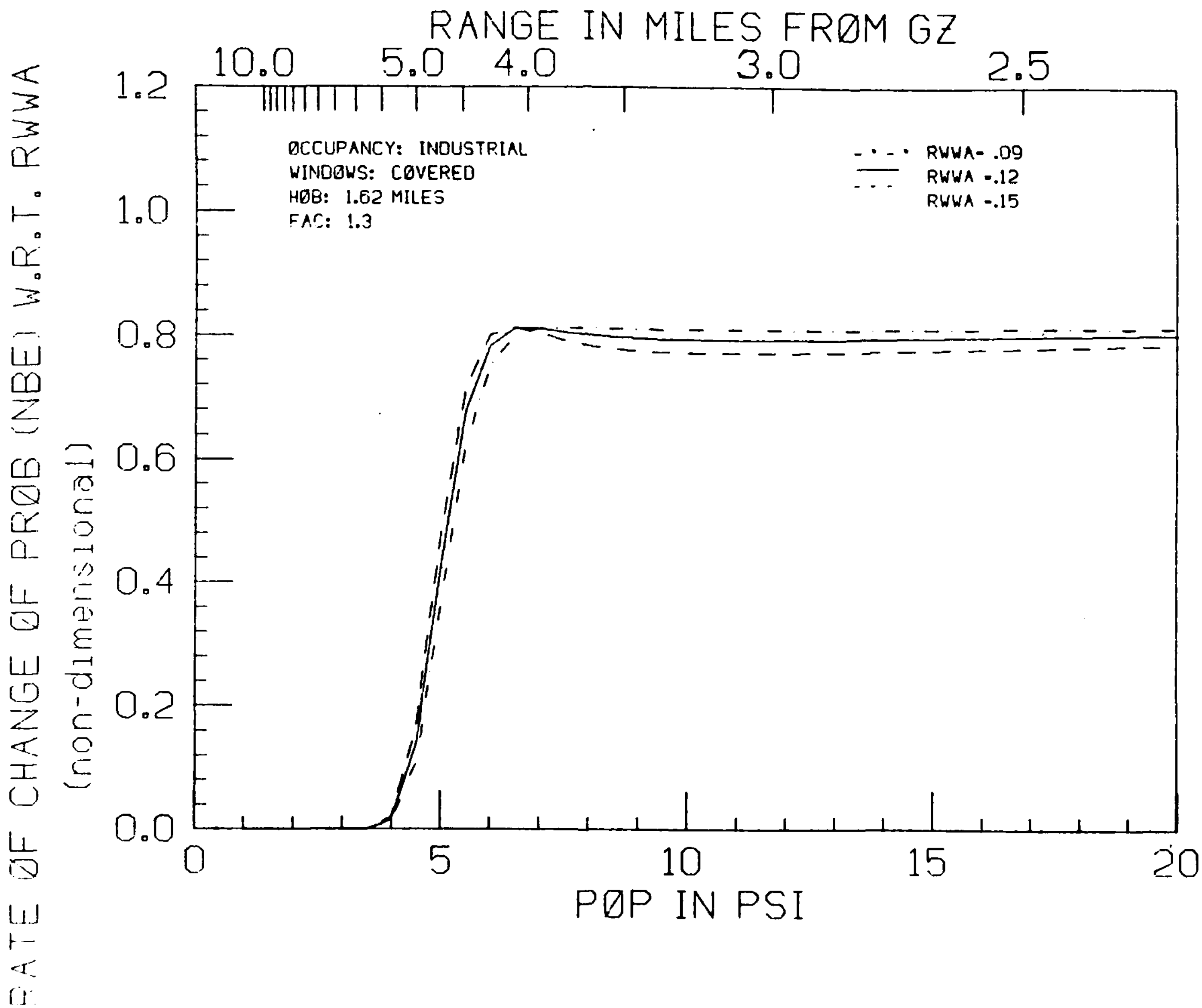
WINDOWS: CØVERED
HØB: 1.62 MILES
FAC: 1.3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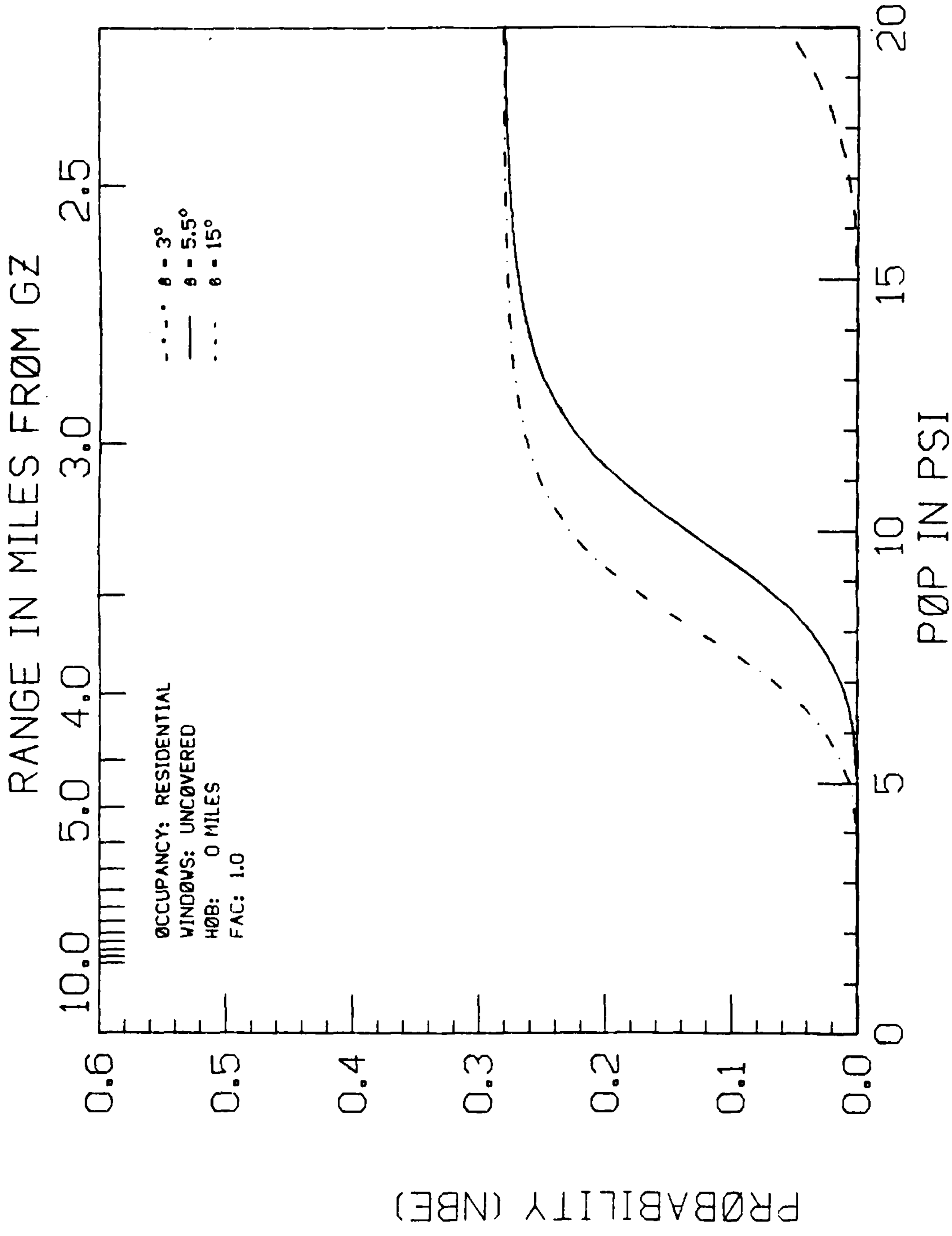
4.0
3.0
2.5
ØCCUPANCY: INDUSTRIAL
WINDØWS: CØVERED
HØB: 1.62 MILES
FAC: 1.3
RWWA- .09
RWWA -.12
RWWA -.15
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
PØP IN PSI
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. RWWA
(non-dimensional)

ROOM FIRE PROBABILITY DISTRIBUTION
SHOWING EFFECT OF VARIATIONS IN HEIGHT
OF ARTIFICIAL HORIZON
($\beta$, ELEVATION ANGLE IN DEGREES)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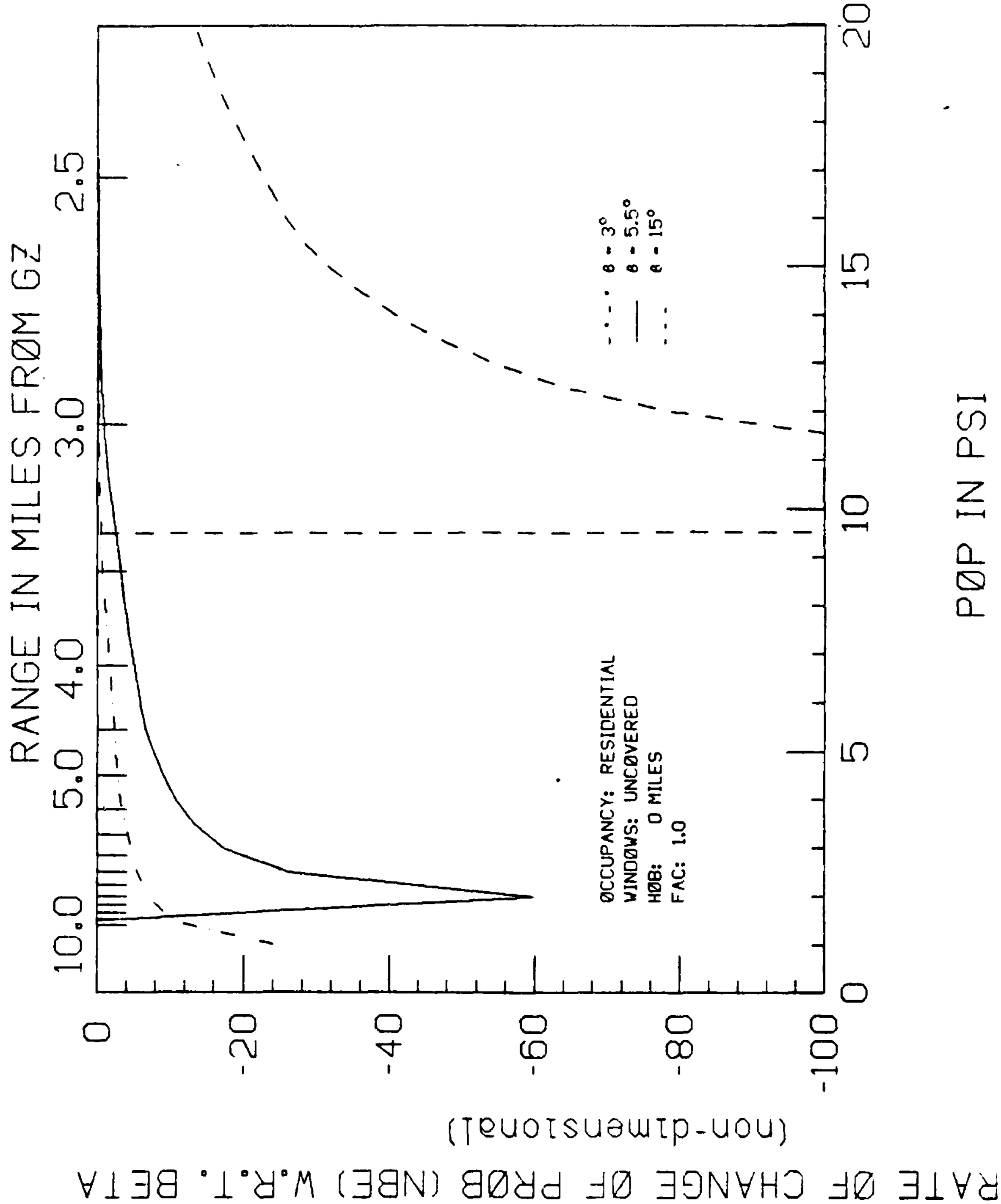
5.0
4.0
3.0
2.5
ØCCUPANCY: RESIDENTIAL
WINDØWS: UNCØVERED
HØB: 0 MILES
FAC: 1.0
β = 3°
β = 5.5°
β = 15°
PRØBABILITY (NBE)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
PØP IN PSI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10.0
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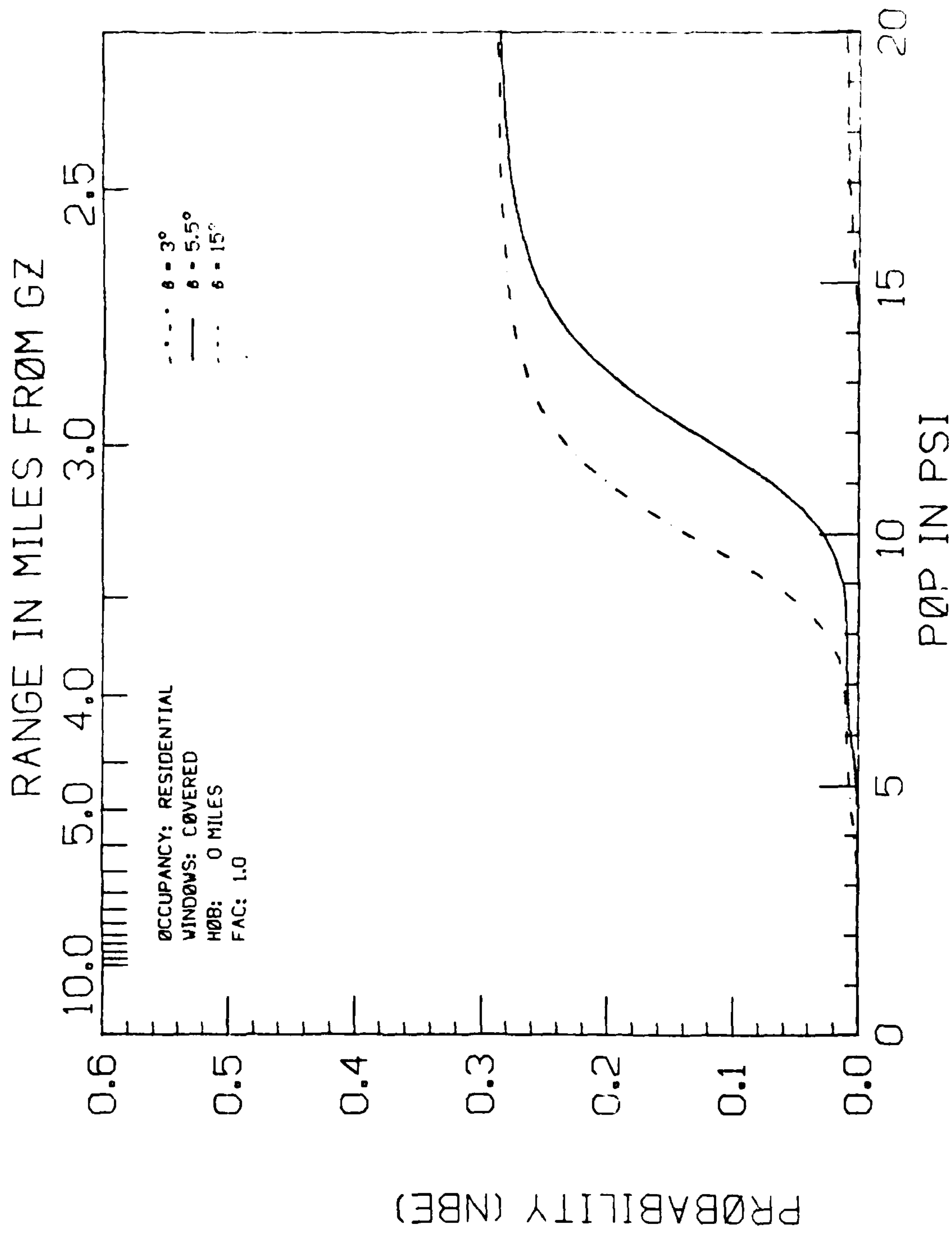
4.0
3.0
2.5
β = 3°
β = 5.5°
β = 15°
ØCCUPANCY: RESIDENTIAL
WINDØWS: UNCØVERED
HØB: 0 MILES
FAC: 1.0
0
-20
-40
-60
-80
-100
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. BETA
(non-dimensional)
0
5
10
15
20
PØP IN PSI


RANGE IN MILES FRØM GZ
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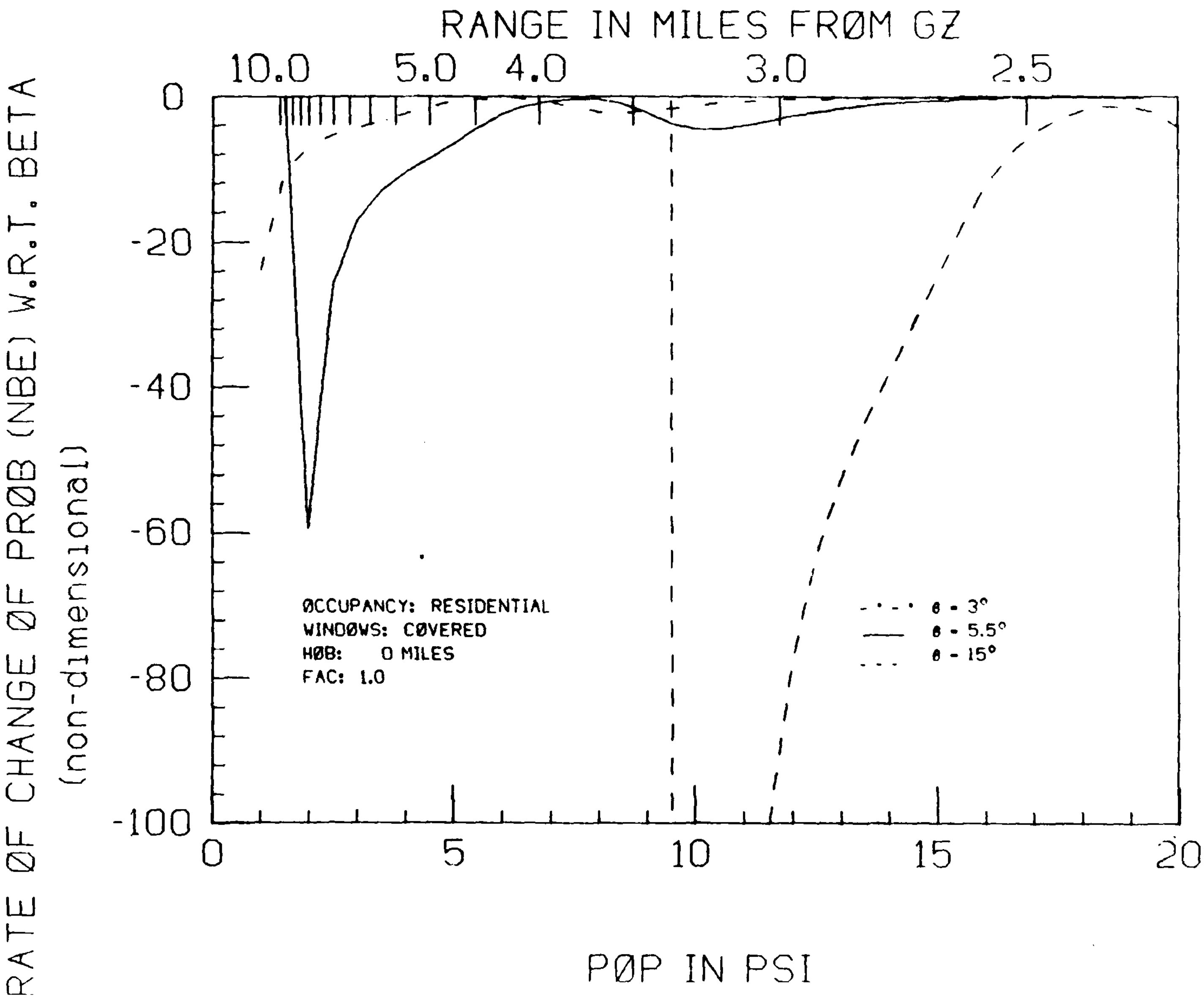
4.0
3.0
2.5
ØCCUPANCY: RESIDENTIAL
WINDØWS: CØVERED
HØB: 0 MILES
FAC: 1.0
θ = 3°
θ = 5.5°
θ = 15°
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
PØP IN PSI
PRØBABILITY (NBE)


RANGE IN MILES FRØM GZ
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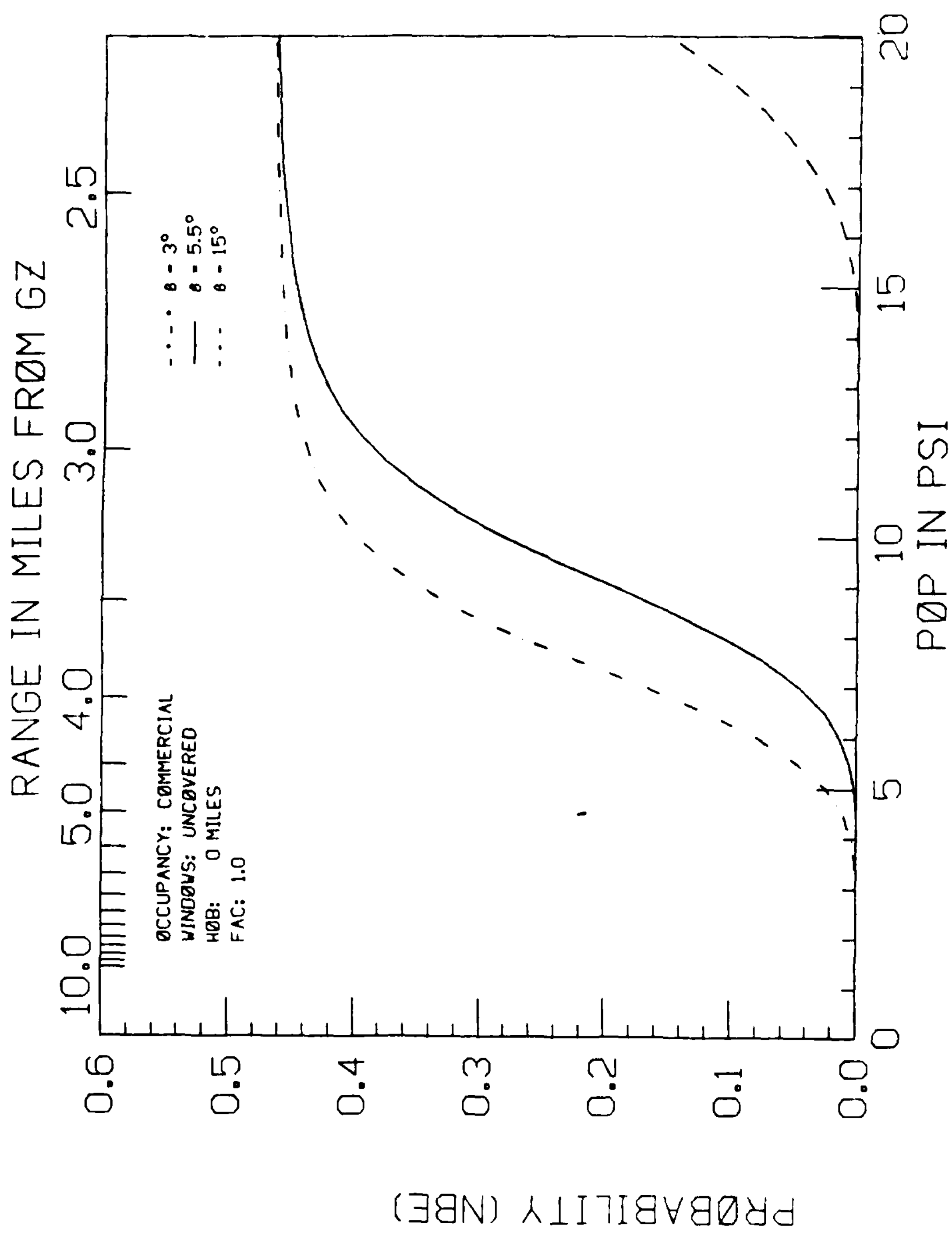
5.0
4.0
3.0
2.5
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. BETA
(non-dimensional)
0
-20
-40
-60
-80
-100
0
5
10
15
20
PØP IN PSI
ØCCUPANCY: RESIDENTIAL
WINDØWS: CØVERED
HØB: 0 MILES
FAC: 1.0
θ - 3°
θ - 5.5°
θ - 15°


RANGE IN MILES FRØM GZ
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4.0
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2.5
ØCCUPANCY: CØMMERCIAL
WINDØWS: UNCØVERED
HØB: 0 MILES
FAC: 1.0
β - 3°
β - 5.5°
β - 15°
PRØBABILITY (NBE)
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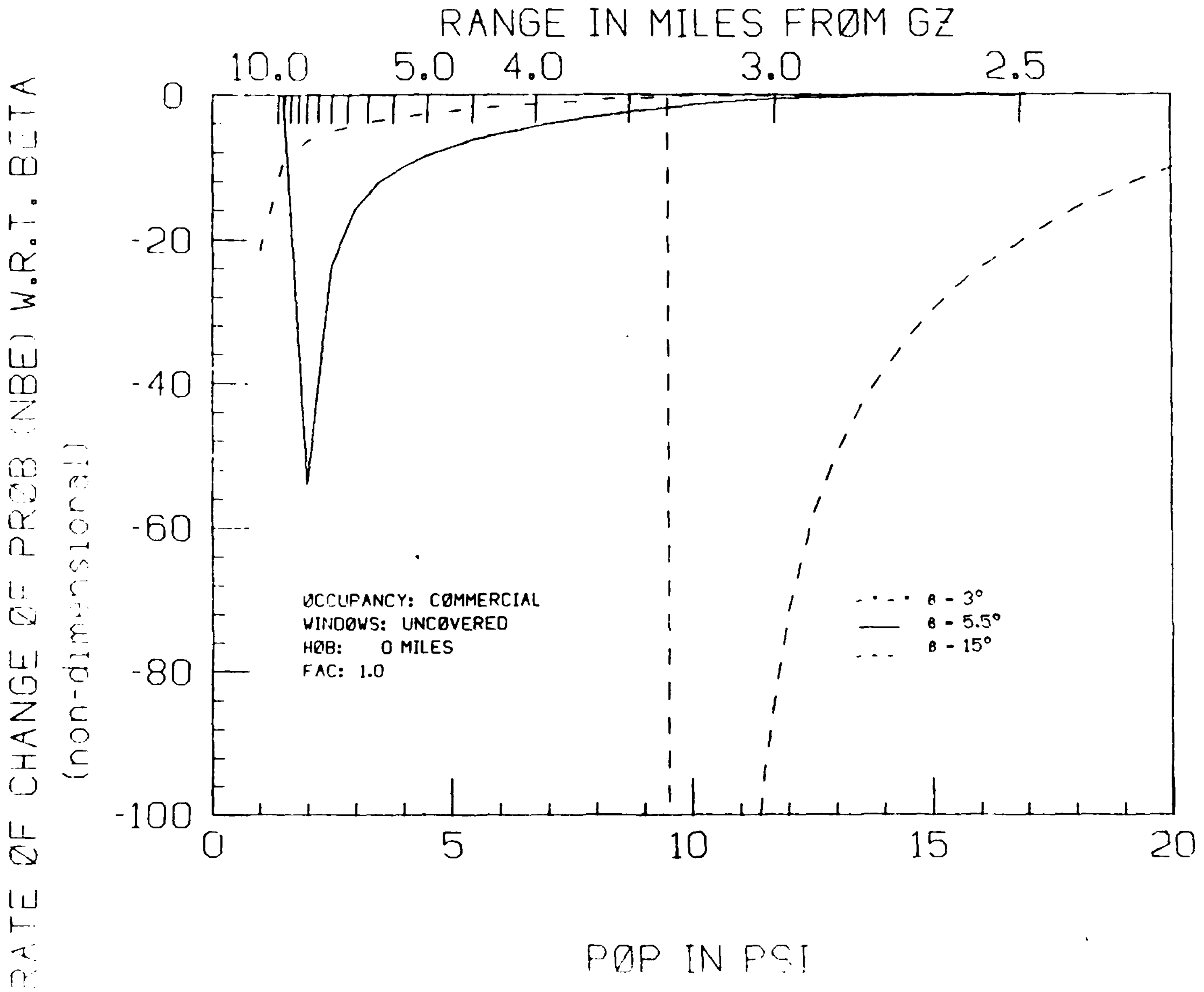
0.1
0.2
0.3
0.4
0.5
0.6
PØP IN PSI
0
5
10
15
20


RANGE IN MILES FRØM GZ
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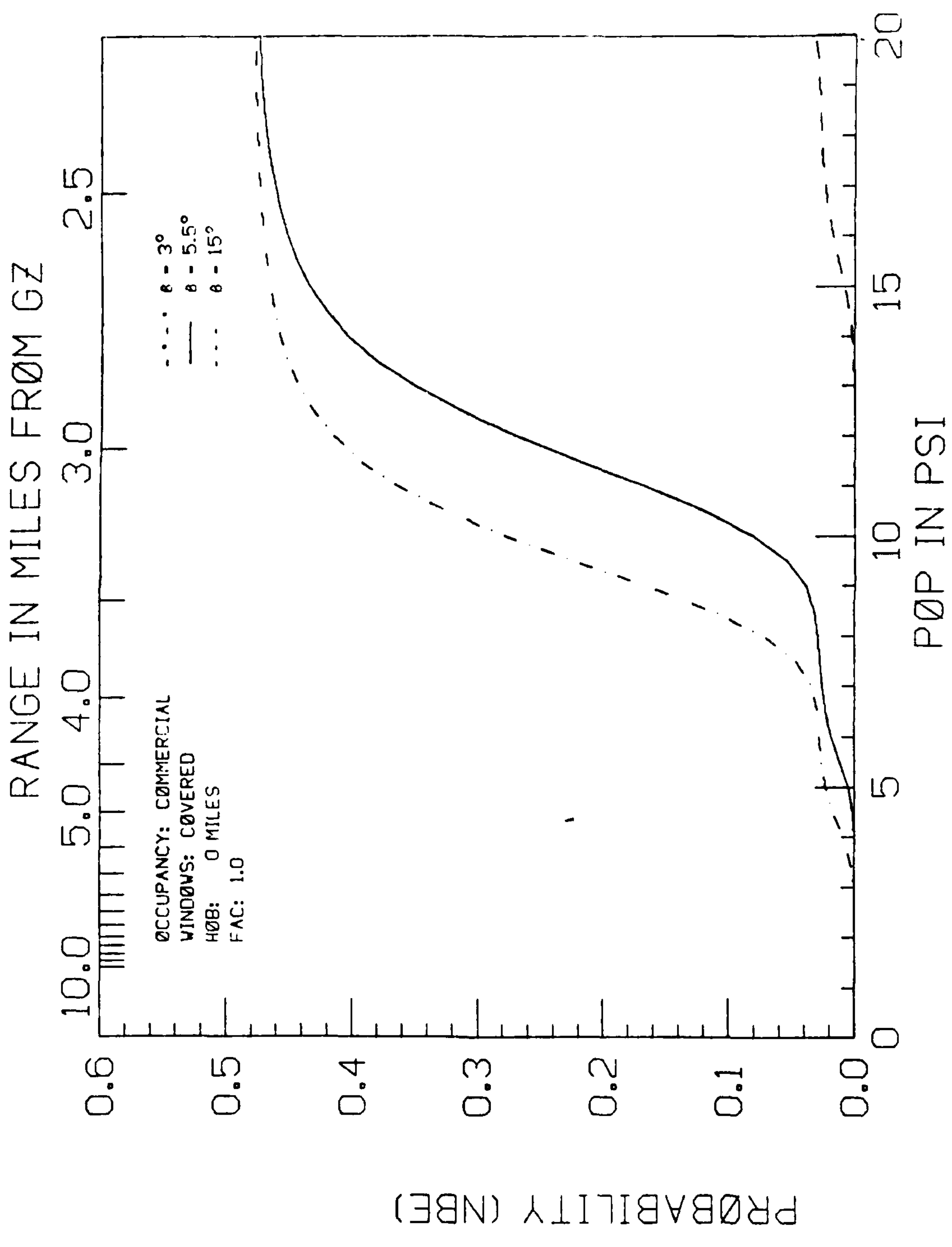
5.0
4.0
3.0
2.5
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. BETA
(non-dimensional)
0
-20
-40
-60
-80
-100
ØCCUPANCY: CØMMERCIAL
WINDØWS: UNCØVERED
HØB: 0 MILES
FAC: 1.0
β - 3°
β - 5.5°
β - 15°
0
5
10
15
20
PØP IN PSI


RANGE IN MILES FRØM GZ
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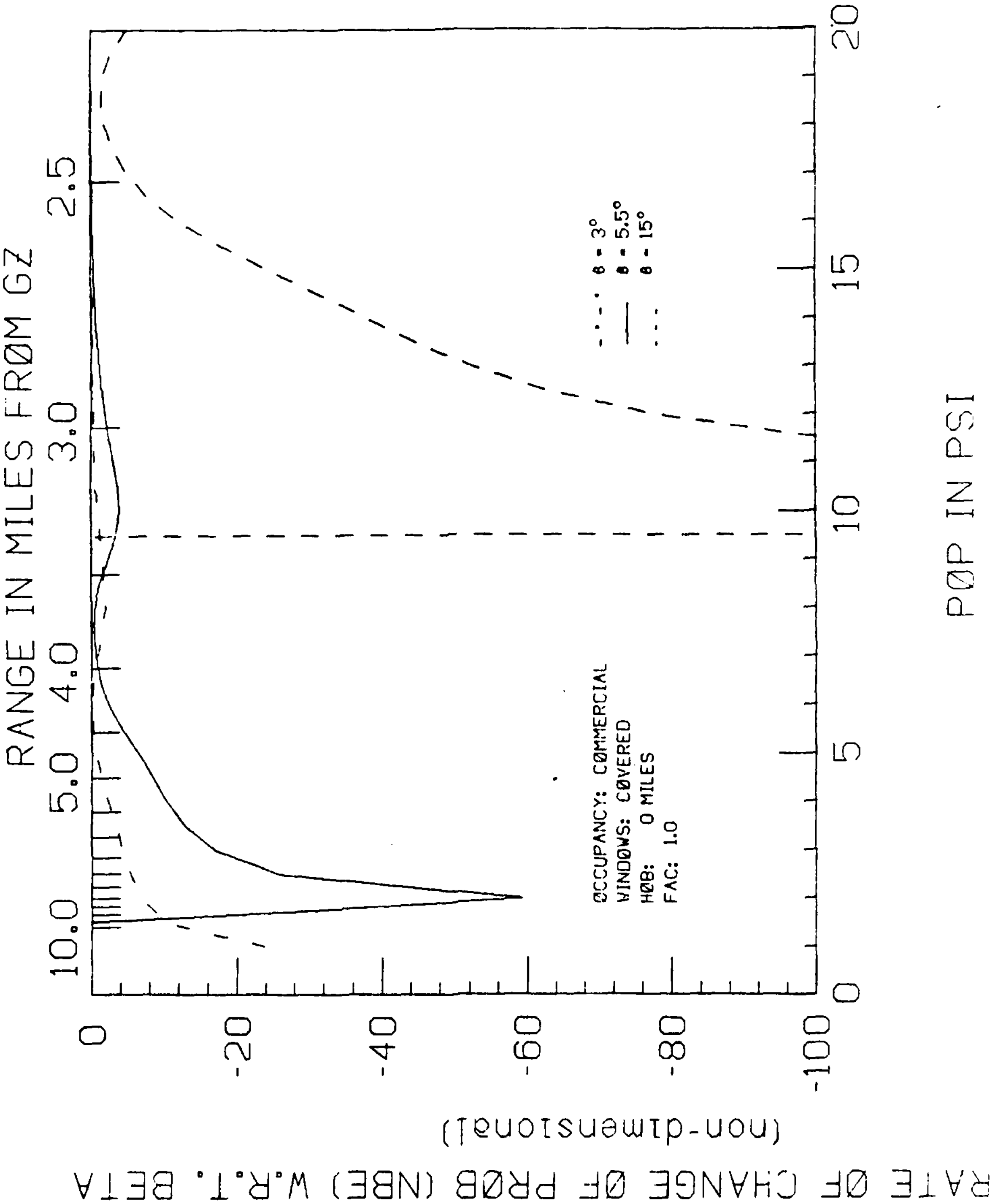
5.0
4.0
3.0
2.5
ØCCUPANCY: CØMMERCIAL
WINDØWS: CØVERED
HØB: 0 MILES
FAC: 1.0
β = 3°
β = 5.5°
β = 15°
PRØBABILITY (NBE)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
PØP IN PSI
0
5
10
15
20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PØP IN PSI
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15
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RATE ØF CHANGE ØF PRØB (NBE) W.R.T. BETA
(non-dimensional)
0
-20
-40
-60
-80
-100
β = 3°
β = 5.5°
β = 15°
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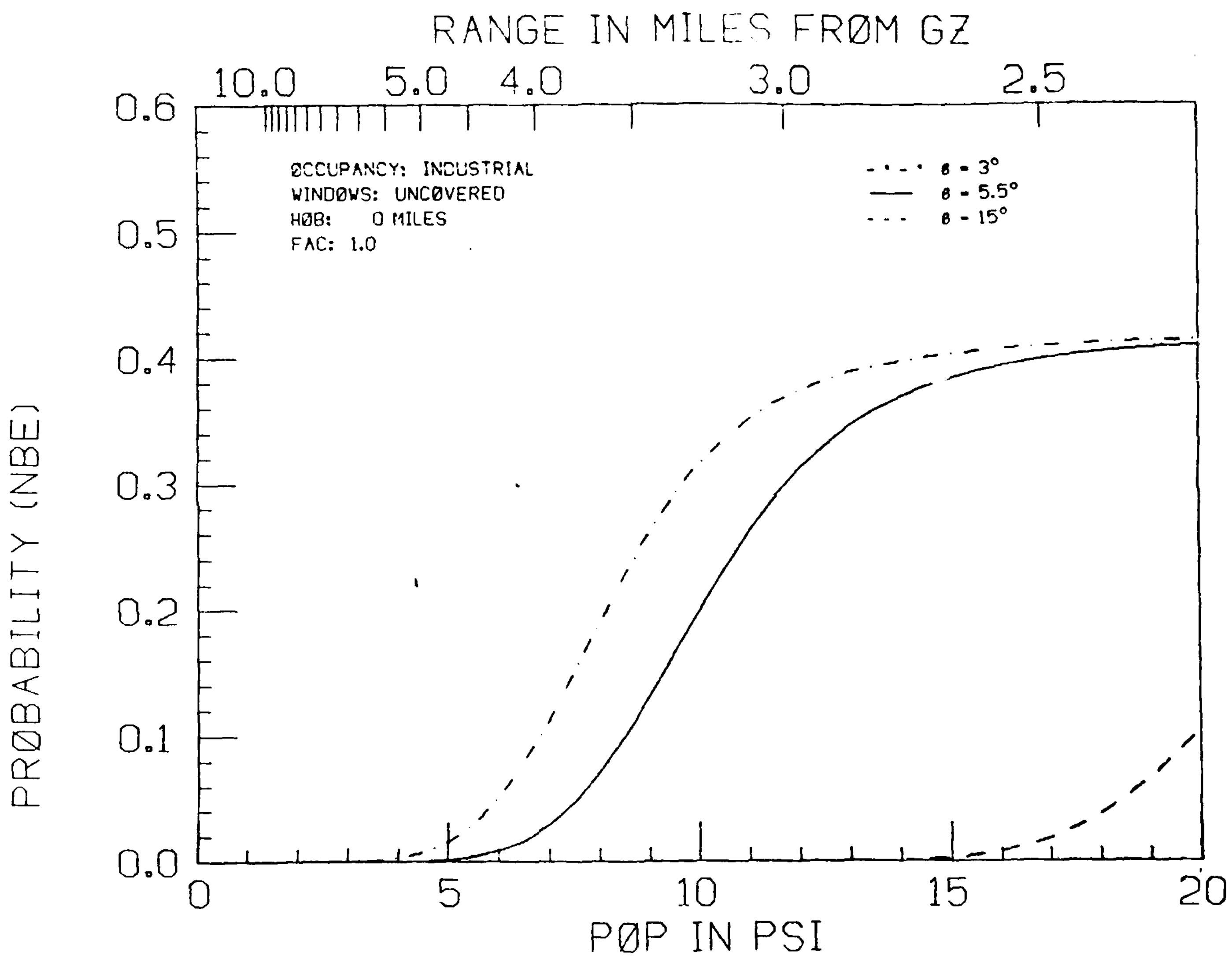
WINDØWS: CØVERED
HØB: 0 MILES
FAC: 1.0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5.0
4.0
3.0
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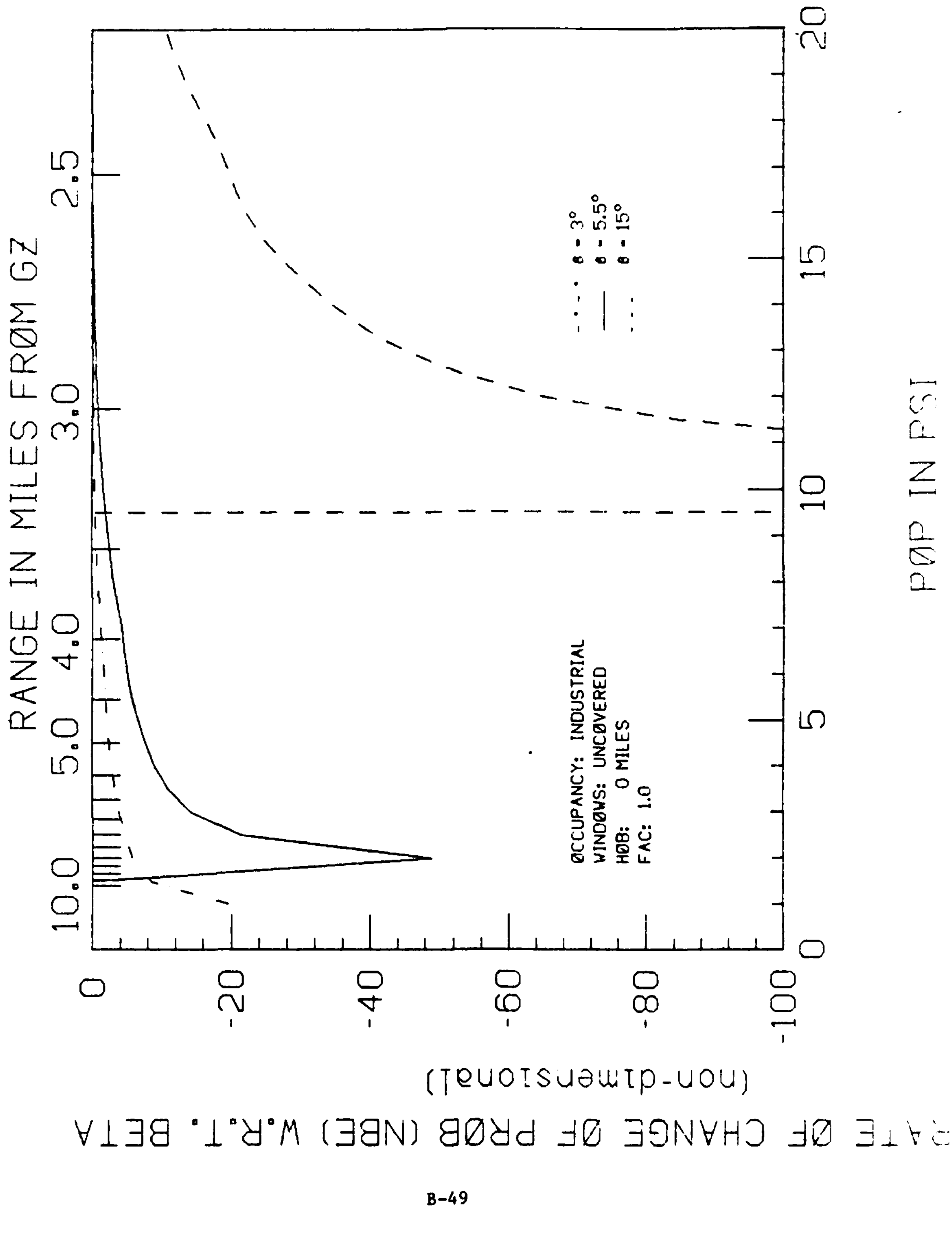
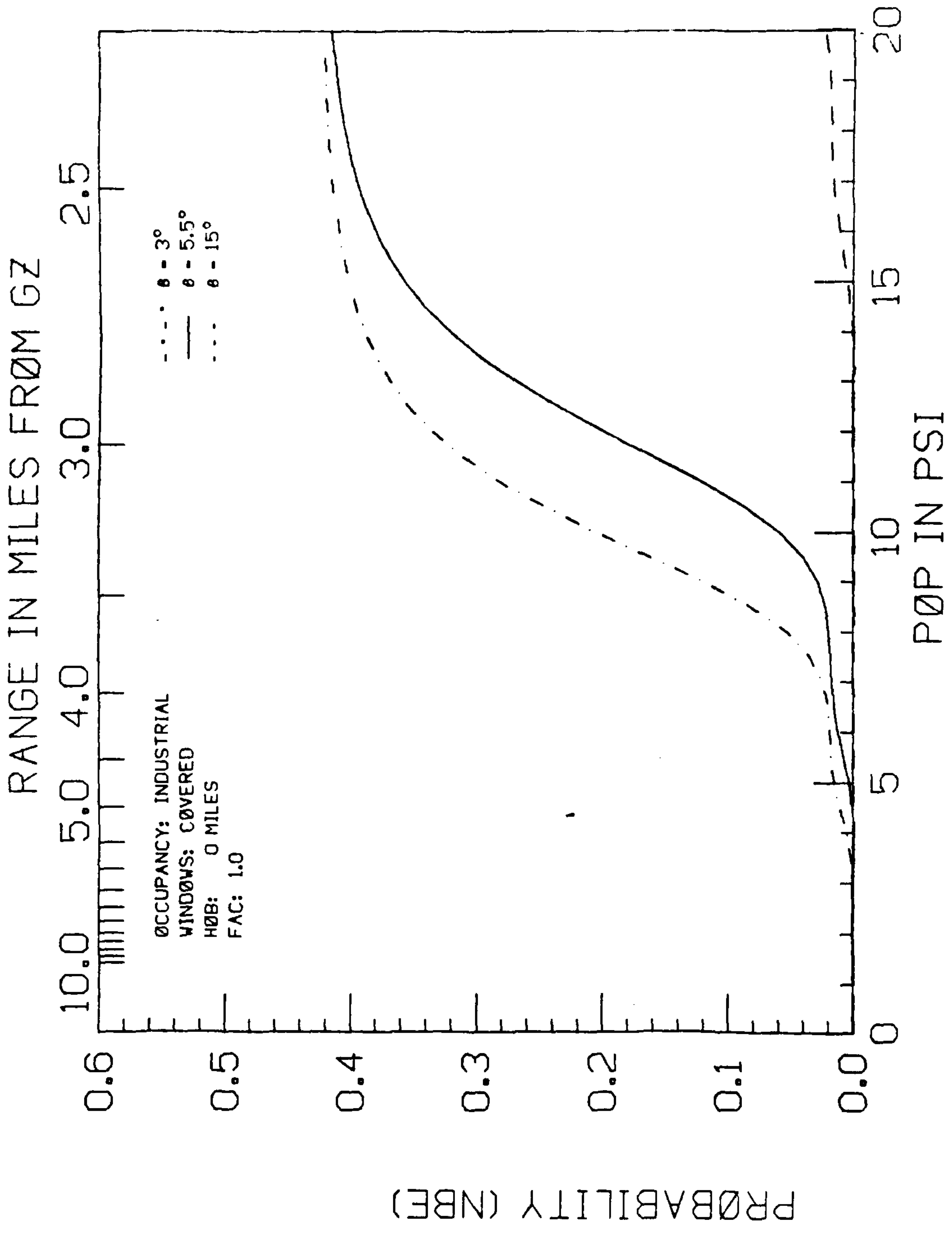
ØCCUPANCY: INDUSTRIAL
WINDØWS: UNCØVERED
HØB: 0 MILES
FAC: 1.0
θ = 3°
θ = 5.5°
θ = 15°
PRØBABILITY (NBE)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
PØP IN PSI



RANGE IN MILES FRØM GZ
2.5
3.0
4.0
5.0
10.0
0
5
10
15
20
PØP IN PSI
0
-20
-40
-60
-80
-100
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. BETA
(non-dimensional)
β - 3°
β - 5.5°
β - 15°
ØCCUPANCY: INDUSTRIAL
WINDØWS: UNCØVERED
HØB: 0 MILES
FAC: 1.0


RANGE IN MILES FRØM GZ
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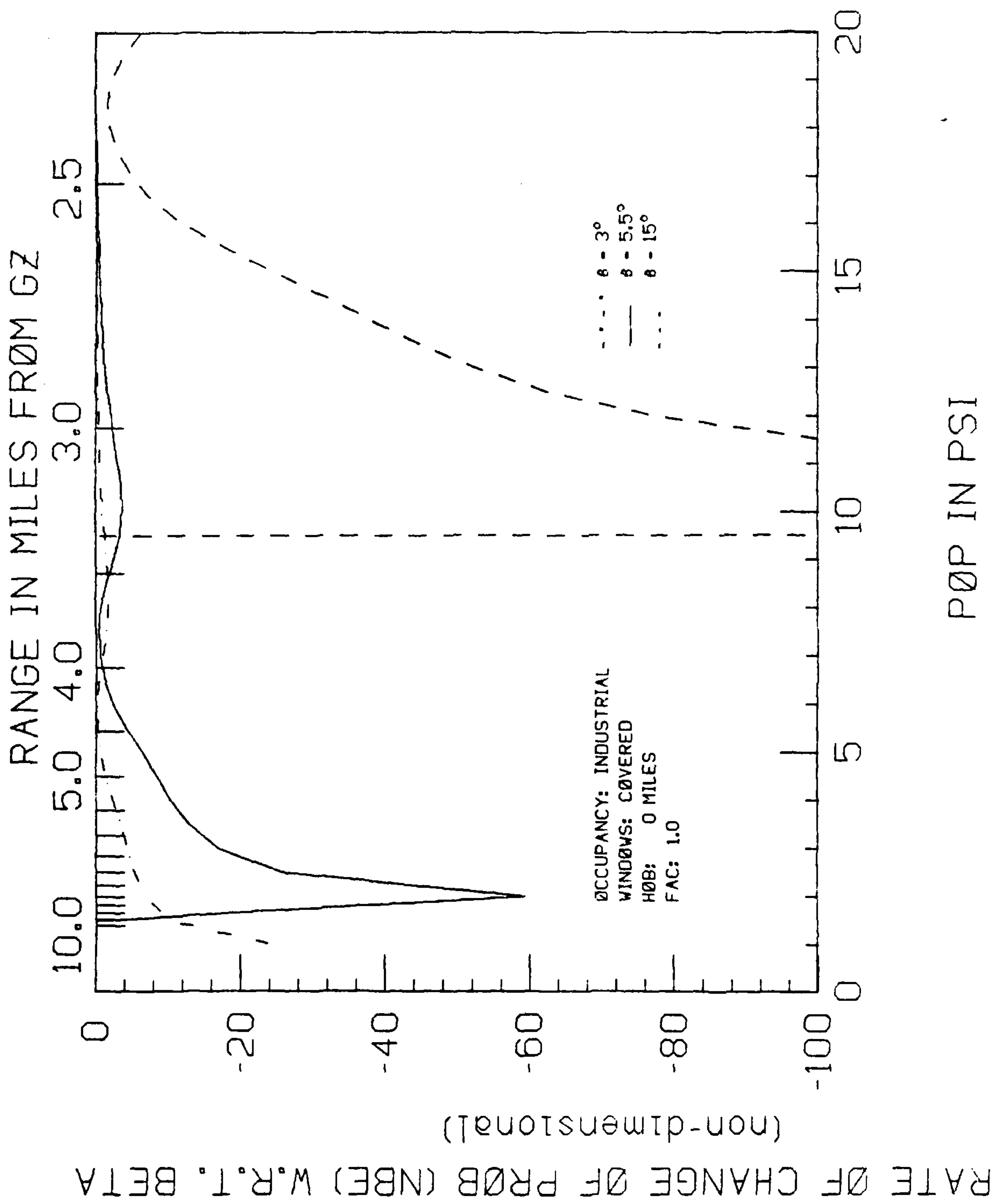
5.0
4.0
3.0
2.5
ØCCUPANCY: INDUSTRIAL
WINDØWS: CØVERED
HØB: 0 MILES
FAC: 1.0
θ = 3°
θ = 5.5°
θ = 15°
PRØBABILITY (NBE)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
PØP IN PSI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WINDØWS: CØVERED
HØB: 0 MILES
FAC: 1.0
β - 3°
β - 5.5°
β - 15°
0
5
10
15
20
PØP IN PSI
0
-20
-40
-60
-80
-100
RATE ØF CHANGE ØF PRØB (NBE) W.R.T. BETA
(non-dimensional)

# BLAST/FIRE INTERACTIONS:

## Analysis of Parametric Sensitivity and Large-Scale Experimental Determination of Ignition Thresholds

Detachable Summary

October 1980

Annual Report
For the Period 1 October 1978 to 31 March 1980

Stanley B. Martin
Raymond S. Alger
John R. Rempel
Peter S. Hughes (Los Alamos Technical Associates, Inc.)

Prepared for:

FEDERAL EMERGENCY MANAGEMENT AGENCY
Office of Mitigation and Research
Washington, D.C. 20472

Attn: Dr. David W. Bensen, COTR

Contract No. DCPA01-78-C-0279
FEMA Work Unit 2563F
SRI Project PYU 7814



SRI International
333 Ravenswood Avenue
Menlo Park, California 94025
(415) 326-6200
Cable: SRI INTL MPK
TWX: 910-373-1246

## SUMMARY

This report describes research activities conducted by SRI International for the Federal Emergency Management Agency in three areas of technical services in blast/fire interaction during the period 1 October 1978 to 31 March 1980. Two of the three areas involve predictions of fire damage and evaluation of the effectiveness of mitigating actions. Requirements for analytical models are reviewed, the sensitivity of their predictive outputs to assumptions, uncertain data, incompletely understood phenomena and parametric dependencies, and possibly erroneous algorithms invented to cover the lack of factual information are investigated, and the net practical effect of these uncertainties on utility and reliability appraised. The third area of technical service entails identifying and planning for field test opportunities. Reported here are the results of an experiment conducted by Los Alamos Technical Associates (with assistance from SRI) using a large, intense thermal radiation source to simulate the thermal pulse of a nuclear explosion in air. Predicted ignition thresholds, based principally on laboratory exposures of small, simple targets, were verified in the field with targets of practical size and complexity. Char depths were also determined and compared with both laboratory and nuclear test data to verify the appropriateness of the simulation technique.

### Formal Analysis of Sensitivity

A first-pass analysis has been completed. Fire effects in urban areas resulting from a 5-MT air burst and surface burst were modeled using the SRI Blast/Fire Model. We did not model fire effects beyond the initial distribution because of the inadequacy of state-of-the-art analytical methodology to deal with the dynamics of fire growth and spread in blast-damaged urban tracts. Initial fire distributions are described in terms of frequency of significant building fires as functions of the independent variable (distance from ground zero or the

corresponding free-field overpressure) for specified values of a variety of parameters. Three categories of parameters are recognized: attack parameters, target parameters, and response parameters. The first two include scenario variations, some of which are inherently unpredictable to the defense planner. Others, however, such as the state of preparedness, at least in principle subject to his control, or weather variables, which are subject to statistically describable periodic and/or seasonal fluctuations, do warrant inclusion in a study of parametric sensitivity. Response parameters are those associated with the physical and chemical processes that govern fire behavior. Their uncertainties are due to technological limitations; these parameters constitute the principal group subject to refinement through research.

In the evaluation of primary fires prior to blast arrival, the current model, while notably broad brushed, is thought to be adequate for many present purposes and reasonably reliable to the extent that interior fires alone determine the fire threat. Prediction are particularly sensitive to atmospheric transport of thermal radiation, but given a specified visibility (in a cloudless atmosphere) the model provides estimates of the free-field flux and fluence that are certainly adequate in relation to field-of-view uncertainties. Clouded atmospheres are another matter, especially when a broken deck above the burst point extends the thermal radiation field (as it presumably did at Nagasaki in 1945) in an unsymmetric pattern around ground zero. The primary-fire reach of surface bursts is further complicated by variations in the artificial horizon (due to both terrain and buildings) to which the thermal radiation field is quite sensitive.

Airblast effects are the major source of the lack of confidence in any current predictions of fire consequences of nuclear attack, although the model's failure to include other potentially important primary fire-start mechanisms (e.g., exterior ignitions and ignition of debris after blast) may rise to dominate at the higher overpressures. In the 2- to 5-psi region, secondary fires can rival primaries in importance, depending especially on airblast extinction of the incipient primary fires and whether the atmosphere or artificial horizon limits the frequency and range of primary fire starts; however, current inadequacies in secondary fire modeling severely limit the comparisons. Airblast extinction introduces a very large uncertainty in estimates of the initial fire distribution. Blast damage introduces similarly large uncertainties in the evaluation of the further destruction due to fire spread and mass fire development.

Supplemental Evaluation of Sensitivity

This study focused on machine tools and their fire survivability as a gauge of the practical requirement for fire damage modeling in a context of threat to critical resources and industries. Records of World War II and a peacetime fire disaster are supplemented by data on blast effects in nuclear tests to show the relative importance of fire as an effect. We developed and advanced a prediction procedure for machine tool survival to accomplish two functions:

1. Provide a general estimate of the national machine tool losses under a given attack scenario.
2. Give specific guidance for local action to minimize machine tool damage.

The order in which the procedural steps are taken minimizes the number of cases that need to be carried through to the more difficult and unreliable fire modeling steps.

Large Thermal Source Experiment

Three aspects of the fuel and its environment were of particular concern:

- Target size, particularly the potential for thermal reinforcement in tall targets.
- Geometry, especially the possible reinforcement in cracks, folds, and reentrant corners.
- Combinations, notably the possible synergistic effects of mixed fine and coarse fuels.

Two tests were run during July 1979 at Kirtland AFB. In general, the results were as predicted and reinforcing effects of size and geometry were minor. Mixed fuel results were somewhat inconclusive because differences in sample packing of simulated debris appeared to have a large, inadequately controlled effect in these experiments.

SRI INTERNATIONAL, Menlo Park, California 94025

**BLAST/FIRE INTERACTIONS** Analysis of Parametric Sensitivity and Large-Scale Experimental Determination of Ignition Thresholds by Stanley B. Martin, Raymond S. Alger, John R. Rempel, and Peter S. Hughes (LATA). SRI Project PYU 7814, 149 pages, Contract No DCPA01-78-C-0279, DCPA Work Unit 2563F, UNCLASSIFIED (October 1980).

This annual report of progress describes activities in three areas of technical services in the research field of blast/fire interactions. Two are concerned with parametric sensitivity in predictive modeling, the third with verification of laboratory ignition thresholds using a large field-test source of intense thermal radiation.

Airblast effects are shown to be a major source of uncertainty in assessment of fire effects of a nuclear explosion. Blast-caused fires may be more important than primary fires in the regions experiencing lower overpressures, but current inadequacies in secondary fire modeling severely limit the comparisons. Moreover, airblast extinction introduces very large uncertainties in estimates of initial fire incidence, and blast damage to structures introduces similarly large uncertainties in the evaluation of the further destruction from fire spread and possible mass fire development.

The large-scale ignition experiments generally confirmed laboratory-based predictions. Mixed fuel results were inconclusive.

Further investigation of several aspects of this problem area are continuing and will be updated in a subsequent report.

SRI INTERNATIONAL, Menlo Park, California 94025

**BLAST/FIRE INTERACTIONS** *Analysis of Parametric Sensitivity and Large-Scale* Experimental Determination of Ignition Thresholds by Stanley B. Martin, Raymond S. Alger, John R. Rempel, and Peter S. Hughes (LATA). SRI Project PYU 7814, 149 pages, Contract No DCPA01-78-C-0279, DCPA Work Unit 2563F, UNCLASSIFIED (October 1980).

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SRI INTERNATIONAL, Menlo Park, California 94025

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