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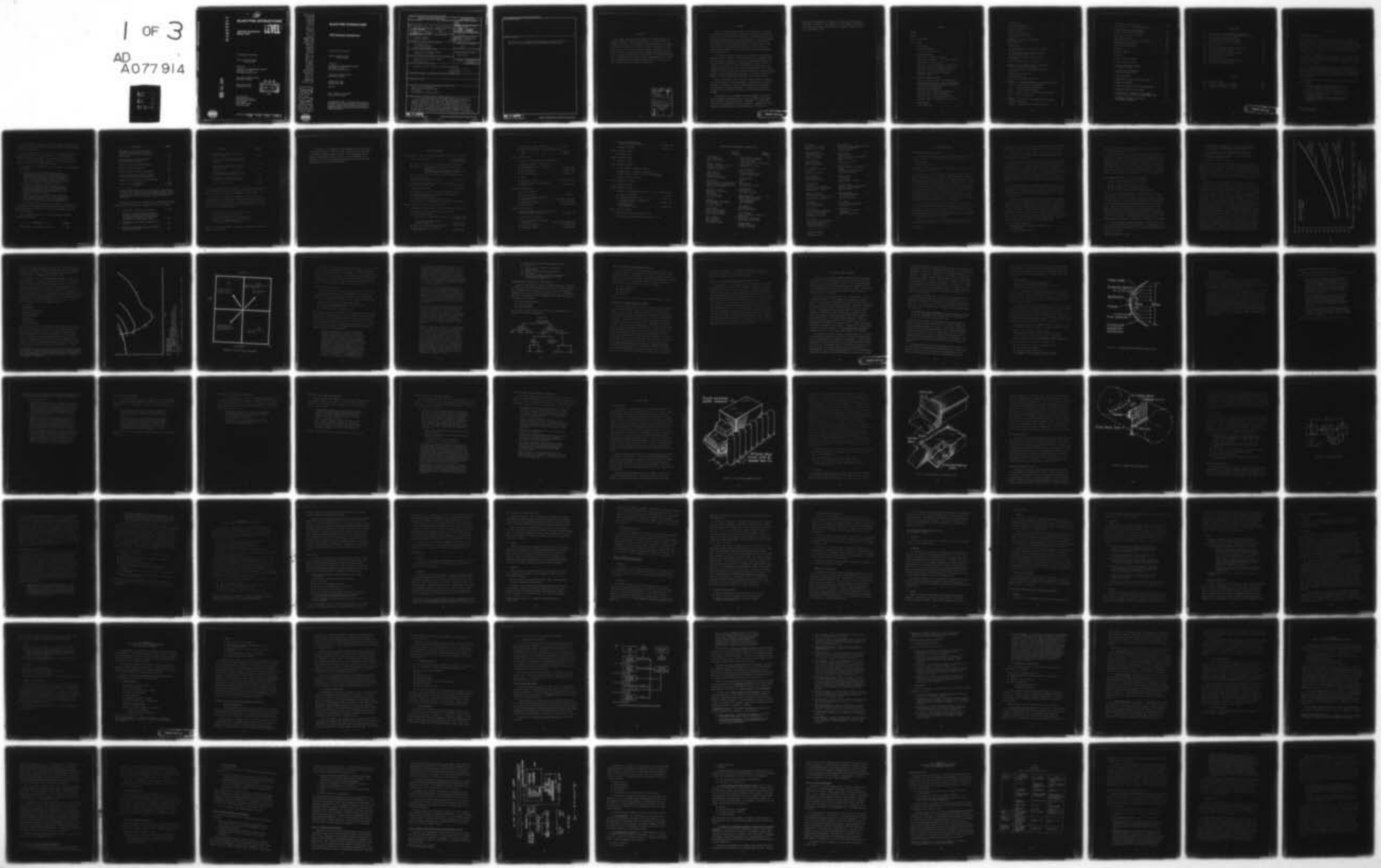

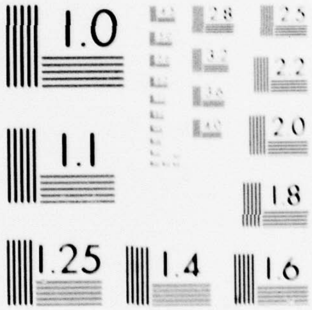
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BLAST/FIRE INTERACTIONS

Asilomar Conference
March 1979

Proceedings of the Conference

Edited by: Raymond S. Alger
Stanley B. Martin

Prepared for:

DEFENSE CIVIL PREPAREDNESS AGENCY
Washington, D.C. 20301
Attn: David W. Bensen, COTR

Contract No. DCPA01-78-C-0279
DCPA Work Unit 2563F

SRI Project PYU 7814
(Published Sept. 1979)

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BLAST/FIRE INTERACTIONS DCPA Work Unit 2563F Proceedings of the 1979

SRI International

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Approved:

Paul J. Jorgensen, Vice President
Physical and Life Sciences

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Fire spread
Fire dynamics in perturbed fuels

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes the proceedings of the DCPA-sponsored Conference on blast/fire interactions held March 18 through 22, 1979, at Asilomar, California. This conference, following within a year a similar conference that was held to reevaluate the status of this area of technology, was convened to allow a selected group of authorities on fire effects, air-blast effects, structural responses, and related technologies to reassess the problem area and to evaluate the contributions made to its solution by recently funded studies. Recommendations

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19. KEY WORDS (Continued)

20 ABSTRACT (Continued)

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ABSTRACT

This report summarizes the proceedings of the DCPA-sponsored Conference on blast/fire interactions held March 18 through 22, 1979, at Asilomar, California. This conference, following within a year a similar conference that was held to reevaluate the status of this area of technology, was convened to allow a selected group of authorities on fire effects, air-blast effects, structural responses, and related technologies to reassess the problem area and to evaluate the contributions made to its solution by recently funded studies. Recommendations are offered for a continuing research program to upgrade the state of the art at a rate consistent with need and national priorities.

SUMMARY

Fire from a nuclear weapons 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 interaction between blast effects and fire effects preclude any reliable estimate of the incendiary outcome of a nuclear attack on the United States. As such, these uncertainties are a major obstacle to defense planning and they interface with national security policymaking at the highest levels.

To rectify the technical deficiencies in predicting the incendiary outcome of a nuclear attack on the United States and to formulate a well-directed program of research, the Defense Civil Preparedness Agency contracted with SRI International in 1978 and again in 1979 to convene a conference of authorities on fire and blast, structural response, and related technologies. This report covers the proceedings of the second conference, and it describes the early-on activities of an optimally funded program of 5-year duration, whose objective is to achieve an analytical method for reliably predicting fire behavior and incendiary outcome.

Within a framework of crisis relocation planning, several questions and decisions need to be resolved promptly. A working list of critical resources is paramount to realistic thinking about the fire problem and countermeasures to mitigate the threat. To avoid delay in strategic planning, this list should be available, at least in preliminary form, by 1980.

A comparison of the recommended and actual funding to date shows that the program is getting under way at less than 60% of the original goal as urged in the 1978 conference. Accordingly, in assembling the revised FY 80 program during the 1979 conference, a somewhat more austere program was acknowledged as a more realistic goal. The focus is

restricted to vulnerability of critical facilities and resources and to the threats to survival of key individuals. This program is nonetheless consistent with the broad objectives of the program as laid down in the first conference in 1978.

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ILLUSTRATIONS

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I INTRODUCTION

Plans for the Conference*

On behalf of the Defense Civil Preparedness Agency and SRI International, welcome to the Second Conference on Blast/Fire Interactions. The first conference, held not quite a year ago, in May of 1978, followed several years of inactivity, at least by DCPA, in the important area of blast/fire research. In fact, no fire technology research was being sponsored by DCPA one year ago.

Last May's conference was the turning point. Over one-half million dollars in research studies have been initiated since that time and all of them are a direct outgrowth of the research recommendations developed by last year's conferees.

One of the purposes of this conference, as in the previous one, will be to skeptically examine the foundation of the technology and conclusions about the fire initation process associated with the detonation of nuclear weapons and the resulting damage produced by combined blast and fire effects.

Several of the critical information needs that we must address are the following:

- Threshold air-blast conditions for the extinction of fires initiated by thermal radiation
- Process of rekindling in fuels perturbed by blast
- Effects of structural damage on the process of fire growth and spread
- Description of debris fields in sufficient detail to permit calculation of fire spread rates and burning rates.

---

*By D. Bensen (DCPA).

The uncertainties associated with these information needs and their importance to strategic defense are discussed further in the proceedings of the 1978 Conference (1).

After a consideration of these and other uncertainties identified during the course of last year's conference, it was concluded that reliable, quantitative estimates of the outcome of a nuclear attack on the U. S. could not be made and a blast/fire research program was proposed to alleviate the recognized deficiencies.

It was proposed to assign first order of business to the development of three models:

- A general urban fire distribution/spread model, applicable mainly to areas of light-to-moderate structural damage; intended to give time-phased frequency distributions of burning and burned-out structures for each different urban use-class (or structural-type) tract as functions of distance from ground zero (or location in an arbitrary coordinate system).
- A "hole-in-the-doughnut" model, applicable to areas of totally collapsed structures, continuous debris fields, and innumerable fires; intended to deal with fire intensity versus time only--the spread of fire being included implicitly only.
- A specific-resource vulnerability model, applicable to a single structure, facility, or resource threatened by fire exposure within the context of a general fire description, provided by one of the foregoing models.

It was invisioned that these models would provide a structure for the program, and, through sensitivity analysis and iteration, would produce quantitative and defensible criteria for establishing priorities for program elements.

The recommended, optimal FY 79 research program on blast/fire studies was as follows:

Study Area	Funding
‡Blast analysis of individual structure	$ 200K

Study Area	Funding
[‡]Complementary blast studies (drag/lift experiments, hydrocode calculations of flow in enclosures, initial experimental verification)	$ 100K
[‡]Initiate search for/and development of blast-fire predictive models	200
[‡]Sensitivity analysis/program planning	60
Repeat secondary fire analysis	100
[‡]Shocktube studies of blowout mechanisms	200
[‡]Initiate development of theory for shock/fire interaction (ideal fuels/geometries)	50
Preparation for participation in MISTY CASTLE	10
Total for FY 79 (Recommended)	$ 920K
(Actual)	$ 530K

[‡]Program elements DCPA was able to fund in FY 79. Two studies, not specifically identified in the recommended program, the use of scale models to describe blast/fire interactions and casualty estimation in a blast/fire environment, were also funded this fiscal year.

Assuming that the entire, recommended FY 79 program had been implemented, this would logically be followed in FY 80 by the following:

1.	Initial blast analysis of city complex	$ 250K
2.	Verification experiments (MISTY CASTLE) on structural response, debris production and distribution, persistence of ignition and fire behavior in blast-damaged targets	500
3.	Complementary blast studies (continued from FY 79)	100
4.	Analytical development of blast/fire models (continued from FY 79)	100

	Study Area	Funding
5.	Experimental complement to blast/fire model development	$ 100K
6.	Sensitivity analysis/program planning and review (includes contractor conference)	50
7.	Experimental verification of doubtful ignition thresholds (large areas of mixed fuels)	50
8.	**Shocktube studies of blast fire inter**actions (continued from FY 79)	200
9.	Development of theory of blast-fire interactions (continued from FY 79)	50
	Total Funding for FY 80	$ 1,300K

Part of our job during this conference will be to review last year's program recommendations, adding, deleting, and revising as necessary, and to develop updated program recommendations for the 1980s.

In format, the conference will comprise (1) general sessions to receive inspirational background information, review current work, and exchange ideas, and (2) workshops to evaluate approaches and results of the current work and suggest emphasis and program requirements for the future. The four working groups are:

1. Initial fire distribution after blast effects
2. Blast/shock effects on structures
3. Predictive modeling of fire spread and threat
4. Evaluation of countermeasure effectiveness; Choice of intervention strategies.

Chairmen, recorders, and members of the various workshops are indicated on the attendance list.

As indicated in the agenda, all the background lectures and reports of particular interest to the blast/shock authorities are concentrated in the Sunday evening and Monday sessions. This arrangement has been adopted to minimize the conflict with a concurrent DNA Symposium on Blast Effects. Normally, general-session presentations would have been interspersed a bit more with the workshops.

Asilomar 1979 Agenda

18 March, Sunday evening - Background Information and Plans for Conference

1. Plans for the Conference . . . . D. Bensen, DCPA
   General Chairman

   - Scope: (Chairman sets the stage; what are the problems?)
   - Procedure: (General session reviews current approaches and results.
     Workshops evaluate approaches and results, and suggest emphasis and program for future.)
   - Desired Results: (A program review and planning document.)

2. Status of DCPA, FEMA,
   Prognostications about the Future . . . . . G. Sisson, DCPA

3. The Strategic Framework: A U.S.-Soviet Comparison
   (What are the Soviets doing?) . . . . . . R. Foster, SRI

4. Current DCPA Directives . . . . G. Sisson, DCPA

   - Designation of critical resources, implements, services
   - Locations and quality of shelters for key personnel (fallout protection only?)
   - Existing protection options and directives
   - Schedule for an implementable Crisis Relocation Plan (CRP).

19 March, Monday morning - Shock/Blast-Wave Effects

1. On Initiation and Persistance of Fires (The initial fire field)

   - Chairman's remarks; objectives, what is needed
   - Report on Misers Bluff
     - Performance of Thermal Pulse Simulation J. Cockayne, SAI
       W. Taylor, BRL
     - The Cushion Experiment and the Unplanned Truck Fire . . . . S. Martin, SRI
   - SRI Blast/Fire Model Sensitivity Analysis S. Martin, SRI
   - Analytical Modeling of Blast/Fire Interactions . . . . F. Fendell, TRW

- Theoretical Scaling of Fire Effects . . . . H. Brode
- Shocktube Experiments: Status and Future Plans
  - SRI . . . . S. Martin
  - BRL . . . . W. Taylor

19 March, Monday afternoon

2. On Structures and Machinery (The Debris Field)

- Chairmans' remarks: Objectives, etc.
- Misers Bluff Results on Structures and Machinery . . . . T. Kennedy, DNA
- Related DNA Work . . . . T. Kennedy, DNA
- Debris Distribution . . . . J. Rempel, SRI

3. On People

- Methodology of Fire . . . . A, Longinow, IITRI
- Shelter Tenability and Population Survival . . . . R. Shnider, CP&R

19 March, Monday evening

4. Tutorials on Modeling

- Dice Throw Picture . . . . K. Kaplan
- Similarity Principles Applied to Blast Effects . . . . M. Kanury, Notre Dame
- NBS Modeling Programs . . . . B. Parker, CFR/NBS
- Modeling Fires . . . . J. Rockett, USDA

20 March, Tuesday morning

1. Predictive (Analytical) Fire Spread Models: Summary and General discussion . . . . . . R. Alger, SRI

2. Countermeasure Evaluations

- Fire Service Demand and Damage-Control Models . . . . L. Pietrzak, Mission Research
- Cost + Loss Modeling . . . . F. Offensend, SRI
- Building Fire Model . . . . G. Berlin, NFPA

3. Future Test Opportunities:
Burbank, Lark, Misty Castle, etc. . . . . T. Kennedy, DNA

4. Organize Work Shops . . . . S. Martin, SRI

20 March, Tuesday afternoon

5. Workshops begin

20 March, Tuesday evening

6. Evening -- open

21 March, Wednesday morning

1. Progress Reports by Workshop Leaders

    - Where group is starting, how progressing
    - Where group is going to try to be by adjournment

2. Workshop activities resume

21 March, Wednesday afternoon

3. Workshops continue

21 March, Wednesday evening

4. Comments from Distinguished Visitors . . e.g., V. Sjolin, Sweden

    - Tungusta Cosmic Body . . . . C. Butler
    - Industrial Hardening in U.S. . . . . C. Wilton, SSI
    - A Parametric Study of Probabilistic
      Fire Spread Effects . . . . L. Schmidt, IDA
    - Downtown Burbank
      Urban Renewal Project . . . . J. Rempel, SRI

22 March, Thursday morning

1. Workshop Activities conclude 8:00 - 9:30

2. Final Summaries by Workshop Chairmen 10:00 - 12:00

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[*] Workshop Chairman

[†] Workshop Recorder

II BACKGROUND MATERIAL

DCPA Mission and Current Activities*

The current DCPA Mission is to save lives in the event of a nuclear attack; therefore, the principal concerns of this conference are:

- Casualties
- Postattack recovery.

Presumably, as DCPA becomes more involved with FEMA, continuity of Government will become another concern.

In the fall of 1977, the Secretary of Defense directed the Program Analysis and Evaluation Division (PA&E) of DoD to determine whether a meaningful civil defense program might be developed without major increase in funding beyond the current annual level of about $100 million. Guidelines suggested that the program should have the potential for saving one-half to two-thirds of the population. By contrast, rough estimates of the current situation are 90 million survivors if nothing is done and 100 million survivors if all the available protection is used. If the new program features population relocation as an option, the protection should be effective even when weapons are retargeted against the relocated population. DCPA was directed to assist in this study.

The attack environment was specified by PA&E and is characterized by a map of the United States showing areas experiencing at least 2 p.s.i. overpressure. These areas contain about 140 million people. The remainder of the population is affected by varying levels of fallout radiation, depending upon the number of ground bursts and the winds presumed to be effective at the time of the attack.

DCPA let a contract to the Systems Planning Corporation (SPC) to bring the various elements of the study together and to hold a series of

---

*G. Sisson

workshops attended by about 50 experts throughout the country who held both pro and con views about the efficacy of a civil defense program.

Programs were postulated at budget levels ranging from less than the current program to a program costing $65 billion and featuring single-purpose blast shelters.

One program involved developing plans to relocate 80% of the population away from high risk areas into buildings which would be buried and covered with soil to provide fallout protection. The remaining 20% (6% key workers and 14% stayputs) would be potentially subjected to direct effects in the high risk areas. This program (known as program D in the SPC report (2) and later modified for budgeting purposes and renamed program D prime) proved to be highly cost effective and saved more than three-quarters of the population, even with retargeting population.

Current assumptions are that program D prime will become the civil defense program. A modest increase in FY 80 funds suggests that FY 80 will become a "ramp" year into program D prime. For purposes of the current study, it is assumed that program D prime will be the program of the near future.

It should be emphasized that the crisis relocation plan (D prime) is a viable option only when there is sufficient time. In the event of a sudden attack, the existing program of fallout shelters would have to suffice. At present, the blast protection of critical industries and facilities is limited to planning how hardening can be achieved with available materials in a short time. No construction funds are available. Also, the list of key people and facilities remains to be defined. Various lists are afoot but none have been blessed by DCPA. Three options in key worker protection are under consideration:

- Last minute evacuation
- Expedient shelters hardened to withstand 50 p.s.i. overpressure
- Upgraded basement shelters.

Obviously, the blast/fire hazards anticipated in a nuclear attack will influence the ranking of these options.

DCPA has very recently assisted in two additional studies, mostly aimed at less than "all out attack" scenarios. One approach directed by the Congress involves a pure counterforce attack. The other involves a series of attack scenarios and is directed by the Office of Technology Assessment (OTA), an arm of the Congress. This study involved red on blue attacks, blue on red attacks of one weapon, a few tens of weapons on refineries, counterforce attacks, and major exchanges. Civil defense measures would vary widely if undertaken in each of those scenarios.

The Strategic Framework: A U.S.-Soviet Comparison*

Three points were emphasized in this discourse:

- Why the Soviets invested in civil defense
- DCPA considerations in analyzing priorities
- How to measure military utility of passive defense.

A brief survey of WWII bombing results emphasized that (1) with some effort, people can survive the rigors of war, e.g., only 1½% of the total population in Germany and Japan were killed by strategic bombing; (2) blast damage to factories and machines, particularly blast destruction of buildings, did not stop wartime production, e.g., in Russia in winter, women continued production in open structures; and (3) firebombing in Japan did destroy machines and reduce production. After WWII the Russians moved machinery and vital equipment from conquered or liberated lands to Russia. Subsequent unsatisfactory production experience led to a new policy: now equipment will be left in place to be operated with local labor, i.e., the seeds of recovery are not uprooted.

In the Soviet grand strategy, the concept of national entity survival is based on a definite set of priorities. Philosophically, these goals are the same in peace and war, so no restructuring is required in the event of a crisis.

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*Based on remarks by R. Foster

- First priority and ultimate objective is the continuity of power of the Communist party of the Soviet Union (CPSU) and its control over all facets of Russian society.
- Second priority concerns communications, command, and control (C^3) i.e., the civilian/military high command
- Third, the government apparatus of the state ministries of production and services
- Fourth, the cadres of key workers.

In this framework, the purpose of Soviet civil defense is to preserve the structure of society, namely, the CPSU--the state apparatus and the saving of lives are secondary. Note that in a clandestine operation or surprise attack preparations, such priorities raise an immediate problem for general lifesaving. It is easy for U.S. Intelligence to see a general evacuation of the cities but no so easy to see the key people going to shelters.

Asymmetries are growing between U.S. and Soviet civil emergency preparedness and civil defense (CEP/CD) concepts and measures, as well as between the respective strategic nuclear offensive forces and active air defensive capabilities. Civil defense is part of the Soviet military and is not becoming a civilian agency. The Soviet civil defense outlay in 1978 would amount to over $1.5 billion; the total military budget is continuing to grow, as shown in Figure II-1, probably at 5% per year (the upper curve). In the mid-1950s, the Soviets initiated a 20-year plan to overcome the West's lead in technology. Each year these RDT&E expenditures increase while the U.S. military RDT&E budget has declined or at best remained unchanged. Soviet expenditures for RDT&E are now about three times that of the United States. Technical education is a major effort in the USSR and by the year 2000, 7 to 10% of the population will have some sort of technical degree. This growth in military continued long after strategic parity was achieved, and is irrespective of SALT agreements or U.S. restraints because the Soviet posture is designed to fight and win a general war in contrast to the U.S. doctrine of "mutual assured destruction." Consequently, the Civil Emergency Preparedness programs assume key people are to be protected to work during nuclear

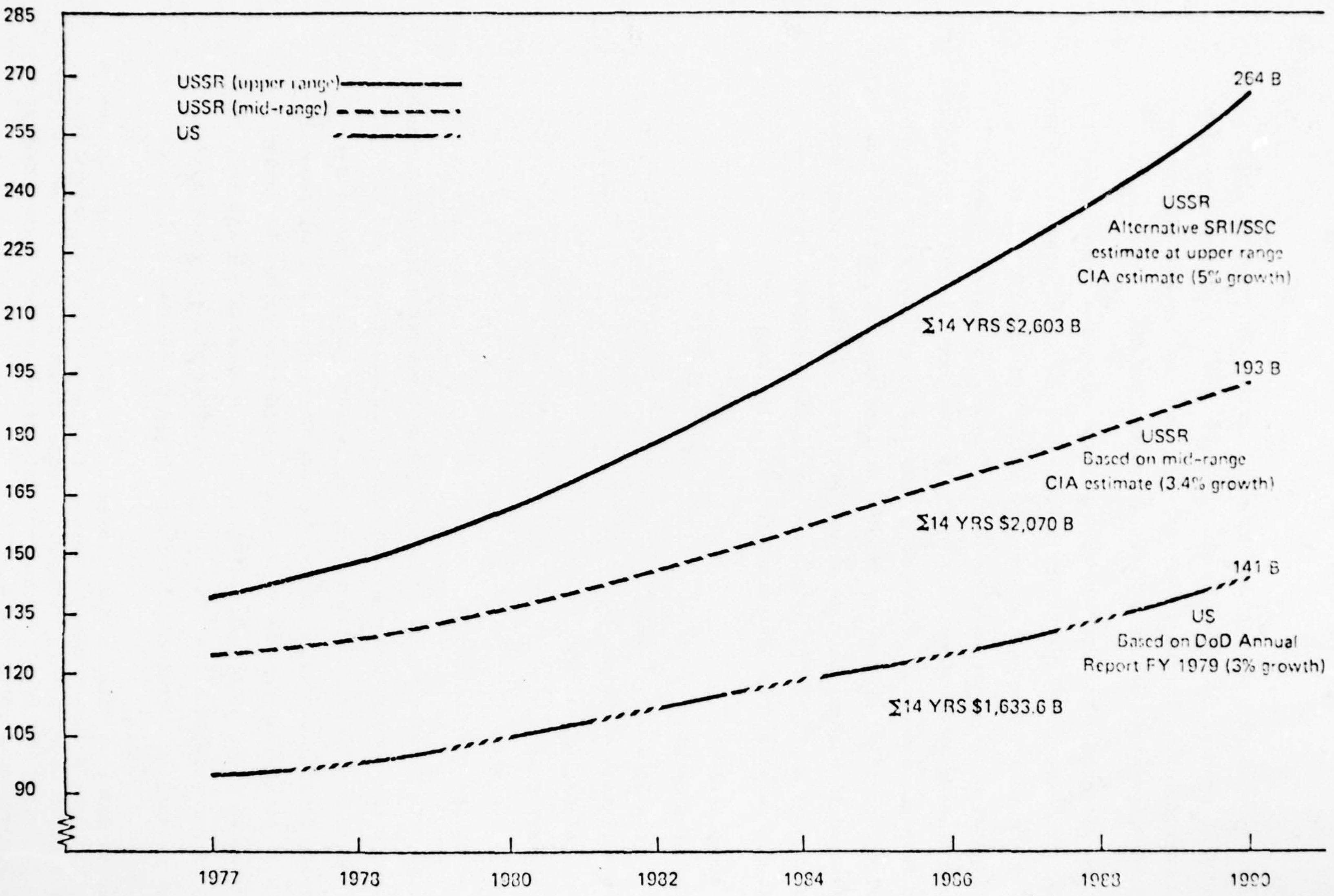

Figure II-1 TWO FORECASTS OF SOVIET MILITARY EXPENDITURES AND FORECAST OF US MILITARY EXPENDITURES, 1978-1990

(In Billions - 1977 Dollars)

Includes military forces, RDT&E, and Pensions war, not just during a post-war recovery period. Figure II-2 shows this concept of continuity of productivity based on the key people working and staying in the cities. They believe they can survive and regain productivity fairly promptly after a nuclear strike.

The difference in U.S. and USSR beliefs regarding the outcome of a nuclear exchange is illustrated in Figure II-3. The U.S. advocates primarily a mutual deterrence concept in which the objective is to keep the general nuclear war outcome in the "No-win" quandrant based on mutual assured destruction. In contrast, the USSR objective is to win both in peace and war.[*] There is a possibility of U.S. national survival if something is done to provide protection, but national destruction is assured if nothing is done about defenses: national assured destruction becomes a self-fulfilling prophecy in the U.S. but not in the USSR. In summary, the list of asymmetries include:

- Objectives
- Strategies
- Political objectives
- Military doctrine
- Defense emphasis
- Weapon size
- Force size
- Strike strategies

Finally, the Soviets are concerned with China becoming a major nuclear power and the potential for a coalition of China, Japan, and the U.S that encircles the USSR; therefore, the Soviets cannot give up any defenses including civil defense, because China is a nuclear power. The U.S. strategic doctrine of assured destruction gives the Soviets a chance to exert political coercion, i.e., nuclear blackmail in crisis diplomacy. Additional information of Soviet strategy for survival and civil defense is contained in Appendix A and References 3, 4, and 5.

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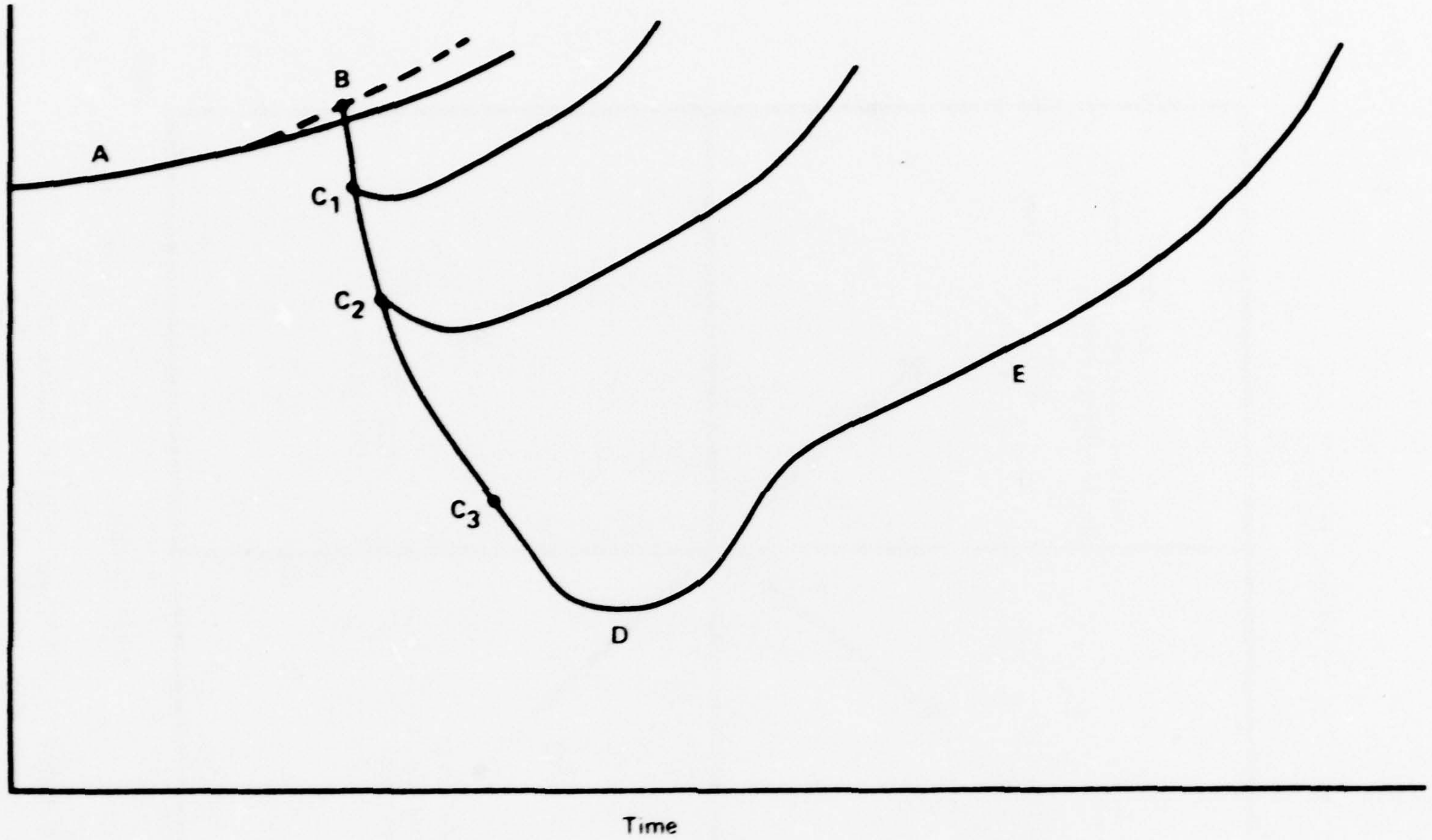
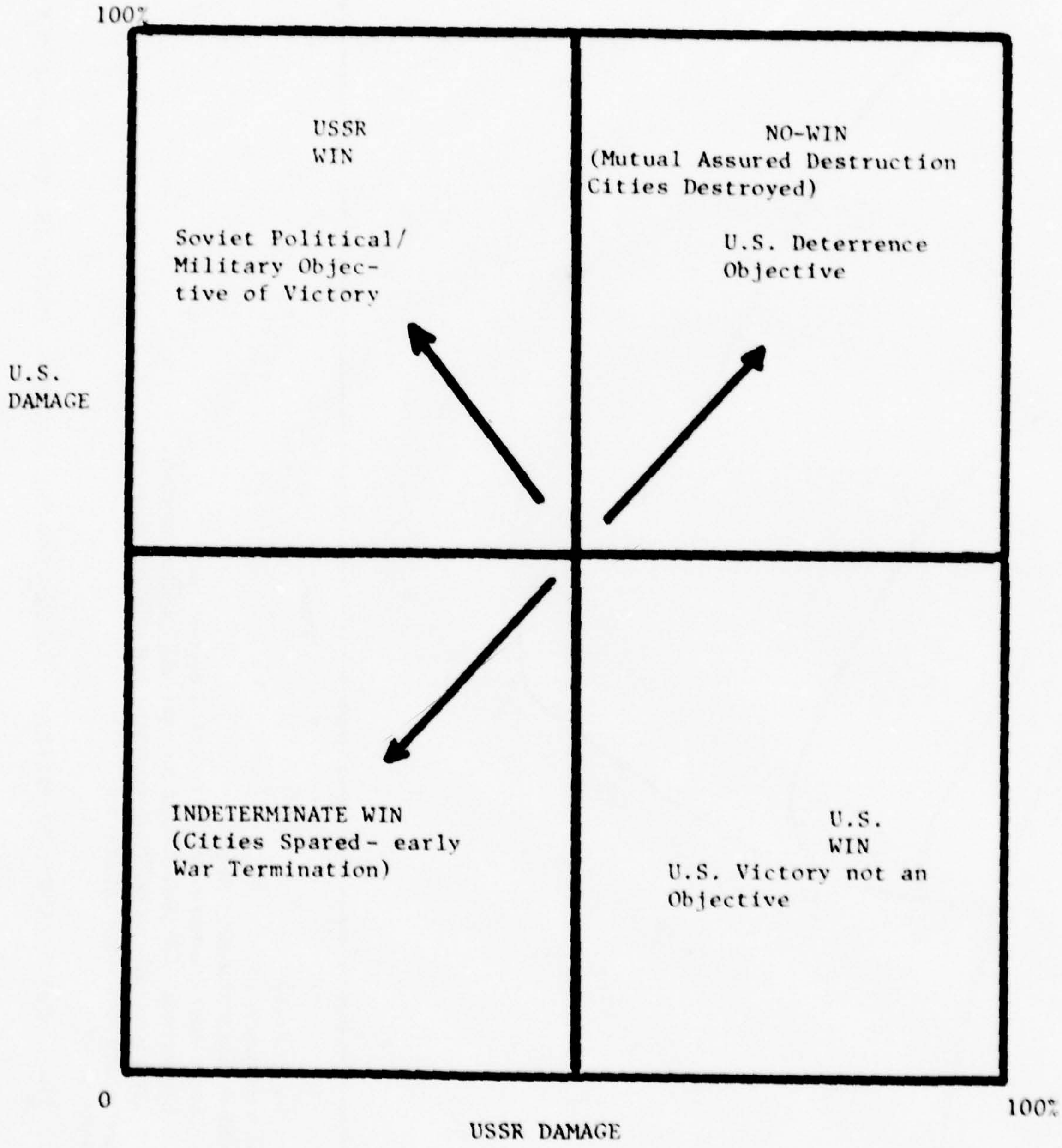
[*] A third point of view is represented by the defense philosophy of Sweden. At this year's conference, we were fortunate to have a representative of the Swedish Government's national defense structure, Dr. Vilhelm Sjölin, who described his country's current defense philosophy. His remarks are summarized in Appendix B.



A = peacetime economy
B = mobilized economy
C = alternative war termination points
    C_1 = Short war: counterforce and collateral damage only
    C_2 = Longer war: CF plus defense industry, ports, other military
    C_3 = Long war: all-out political, economic and military targeting
D = recuperation and reconstitution
E = recovery

Figure II-2 THE MEASUREMENT PROBLEM: EVALUATING THE ECONOMICS OF SOVIET CIVIL DEFENSE

FIGURE II-3



OUTCOMES OF STRATEGIC NUCLEAR EXCHANGES

The Soviet Union has never formally disavowed nor, in any real sense, retreated from its ultimate objective of world communism by whatever means are available and effective, including cataclysmic destruction of the capitalistic bases of power. The United States must remain alert to this threat of violent overthrow, including overt attack, and develop suitably flexible response strategies to replace the dangerously inflexible concept of deterrence through "assured destruction."

Modeling Blast and Fire Effects

The 1978 DCPA program objectives listed in Reference 1 stated that "our technical objective will be the development of one or more good-confidence, analytical models of fire behavior and incendiary-damage production. At present we anticipate a need for three separate models:

- A general urban fire distribution/spread model
- A "hole-in-the-doughnut" model, applicable to areas of totally collapsed structures
- A specific-resource vulnerability model.

Since modeling is such an important factor in planning the DCPA program, the subject was emphasized in the present conference with tutorial presentations and reviews designed to define the goals and establish the current status of modeling for potential use by the blast/fire community. Both experimental and theoretical modeling are pertinent to the considerations of the workshops. The following quotation from Reference 6 defines these several modeling concepts.

> "Technical discussions often confuse experimental modeling and theoretical modeling. Experimental modeling notably includes scaling (a size reduction, in which a small-scale model is studied to derive needed information concerning a large-scale prototype) but in general encompasses any abandonment of detailed physical reality in the interests of economy or generality. Geometrical simplification or substitution of relatively inexpensive materials are examples of generalizing at the expense of detailed description. Theoretical modeling means an analytical or numerical description of the essential features of the phenomena so as to determine output information of interest. As an example, the extent of a fire or its response to suppressive action,

is a function of descriptors in the form of design variables and/or operational procedures. Theoretical modeling underlies reliable experimental modeling in an essential way. Moreover, for some problems a combination of theoretical and experimental modeling is vastly superior to alternative procedures. Here model experiments are used to test and correct a theoretical model. The final model may then be confidently applied with parameters modified to correspond to conditions difficult and expensive to achieve experimentally.

"It should be understood that modeling is not a substitute for creative engineering solutions. It is distinct from the processes of invention or synthesis from which useful designs or procedures are proposed. It is true that a theoretical model can provide insight to guide creative engineering solutions, but the true role of experimental modeling is to evaluate alternative proposals and to provide quantitative data necessary for optimization and implementation.

"Experimental modeling thus shares a general role with engineering analysis on the one hand and with full-scale or otherwise fully realistic testing on the other. Which of these three procedures is preferable depend on circumstances. If the problem elements are well delineated and their quantitative interrelations known, analysis is appropriate. If a physical situation with very few variables or specific cases is of interest and can be inexpensively replicated, then direct testing is a logical procedure.

"Because of the great complexity of fire phenomenon, confident engineering analysis is rarely possible. Fire is intrinsically an accidental occurrence, and the conditions for straightforward test programs are rarely met. Not only must a set of accident scenarios be considered, but none of the scenarios can be stated with precision. Thus, even fully realistic testing will not by itself provide satisfactory information unless the results can be confidently generalized to a range of conditions different than those of the test. For many problems, experimental modeling offers the only economical means of achieving sufficient parametric variation and physical insight for such generalization. An example is the understanding of detection and extinguishment procedures for fires.

> "In summary, the reasons for experimental modeling are to provide:
>
> (1) Greater control of variables influencing system behavior
> (2) Economy in solving engineering problems
> (3) Convenience
> (4) Tests of the validity of theoretical modeling and thus derived generalization to a range of conditions of concern."

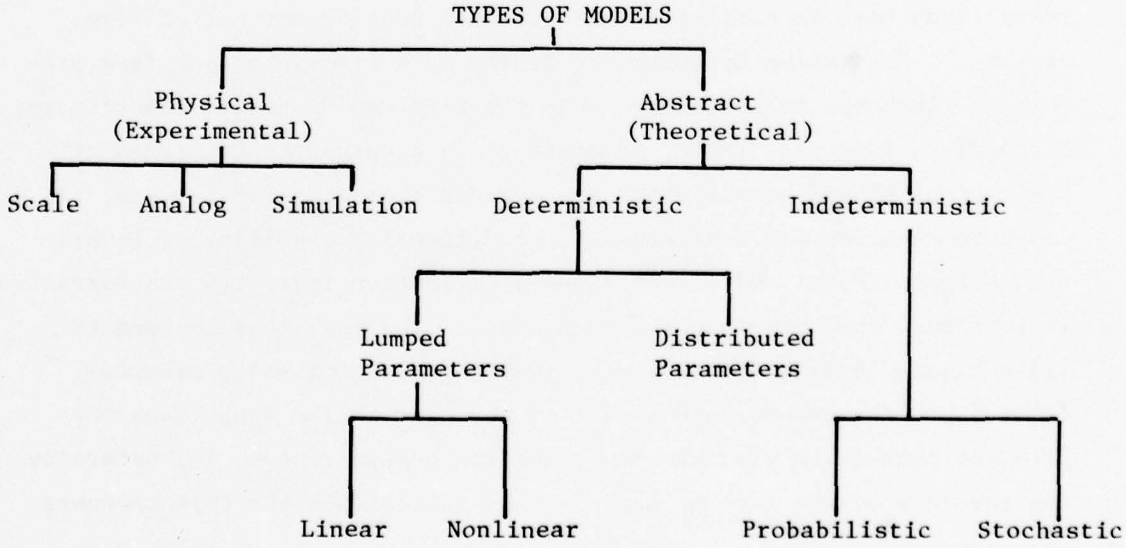
Similarity Concepts Applicable to Blast Effects

Figure II-4 (from Kanury's lecture on modeling responses of structures to air-blast loading) further illustrates the variety of models available. Here the emphasis was on scaling laws relating a small-scale modeling experiment with a full-sized blast/structure interaction. By dimensional analysis he established a group of nondimensional variables pertinent to three parts of the problem:

- The room filling process
- Flow in the room
- Collapse dynamics

These variables are described and several pertinent nondimensional relationships are derived in Appendix C.

Figure II-4



NBS Ad Hoc Committee on Mathematical Modeling

Dr. John Rockett described analytical models that can predict detailed fire behavior from a physical and chemical description of the potential fuel and its environment. Most of these models are limited to simple fuel geometries in a single room; however, some progress to spread through more than one room has been achieved. Rockett reviewed the status of these fairly basic models in four categories:

- Field equations
- Coupled phenomena
- Steady state
- Transient

Appendix D contains a list of the models and some additional comments.

NFPA Model for Rating Building Fire Safety

The NFPA Building Firesafety Model is one model that accommodates fire spread over multiple rooms. Dr. Geoffrey Berlin described the model in some detail and a complete description is available in Ref. 7. As indicated by the name, the objective for the model's development was to provide an alternative to building codes to rate the fire safety of a building. The procedure employs a Monte Carlo simulation based on transitions between critical stages of fire development called fire "realms." Six realms describe the growth of a fire in a room from preburn to flashover and determine when the fire can spread to other rooms. Transitions from one "realm" to another are governed by two types of statistical distributions which are derived from actual fire data. A discrete distribution indicates the conditional probability of transition between realms and a continuous distribution indicates the variation in residence time possible for each realm. The model can be used to (1) evaluate hazards due to the accumulation of combustion products, (2) measure the escape potential from any room in the house when the fire and combustion products block certain escape routes, (3) determine the severity of the fire at any time and (4) compare the effectiveness of various countermeasures. Unfortunately, suitable fire data are severely limited and the current results should only be considered as illustrative examples and not definitive results.

Review of Fire Spread Models Pertaining to Nuclear Attack

In preparation for this Symposium many of the prospective attendees were asked about fire spread models pertinent to the fire problem following a nuclear attack. A copy of the letter of inquiry is included in Appendix E along with a survey paper based on the replies and reports describing the models previously developed for the 5-City Study. This summary emphasizes the need to determine what vital facilities and which people are to be protected in or near the cities in the crisis relocation plan. Without such a determination, it is difficult to evaluate the best approach to the blast/fire problem, i.e., fire spread models that predict burned-out areas for a particular attack scenario versus vulnerability ratings that focus only on the critical facilities and their immediate environment. The report concludes with a list of questions that needs to be answered and decisions to be made in order to establish detailed directions and guidance for the DCPA program. These issues were not settled by this conference. Consequently, every effort should be made to resolve the questions in the near future.

III REVIEW OF CURRENT PROGRAMS

Several active Work Units (2563E and 2563F) have been in existence since last fall; consequently, the work is underway and there is some progress to report (e.g., Appendices E and F). Work Units commencing with 2564 have just been established, work has not commenced, and the oral presentations were limited to a discussion of plans. The following excerpts from the oral presentations follow the order of work unit numbers instead of the program.

Units 2563E and 2564A are intended to be complementary, with "E" examining the theory of shock phenomena that extinguish or enhance a flame and "A" providing the experimental basis for and validation of the theory. In describing the theoretical approach, Frank Fendell emphasized his interest in flame spread, particularly under wind-driven flame conditions. The background review included models for flame spread by John DeRis, Howard Emmons, and Forman Williams. Elements of these models were applied to the Steiner tunnel (ASTM E-84) test which is a well-studied example of flame spread under wind-driven conditions. Figures from NBS technical note 945, "An Investigation of the Fire Environment in the ASTM E-84 Tunnel Test," by W. J. Parker, were used to illustrate the wind-driven fire behavior. Emphasis was on the detailed temperature and flow conditions of the gas and the physical-chemical properties of the fuel. The effort under 2563E has just commenced.

As indicated by the work statement, 2563F provides back up material for the Blast/Fire Conference in the form of analysis and summary papers as well as preparing the proceedings of the conference. Stanley Martin described the sensitivity analysis that is being performed with the SRI fire model, i.e., an updated version of the URS model developed for the Five-City Study. The primary objectives are to provide guidance to working groups 1 and 2 regarding the importance of the various parameters involved in the blast/fire interactions and thus, the precision required in their determination. Particular attention was focused on the inherent uncertainties that cannot be removed with any amount of experimental or theoretical effort, e.g., uncertainties in the weapon thermal output and atmospheric transmission. The effects of controllable variables such as type of occupancy, window coverings, number of rooms or compartments, ignition thresholds, etc., were illustrated with numerous curves of burnup probability versus distance from ground zero or overpressure. Under Task 2, Appendix E provides background material for Workshop 3 by summarizing the status of fire-development, spread, and damage models with emphasis on the factors that must be resolved if such models are to satisfy DCPA requirements.

Under Work Unit 2564A, the initial blast/fire experiments on the DNA-DCPA shocktube at Camp Parks, California will initially focus on "shearless displacement" as a mechanism for extinguishing flames with a shock wave. As a background for the proposed experiments, Martin reviewed the evidence responsible for our present uncertainty about blast/fire behavior:

- The URS shock tunnel experiments on Class A fuels prior to 1970
- The SRI experiment at Mixed Company on Class B fuel in 1972
- Martin's Misers Bluff experiment in 1978

Slides and motion pictures of the Misers Bluff experiment showed the pillow fuel sample before and after the test in which the upholstery was extinguished presumably by the shock. Unfortunately, combustion products from the flash bag (ELS) ignition source completely obscured the motion picture view of the test sample during the crucial period between ignition and the arrival of the shock wave; consequently, no evidence was obtained regarding the mechanism of extinguishment. Additional information about past tests and future plans are included in Appendix F.

Before describing the thermal flux simulator concept planned for Work Unit 2564B, John Cockayne described SAI's historical activities with thermal sources, e.g., solar furnaces, flash lamps, flash bags, and hybrid systems combining flash lamps with a thermochemical reaction torch. The performance of two systems (1) the mylar bag containing aluminum powder in oxygen and (2) a quasi-continuously burning torch fueled with aluminum powder and oxygen were demonstrated with motion pictures. DCPA's operational requirements for a thermal source were listed as

- Repeatability
- Low cost and minimum development work
- Insignificant overpressures generated by the source
- Short turn-around times in operation

Figure (III-1 illustrates the hybrid system proposed by SAI for use in blast experiments. Most of the thermal flux comes from the aluminum-oxygen torch and a simple optical system directs most of the energy onto the target. The exhaust system keeps the combustion products (Al_2O_3) away from the test sample.

John Rempel reviewed the history behind Work Unit 2564C including (1) the early work on structures by Beck and Wiehle, (2) his own studies of airflows through small openings, (3) Longinow's trajectories for people, (4) the studies of collateral damage to German villages, (5) model building tests at Dice Throw, and (6) the computer program used in preliminary debris displacement calculations for the 1974 DCPA Program. Details of the proposed new work are given in Appendix G.

In preparation for Work Unit 2564E, "Theoretical Scaling of Large Fires", Hal Brode reviewed the physical parameters involved in fires:

- Source--yield, time of pulse, spectrum
- Environment--visibility, winds, temperature, humidity
- Fuel array--size, orientation, location, reflections
- Blast effects--suppression, extinction, fanning, temperature

Factors that influence the blast/fire interaction are:

- The growth and structure of the boundary layer
- Velocity of flame snuffing
- Fuel bed size and orientation
- Alignment of fuel bed plane and blast direction

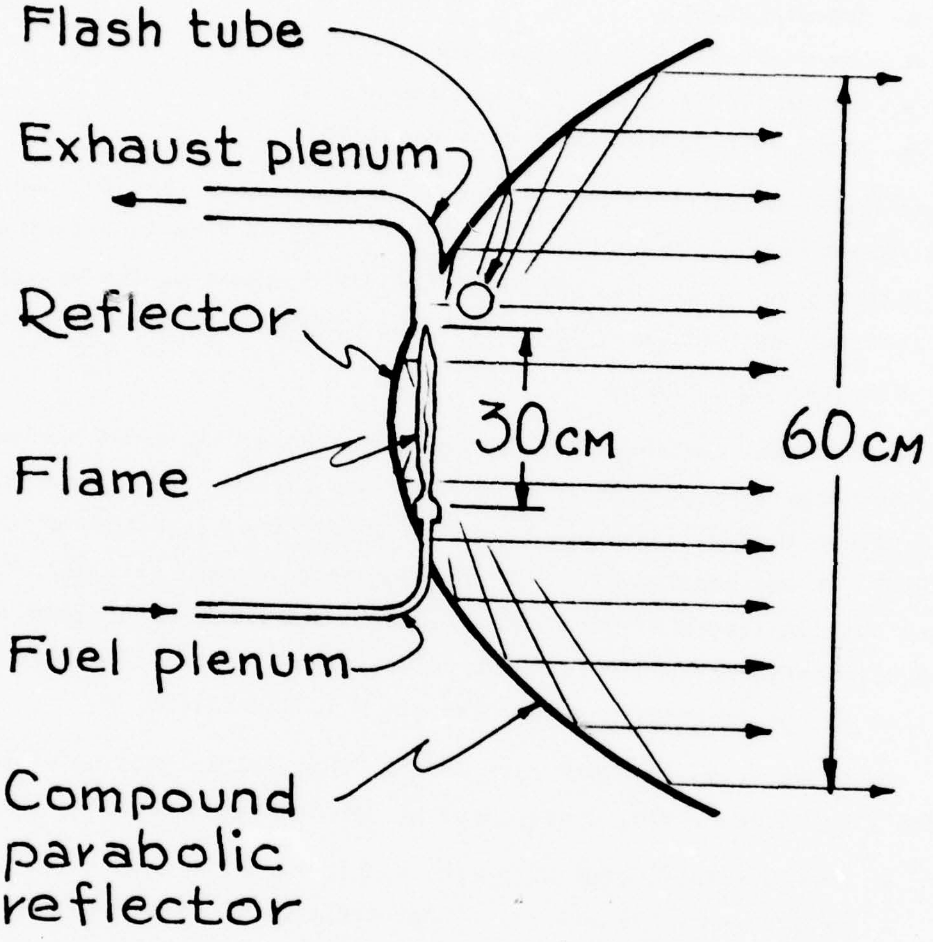


FIGURE III-1 PROPOSED HYBRID HIGH INTENSITY THERMAL SOURCE

- Stagnation locations
- Hot gas movement over fire
- Multiple bursts

The ideal case would correspond to a clean shock wave impinging on an isolated flame. Besides departing from the ideal shock front, shock tube experiments frequently require dimensional scaling and the attendent complications of extrapolating from one size to another.

In preparation for Work Unit 2564D, Longinow reviewed the historical background and factors involved in establishing the statement of work for personnel survivability. Effects to be survived include prompt and secondary radiation, translation and flying debris, and flames. The problem definition included structural analyses of shelters and their near neighbors, an examination of the distribution of people, and an analysis of the people response. After discussing various models appropriate to various portions of the study, he concluded with information about threshold velocities for injury due to impact and various strategies for falling.

Work Unit 2563E, "Blast/Fire Interaction Theory"

TRW shall initiate development of a theory for blast/fire interaction. Specific work and services shall include:

1. Apply innovative mathematical procedures, involving Laplace-transform and Wiener-Hopf-type splitting operations to expose critical hyperbolic aspects of the diffusive phenomena and to broaden the class of Stefan problems amenable to analysis. In particular, the type of wind-aided flame spread involving the sudden onset of a forced-convection high enthalpy environment of the Steiner tunnel shall be subjected to quantitative analysis.
2. Utilize the significant features of the underlying physics common to both the Steiner tunnel and the blast/fire problem, and develop a basis for the identification of conditions that differentiate fire extinction from fire enhancement and thus contribute to an improved understanding of blast/fire interaction.
3. Develop an advanced model of wind-aided flame spread, that includes finite-rate kinetics and radiative/ transfer in a physically realitstic fashion, suitable for use as a guide for the design, conduct, and interpretation of experiments.

Appendix H contains additional details about this work unit.

Work Unit 2563F, "Sensitivity Analysis of Blast/Fire Predictions and Services to Assess and Document Status of Technical Knowledge"

SRI International shall:

1. Use the SRI blast/fire model to determine the relative importance of the various input parameters for predicting blast/fire interactions. Perform a sensitivity analysis to determine the effects of assumptions about (1) the debris description, (2) primary ignitions and (3) secondary fire starts on the blast-fire damage estimates. The study will use the data base acquired for San Jose in the five city study.
2. Summarize the status of fire-development, spread, and damage models with particular emphasis on the consequences of the implicit and explicit assumptions incorporated in the models. Prepare a paper for the FY 79 planning conference outlining the strengths, weaknesses, and factors that must be resolved if such models are to satisfy the needs of the overall blast/fire program.
3. Assess and document the status of technical knowledge on nuclear weapon detonation-induced blast/fire interactions. This shall include: planning, organizing, and hosting a technical conference on blast/fire interactions; and preparing documentation, which will include the proceedings of the conference, and an analysis of the findings and priorities for future research needs relevant to the problem of blast/fire interactions.

Work Unit 2564A, "Shocktube"

SRI International shall evaluate the resistance to shock-wave blowout of established flaming combustion in composite fuel arrays of representative, practical composition. Specific work and services shall include:

1. The influences of fuel bed configuration, orientation, and surface texture on shock-wave blowout shall be investigated using the SRI-developed blast/fire shocktube.
2. Scale effects, such as the minimum length necessary to prevent extinction of flame by shearless displacement, will be investigated, and effects of non-free-field shock interactions, such as those experienced by fuels inside enclosures, by including in the test section nonfailing baffles and fixed apertures to represent perturbations due to walls and windows.

Appendix F provides the background information pertinent to the shocktube experiments.

Work Unit 2564B, "Thermal Flux Simulator"

Science Applications Inc. shall 1. Establish the requirements for a nuclear burst thermal flux simulator for weapons in the 1 MT range, and 2. Plan the development of a thermal flux simulator configuration that would satisfy these requirements and constraints. Specific work and services shall include:

1. Establish a detailed set of simulator requirements, including design goals and constraints, and initiate an investigation of the state-of-the-art for the various applicable technologies.
2. Develop plans for a simulator concept, including: experimental and engineering results and specifications for a prototype module(s).

Work Unit 2564C, "Debris Distribution"

SRI International shall develop and test a means of predicting the distribution of debris and contents in a one-story NFSS building as related to the concurrent threat of primary fire. Specific work and services shall include:

1. Use available mathematical models and computer programs in building response, debris translation, and room-filling to develop a unified program for estimating damage to structures and debris transport for use in blast/fire interaction studies.
2. With the program developed in item "1" above, distribute the debris field as a function of time in one story of a low-rise NSS building at two overpressures, one corresponding to a location in the risk area and another at a range where exterior walls experience incipient collapse.

Appendix G describes in detail the work planned for this work unit.

Work Unit 2564D, "Personnel Survivability"

IIT Research Institute shall develop a rational analytic procedure capable of realistically treating the phenomenological interaction of blast and fire as this influences personnel survivability. Specific work and services shall include:

1. Assess the value of existing blast/fire survivability data and formulate a systematic approach for evaluating personnel survivability in a blast/fire environment. This initial study shall concentrate on a detailed analysis of a local grouping of structures, including shelters which could be of conventional or expediently upgraded construction. Preliminary structures in the direct vicinity of the shelter shall be limited in variety with carefully detailed descriptions developed for each. These shall include (but not necessarily be limited to):
    a. Single family residential (with and without basement) framed construction
    b. Multifamily residential (with and without basement) masonry construction
        - Reinforced concrete frame construction
        - Flat plate or flat slab construction
2. The analytic approach shall include a time-dependent, mechanistic model of fire spread, fire suppression and rescue operations within the shelter, the building that houses the shelter, and the local (study) zone of surrounding structures. A major modification to the study zone would be blast damage and the distribution of debris produced thereby. Blast-fire interactions as they affect personnel survivability shall be included quantitatively. State-of-the-art estimates, with provision for variation and modification in the future, shall be incorporated where definitive data are currently lacking.
3. Provision shall be included in the model for preattack countermeasures and variation in population location. Routines shall be developed on an individualized structure-bystructure basis to identify the net results of immediate weapon effects on blast damage and population casualties.

Work Unit 2564E, "Scale Modeling of Large Fires"

Pacific-Sierra Research Corporation shall develop a theoretical basis for small-scale modeling of fire effects in specific target areas, and plan a program for experimental simulations of fire effects caused by nuclear detonations. Specific work and services shall include:

1. Review pertinent experimental and theoretical findings as related to nuclear-explosion-induced fire in cities. Include a review of the modeling theories as applied to room and corridor fires, and certain pollution modeling studies, with an assessment of the pertinence to mass fire spread modeling.
2. Develop a small-scale modeling theory for nuclear-explosion-induced city fires. This entails identification of the dominant effects in the different phases of the fire development and definition of the important dimensionless groups which must be preserved in model experiments.
3. Definition of standard models for use in wind tunnel and shocktube simulations.
4. Definition of advanced modeling technology (for thermal flash and fire initiation) which can be applied to development of realistic small-scale simulation of fires initiated by nuclear burst(s).
5. Definition of wind tunnel and shocktube experiments which would resolve key technical problems, verify existing theoretical models and provide guidance for development of more sophisticated and inclusive theoretical models.
6. Based on Tasks 3, 4 and 5, appropriate full-scale simulations will be recommended. Candidates for thermal pulse and blast wave simulators (such as detonation of LNG) will be investigated.

IV RELATED WORK

Misers Bluff Test

William Taylor, Stanley Martin, and Tom Kennedy described various Misers Bluff tests that are pertinent to the blast/fire program. Figure IV-1 illustrates the SAI mylar bag thermal sources used to irradiate various vehicles and aircraft in a simulation of the thermal pulse from a nuclear weapon. In the 5280 shelter case of Figure IV-1, the aluminum powder and oxygen in the bags were flashed 2.3 seconds before the 120-ton ammonium-nitrate/fuel-oil (ANFO) charge was detonated. Motion pictures showed the performance of the flash bags and the arrival of the shock wave. The temporal history of the overpressure experienced by the test specimen shows some distortion of the shockwave as it passes through the small volume of hot gasses generated by burning the aluminum powder. Developmental efforts on the thermal source are focused on reducing the obscuration from unburned aluminum deposited on test surfaces and eliminating the mylar bags. Motion pictures of a bagless SAI experimental burner in operation demonstrated the concept which has the additional advantage that the thermal pulse shape can be controlled for very long times.

Martin's pillow experiment made use of a mylar bag source positioned to irradiate a navy aircraft. As described previously under Work Unit 2564A, the source apparently ignited the pillow, as intended, but powder obscured the entire sequence of events so that the monitoring motion pictures show nothing of the ignition and extinguishment. Other motion pictures taken from a more advantageous position were not available during the conference.

Kennedy described a demonstraton of blast damage on protected and unprotected heavy machine tools. The objective was to document the results in a motion picture that could be used to create an awareness

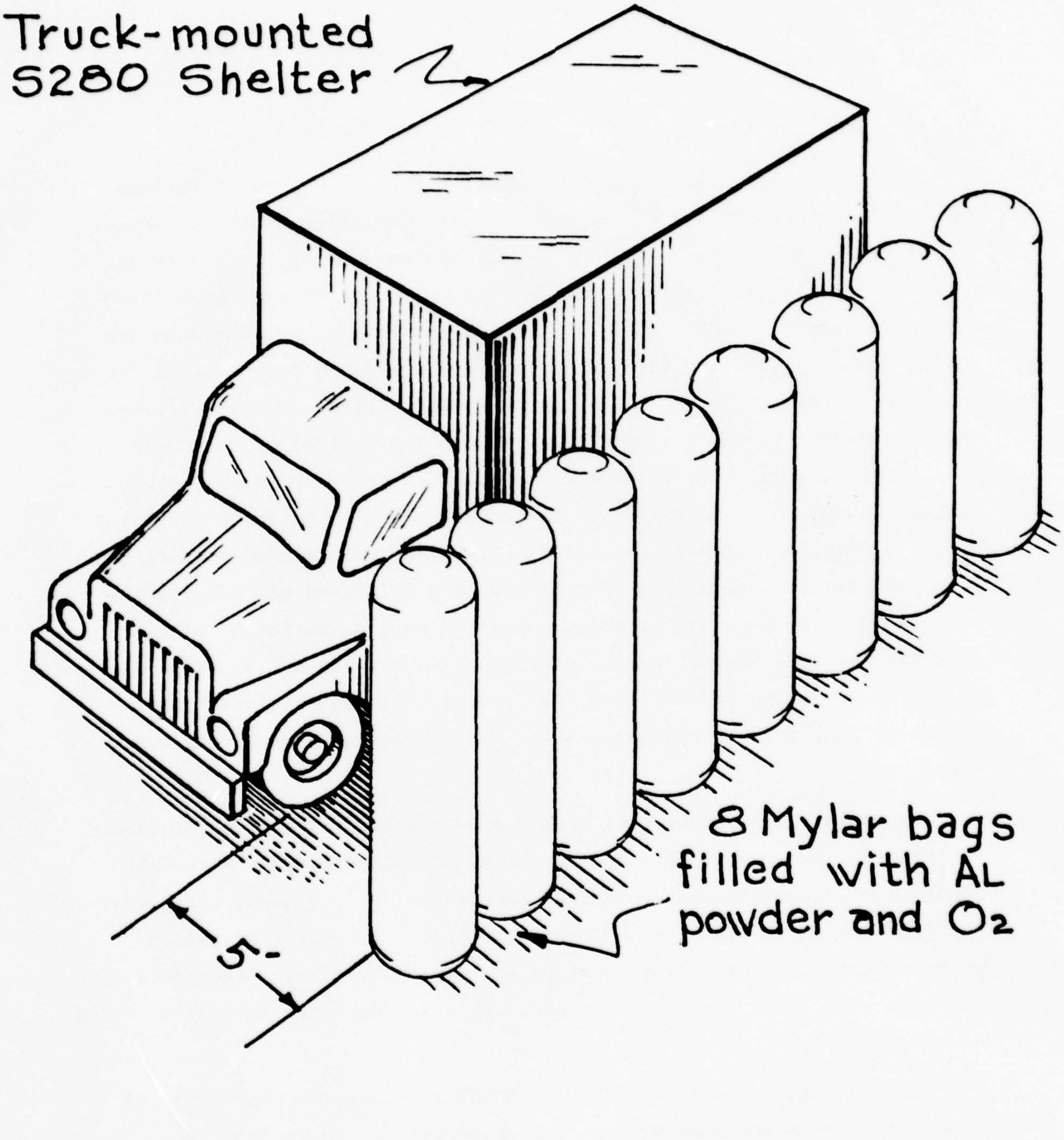


FIGURE IV-1 SAI MYLAR BAG THERMAL SIMULATOR that equipment can be protected from extremely high overpressures. Obviously, such results are very important to DCPA considerations about vital machinery and the potential for postattack recover. Figure IV-2 schematically illustrates the test arrangement. Two identical steel frame buildings were erected at about the 300 p.s.i. overpressure point and filled with a variety of industrial equipment, e.g., lathes, mills, drill presses, tables, filing cabinets, oscilloscopes, ovens and other government surplus items. A nonreinforced concrete block wall facing ground zero provided missiles to increase the potential for impact damage. One shop was left unprotected, the other was protected (as indicated in Figure IV-2) with dirt fill over the equipment covered with bags of aluminum chips or other crushable material. Eleven of the fourteen heavy items in the protected building were recovered and operated after the test. However, the unprotected building was completely destroyed and the contents wrecked. On a subsequent 120-ton shot, some equipment exposed to the blast out in free air was severely damaged by tumbling. Motor mounts and long columns are particularly susceptible. Soviet weapons have a larger throw weight than their U.S. counterparts; therefore, at the same distance from ground zero, the U.S. will have to protect against about four times more overpressure than the Soviets; e.g., 150 versus 40 p.s.i.

The DNA tentative test schedule was discussed with particular emphasis on shots where opportunities for piggyback blast/fire experiments exist. Three good possibilities are:

- 120-ton ANFO shot at White Sands, summer of 1980
- Misty Castle II; 600-ton ANFO shot at Fort Hood, 1981
- Misty Castle III; 500- to 600ton ANFO shot at Fort Hood, Jan - Mar 1983

Dice Throw Test

Ken Kaplan showed a motion picture with sound that he recently produced for DNA covering blast effects at Dice Throw. This shot involved 600 tons of ANFO detonated in New Mexico on October 6, 1976. Some of

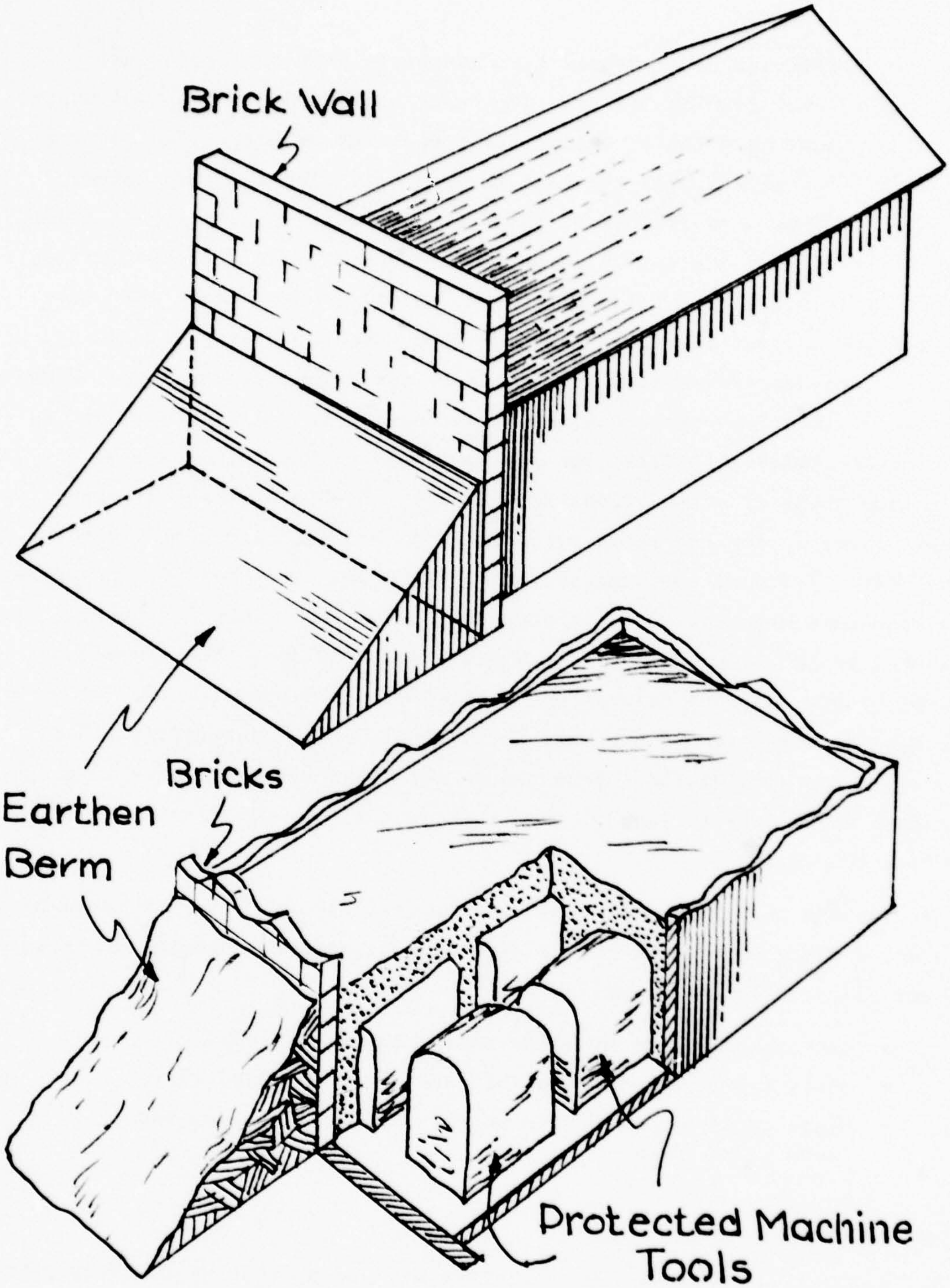


FIGURE IV-2 BLAST PROTECTION FOR ESSENTIAL EQUIPMENT the items tested were a drone helicopter, aircraft shelters, personal shelter, expedient shelters, trusses, wheeled vehicles, and tractors. Thirty-one experimental programs were conducted by 29 agencies. Much of the information is particularly pertinent to countermeasures for protecting critical equipment and key people. The film is available from DNA (SPTD) for other viewings. In the tests of equipment protected by burying under a layer of crushable material and a layer of earth, the depth had to permit arching forces in the earth which relieved some of the direct load on the equipment. Various trench type personal shelters were tested; e.g., a trench covered with a hollow core door and earth survived 15 psi with some damage. Communication tests through the dust cloud at high frequencies (e.g., 300 MHz to 10.2 GHz) indicated that transmission was greatly reduced. Survivability of aircraft in the air, on the ground, and buried in protective shelters was also examined.

Shocktube Experiments

Bill Taylor described some thermal shock-blast experiments performed with an SAI source in the BRL 8-foot-diameter shocktube. Figure IV-3 illustrates the arrangement for avoiding the shockwave distortion that occurs when the shock passes through a layer of hot air. The test sample is mounted on a rotating platform which rotates 180° between the time of the thermal pulse and the arrival of the shockwave; consequently, the shockwave encounters the hot air after passing the sample. A group of aluminum-oxygen burning nozzles is operated in parallel to try for a flux density of 65 to 70 cal cm^{-2} sec^{-1}. Curves of the spatial and temporal characteristics of the thermal pulse were shown.

Industrial Hardening in the U.S.

Chuck Wilton reported on a related task (Work Unit 1124C) which involves expedient countermeasures to protect essential industries and key workers. The emphasis is on the crisis period and what protection can be achieved in 72 hours. Necessary information is covered by nine booklets that deal with organization and education, protective housekeeping, equipment inventory, structural analysis, resources inventory,

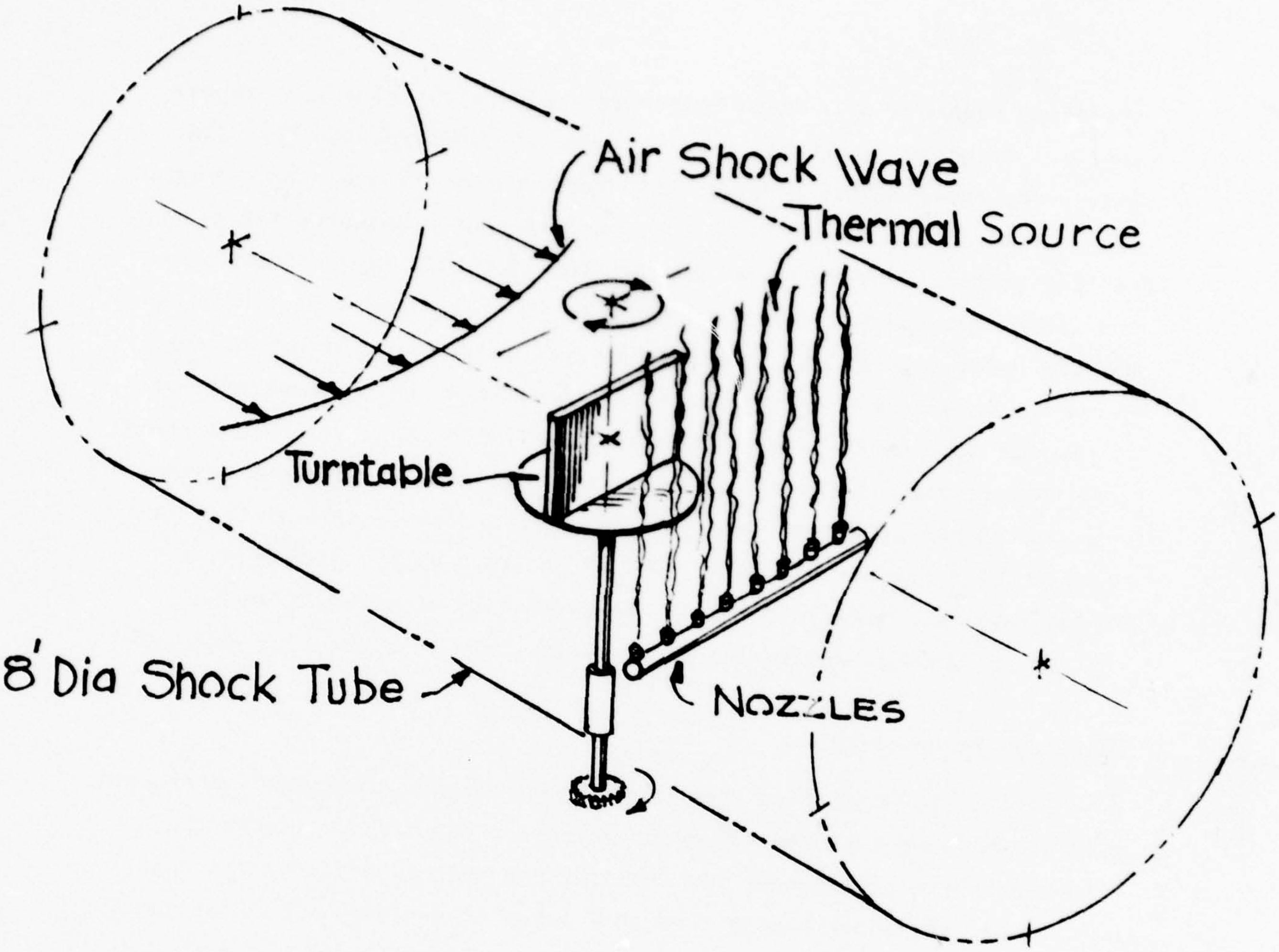


FIGURE IV-3 THERMAL SOURCE FOR SHOCK TUBE employee and dependent welfare, and key worker shelters. Based on the Defense Industrial Plant Equipment Center (DIPEC) listings, 80% of the industries have been grouped into 40 categories which are used to obtain rough estimates of blast damage. Hardening methods have been applied in paper studies to nine plants and physically to several plants. (Incidentally, in exercises to identify the key workers, management frequently fails to make the list.)

Fire Tests at NBS

Bill Parker used the diagram in Figure IV-4 to explain the strategy of fire testing at NBS. The goal is to establish correlations between the laboratory test results and the behavior of room fires involving the same fuels. Analytical models provide the bridge for this correlation as well as a relation to the reduced scale models. Three classes of laboratory tests are employed: index tests, ease of ignition tests, and fundamental tests. Some of the details discussed include:

- Fire development in a typical room corner test, i.e., the build-up from flame extension to flameover (when flames go out of the room opening), to flashover (when combustibles on the floor ignite)
- The heat and mass balances in room fires, particularly the problems with mass balances in rooms with combustible walls
- Scaling rules and mass loss studies in reduced scale models
- Flame spread tests and the measuring apparatus
- The heat release calorimeter
- The use of oxygen depletion to measure the heat released in room fires.

Shelters and Survivability

In one mode of the CRP, key workers seek safety in shelters during and immediately after periods of attack. Under such conditions, the question of shelter habitability becomes crucial. Ruth Shnider reported on an analytical model (Appendix I) to calculate the fraction of people

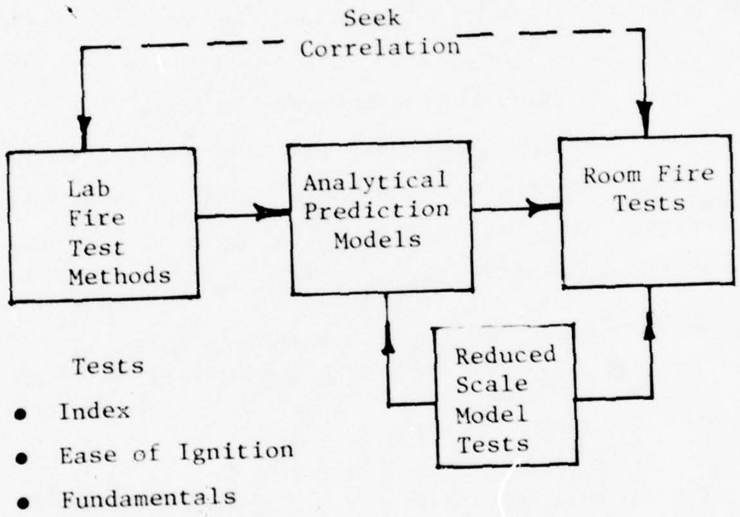


FIGURE IV-4 FIRE TESTING AT NBS

forced out of shelters and those who survive. Based on the URS model for the Five-City Study, which found that most fires burned themselves out within four generations, the model considers both primary and secondary fires and a four-generation limit. In the absence of data for the calculations, estimates are used to provide three casualty ranges, i.e., low, median, and high. Calculations are underway for various types of shelters in various overpressure regions and tract classifications. Some early results indicate the magnitudes to be expected in open residential tracts where debris layers are relatively thin. Under these conditions, no fatalities would be expected in the 2- to 5-psi overpressure region for shelters in strong basements. Similarly in the 5- to 9-psi regions, the fatalities should be less than 3%.

Countermeasure Optimization

Countermeasures are the ultimate goal of the blast/fire program. Two speakers described some aspects of optimizing countermeasures. *Larry Pietrzak described a fire demand computer simulation model for* determining the water requirement to suppress fires in various states. The paper reprinted in Appendix J covers the main features of the talk. In general, the Fire Demand Model simulates the actual fire dynamics, interactions, and performance of the fire suppression system in a realistic and understandable way on a computer. The objective is to improve suppression system performance (hardware and tactics) and more effectively use the limited water, manning, and equipment resources in protecting shelters and key industries in a post-attack survival environment, specifically:

1. Improving fire suppression equipment performance: Simulations permit one to try many combinations of hardware parameters over a wide range of fire conditions to understand sensitivities and help focus hardware development and experimentation onto conditions that are most stressful and offer the greatest potential for improving equipment fire control performance.

2. Improving fire suppression application and tactics: Simulations that incorporate both firefighting operational times and hardware performance permit one to conduct operations research type studies to identify optimal tactics and preattack firefighting plans for specific critical risk types.

Fred Offensend described the decision analysis approach to the choice between options for fire protection. This approach is based on minimizing the "cost + loss ;" i.e., the cost of the option plus the fire losses anticipated when the option is in operation. If we had perfect information about the future for each possible strategy, it would be a simple matter to reach such cost-effective decisions. Unfortunately, decisions have to be made in the absence of perfect clairvoyance and often in the face of conflicting opinions. The decision analyses approach provides an organized procedure for making such value judgments based on the best available information. Typical steps in the analysis are:

- Identify the alternatives
- Establish outcome measures, i.e., a yardstick to evaluate the outcome
- Synthesize the cost + loss model covering the appropriate amortization time periods
- Develop the best available input data
- Exercise the model to reflect current conditions, i.e., establish the status quo and validate the probability assignments
- Exercise the model for each of the alternatives or combinations of alternatives
- Provide the decisionmakers with the various cost + loss results so they can make a decision.

Judging from the discussion following this presentation, there are strong and diverse opinions about how to make a decision in the absence of complete data.

V WORKSHOP 1:
INITIAL FIRE DISTRIBUTION AFTER BLAST EFFECTS

Fire caused great damage and many casualties in Hiroshima and Nagasaki, but we have only fragmentary reports of the actual details. The nature and extent of the intense thermal pulse from nuclear explosions are well documented by Glasstone and Dolan (1977) and by Brode (1968). What is not known is:

- How many fires were ignited by the thermal radiation?
- How many of them were blown out by the blast?
- How much transporting of firebrands took place?
- How many secondary (blast disruption) fires were created?

The state of the predictive art as it existed for incendiary effects in 1970 is summarized by Martin (1978).

Hiroshima and Nagasaki were destroyed by bombs of 10 to 20 kilotons. The world now knows weapons more than a thousand times as powerful. Since the thermal fluence increases with yield for a given blast overpressure (until atmospheric attenuation dominantly intercedes) and since we have no urban-target experience at all for the larger yield weapons, it is especially important to be able to sort out the separate roles that thermal and blast effects play so that we are not forced to make orders-of-magnitude extrapolations from an uncertain kiloton-yield base.

Approaches to these questions are suggested in the following sections:*

- Large Area Radiant Ignition
- Extinguishment and Intensification of Fire by Blast
- Experiments in Blast Extinction of Fire
- Influence of Multiple Bursts on Fires and Fire Spread.

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*Members of Workshop 1 are Norman J. Alvares, Jana Backovsky, Harold L. Brode (Chairman), Francis Fendell, Tom Goodale (Recorder), A. Murty Kanury, Stanley Martin, William Parker, and Ruth Shnider.

In general, these sections suggest that the influences of blast waves on fires remain largely unknown or uncertain.

At the previous Asilomar Conference on Blast/Fire Interaction (Martin, Alger, 1978), interest centered on the 2-5 psi region (14-35 kPa) for bursts of 1-5 MT. Multiple bursts were not considered, although a limited knowledge of weapons availability and targeting methods strongly suggests that many urban targets may expect more than one nuclear burst in a general war. Similarly, no thought was given to ignitions in an urban environment already disturbed by previous bursts, or already in flames with well-established fires from an earlier explosion. The broader questions as to the relative frequency of primary (thermally ignited) fires and secondary (blast-caused) fires were not examined last year, although the question has been with us since Hiroshima. Consideration of the effects of blast on well-established fires was also absent in the previous conference.

Research Plan

In response to these and other related questions, members of Workshop 1 suggested the following research areas to deal with those specific aspects of blast/fire interactions, affecting the blast-perturbed, initial-fire distribution, that they were able to identify. Priorities were not established but the areas of greatest urgency are first on the list while items of less urgency or importance are farther down.

- Shocktube Experiments on Blast Extinction of Fires (Work Unit 2564A)
- Blast/Fire Interaction Theory (Work Unit 2563E)
- Secondary Fires
- Ignition in Blast-Damaged Structures
- A Program for Fire/Blast Interaction Research
- Role of Firebrands in Fire Spread
- Ignition of Practical Fuel Arrays--large areas of mixed fuels
- Fire Initiation in Blast-Damaged Structures--ignition of debris by residual radiation (after blast arrival)
- Special Problems of Multiple Bursts--e.g., effects on fires and fire spread.

Research projects in the first two areas listed are already funded by DCPA. Shocktube experiments will be performed by SRI in the newly completed facility at Camp Parks, California. Initial attention will be investigating shearless displacement as a practical mechanism for fire extinction. Simulations of the Mixed Company experiments will be conducted at reduced scale. As a complementary effort, TRW is attempting to extend the utility of their mathematical model for wind-driven fires to provide a theoretical basis for predicting wind effects and to aid the interpretation of experimental results. Brief descriptions of these projects have already been given in Chapter III. A detailed work plan for the shocktube experiments is given in Appendix F. Appendix H is a program statement for TRW's theoretical effort under Work Unit 2563E.

Program statements developed by Workshop 1 participants for the research areas that are not currently funded* are presented in the following pages and constitute the remainder of the Workshop 1 report.

Secondary Fire

1. Objective

The purpose is to determine the importance of secondary fires relative to primary-ignition fires from nuclear attack, as precursors of spreading fires in urban areas.

2. Background

Considerable information is available concerning ignition potential of various ignitables within buildings. In addition, some data exist regarding blast damage to small structures. Unfortunately, not as much experience with large structures is available. Some gross projections of blast damage to industrial structures (i.e., petroleum reactors, power heat exchangers, smelters, fabricators, etc.) have been made. Almost nothing is known of the condition of power and service equipment, and little is known about the structure and contents of light industrial

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*Since the conference, an opportunity arose to get information on ignition of large areas of geometrically complex and mixed fuel arrays at a modest cost. This information should be available in the very near future.

and residential structures after blast.

The question then is: What is the risk of a residential or commercial/industrial complex being sufficiently disturbed that easily ignitable fuels are exposed, thus providing more ignition sites relative to the risk of fire starts from disruption and ignition by nonthermal radiation means?

What is lacking is an appreciation for the frequency and severity of fire starts from both secondary (blast-induced) and primary (thermal-induced) sources. The relative importance of both sources is important to any assessment of the ultimate fire hazard and the likely success of any preventive or suppressive efforts.

3. Program

Develop a rationale for estimating the frequency of fires in urban/industrial (U/I) areas due to (1) primary thermal ignitions in an undisturbed area (first burst--a job largely already done in Five Cities Studies,* etc.), (2) secondary fires caused by first blast wave as a function of yield, distance, and type of U/I area, (3) primary fires caused by thermal from a subsequent burst on an already blast-disturbed area, and (4) secondary fires in an already disrupted environment.

4. Approach

This problem has so many potential factors that precise treatment is not likely to be rewarding. An early approach, largely analytical and approximate should:

- Review what has been published on this subject (internationally)
- Review contemporary disaster data.

Ultimately, what is needed are estimates (based on actual surveys) of the release or exposure of potential ignitables and/or fuels, the potential sources of secondary ignitions, and the absolute as well as relative frequency of each ignition type. Also needed are the blast

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*Without benefit, however, of a method for including blast/fire interactions.

resistance or response of containing structures, and the thermal response of such structures (external fires can spread to interiors, also). The blast interaction with ignitions and well-established fires, with both primary and secondary fires, should be included in such estimates. The areas of dominance of secondary (or primary) fires should be indentified, and the effect of multiple bursts on the frequency of each should be estimated.

5. Summary and Conclusions

The relative importance of secondary fires is not well established for a single nuclear burst on an urban or industrial target area. In order to deal with the more complex problem of fire in an area exposed to more than one weapon, the absolute as well as relative frequency of both primary and secondary fire starts must be estimated. In addition, the consequences of blast disruption on the frequency of both primary and secondary ignitions from a subsequent burst must be approximated. While this may demand considerable judgment and qualitative evaluation, the detailed study of specific example areas could be most illuminating.

Ignition Thresholds of Fuel Arrays of Practical Size and Complexity

1. Objective

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.

2. Background

To estimate the number of primary ignitions due to the thermal radiation from nuclear detonations it is necessary to know the incident flux history and the ignition thresholds of the exposed materials as a function of weapon yield (pulse shape). Scaling rules for thermal radiation have been established based on a large number of field measurements over a wide range of **yields, heights of burst, and distances from ground zero.**

Atmospheric transmission of the air at the test sites has been deduced from these data.

Additional measurements of atmospheric transmissions have been carried out in urban atmospheres. For example, Schleiger (1961) at NRDL made measurements in Los Angeles with a xenon flash lamp over distances in excess of 12 miles. The ignition of a large range of household materials as well as forest fuels and military equipment available in the 1950s was measured at the Naval Applied Science Lab. Exhaustive studies of the ignition of alpha cellulose (a special black paper) were carried out at NRDL and elsewhere. These data were restricted to small planar vertical surfaces.

Questions have arisen concerning the effect of specimen size and geometrical configurations like sofas which may tend to trap heat. Some work by Tom Waterman at IITRI has indicated that after the thermal pulse is over, the flame on a thick cotton batting cushion may extinguish and not rekindle unless there is a joint present. In a paper by Alvares (1974) an increase in ignition sensitivity with exposure surface height was predicted. A 4-by-4-foot bank of quartz iodine lamps at NRDL was capable of igniting whole pieces of furniture and hanging drapes. However, this work was just beginning at the time NRDL was closed. Consequently, there were no results reported for the facility. Murty Kanury has prepared an extensive review of the ignition work done up through the early 1970s. Takashi Kashiwagi at NBS has been studying the fundamental processes of the ignition of combustible solids. A highly developed prediction capability has been established for idealized fuels (most particularly for single, geometrically simple targets), but it is uncertain how well this can be applied to practical situations.

3. Program of Research--Tasks

- Review prior ignition work and current state of the art.
- Conduct a series of exposure tests to study ignition.
- Derive scaling relationships to generalize thermal ignition characteristics.

4. Program of Research--Approach

A review of the literature and contact with the workers in the field is in order to establish the state of the art on the effect of size and specimen configuration on radiant ignition of charring and noncharring solids. An early goal is to determine the materials and configurations which should be examined in an experimental program. This determination should be aimed at providing the ignition data required by the fire growth models.

Secondly, a large-area, high-intensity radiation source in the proper range to adequately simulate the thermal radiation from a nuclear detonation should be identified and acquired or designed and built. This might be a bank of lamps.

Thirdly, it is recommended that an experimental program on well-characterized but realistic materials be carried out. The time to ignition and the surface temperature versus incident flux should be determined as a function of specimen height, thickness, and configuration. Combinations of materials should also be examined.

Fourthly, theoretically based scaling relationships for specimen size and configuration should be developed.

5. Summary and Justification

Fire remains potentially the most devastating consequence of nuclear attack, yet because of the uncertainties and unpredictable nature of fire initiation and spread, neither attack planning nor civil defense measures deal realistically with this threat. While many factors contribute to the uncertainties, the probability of sustained ignition from the thermal pulse from large-yield nuclear explosions is a most important aspect. Current understanding is limited. A modest program could materially reduce this area of uncertainty. With more exact knowledge of when fires will persist and where they will not, planners should be better equipped to deal with fire-threat situations. It is a prerequisite to evaluating the consequences of blast/fire interactions.

Since simulations of the thermal pulse are possible, and atmospheric nuclear tests are not, ignition susceptibilities is one effect that can still be studied. The potential for saving lives and limiting damage is high, measured in billions of dollars. The cost of a reasonable extension of our understanding of ignition thresholds is in the hundreds of thousands of dollars.

Fire Initiation in Blast-Damaged Structures and the Resultant Debris

1. Objective

The purpose of the research is to evaluate the potential for thermal ignition of blast-exposed fuels.

2. Background

As an airburst occurs, the initial intense thermal radiation, which decreases with distance from ground zero but lasts for some time before fading, is responsible for the primary ignitions. In many cases, these fires are started before the blast wave arrives. The blast can influence these fires, but it can also damage the structures and expose interiors and potential fuels and thus form an array of fire-susceptible debris as well as raise a cloud of dust and smoke. Although the thermal radiation flux is decaying with time, there is continuing thermal radiation after the blast and the question is: Will ignition of the debris occur in this residual thermal radiation stage after the blast arrival?

The expected conditions are: disturbed and redistributed fuel arrays; relatively low radiant fluxes; winds; dust clouds; and the presence of pilot ignition sources from the remains of primary fires and blast-generated secondary fires.

3. Program

Define the transblast and postblast environment (fuel array and exposures). Estimate the potential for thermal ignition, including obscuration by dust and smoke. Calculate the consequences relative to other fire sources.

4. Approach

The degree of exposure of ignitables during and after the blast passage must be estimated, and the extent of dust and smoke obscuration should be included. Then an estimate can be made of the potential for ignition by the tail of the thermal pulse. This is more likely a hazard at higher overpressures from larger yields.

The early part of the thermal pulse has higher flux levels, and for many fuels has a better chance to ignite, but the blast may expose so many more materials susceptible to ignition that the less effective tail of the pulse may still cause a significant fraction of the persistent fires at some ranges. Thermal exposures can be calculated, blast exposures can be estimated, and an approximate evaluation can be constructed.

Using estimates of time to the (second) maximum in the thermal pulse (Brode 1968) and estimates of shock time of arrival as a function of overpressure and yield (Brode 1970) together with the fraction of the thermal pulse delivered after shock arrival (Glasstone, Dolan 1977), one can calculate the postshock thermal exposures. Above 5 psi, more than 20% of the thermal fluence comes after the shock for yields above 20 KT. At 15 psi, more than 35% comes after the shock. Above 25 psi, nearly half comes postshock. At 50 psi, nearly 75%, and at 100 psi, more than 90% is delivered after shock arrival.

5. Summary and Conclusions

A sufficient fraction of the thermal fluence (from all yields 10 KT-10 MT) is delivered after blast arrival at overpressures of interest in urban/industrial areas that the ignition probability in blast-disturbed complexes should be evaluated.

The Influence of Multiple Bursts on Fires and Fire Spread

1. Objective

The objective is to understand and to provide reliable predictions for the fire hazards in urban and suburban areas when more than one nuclear explosion occurs in or near a community.

2. Background

Since the severity of effects decreases rapidly with distance from a nuclear explosion, it is entirely appropriate that much of the work on nuclear fire hazards has concentrated on the effects from a single burst. However, the likelihood of more than one burst having an effect on many urban areas increases as the threat grows, and most hypothetical applications of current Soviet forces expose many areas to multiple bursts. Several destructive and complicating consequences of multibursts seem obvious:

- The debris created, the flammable fuels spilled and exposed, and the structures damaged by one burst make an area more susceptible to thermal ignition and fire spread from subsequent bursts.
- Fires started by one burst may be further spread via firebrands blown about by a second blast.
- The smoke and dust raised by a prior burst may significantly reduce the thermal exposure to susceptible fuels and so partially mitigate the fires from following bursts.
- The collapse of structures and the burial of ignitable fuel under masonry, plaster, and other less combustible rubble could decrease the probability of thermal ignitions from subsequent nuclear explosions.
- Dependent on the extent of collapse and the structural types, collapsed buildings may burn slower and less completely if ignited.

At present, none of these possible consequences has been subjected to careful analysis, and yet each could affect the consequent fires.

3. Approach

The response of built-up communities to either blast or fires is most complex. At the same time, large-scale tests with multiple exposures are not directly feasible. Since there is no direct prior experience to draw on, fairly extensive simulation and modeling efforts may provide the best approach to understanding the possible fire effects from multiple nuclear bursts. Before carrying out large simulations, the most probable major factors should be identified, and the features to be modelled in any simulation experiments defined. Such a study necessarily includes estimates of response that cannot readily be verified. Reasonable variability bounds for such poorly understood parameters should be established and used in sensitivity analyses as an aid to determining the major factors and the extent that they need refinement.

4. Tasks

- Perform an analysis of the factors governing fires from multiple bursts and identify those of major importance. Determine how these factors could be more precisely defined.
- Design simulations and experimental/theoretical programs to accomplish these improvements in multiburst fire factors.
    - Establish thermal ignition probabilities vs yield and range for both blasted and undisturbed targets, using thermal pulse simulators and modelled debris.
    - Blast effects on well-established fires, using shock tubes and/or high explosives on scale models.
    - Subject models to repeated shocks with varying time separation plus thermal load simulations, measuring optical (thermal) properties in the dusty, smoky environment, and noting fire starts.
    - Catalog fire characteristics in collapsed structures, measuring burning rates, temperature, and CO/CO_2 gas concentrations.
- Suggest large-scale tests to illuminate or verify these findings.

5. Summary and Justification

If multiple bursts prove to be much more effective than single bursts (e.g., if three 1-MT weapons on a city, spaced in time by 15 minutes to half an hour were more devastating than one 5-MT burst, and that fires and fire spread became a more serious problem in that way) then this research will have helped to focus on a principal defense and recovery problem and may aid in directing civil defense efforts toward greater emphasis on fire protection, fire prevention, and fire suppression efforts.

The Role of Firebrands in Fire Spread

1. Objective

The object is to define the importance of firebrands from either early thermal ignitions or well-established fires in contributing to fire spread and fire hazards.

2. Background

Fires initiated by the fireball radiation are disrupted, disturbed, and redistributed by the blast wave and the associated high velocity winds. The spread of fire in this transiently decaying forced convection may involve transport by firebrands with consequent new spot ignitions. The firebrands, whose origins are in the primary fires, are scattered by the blast wave. The flight of the brands and the range they reach depend not only on the blast strength, the wind speeds and durations, but also on the brand size, weight, and shape. This distribution itself is dependent on such factors as the nature of the burning fuels, the level of peak overpressure, the weapon yield, and other parameters.

For a single burst, the duration between the arrivals of the thermal pulse and the blast wave help to determine for a given fuel whether its combustion has become well enough established in the fuel to lead to burning brands. This establishment may be critical in determining whether or not the flames are blown out by the blast; if they are, whether glowing ignition continues and rekindling is possible; and if the burning debris particles can be torn loose and wind transported. High wind velocities are expected to either extinguish the glowing embers (if they are very small in size) or intensify them (if they are large in size). The size, mass, shape, and state of glowing of the brands would influence not only the flight in the wind but also their effectiveness as ignitors wherever they land.

The preceding description involves various physical and chemical phenomena of consequence in determining the spread rate of fire. The basic concepts are well-known, albeit in generalities of combustion, heat transfer, fluid dynamics, and other disciplines. A study to integrate these sciences as applied to the evolution, transport, and effectiveness as ignitors appears to be important in the DCPA program.

3. Program

- Review the scant literature on fire spread by firebrands.
- Develop laboratory experiments and analytical models which would delineate the conditions under which firebrands are produced, transported, and become effective agents of fire spread in a nuclear situation.
- Create from this knowledge a model for estimating the effects of firebrand transport by blast.

4. Literature

- Forest service work (Rothermal)
- Monte Carlo simulations (Aerospace Corp. IDA)
- The work of Tarifa and Taralbo
- Turbulent flame spread concepts at large-scale Reynolds numbers.

5. Summary and Justification

Research on the role of blast-generated firebrands in the spread of fire subsequent to nuclear attack can contribute to our appreciation of the potential for fire damage in urban areas. This study will fill a critical gap of information. Whether it is considered as a (multiple) ignition problem or a discontinuous fire spread problem, it is important in locating the furthermost boundaries of a topography to which the effect of fire will reach. This is important in delineating areas in which shelter development is required.

The context of multiple bursts makes this a unique problem, not previously treated.

VI WORKSHOP 2:
BLAST/SHOCK EFFECTS ON INDUSTRIAL PLANTS AND OTHER CRITICAL ELEMENTS*

This workshop was interested in the response of structures to air-blast loadings only as a basis upon which to build a prediction technique for blast wave interaction with structures and their contents, because of the latter's ability to radically change fire initiation/growth/spread between preblast and postblast conditions.

Critical needs for missing study results, other data, and tests were to be again identified (as they were in the 1978 conference) and updated; especially important was to be the consideration of tests that could be added to DNA tests already scheduled and funded.

Key items of concern to this workshop and needing further work were enumerated in the leader's closing briefing:

1. Research Studies

   - Collapse of building frames
   - Debris translation
   - Exterior and interior wall loadings
   - Blast flow in basements
   - Blast shielding
   - Collapse of structural elements
   - Debris fragmentation and interaction.

2. Blast Effects on Buildings

   Objective: Provide a method for predicting
   - Collapse of buildings
   - Debris transport and deposition.

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*Members of Workshop 2 are: K. Kaplan, T. Kennedy, A. Longinow, H. L. Murphy (Recorder), J. Rempel, W. Taylor, C. Wiehle (Chairman), and C. Wilton.

3. Approach

- Blast effects on city complex
- Crude first cut using available analytical tools and experimental data
- Upgrade structural collapse and debris prediction capability
- Develop simplified debris deposition method
- Complementary research studies.

A brief comment on the state of the art of debris prediction follows. The 1978 conference report description of the state of the art, appearing in the output statements of Workshop 2, is still quite accurate both in outline and details and is repeated below with only minor corrections. The collapse under blast loading of small panels, beams, and floors located on one floor of a single building can be generally described; dynamic response of frames through to collapse cannot. Movement of single debris elements in a specified airflow can be computed; interactions among debris elements cannot. Blast wave interactions with isolated buildings are known in some detail; the shielding of one structure by another is not understood with enough accuracy to apply the known techniques of structural element failure prediction to a city complex. Interior room flows during the early episode of blast entry and in the neighborhood of openings can be described well enough; interactions among flows and long-duration circulatory patterns are less well understood.

Collapse of Structures and Debris Distribution Predictions

1. Single Building Studies

"Single buildings can be analyzed with present tools, knowledge, and computer programs to determine their resistance to blast, their breakup, and distribution of their debris. To accomplish this, buildings need to be classed by type of contruction, but this can be done without difficulty.

"State-of-the-art techniques consist of computer programs as well as a considerable body of experimental data that can be used to analyze the dynamic response and collapse of various building elements and whole buildings. These programs have been used with blast-loading techniques to predict the collapse of elements in a variety of National Shelter Survey buildings. These procedures can roughly predict the amount of debris from collapsing building elements, but because of unknowns in the loading on each wall of a complex building geometry (as well as the effect of collapsing walls on subsequent loading), the problem can only be bounded, not solved explicitly.

"Programs are also available to analyze the elastic and inelastic response of structural frames. At present these programs do not include collapse mechanisms, but the output can be used to reasonably estimate the probability of frame collapse. The translation of debris produced by collapsing building walls can also be predicted with current programs. These programs require input in the form of the wall velocity at collapse and the size of fragments. The final disposition of the postulated fragments can also be predicted with these models, but to date this capability has not been experimentally verified."

Because of the increasing interest in the industrial and economic sector, special emphasis needs to be devoted to industrial types of structures. It is recognized that many industrial structures are very weak with regard to blast, but the size and distribution of the fragments are required both for fire spread and equipment damage prediction.

2. Building Contents Debris

"The distribution and breakup of contents caused by an entering blast wave can be predicted for certain idealized situations. If the only opening to a room is in the wall that is struck head-on by the blast wave, the subsequent flow (including entrainment of light debris within the room) can be approximated with existing tools. These methods include mathematical analysis (RIPPLE and/or simple roomfilling) verified by reference to results of past experiments (URS tunnel, BRL model basement, and Dice Throw structures 1 and 2). This information may also serve to describe the flow adequately for purposes of predicting extinguishment of primary fires and creation of secondary fires.

"In the more general case, however, when the openings are in different walls, the analyses are appreciably more complex, and new analytical methods will be needed to handle the situations involving intersecting flows. The same is true of flows through connecting rooms. The presently available methods are probably not good enough to adequately define debris distributions.

"Similarly, we have adequate tools to treat the collapse and breakup of a wall struck head-on and to analyze the conversion of structural elements into debris. The principal weakness is a lack of understanding of how fragmentation occurs in a sufficient variety of wall types. Also, experimental verification of the debris translation model is required. Structual debris, when it occurs, would likely be superimposed on room-content debris."

3. Building Interaction

"The debris in a built-up area depends on the nature of the buildings in the zone in question. Parameters entering the problem include:

- Relative location of buildings
- Sizes
- Structural systems
- Relative strengths
- Orientations relative to the blast direction
- Building contents
- Times to failure/collapse.

"The blast wave is expected to be altered by these parameters, thereby producing a debris pile substantially different from that produced by the same buildings if located in the open, whose individual debris elements are simply superimposed. This problem is not well understood, and the importance of individual parameters is not well known. Good tools are not available, but crude estimates can be made using existing tools."

4. Multiple Buildings

"The extension of single-structure blast-loading information into a city complex has not been realistically accomplished. Previous studies used models of structures of uniform size. New work is needed to investigate nonuniform-sized structures (shadowing), blast wave propagation down streets (channeling) and other phenomena that could affect structural loading and subsequent debris distribution within a city. Again, proven tools are not available, but crude estimates can be made."

5. Multiburst Effects/Response

"The airblast and ground shock environment that results from two or more closely timed detonations is at present not well understood; the Defense Nuclear Agency (DNA) is working now (April 1978) to provide environment definition data. The response of a given building to two or more loadings is to some extent understood; however, the uncertainties associated with the first loading are compounded by their impact on the starting point assumptions for the beginning of the second loading calculations, making the second and succeeding loading calculations less and less credible. No data exist on multidetonation-formed debris and, to our knowledge, no attempts have been made to examine analytically debris formation from more than one detonation.

"The study of multiburst-formed debris is not thought to require high priority at this time, since the state of knowledge from single bursts is weak. As work advances with respect to single-burst effects, multibursts may be considered.

Research Program (May 1978)

"A two-path program was proposed in 1978. One path continued the logical development of computational and experimental techniques to predict the translation of interior contents and structural debris and their distribution. These are defined as complementary efforts and are discussed in the following subsection.

"The main thrust of the program, which is outlined in Figure VI-1, is a step-by-step research program to develop structural damage and debris data required for the blast-fire interaction program. The first two steps of the program, Analysis of Individual Structures and Analyze City Complex (Crude Cut), can realistically be accomplished in 18 months to make possible rough approximations of the debris distribution within a city.

"The first step, Analysis of Individual Structures, includes the following:

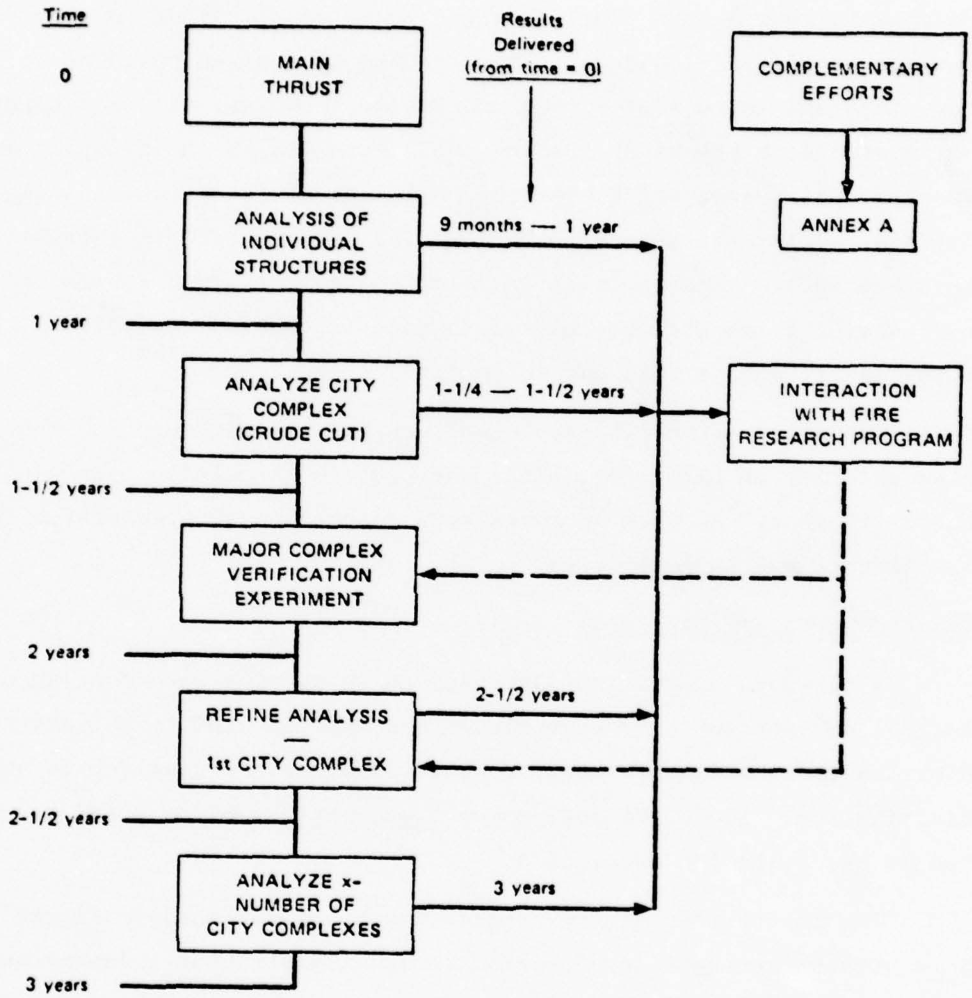

FIGURE VI-1 BLAST-STRUCTURES-DEBRIS RESEARCH PROGRAM

> "Develop structural damage and debris contours for each of the building categories/types as a function of air blast overpressure. These contours will be derived using available computational techniques that will need to be refined and automated. Estimated time of completion of this task is 12 months; however, portions of the work, by specific building type(s), will be available in 9 months.

"The second step, Analyze City Complex (Crude Cut), uses the results from the first step to approximate roughly the debris distribution within a targeted city. Currently, San Jose, California, is suggested because of the excellent data base available. This step is very important since it yields early major data for fire researchers, and also points out the areas where further extensive research is required.

"The third step, Major Complex Verification Experiment, may consist of one large or several small experiments; they will be better defined during the early phases of the program, but are planned to include a multistructure, small building test during the Misty Castle event, shock tube tests of structures and structural elements, and laboratory tests. This task should be finished by the end of the second year.

"Based on the results of the tests and inputs from the fire researchers, plus results from the Complementary Efforts, a more accurate debris distribution pattern will be developed for the first city complex, San Jose; Figure F-1 shows this step, Refine Analysis - 1st City Complex.

"The final step, Analyze x-Number of City Complexes, applies the developed technology to other cities to test the systems, determine differences among cities, and furnish a broad data base for use by the blast/fire research community. The total program is estimated to take 3 years; a preliminary cost estimate for the first two steps and related complementary efforts is $600,000 to $700,000.

"Complementary Efforts. The principal complementary efforts of the research program listed by Workshop 2 are given below:

- Debris interaction: investigate the importance of multiple debris-debris interaction on the final debris pile
- Drag and lift coefficients: develop experimentally a list of drag and lift coefficients for representative debris pieces, including furnishings.

- Debris catalog: develop and computerize a debris catalog for a set of buildings by floor level.
- Interacting flows: using hydrodynamic codes and shock tube experiments, develop an engineering method to predict flow patterns and drag on contents in a room with openings on adjacent and/or opposite walls.
- Multiroom flow patterns: develop engineering methods for predicting flow through a complete floor plan of interconnected rooms.
- Oblique incidence: calculate loading and clearing of pressure fronts reflected at oblique incidence from exterior walls and roofs in a manner analogous to current methods for estimation of head-on reflected blast waves.
- City complexes: improve our understanding of diffraction of blast waves through, and perturbations of flow over, city complexes, exposing models in shock tubes and at high explosive field tests. These models should reflect the size variation and distribution of structures present in cities or in an actual candidate city. (Some shock tube efforts to study drag on rectangular blocks in tandem and a few pressure distributions among uniformly distributed identical rectangular blocks have been reported.)
- Trajectory verification: develop confidence in results of calculation debris trajectories by experimental verification. Currently used drag and lift coefficients, as well as spring constants controlling debris-ground interactions, are pure extrapolations from other fields of engineering. Past full-scale high explosive experiments may provide some evidence for this verification of the documentation is adequate.
- Hysteretic behavior: extend available resistance functions for exterior and interior wall elements to include hysteretic effects, so that dynamic response can be predicted for reversal of load function on walls.
- New wall types: develop resistance functions for wall types that have not been previously treated, but are important to blast/fire interaction.
- Structural properties: perform laboratory tests to determine dynamic material properties to supplement available data (e.g., timber elements such as floors and stud walls).
- Mixing of debris types: study interaction of debris between various types of buildings, e.g., industrial buildings and residences.
- Frame analysis: examine available dynamic inelastic building frame programs for possible application to nuclear weapon effects, and modify candidate program to include collapse mechanisms.

- Model use: determine how small a scale can be used for structural and debris models and yet provide adequate degree of confidence in resulting data."

Research Program - Update of April 1979

1. Developments During Past Year

Progress during the past year includes:

- Extension of techniques for the calculation of exterior wall loading to the case of an arbitrary number of openings and oblique shock incidence.
- Development of a calculation method for pressure oscillation and shock impingement on the interior surfaces of walls (only for the case of head-on incidence on the exterior).
- Measurement of shock pressures against the exterior surfaces of model (European) residences arranged in a row.
- Further development of quasi-empirical resistance functions (based on Dice Throw observations) that improve the understanding of the response of unreinforced masonry load-bearing walls to blast.
- Expansion of the power of the structural response computational system to treat small collections of one-story buildings (provided airblast shielding effects can be neglected or supplied ad hoc).

2. Current Work

Work currently funded or underway that is pertinent to the subject of Workshop 2 includes:

- A shock tube model study of airblast pressures interior and exterior to a (European) residence.
- An application of existing calculational methods (structural response and debris movement) to describe a wall and furniture debris field in two overpressure regimes, i.e., 2-5 psi and 30-50 psi.
- An extrapolation and interpolation of airblast pressure histories (observed in a very idealized city complex model) to prediction of shielding in a small European town.
- An effort to correlate observed wall debris movement (at the URS tunnel and in the Dice Throw German buildings) with results of calculations of translation of single debris elements.

- Aerial photography: If the general countrywide fire vulnerability is to be evaluated, there is a serious problem associated with being able to determine exactly what a city(ies) looks like. Obviously each city in the U.S. cannot be considered as a unique complex. There are currently planned efforts to utilize overhead photography to evaluate and characterize cities. The ultimate objective of these efforts is the ability to determine structural types present in a city and to provide typical city layouts. This will allow for the large numbers of existing cities to be reduced to a few typical configurations and for structural information to be obtained without making detailed ground evaluations. The results of these efforts should feed into the debris formation problem and, with the development of some type of typical debris overlays, may greatly reduce the number of cities studied and simplify the problem of debris field prediction.

3. Recommended work, High Priority

Major research deficiencies now visible in the near term can be grouped into four categories:

- Analyze city complex (crude cut)
- Dynamic building frame response (frames in steel, wood, and R/C)
- Building airblast shielding
- Debris interactions
    - Between debris and wall
    - Among debris elements.

As work progresses, other deficiencies may appear, of course; for example, the attempts to predict debris element movement may uncover a serious lack of understanding of aerodynamic mechanisms or of the interaction between floors and debris elements or between the ground and debris elements.

Further details on the above four work areas are as follows:

A. Analyze City Complex (crude cut). In the report on the May 1978 conference, Workshop 2 gave this task second priority (see section above on Research Program, May 1978). The consensus of the March 1979 Workshop 2 experts is that this task should be funded promptly by DCPA, because of its absolute necessity toward moving the fire research program forward. The consensus is that the task should be accomplished using present techniques in order that the results may be tested by the fire researchers; if they are found to be adequate to the need, further research may be evaluated as to its urgency, from a need for major improvement to no need for further research--at least for fire research purposes.

Appendix K, Topic 1, is a task description for the proposed research.

B. Frame Response. There is no reason for assuming that, in a frame building, the outside wall panels will invariably fail prior to the frame. In any case, a certain amount of load is transferred to the frame before the panels fail. In the 30-50 psi pressure regime, this transferable load may be substantial, resulting in the collapse of both frame and panel; further, recently built earthquake-resistant columns in a building of, say, four or more stories may tear up the floor slab over a basement(s) as the building frame is failed by the blast. Any description of the debris field based solely on panel failure could be erroneous or misleading.

C. Airblast Shielding. At the present time (March 1979) all that can confidently be said about airblast building shielding is that it is probably important and could control wall panel response over a large area of any city. Experiments with models of city complexes have demonstrated drastic shielding effects; both increases and decreases in loading can result. Because a city is normally an irregular complex, the research should be directed toward understanding of the shielding produced at all points in the wake of a single building; this result should then be applied repeatedly to a typical city complex to produce the first cut solution.

D. Debris Interactions. The impact of a substantial debris element against a wall or floor could be equivalent to: (a) a shearing load of short duration in the impacted structural component, and (b) an impulsive load of longer duration against the component. Were the wall materials homogeneous, principles of solid mechanics could be applied to solve (a). It is likely, however, that laboratory tests using actual wall materials will be required in addition to theoretical approaches.

In contrast, the impulsive load (b) can be treated as a whole wall impact exactly as that produced by airblast. The existing models should be used to predict this effect.

Debris elements interact among themselves. Elucidation of this effect, as well as understanding of the initial fragmentation of the structural component, will be difficult. For the present, only a parameter study is recommended--that is, a determination of the outcomes of various interaction scenarios. The debris elements may impact and henceforth travel together, or they may break into small fragments of an arbitrarily chosen size.

4. Future Experiments (HE)

There are no ongoing programs designed to look experimentally into debris formation or translation and, because it is unclear what the specific fire-related requirements are, it is not known what types of experiments should be designed. Following the development of the first citywide debris study (crude cut) and the interaction with the fire experts, it should be possible to design an experiment(s) to better understand the important parameters. The upcoming DNA test in 1981 should be timely because by that time the important problems should be known.

The last good work along these lines was done about a decade ago by Bell Telephone Laboratories for the Safeguard System. These results show that it is possible to conduct meaningful experiments at a small scale using high explosives as a test source. Using the BTL work as a basis, plus analysis of the laboratory tests, it should be possible to design an experiment(s) that will significantly improve our ability to understand city debris. It may even be possible to conduct meaningful combined ignition/blast experiments on a large scale using thermal simulation in combination with a large HE source.

5. Other Research Topics

Other topics of research considered important by the Workshop 2 group are included in Appendix K.

VII WORKSHOP 3:
PREDICTIVE MODELING OF FIRE SPREAD AND THREAT*

This work group generally concurs with the findings of Workshop 3, reported in May 1978. We endorse the program recommended at that time and offer the following five suggestions as expansions to that program:

- Increased utilization of Five City Study results
- Preliminary analysis of critical resource fire vulnerability
- CO production and mobility
- General model of fire spread and threat
- Target specific model for critical resources.

Tasks 1 and 2 are designed to provide near-term procedures and results permitting reasonable estimation of fire damage and threat to specific urban areas and critical resources (sheltered personnel and key industry). Task 1 proposes a technique by which results from the Five Cities Study can be extrapolated to approximate other specific urban targets, thus eliminating the necessity for exercising the full fire spread model. Task 2 is designed to provide a quick assessment of the fire susceptability of resources (people, housing, utilities, transportation, food and industrial capacity) in terms of a fire damage assessment rating.

Task 3 was introduced here to focus attention on a much needed and missing element in establishing casualty estimates: the production and transport of CO from fires in various regions of blast damage. The design of fire countermeasures for the sheltered population is particularly dependent on the CO concentration, i.e., multiple vent versus button-up.

Realizing that extensive expansion of present fire spread models is required to accommodate various levels of blast damage, we recommend

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*Members of Workshop 3 are R. Alger, C. Chandler, R. Fristrom (Recorded), J. Rockett, L. Schmidt, R. Small, and T. Waterman (Chairman).

developing a modular model (Task 4). A modular model is a framework that accommodates many submodels. Each submodel can represent the current state of the art in its domain. The advantage of a modular primary model is that any submodel can be upgraded without significant impact on the remainder of the system. Various versions of each submodel can be made available to suit the purpose of each program user. Thus, quick and cheap damage approximations and more expensive detailed research investigations can use the same basic framework.

In a similar manner, changes in blast effects can be incorporated by varying appropriate submodels without complete redevelopment of the total model. The primary purpose of this model is still the general prediction of fire spread and threat to the urban area as a whole; detailed examination of specific subtargets (locations with people and critical resources) is recommended as Task 5.

We recommend that the specific target model (Task 5) also be modular. Thus, introduction of a new class of target will be accomplished by incorporating a new submodel. This model looks at a local target area within the total area affected by a weapon(s) burst; it is used with, but decoupled from, the urban fire spread model to provide appropriate boundary conditions for the local target area of interest. Should Task 4 not be implemented, or not completed upon development of this model, current fire spread models or Task 1 extrapolations from the Five-City Studies could be employed to provide these boundary conditions. As its name implies, the specific target model will permit detailed input of the target structure within a limited area. In contrast, the urban area model will treat a large area but in lesser local detail.

Slightly expanded descriptions of each task follow, with first-cut estimates of effort required for each.

Task 1: Utilization of Five City Study Results

The fire spread assessments in the Five City Study provide DCPA with an overview of fire development and spread that permits some general planning of countermeasure activity (sheltering requirements and/or population mobility). Application of the results to other specific cities in terms of loss predictions (casualties or critical resources) requires that means be developed to represent the fire-related characteristics of the new city in terms of the cities studied.

A program is recommended to develop tools with which the utility of the Five City Study results might be expanded. Three steps are essential to this expansion:

1. Tract Characterization

An equivalence must be established between each segment tract of the city to be studied and a segment of one of the five cities. If possible, the descriptors should be obtained from existing machine readable catalogs. Census data are recommended as a potential source. The first step is to determine their suitability, particularly in nonresidential areas. Other sources such as the National Fallout Shelter Survey may provide the needed supplemental information. As a last resort, aerial photography, land use maps, or Sandborn maps might be used.

2. Predicter Technique Development

Once the relation of new target track to Five City Study tracts is established, techniques must be devised to transform the Five City Study fire spread to spread over the new target. Potential approaches are:

- Direct transfer of damage patterns
- Application of each tract type spread rate and distance observed in the five cities to similar tracts in the new target, assuming an ignition pattern based on a simple ignition/blast model.

3. Utility Assessment

Two suggested procedures to validate the developed predictor technique are:

- Predict the results for one of the five cities based on data transferred from the other four and compare these results to those obtained directly from the fire model.
- Select a new target city unlike any one of the five and compare its fire behavior as predicted by data transfer and application of the fire model.

This program strives to maximize the utility of the Five-City Study data. Although the results are approximate, they will provide DCPA with an interim tool for damage assessment, risk analysis, shelter requirements, population relocation, etc. In addition, the results can be combined with the output from Task 2 to evaluate the survivability of a particular industrial resource in a given attack scenario.

A 6 to 12 man-month effort should complete Task 3(a).

Task 2: Fire Hazard Analysis of Resources

Section II mentioned briefly two approaches to blast/fire damage assessment:

- The fire spread scenario that follows chronologically the development of the fire from ignition through full involvement, spread, and burnout
- A vulnerability rating that focuses only on the critical structures and their ability to survive a fire in their environment.

The second approach commences with the vulnerability assessment and estimates the potential for loss on the basis of areas that exceed the survivability threshold, as illustrated in Appendix E. Both approaches ultimately require information about the ability of the critical structures to survive blast and fire. Particular objectives of Task 2 are to provide sufficient vulnerability data about the critical facilities to satisfy both approaches, specifically to:

- Categorize the fire susceptability of resources and resource components (by resources we mean industrial capacity, food, transportation, utilities, housing and people)
- Inventory surroundings to assess probability of fire exceeding the susceptibility of the resource
- Combine the first two items above into a damage assessment rating
- Advise on potential countermeasures.

The envisioned approach would gather data about the prevalence of critical structures in the various NFPA building classifications (i.e., fire resistant, noncombustible, heavy timber, ordinary, and wood frame). In addition, the structures will be cataloged according to their ability to withstand structural collapse; a minimum of three wall categories are required, namely, loadbearing, weak attachment to the frame, and strong attachment to the frame. Appendix E illustrates how the data could be used in the hazard analysis. Existing sources of appropriate data are NFPA, insurance underwriters, fire protection engineers, and a quick and dirty survey of sample industries. This task should be completed in FY 80 and the estimated manpower requirement is 2 to 3 man-years.

Task 3: CO Production and Mobility

Experience with civilian fires indicates that the major cause of fatalities is likely to be carbon monoxide poisoning. Existing models do not allow an evaluation of this hazard; therefore, CO exposures represent a major unknown in evaluating survivability of populations in strike areas. This information should be applied to inhabited critical targets. Critical targets which contain materials and equipment will not in general be affected by CO. The required information is the time interval during which the local CO concentration exceeds the lethal dose.

If this time exceeds the available local air supply, lethal air will be introduced into the shelter. (It is assumed that the inhabitants can monitor the air and decide when to bring in outside air.) Nonuniform distributions of the CO may mitigate the problem so spatial-temporal duration information is important. This distribution might be obtained from existing data or, if necessary, by new information.

Initially, the required information might be derived from an examination of existing detailed CO measurements from Flambeau and other large-scale fire tests. This information could be correlated with the characteristics of the description of the critical target.

Presumably, the second cut would preserve information from the initial correlation and modify it with temporal fire characteristics from the fire spread model to give the concentration rate and history.

The third level would combine information from levels one and two with site specific details from the target descriptions, which will modify the generation rate and dissipation. This would require meteorological information.

The three levels are all feasible in principle. Level 1 would require perhaps 6 man-months to investigate and document. Level 2 possibly requires 1 man-year of effort beyond level 1. Level 3 probably requires a research effort, which should be carefully defined to match available input to the model and should only be attempted if there is reasonable hope of obtaining the required inputs.

Task 4: Modular, General Fire Growth, and Spread Model (CIFEP)

The following recommendation suggests how the General Fire Spread model might be organized; however, it is not final or ready, for example, to be incorporated in a request for proposals. We found the algorithm shown schematically in Figure IV-1 convenient as a vehicle for conveying the general ideas.

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[*] City Fire Environment Program

CITY FIRE ENVIRONMENT PROGRAM (CIFEP)

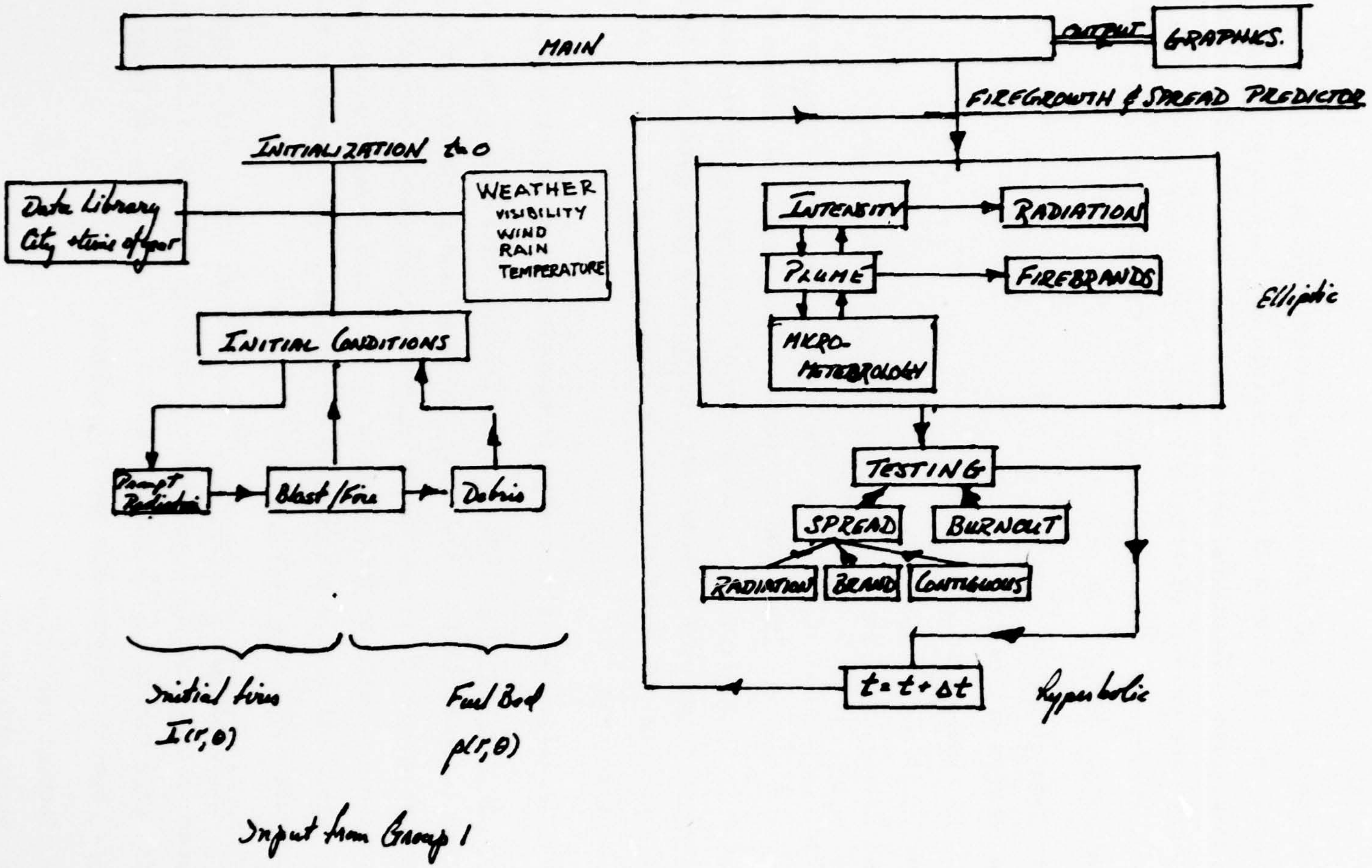

Figure VII-1 City Fire Environment Program

One purpose of this model is to provide input to another algorithm which analyzes the survivability of certain key facilities located in known structures. Specifically, the model describes the exposing fire which, with the passage of time, may pass, envelop, or surround the critical structure. The model characterize the exposing fire by time-varying values of:

- Radiation flux
- Oxygen depletion
- CO concentration
- Local winds
- Firebrand arrival as observed at the target structure.

For discussion, we visualize the model to be a main program that manages the entire calculation sequence and modulates the interaction of submodels to achieve a maximum degree of decouppling in the sense that changes to any one submodel will preferably propagate only into the main program. Coupled to the main program will be a set of functional subprograms.

We visualize the main program as containing four major elements:

1) An input module. This element accepts city survey data, in a form that is convenient to the survey process, and translates it into the fire parameters required by the rest of the program. Presumably, the input module will be sensitive to any new data demands occasioned by the substitution of one submodule for another. The output of the input module would be a city descriptor library.

2) An initialization section. This element would call a number of submodels based on the results from Workshops 1 and 2 to reconfigure the city as a result of the nuclear attack, i.e., modify the descriptor library. Specific submodules would consider:

- Thermal radiation
- Blast effects

- Debris generation
- Weather.

An additional output of this initialization section would be the number and distribution of sustained ignitions. In summary, this section provides the time-dependent calculation with initial conditions:

- Fuel bed descriptors corrected for attach damage
- Distribution of initial fires.

3) The fire growth and spread predictor proper. This, in turn, will have two subsections: an elliptic section, which considers the fire at a particular instant, and a hyperbolic section, which allows growth in time. The elliptic section considers the fire intensity, toxic gas (CO) production, the fire plume(s) it drives, radiation field, induced micrometeorology and brand throw, all in an interactive sense--i.e., these are tightly coupled effects. The hyperbolic section will test for changes in the overall fire size due to:

- Burnout
- New ignitions due to firebrands
- New ignitions due to radiation
- Contiguous spread.

This section also tests for changes in intensity to the existing fire and incremental fire. Note that time increments could be fixed or implicit.

4) Storage of fire descriptors needed by the key facility survival algorithm. It would also develop (graphical) outputs to permit understanding of the predicted fire behavior. The modular structure should allow rapid construction of a complete, albeit crude, model. Subsequent refinements of individual models involve a minimum disruption to the main program and can be made without requiring simultaneous modification of other components.

Note that some components of this model already exist and could be restructured for assembly into this algorithm fairly quickly. However, others (such as the CO concentration at ground level) may require significant development to progress beyond a rudimentary structure. An important management input to the modeling process will be identification of critical but poorly understood components where research is needed to provide physically sound phenomenological descriptions and data needed to describe adequately these components. Approximately, 3 man-years would be required for an initial running capability.

Task 5: Specific Target Model

This model will predict thermal damage to specific elements in a target area. The model framework will handle either (1) classes of targets or (2) a specific target element with its individual characteristics. Also, the model is sufficiently general to handle either complex fire analyses or simple tabular lookups of resulting damage. Inputs to the model are the fire environment, target characteristics (including thermal hardening), blast effects (including blast damage), and fuel carried into the target by the blast wave. The fire environment could be defined by the Modular Fire Spread Model or by a standard temperature time curve.

The model output is the fraction of people or items such as machine tools, inventories, etc., that survives. In some cases, the output may be sufficiently detailed to describe the salvage requirements. In form, the output can be tabular listings, or data files suitable as input to other types of damage assessment calculations. Model algorithms could consist of physical calculations, semiempirical building fire spread calculations, or fire protection engineering rules. The model will be modular in construction to permit ready addition or substitution of damage prediction algorithms. The model will be compatible with the modular fire spread model but will be decoupled with existing fire spread models or extrapolations of the Five City Study results (Task 1).

A 2 man-year effort is estimated for initial model development to a useful state.

VIII WORKSHOP 4:*
EVALUATION OF COUNTERMEASURE EFFECTIVENESS: CHOICE OF INTERVENTION STRATEGIES

Objectives and Scope

The most important objectives of a unit defense program under the civil defense act of 1950, as amended, are to maximize life saving of the population in the event of war and to effectuate emergency repairs immediately after an attack to facilitate entry into a period of postattack recovery. This conference has characterized three zones of interest in the attack environment:

- A close-in zone where destruction is so great that survival is not possible.
- A zone where only light to no damage is expected.
- A zone where many survivors might be expected, but varying levels of fire and blast damage occur.

This workshop has concentrated its efforts on the latter zone since a great deal of past research has led to a relatively good understanding of conditions in the other two zones.

The matrix shown in Table VIII-1 lists countermeasures that would be necessary or desirable in a civil defense program to support pursuit of its objectives. The degree of effectiveness in achieving these objectives is closely related (within reasonable bounds) to the cost of the program. The following discussion assumes that the nation will not embark on civil defense programs costing more than two to three times the present program--thus eliminating major blast shelter programs for the foreseeable future, but major emphasis will be given to a program in which plans are made to relocate the populations away from military and industrial targets. Thus, this matrix is constructed in the context of an attack in which 80% of the population has been relocated to regions of lower risk;

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*Members of Workshop 3 are G. N. Berlin (Recorder), C. P. Butler, L. Pietrzak (Chairman), G. Sisson, and V. Sjölin.

Table VIII-1

CRISIS RELOCATION

Scenario - Key Worker and Critical Resource Protection

Time Frame	Fire/Blast Countermeasures	Hardware	Software
Peacetime	· Public awareness (warning)	Sirens purchasing	Publications, movies, TV programs, locations of sirens
	· Mass education	Props (vent and sanitary kits), firefighting training, simulator	Firefighting and weapons effects, training, and manuals
	· City shelters (specific purpose and in place)	Construction, retrofitting, supplies	Design manuals and location
	· Firefighting equipment (optimization and purchasing)	Equipment performance optimization, emergency water resources	Optimal firefighting strategies and tactics, prefire planning; emergency water storage and location planning
	· Key worker (identification and organization)	Communication equipment	Types, number and organization
	· Emergency operating center	C^3, facilities	Manuals and training, location and number
	· RADEF equipment purchase	Instruments	Number, location, training manuals
Crisis (3 days to 2 weeks before)	· Increased readiness actions (individual and industrial hardening	Tools and machinery	Planning guidance manuals and checklists
Survival (During fires and fallout--minutes to 2 weeks)	· Protective postures · Fighting/rescue · Fire-caused relocation and rescue · EOC operations at directions · Life support	Execution of survival actions	Execution of survival actions
Postsurvival (Postfires and fallout--a few weeks)	· Critical equipment weather protection · People protection · Equipment/shelter salvaging	Execution of post-survival actions	Execution of post-survival actions

countermeasures have been carefully thought out during peacetime and implemented in a crisis period.

Of course, the crisis could develop in a very short time, in which case relocation would not be possible. Thus, in principle, a similar matrix could be developed for the in-place population and countermeasures would be developed for that situation. Such an in-place option is, in fact, a part of current civil defense planning. However, without an extensive blast-shelter program, studies to date show that in a massive nuclear exchange with a short warning period, losses of people and equipment would be staggering and self-help countermeasures would be only marginally effective. Thus, the emphasis is on a key worker scenario.

Summary of Countermeasures and Analytical Tools

Table VIII-1 summarizes the suggested countermeasures; more details are provided in the next section. As indicated, the table assumes a scenario wherein some 80% of the population has been relocated to remote areas prior to the attack. It further assumes that the life safety protection is provided primarily for "key workers," who constitute about 6% of the population.

The countermeasures shown are divided into four time frames:

- Peacetime--the time prior to onset of a nuclear threat or crisis.
- Crisis Period--approximately 3 days to 2 weeks before a nuclear attack occurs.
- Survival Period--the period beginning with and immediately following a nuclear attack during which blast fires and fallout effects pose an immediate life-safety threat. This period may last up to 2 weeks from the actual initial attack.
- Postsurvival Period--as used here this means that period: (a) after a buildup of crisis, which is resolved through negotiation and the situation reverts to normal or, (b) an attack period has occurred, fires are controlled or allowed to burn out, and fallout radiation levels have subsided so that people can leave shelter, at least for sufficient lengths of time to accomplish vital actions. Damage on such scale as would be suffered under a major nuclear exchange has sparked heated controversy about whether a nation could

> recover from such an attack. As of this time, "recovery" strategies have not been defined and any actions taken through civil defense measures would be directed to the harsh reality of trying to maintain adequate protection from the weather, obtain food and potable water, treat the injured, and control disease. A nationwide assessment of survivors and surviving resources would perhaps lead to a system of resource management that could lead to recovery. The questions of continuity of government and priorities for the use of resources are major questions that must be resolved and that are beyond the scope of this discussion of countermeasures, the emphasis of which is rather directed to immediate survival.

As indicated in Table VIII-1 during the "peacetime" and "crisis" periods, the countermeasures, in general, have a hardware aspect and a software aspect. Hardware implies that facilities, equipment, and instruments of some kind must be constructed, purchased, or developed. Software implies that certain processes, plans, manuals, or training courses must be developed. These are discussed further under each countermeasure heading.

Analytical Tools

In general, analytical tools are needed to assess the relative effectiveness, improve the performance, or to develop procedural design or training guidance associated with the various countermeasures. A number of techniques are available that could assist in accomplishing this. The following briefly reviews them.

Decision Analysis--these techniques may be used to evaluate the effectiveness of the individual countermeasures and the combined effect of all countermeasures. Evaluation of effectiveness or potential payoff of a countermeasure might be based on the best estimate of experts, an historical analysis of previous large fire blast situations, or computer simulation model predictions. As more and better information becomes available through research, the estimates of effectiveness can be improved. Examples of this approach are the "Cost and Lost Modeling" approach of Offensend and the "Building Fire Model" of Berlin, both presented at the conference.

Computer Simulations and Models--i.e., realistically representing the external environment and performance of a countermeasure using mathematical models that are faithful to the phenomenology and governing laws involved and that are programmed for computer processing. Although regression analysis or curve-fitting of experimental or empirical data may be used in the internal structure of the simulation, one is not just extrapolating and interpreting experimental data. Rather, one is simulating the actual dynamics, interactions, and performance of the system in a realistic and understandable way on a computer. The objective is to better understand system (hardware and software) behavior for the following reasons:

- To improve hardware performance: Simulations permit one to try many combinations of hardware parameters over a wide range of environmental conditions to help focus development and experimentation onto conditions that are most stressful and that offer the greatest performance improvement potential.
- Simulations that incorporate both operational features and hardware performance can be used in operations research type studies to optimally allocate resources, develop operational plans, training manuals, etc.

An example of a simulation model is the "Fire Demand (Supression) Model" presented by Pietrzak at the conference. This model can be used to improve the water suppression effectiveness of suppression equipment using fire-hose nozzles to minimize water waste. An extension of this model to include operational time data for various firefighting activities would permit its use in analyzing fighting tactics, and manning/equipment combinations that most effectively use the limited water manning and equipment resources in a postattack fire survival environment. A firefighting operational simulation could also be used as a training device to realistically present the progression of events and the dynamics of firefighting using television-like graphic "CRTs" and "light pencils" that permit a trainee to interact directly with the computer.

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BLAST/FIRE INTERACTIONS. PROCEEDINGS OF CONFERENCE HELD AT ASIL--ETC(U)
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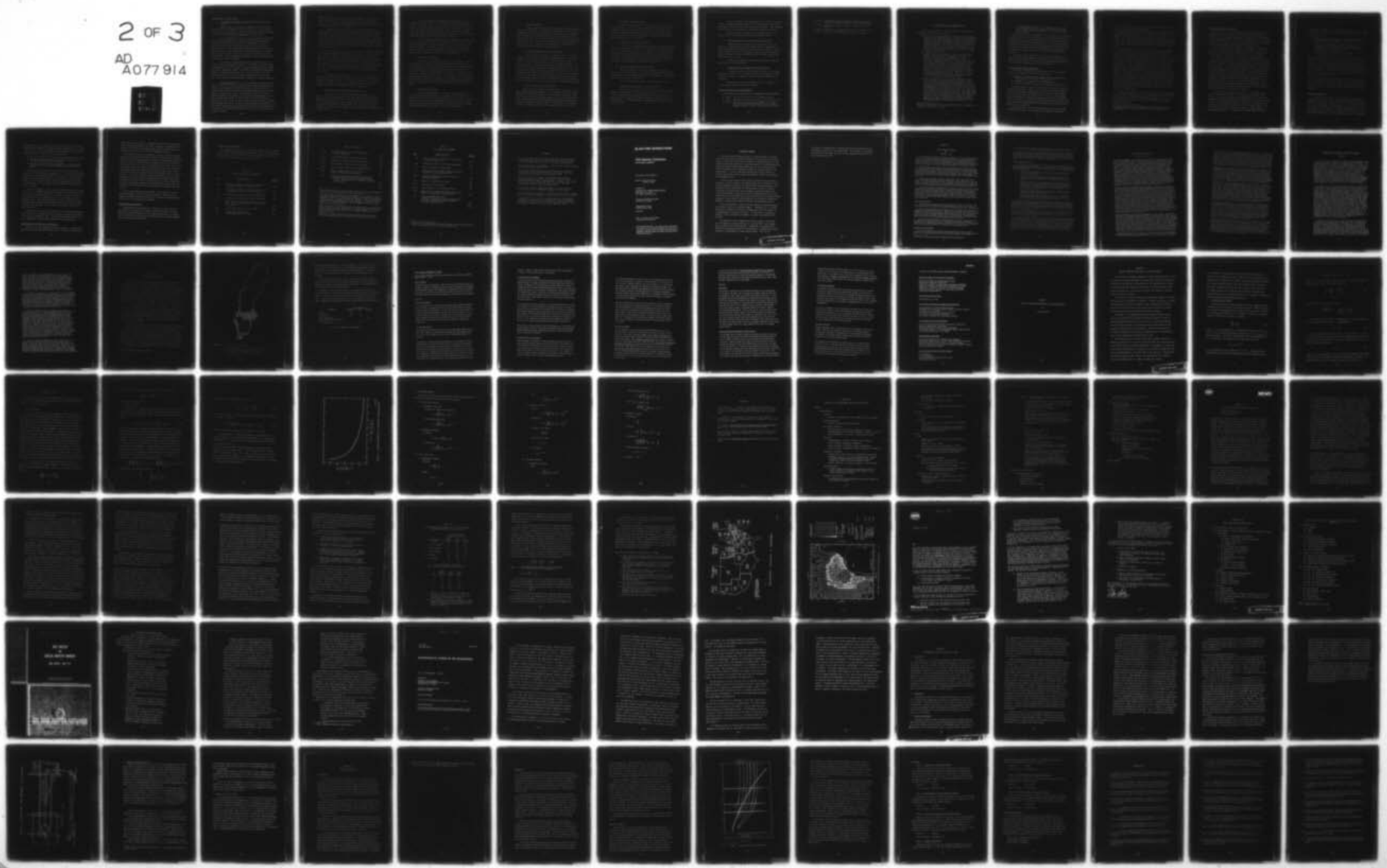

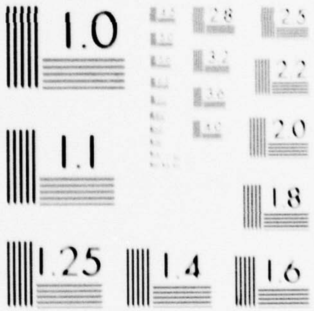

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Countermeasures in More Detail

1. Fire Fighting Equipment and Tactics (Peacetime and Survival Periods)

Smaller Fires--firefighting equipment should be provided for smaller fires in the immediate vicinity of shelters. Kits containing shovels, heavy leather gloves, hard hats, burlap bags, and stirrup pumps will suffice for singlehanded extinguishment of small fires.

Cost effectiveness of stirrup pumps versus back-pack 10-gallon water tanks with handheld nozzle pumps should be evaluated for use on fires near shelter doors and shelter air intake ports. Surveys of water supply must include the origin of the water and the source of pressure (e.g., electric pumps drawing water from wells or gravity water from reservoirs). Other questions to be evaluated include: Are there automatic shutoff valves on line which close when subjected to severe ground shock? Do shelter manuals show sources of water and nearest point for control by shelter personnel?

Wall hung fire extinguishers should be distributed in easily visible locations throughout the shelter. The number per shelter should be determined by the fire department. Each extinguisher must have simple instructions permanently posted. Provisions for recharging extinguishers should be included in all shelter kits. Also, each shelter fire kit should include a few tools, such as pipe wrenches, pipe cutters, and hose clamp fittings for making emergency connections to damage water mains.

Fighting Large Fires--in a fire environment following a nuclear blast, there is a need to fully optimize both firefighting equipment performance and strategies and tactical procedures to make the best use of limited manpower and water resources for fighting large fires in or around shelters or key critical risks. The fire-hose nozzle is a key firefighting equipment item in that the flow rates and characteristics of the water spray directly impact the total amount of water and manpower rerequired to put out a fire. At present, there are no fire control performance standards and tests to be used in nozzle purchase specifications. In this regard, measurements have indicated that current nozzles frequently do not deliver their rated and advertised flow rates (e.g., deficiencies up to 40% are common)

Furthermore, questions such as specific characteristics of the spray (water droplet sizes, etc.) directly impact fire control performance, how they can be measured, and how improvements might be achieved have not been adequately addressed or standardized.

Appendix J describes some recent research that indicated what might be done to reduce water waste and improve the performance of nozzles. For example, improved performance would control more intense fires with a given hose size. Conversely, if smaller flow rates could be used without reducing fire control effectiveness, smaller hoses with lower weight and lower nozzle reactions would be possible. This would mean quicker initial attacks and/or more simultaneous attack points with improved fire control times and water usage.

Also, for large shelters and fires, the use of pumping kits having gasoline-driven pumps with appropriate hose connections should be studied. Such pumping kits must have carefully designed instructions posted on permanent mounts showing alternative water supplies (i.e., if water mains fail), all of which can be reached by hand hose. For example, for key worker shelters or critical risks near the ocean, gasoline-driven desalination might be supplied, if alternate water supplies were difficult to fine. In such shelters, hose reels with both suction and delivery may be effective.

In fighting larger fires, there is also a need to optimize fire-fighting strategies and tactics to make full use of the available water, manpower, and equipment resources. Operations research studies and prefire planning for shelters and key critical risk categories are necessary to identify optimal tactics and manning/equipment combinations.

2. Public Awareness and Mass Education (Peacetime)

In a time of peace, two broad educational programs can be organized--a public awareness program and a mass education program. These programs differ mainly in terms of intensity rather than intent, which is to inform the general public about the necessity for, and the purpose of, civil defense preparedness. Such programs would provide the essential information concerning a large thermal or nuclear attack and the important readiness actions.

The public awareness program would provide simple, easy to remember facts for survival. As is present practice, this program would involve the testing of alert devices such as sirens and radio interruptions. Television announcements should also be considered. In support of the information available from DCPA, similar information should be announced through other organizations, such as the National Fire Protection Association and equivalent law enforcement organizations.

The mass education programs would be conducted as a regular part of the secondary and adult education programs in each community. Props such as ventilation, sanitary, and medical kits, should be used as part of these programs. In addition, regular refresher courses for public safety officers should also be mandatory. On occasion, community "war games" could be organized to test the overall preparedness.

3. City Shelter (Peacetime)

Some form of protection is necessary for key workers--a special blast shelter, an expedient shelter providing a blast and fallout protection and built in a time of crisis, or a structurally upgraded basement of an existing building (another option would be for the key workers to escape the risk area if warning times were sufficient). The latter three options are considered in this study. If the blast fire environment were understood well enough, judicious selection of building sites or upgradable buildings should permit a high probability of minimizing the fire threat. Shelter designs, construction guidance, equipment, and materials would be needed.

4. Key Workers (Peacetime)

Current study is underway to identify critical industries and key workers who would operate them. For purposes of this study, it is assumed that 6% of the risk area population fall in the key worker category and their places of duty occur throughout the risk areas. Plans will be explicit about key worker identity, their place of work, means of communication and procedures to take shelter or evacuate upon warning.

5. RADEF (Peacetime)

A large number of radiological monitoring instruments have been distributed throughout the country and a considerable effort has been undertaken to train radiological monitors to operate these instruments. Special guidance will be needed for key personnel operating in blast damaged zones where fires will be widespread. It will be vitally important to ensure that the instruments are protected from blast damage and that the monitors be conscious of the likelihood of widespread fires and noxious gases in addition to fallout radiation.

6. Increased Readiness Actions (Crisis Period)

Over a period of many years, an extensive list of increased readiness actions has been developed to maximize survival in the event of attack. As it mounts, each level of threat triggers a series of actions. It is conceivable that these actions should be reviewed in anticipated regions of light to heavy damage to evaluate priorities. It is in this crisis period that all the guidance materials, the education effort, and the amount of training could pay off very effectively if the operational environment is well understood. This light to heavy damage zone, by its very nature the object of attack because it contains most of the important industry, deserves special study to develop appropriate increased readiness actions for protecting people and equipment/machinery.

7. Protective Postures (Survival Period)

Many actions can result in improved chances for survival if one understands the attack environment, e.g., lie down in basements, remove window glass and potential missiles, avoid thermal pulse exposure, seek best blast protection upon warning, and move to best fallout protection after controlling fires and if informationional materials have been developed and people have been made aware of the knowledge. Considerable research is required in this area in the region of blast-fire effects.

8. Life Support (Survival Period)

During the survival period, it will be necessary to evaluate the availability of basic life support materials such as medicine, food, and water. Because this period may last as long as a few weeks, the location, conditions and need for the essential items must be identified. This may require the use or development of criteria for redistribution and the transportation of these items.

9. People Protection (Survival Period)

Following the period where basic survival was the main concern, it will be necessary to consider the restoration of the public protection and safety. Since the survivors will be attempting to resume production of the necessary goods and provision of services, organization of fire fighting, law enforcement, waste disposal, and water distribution services is necessary. In this respect, a manual providing flexible guidelines, procedures, and organizational methods must be developed.

10. Emergency Operation Centers (Peacetime)

EOCs are essential to all crisis management and recovery activities. These centers have to be established and equipped in peacetime. Their objectives are to gather information, assess damage, predict threats, set priorities, and direct operations.

Location and function criteria should be topics of research.

11. Emergency Operation Centers (Survival Period)

Many EOCs will not survive attack or will survive with limited capacity for operations. For those situations, first efforts must be to receive information on radiation levels, fire threats, etc., and pass this information to shelters and other inhabited facilities facing increasing threat. Information might be supplemented by directives to take specific actions.

As soon as possible, local EOCs will have to report for regional centers on damage and threat conditions. By these efforts, the central government will get an overall view on country-wide damage. This knowledge will constitute the background for interregional assistance later on.

Research might be necessary on how to establish EOCs after attack or how to reestablish EOC capacity for damaged centers.

12. Fire-caused Relocation and Rescue (Survival Period)

Immediately after attack, the fire threat will have to be surveyed. As shelters with survivors become exposed to approaching fires, evacuation and relocation of shelters will be necessary. In many cases, shelter exits will be covered with debris and rescue operations will be necessary. Fallout conditions and lack of heavy equipment may limit these resuce efforts.

Research topics might include methods for debris removal and effectiveness of various machines.

13. Equipment/Shelter Salvaging (Postsurvival Period)

To maintain usability, many shelters will have to be cleaned up after the attack. Piles of debris will have to be removed to reduce the future fire threat. Damaged structural elements might have to be repaired.

Research topics could be assessment tools to determine if a certain damage condition constituted a hazard.

Initial Research Project Recommendations

The following is an initial list of recommended research projects:

- Task 1: Site selection criteria for key worker shelters
- Task 2: Should key equipment be relocated or protected in place?
- Task 3: Optimization of firefighting equipment performance and tactical procedures to make best use of limited manpower and water resources during the survival period

- Task 4: In what other areas can computer simulation and decision analysis techniques be applied to fire countermeasures?
- Task 5: What are the essential industries and who are the key workers?
- Task 6: Production of firebrands in blast/fire interaction zones
- Task 7: Recovery of film showing blast/fire (i.e., DASIAC).

IX PROGRAM SUMMARY AND RECOMMENDATIONS

Three factors pertinent to the FY 80 program stand out from the discussions of the previous sections:

- First, there is general agreement with last year's program objectives and recommendations as repeated in the introductory remarks to this year's conference by Dr. Bensen. Last year's conference concentrated on what was needed to answer DCPA's questions about blast modifications to the fire threat from nuclear detonations. This year, the emphasis was on how to obtain the answers most efficiently and expeditiously. At the time of this conference, the FY 79 program was just beginning; therefore, there were no results to cause a change in direction or emphasis.

- Second, within the framework of a crisis relocation plan (DCPA's first option), several questions and decisions must be resolved promptly. A working list of the facilities, equipment, and people that are judged to be critical* is paramount to realistic thinking about the fire problem and countermeasures to mitigate the threat. This list should be available, at least in preliminary form, in time for the FY 80 program. A related problem concerns priorities in terms of the fraction of attention to be focused on the cities as a whole versus specific attention to the items on the critical list. The analysis of the fire-spread problem can be greatly simplified if the noncritical structures can be neglected (probably 90 to 95% of a city falls in this noncritical category).

- Third, a comparison of the recommended and actual funding for FY 79 shows the program is getting underway at about 58% of the original recommendation; consequently, most of the work units are commencing at reduced speed and several programs will not start this year. Obviously, the milestone accomplishments must retreat in proportion to the short fall in the budget, and the priorities in the FY 80 program must allow for both the unfinished prerequisites and a budget that also may be less than optimum. This fiscal constraint emphasizes the need for a prompt decision on the scope question. When the revised FY 80 program was assembled, an austere budget was assumed; therefore, the program presented in the introduction cannot be achieved fully in addition to the

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*Critical in the sense of survival, national viability, continuity of authority, and economic recovery.

unfunded remnants from FY 79. To reduce the fiscal strain, the recommended priorities assume less ambitious goals that focus primarily on the vulnerability of critical facilities and key people.

The program elements recommended for FY 80 and FY 81 are summarized in Tables IX-1 and IX-2, respectively. Tasks are grouped according to workshop topics (i.e., roman numerals); priorities within a group are indicated by capital letters commencing with A as the highest priority. Since priority comparisons between groups generally are difficult, all priorities of a given letter are assumed equal unless the results from one workshop or group are prerequisite to decisions and planning in another.

In view of future uncertainties, it may seem presumptuous to lay out a multiyear program; however, the intent is to reflect technical needs rather than political trends and to establish research goals within a time frame commensurate with the perceived needs.

Initial Fire Distribution Afterblast

Work Group I reaffirmed the importance of three of the program areas in the original FY 79 and 80 lists, namely:

- Theoretical and experimental studies of extinguishment and enhancement of fires by blast intractions.
- Secondary fires produced by a nuclear detonation.
- Ignition thresholds for large area mixed fuel configurations.

The basic question raised by these elements in particular and the conference in general is "where are the fires," i.e., what conditions of fuel and environment cause primary fires to persist and secondary fires to develop after the passage of a blast wave? A long-standing question concerns the relative importance of the primary and secondary fires. In the Five City Studies, which neglected blast/fire intractions, the primary fires predominated and received most of the attention then and also at the conference.

This superiority is not assured when blast effects are included; therefore, the secondary fires should not be completely bypassed in

FY 80. Part of the problem is the question of how to improve significantly on the earlier work of Kendall Mall*.

In keeping with the emphasis on critical facilities and industries, the approach suggested by Group I is to examine the potential for secondary fires in or near the structures on the critical list. This study can be combined with the fire vulnerability investigation proposed as Task III-b. The concern for residential and commercial areas could be left until results are forthcoming on the survivability of primary fires.

Although ignition thresholds have a strong impact on the number of primary ignitions, these ignition studies can be deferred until the results of the critical facility vulnerability study is completed (including the blast damage assessment) which will provide a better picture of the fuel materials and conditions where ignition thresholds could be of importance. In the revised lists for FY 80 and 81, the potential work units are listed in descending order of priority. The shock tube experiments are listed above the theory because some observations are needed to suggest further hypotheses and to guide the theoretical development. Participation in shots of the Misty Castle Series is a matter of timing to ride piggyback on the DNA tests. Since there are not many of these shots, they should be used if at all possible to extrapolate the shock tube results to full-scale geometries and to scale the departure from the positive-phase duration of nuclear explosions. Planning for the proposed modest effort should commence early in FY 80 to be ready for the summer tests.

The blast fire program for FY 81 follows the same priority arguments as FY 80, with two modifications: one, the secondary fires study in critical facilities is assumed finished; two, the larger (i.e., 600 tons) Misty Castle field test deserves a much larger field effort than the smaller FY 80 test.

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*J. McAuliffe and K. Moll, "Secondary Ignitions in Nuclear Attack," OCD Work Unit 2534A, Stanford Research Institute, Menlo Park, CA (July 1965).

Blast/Shock Effects on Structures

The 1978 blast/fire report emphasized that a joint effort between Workshops 2 and 3 was required to determine the debris field detail needed for the fire spread calculations. As noted by the 1979 Workshop 2, this information has not been forthcoming and another year should not escape before the question is resolved. Appendix E contain some suggestions regarding the detail required for the foreseeable future.

In the vulnerability rating approach to evaluating the potential losses of critical facilities, equipment, and supplies, two principal factors are involved: (a) the combustability of the structure and its contents and (b) the ability of the structure to remain standing.

Fire damage is most likely to occur when a combustible structure collapses so that the flames are in intimate contact with the vital contents--in contrast to a standing structure where most of the heat remains above the contents. Two degrees of damage would probably suffice for the vulnerability rating. The number of types of industrial and utility structures required for the analysis remains to be established but the minimum would not be less than three based on the types of wall structures (i.e., load bearing walls, frame structures with strong panel attachment, and frame structures with weak panel attachments). We hope that these questions of categories can be resolved under the current Work Unit 2564C. However, the determination of overpressures for collapse of the various categories would be undertaken in FY 80 under Task II-A, "blast analysis of individual structures."

Task II-B, the initial blast analysis of a city complex (alternately referred to as a "Rough cut description of the debris field") involves similar questions about the required detail. As indicated in Appendix E, the existing IITRI and URS models treat four types of tracts or city areas: residential, industrial, commercial, and institutional. Therefore, such categories could suffice for the type of debris. The FY 78 fire/blast report recognized six degrees of damage ranging from an undamaged structure to an essentially continuous field of debris.

Considering the mechanisms of fire spread employed in the fire spread model, these six damage levels could be combined to form three for the rough cut description:

- Standing structures that burn with a good view factor to enhance radiative heat transfer to the neighboring structures (levels 1 through 3 in Ref. 1).
- Structures that collapse on their own foundation; heat transfer is still by radiation but the view factor is substantially reduced by the low profile of the collapsed building (levels 4 and 5 in Ref. 1).
- Continuous debris fields where fire spread can occur by both radiation and creep (level 6 in Ref. 1).

Of course, firebrands can be effective under all three degrees of collapse. Tasks II-A and B are assigned first and second priority, respectively, in Group II because of the importance assigned to these efforts by the work group and because of their prerequisite nature to tasks in Group III. "Complementary Blast Studies" were shown on both the original research programs for FY 79 and 80 and Task 2564D falls in this category; however, the impact on other workshop areas is not as critical as Tasks II-A and B.

The FY 80 program shows the emphasis on the field test at Misty Castle II (Task II-A) and a continuation of the individual structure analysis (Task II-B). Again, the complementary studies receive third priority in Group II because they are not critically linked to other schedules.

Fire Spread and Threat

The concept of fire-spread modeling and threat analysis was the principal concern of the study areas labled "Initiate Search for/and Development of Blast-Fire Predictive Models," and "Analytical Development of Blast/Fire Models," respectively, in the original FY 79 and FY 80 programs. Working Group III converted these broad titles into the four specific tasks listed in the revised FY 80, 81 programs. Tasks III-A (Fire Vulnerability of Critical Resources) and III-B (Increased

Utilization of Five City Results) receive first priority in FY 80 because they are designed to provide preliminary evaluations (i.e., within a year's time) of the fire threats to typical American cities and critical facilities as outlined in the workshop report.

Two factors limit the results that can be obtained with Task III-B:

- The inherent limitations listed in Appendix E--particularly the lack of provision for blast damage.
- How well other cities can be simulated by a suitably weighted composite of the five cities surveyed for the original data bank.

Tasks III-A and C focus on the critical facility problem from the two points of view described in Appendix E, i.e., the firespread scenario versus the fire vulnerability rating. The results of these two efforts should clarify the approach that is most effective for the CRP option. Actually, the two efforts are not completely independent since the specific model needs critical-resource fire-vulnerability information as one of its inputs.

In FY 81 the emphasis turns to a generalized model that can accommodate the fire and debris distribution information from Workshops 1 and 2 and provide a general picture of fire spread or couple fire environment information into the compatible specific target model to yield detailed results. The generalized model involves a substantial effort continuing over several years and should receive greater support in the off years when the budget is not strained by the Misty Castle test or other field tests.

A fifth task, "CO Production and Mobility," has been deferred beyond FY 81 because it (1) depends on the fire picture generated by Workshops 1, 2, and 3, (2) becomes an input to the "generalized model" and (3) can be circumvented by suitable CRP arrangements and countermeasures.

Countermeasures and Intervention Strategies

Logically, the main implementation of the Workshop 4 output begins when the threat has been defined sufficiently to permit an evaluation of countermeasure effectiveness. Consequently, the FY 80 and 81 programs show a very modest effort in this area. Workshop 4 recommended seven projects for the initial research program; three of those have been included in FY 80, one in FY 81, and the remainder deferred.

The highest priority was assigned to the list of essential industries and key workers, Task IV-A, because this information is urgently needed by all four workshop groups. Actually, the determination of such critical facilities and workers goes beyond the mission of the blast/fire program since it is a vital consideration in the total crisis relocation plan. While the task is listed in the FY 80 program, the asterisk indicates the work should be performed at a higher level in the overall CRP program; the funds have not been included in the FY 80 total estimate. The timing for Tasks IV-B (Site Selection Criteria for Key Worker Shelters) and C (search of DASIAC Files for Field Test Evidence of Blast/Fire Interactions) is not particularly critical, although the blast/fire interaction evidence from old field tests would be most useful before all the questions have been answered in the shock tube experiments.

Before countermeasures are discarded, it is desirable to have an unbiased procedure to evaluate cost effectiveness. (Application of Computer Simulation and Decision Analysis to Blast/Fire Countermeasures) Task IV-A in FY 81 provides this procedure.

Program Planning and Review

Program element V-A provides for a variety of service functions that include the contractors' conference and annual report, the preparation of background statements, and a general surveillance of related blast and fire activities such as the training fires in downtown Burbank and the destruction of Lark, Utah.

Recommended Program Funding

The following tables provide an itemized listing of program elements for FY 80 and 81 with recommended funding levels based on the assumptions discussed above. These are offered to assist in program planning, but in no sense do they represent an official DCPA estimate.

Table IX-1

REVISED FY 80 BLAST FIRE PROGRAM*

Task	Work Unit Title	Funding (K $)
I-A	Shock Tube Studies of Blast-Fire Interactions† (continued from FY 79, includes 2564A)	200
I-B	Development of Theory of Blast-Fire Interactions (continued from FY 79--2564A and 2564E)	100
I-C	120-Ton Misty Castle Verification Experiments‡	50
I-D	Secondary Fire Analysis of Critical Facilities	50
II-A	Blast Analysis of Individual Structures, Specifically the Critical Facilities (continued from FY 79--2564C)	100
II-B	Initial Blast Analysis of City Complex	160
II-C	Complementary Blast Studies (continued from FY 79--2564D)	100

Table IX-1 (Cont'd)

III-A	Preliminary Analysis of Fire Vulnerability of Critical Resources	250
III-B	Increased Utilization of Five City Results	50
III-C	Target Specific Model for Critical Resources	80
IV-A	Define Essential Industries and Key Workers	30[†]
IV-B	Site Selection Criteria for Key Worker Shelters	40
IV-C	Search of DASIAC Film File for Field Test Evidence of Blast/Fire Interactions	30
V-A	Sensitivity Analysis/Program Planning and Review (includes contractor conference and observations of other burn programs, e.g., Burbank, California and Lark, Utah)	60
		1270

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[*] Priorities are indicated by the capital letters in the task designation. All A's are equal first priority, B's are second, etc.

[+] Although thermal radiation source development, as an adjunct to shocktube experimentation, is mentioned as a part of the program developed in Workshop 1 (and is included in Work Unit 2564B), it was not specifically listed among the recommendations of that workshop. To provide timely support of the shocktube efforts, this development also merits a high priority (see footnote below).

[‡] Since the time of the Asilomar meeting, the Misty Castle test planned for 1980 has been cancelled. Therefore, any funding planned for this task can be deferred or (preferably) used to develop thermal sources for shocktube studies.

[†] Task IV-A is vitally needed but it is not within the mission of the blast/fire program and is not included in the total cost estimate.

Table IX-2

FY 81 BLAST/FIRE PROGRAM[†]

Task	Work Unit Title	Funding
I-A	Shock Tube Studies of Blast-Fire Interactions (Continued from FY 80)	100
I-B	600-Ton Misty Castle Verification Experiments	200
I-C	Theory of Shock Fire Interactions	100
I-D	Experimental Verification of Doubtful Ignition Thresholds (Large Area-Mixed Fuels)	80
II-A	Verification Experiments (Misty Castle) on Structural Response	400
II-B	Analysis of Individual Structures	100
II-C	Complementary Blast Studies	100
III-A	General Model of Fire Spread and Threat	200
IV-A	Application of Compute Simulation and Decision Analysis to Blast/Fire Countermeasures	100
V-A	Program Planning and Review (includes contractors' conference and contact with other burn programs such as Burbank, California and Lark, Utah)	60
		1440

[†] Priorities are indicated by the capital letters in the task designation. All A's are equal first priority, B's are second, etc.

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BLAST/FIRE INTERACTIONS

1979 Asilomar Conference

DETACHABLE SUMMARY

Proceedings of the Conference

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DETACHABLE SUMMARY

Fire from a nuclear weapons 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 interaction between blast effects and fire effects preclude any reliable estimate of the incendiary outcome of a nuclear attack on the United States. As such, these uncertainties are a major obstacle to defense planning and they interface with national security policymaking at the highest levels.

To rectify the technical deficiencies in predicting the incendiary outcome of a nuclear attack on the United States and to formulate a well-directed program of research, the Defense Civil Preparedness Agency contracted with SRI International in 1978 and again in 1979 to convene a conference of authorities on fire and blast, structural response, and related technologies. This report covers the proceedings of the second conference, and it describes the early-on activities of an optimally funded program of 5-year duration, whose objective is to achieve an analytical method for reliably predicting fire behavior and incendiary outcome.

Within a framework of crisis relocation planning, several questions and decisions need to be resolved promptly. A working list of critical resources is paramount to realistic thinking about the fire problem and countermeasures to mitigate the threat. To avoid delay in strategic planning, this list should be available, at least in preliminary form, by 1980.

A comparison of the recommended and actual funding to date shows that the program is getting under way at less than 60% of the original goal as urged in the 1978 conference. Accordingly, in assembling the revised FY 80 program during the 1979 conference, a somewhat more austere program was acknowledged as a more realistic goal. The focus is

restricted to vulnerability of critical facilities and resources and to the threats to survival of key individuals. This program is nonetheless consistent with the broad objectives of the program as laid down in the first conference in 1978.

Appendix A[*]

SOVIET TARGETING STRATEGY
BY
WILLIAM T. LEE

Both the US and the USSR reject initiation of nuclear war by an "out-of-the-blue" surprise attack as an instrument of national policy. Both expect nuclear war, if it occurs, to arise out of a crisis. At the same time, each superpower suspects the other of harboring dark designs for a surprise attack should the circumstances appear propitious, or if some desperate and reckless leader comes to power. In all cases, the "bottom line" is how each superpower proposes to use its weapons: What targets are to be attacked? What degree of damage is to be inflicted? What are the politico-military objectives, if any, of strategic nuclear strikes once deterrence has failed?

Public discussions of such matters in the US are dominated by two perceptions of how the Soviets would use their nuclear weapons. The most prevalent perception is a "mirror image" of the US "assured destruction" concept: attack US cities with large weapons to inflict as many millions of casualties and as much damage to production facilities as possible. The second, less prevalent, perception stresses the danger of a Soviet attack on US strategic nuclear delivery systems -- ICBMs, heavy bombers, and submarine-launched ballistic missiles (SLBMs) in port -- while withholding strikes on our cities to see if the US would capitulate after losing most of its land-based strategic nuclear forces.

In SALT, the US has sought to constrain or reduce Soviet forces so that they would be effective only against US population and urban infrastructures. Thus, we have tried to limit the number of "heavy" Soviet missiles that threaten our land-based missiles while granting the Soviets numberical advantages in missiles that are effective against US cities and other soft targets. The Soviets, on the other hand, have held out, very successfully, for high limits on both "heavy" ICBMs and total "strategic" launchers while avoiding specific constraints on missile characteristics.

There are two essentials to understanding Soviet performance at SALT. First, Soviet targeting strategy differs from popular US perceptions, more so from the purely countervalue perception than from the mixed counterforce/countervalue version. Second, Soviet strategic targeting strategy applies to both Eurasia and the United States. While we equate "strategic" to "intercontinental", the Soviets do so only in the context of SALT, where accepting our definition of "strategic" is in Soviet interests. To the Soviets, Europe and adjacent areas in Asia are of equal, if not greater, strategic importance than the "transoceanic" dimension. Both Soviet targeting strategy and the Soviet concept of strategic dimensions have had, and probably will continue to have, much influence on SALT negotiations.

SOVIET TARGETING STRATEGY

Since World War II, the Soviets have consistently argued that defeat of an adversary's armed forces is the first and primary objective of military operations in a nuclear war. To defeat a nuclear-armed enemy, it is necessary first to destroy his nuclear weapons and means of delivering them.

One of the most authoriatative public statements of Soviet targeting strategy was made by the Commander of the Strategic Rocket Forces (SRF), Marshal Krylov, in September 1967. (Krylov was SRF Commander from 1963 until his death in 1972). Consistent with the view that even a nuclear war should be conducted for positive ends, Marshal Krylov stated that the objective of such a war would be "victory" for the USSR. According to Marshal Krylov, the principal targets of the SRF would be the enemy's delivery systems and weapons storage and fabrication sites; military installations; military industries; centers of politico-military administration, command, and control.

This listing of targets, presumably in approximate order of priority, is designed to fight a war rather than to retaliate against cities. It has nothing in common with "maximum-fatality" targeting and is not consistent with any simple "assured-destruction" objective. The list is, however, consistent with the damage-limiting missions of Soviet forces, and is consistent with the "victory" objective interpreted to mean survival as a national entity, and postattack recovery.

THEATERS OF MILITARY OPERATIONS

The general principles of Soviet nuclear targeting strategy must be applied in specific geographic areas of strategic military operations. The targets located in each geographic area differ, and Soviet politico-military objectives are not identical in all potential areas of conflict.

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[*] Reprinted from American Strategic Defense Association Newsletter.

In the Soviet view, "the theater of military operations (TVD)" is defined as the land or sea area within the limits of which armed forces during war execute a single strategic mission.

For the conduct of strategic nuclear operations, NATO probably represents at least three, probably four, TVDs -- one or two in Central Europe and one each on the north and south flanks. China, Japan, Korea, and Okinawa probably constitute one or two more TVDs. Finally, there is the "transoceanic" TVD: the US and its military bases in the Atlantic and Pacific basins. To the Soviets, each of these TVDs is equally "strategic" although the Central European TVDs may be first among equals in Soviet strategic force planning and resource planning.

TARGETING STRATEGIES FOR THE TVDs

Certain general factors affecting the conduct of strategic nuclear operations in the TVDs are stated in Soviet writings. Although these factors apply to all TVDs, variations probably exist because the Soviets recognize the differences in the target arrays found in each TVD, and Soviet politico-military objectives vary with the TVDs. The principal factors governing targeting strategy for each TVD appear to be:

- Political factors will dominate the course and conduct of a nuclear war between the USSR/Pact and US/NATO because in such a war both sides "will pursue their own decisive political ends".
- The theses and application of Soviet military strategy are derived from the political strategy of the Communist Party of the Soviet Union (CPSU). Soviet strategic nuclear forces will be under the direct command of the top political leaders.
- Two basic options exist: (a) use large weapons that can inflict heavy damage on "individual states" and "would retard the social progress of their peoples for a long time" and (b) use smaller weapons that can defeat the enemy "without doing essential injury to the economy or populace of states whose aggressive rulers unleashed the war". Only the Soviet political leaders can make the decision as to which option would be exercised.
- First-priority targets are the enemy's nuclear delivery systems, nuclear weapons stocks, and associated command control and communications, followed by other components of the enemy's military forces.
- In attacking the enemy economy it is essential to select the most vulnerable points where destruction would disorganize economic support of the war effort. While collateral destruction cannot be avoided, "the objective is not to turn the large economic and industrial regions into a heap of ruins".

This general principle of destroying only what is necessary to achieve the Soviet political and military objectives is further expressed in discussions of what are the most vulnerable (i.e., vital) components of any given target array. Some of this discussion is related to contemporary economies; some of it appears in Soviet critiques of Allied strategic bombing operations in World War II. The Soviets do not consider general attack on all types of industrial targets to be either necessary or militarily effective. They are particularly critical of the political and military futility of attacking population and cities.

In general, the following economic activities appear to be the most lucrative first-priority targets for prohibiting the replacement of nuclear delivery systems, nuclear weapons, and other military assets and for limiting capabilities to use surviving military forces effectively: transportation, power stations, facilities producing liquid fuels, chemical industries, selected bottleneck facilities in other industries.

All the evidence known to the author explicitly or implicitily indicates that Soviet nuclear targeting strategy against the US is generally the same as for other TVDs. On the other hand, since the Soviets have no ambition to occupy the US they not only must seek to destroy our military/forces in being at the beginning of the war but also must prevent the US from reconstituting its military forces. Hence, Soviet targeting of US industry might be more extensive than in Europe and Japan, and targeting selected US cities (politico-administrative centers), might be more comprehensive than in Europe. Soviet literature indicates that nuclear targeting in all TVDs would be selective both with regard to the targets attacked and the degree of damage inflicted. While we need more information on what "selective" means to Soviet nuclear strike planners, the principle clearly is far removed from declatory U.S. concepts of mass destruction of population in nuclear attacks on USSR.

THE STRATEGIC DEBATE -- SPRING 1978

by

William B. Marty, Sr.

"The Theology of Strategy" by Henry Trofimenko, historian and head of the Foreign Policy Department of the USSR Academy of Sciences' Institute of the USA and Canada, ORBIS, Fall 1977. Theme: America's evolving body of strategic doctrine has been spawned not in realistic terms but only by faith and unquestioning beliefs. U.S. strategic doctrines have changed in response to the growth of Soviet retaliatory forces from "massive retaliation" (1945-1960) to disarming first strike (1960-1970) to limited strategic strikes (since 1970), which has now been modified to include counterforce warfighting. As doctrines changed, so did excuses for new American strategic weaponry. Also, new American technical ideas, such as ABM, generated new doctrines. Hence, in the U.S., weapons dictated doctrines, not doctrines dictating weapon requirements. The author claims America's ruling elite propelled an unnecessary arms race by false claims of a bomber gap (mid-1950s); a missile gap (early 1960s); an ABM gap (late 1960s), a throw-weight gap (early 1970s); now it is a civil defense gap. Soon, these will be followed by a missile-accuracy gap and a deterrence-potential gap. As a reaction, the Soviet Union created a "retaliatory strike capability" and then steps were taken to improve its civil defense system. According to the author, the Soviet Union: rejects the first-strike doctrine; does not consider "the enormous U.S. civil defense programs" a security threat -- nor is its own; contends military strength does not automatically translate into political power; agrees with those who think a limited strategic war would become an all-out urban and industrial attack; is sure the problem of national security can be solved through measures to limit and reduce armaments. Comment: Compells attention for views seen through a different lens. Recommended reading not only for what the author asserts and documents but also as good mental exercise on what the author steers clear of.

"Carter Plays With Fire -- Obsessions With Nuclear Strategy" by Alan Wolfe, Nation, September 24, 1977. Theme: America has few options on which to base its nuclear strategy and this creates an obsession in an Administration trying to find a middle ground that isn't there. The 1977 report on nuclear options devised by the Congressional Budget Office (CBO) proves a point it never wanted to make -- there are no serious options; either one plans to use nuclear weapons some day or one does not. There is no in-between that is tolerable. CBO's three options are basic to any debate. First is "finite deterrance", a minimal strategy of only a retaliatory attack on non-military targets, which allows the cancellation of the B-1, the MX ICBM, and cruise missiles. Also, all three components of the triad could be reduced, allowing more funding for conventional forces. Second is "limited nuclear options", really finite deterrence plus a capacity to wage a "low-level general war with nuclear weapons", allowing cancellation of the B-1 and MX but requiring deployment of sea-launched cruise missiles, advanced interceptor aircraft, and improved warning systems. Third is a strategy of "essential equivalence" based not on military assumptions but on psychological ones that leave no doubt the U.S. will continue to assert its world position and reassure its allies America will meet its commitments, requiring development of the B-1, MX, building Trident submarines, and increasing the planned inventory of cruise missiles. Author Wolfe asserts that the second option would lead to all-out war, making the strategy self-defeating. Doves prefer the first option, which, as a return to the Dulles era of massive retaliation, is philosophically repugnant to liberals, such as Paul Warnke. The third option would be favored by Congress, military and industrial interests, and those like Paul Nitze. Comment: One viewpoint that attempts to sort out some painful fundamentals in the strategic debate.

"Strategic and Arms Control Implications for Laser Weapons" by Barry J. Smernoff, researcher at Hudson Institute, Air University Review, Jan/Feb 1978. Theme: During the next 25 years, the art of warfare may be revolutionized by laser weapon technology -- high energy beams of coherent light that could destroy military targets. To develop laser weapons, the U.S. and the Soviet Union are spending heavily on research and testing. Bombers, ICBMs, cruise missiles and satellites could be destroyed at great distances by ground-based lasers if the technology can be developed. Airborne lasers could be deployed. Anti-laser-lasers could be installed in satellites. Arms control negotiations would likely be complicated if laser research advances to a new era in armaments. Author Smernoff, an Associate Member of ASDA, suggests that the time may come when deterrence is based on laser-defensive weapons rather than an unstable nuclear balance. Comment: May be no more science fiction than early visions of nuclear weapons. Of interest because of its light on possible future strategic defense measures and its relationship to a statement by arms control chief, Paul Warnke, of April 3, 1978, "The technology to create and put into the field, weapons that can upset the strategic balance and make future arms control even more difficult still threatens to outpace the arms control process."

"Reviewing the Arms Race" by Samuel F. Wells, Jr., of the International Security Studies Program at the Wilson Center, Washington, D.C., World Issues, June/July 1978. Theme: There are good reasons to be pessimistic about gaining Senate approval of SALT II. First, the rapid pace of technology undermines the basis for stable deterrence. New systems are on the verge of becoming operational. Second, there is doubt over Soviet commitment to arms control and arms reduction. There is much evidence the Soviets reject the concept of mutual assured destruction. They continue to invest heavily in civil defense, work on defensive radars, and test new versions of ABM defense. Overall, the Soviets are going ahead full bore for superiority in spite of SALT agreements. In sum, the Administration may not be able to convince the Senate (and public opinion) to approve a SALT II agreement. The chances of any future agreement look dim, even if SALT II is approved. To obtain significant reductions in strategic arms, the U.S. must demonstrate to the S.U. that we intend to match their level of effort and not hold back unilaterally. Comment: Professor Wells frankly admits that when he said in 1977 we must "try harder" he meant unilateral steps to make progress in arms control. But, nine months later, on the basis of new information he now means we should match the Soviet effort -- for we have no other choice, unilateral actions won't work.

"The Scope and Limits of SALT" by Richard Burt, Washington correspondent for the New York Times, Foreign Affairs, July 1978. Theme: SALT II will receive rough treatment in the Senate because at least one-third of the Senators may decide that no SALT agreement is better than a bad one. Author Burt traces the history of SALT, details the 13 points of the likely treaty, explains the protocol to go along with the agreement, and describes the expected statement of principles for future SALT discussions. Arguments for and against the three-part SALT package are compared. Controversies surrounding the complex package will produce an equally complex debate. The price for Senate approval is likely to include upgrading of Minuteman III, speedup of Trident submarine and cruise missile procurement, and a second look at the B-1 -- all measures the Carter Administration wants to avoid. Comment: This discourse defines with clarity the elaborately interrelated elements of the SALT II package and suggests several crucial by-products of the agreement.

"Repeating History: The Civil Defense Debate Renewed" by William H. Kincade, Executive Director of the Arms Control Association, International Security, Winter 1978. Theme: "The enduring realities of national power and thermonuclear weapons imposes on the United States and the Soviet Union a hostage relationship which American strategic nuclear policy cannot escape and can ill afford to ignore." Author Kincade advances a strategic concept of "mutual vulnerability", a variant of MAD, by which he means the certain destruction of basic economic capacities -- not just defense industry. Mutual Vulnerability would eliminate targeting of population as such, would require fewer warheads, eliminate the need for a hard-target kill capacity and so stabilize deterrence. Civil defense measures are dismissed as of no value in view of large arsenals of nuclear warheads and the immense destructive power of these weapons. Comment: The article, although supposedly on the civil defense debate, is actually an attempt to refurbish the concept of mutual assured destruction. This requires the author to attempt to prove that civil defense is an enterprise with no hope of success either in the U.S. or the Soviet Union. The environment of reduced strategic arms on both sides is not considered seriously. Recommended reading as a well-written treatise on the views of the more radical wing of the arms control community.

"The Coming U.S. Strategic Debate" by Lt. Gen. Daniel Graham, USAF (Ret.), Defense and Foreign Affairs Digest, March, 1978. Theme: Two schools of thought are locked in furious competition: one advocates peace-through-strength and the other peace-through-trust. The strength school asserts that the Soviets: are expansionists building warfighting rather than deterrent forces; seek overall military superiority and protection for its population; and use the SALT talks to gain strategic advantages. The trust school contends: the threat to the U.S. is really the existence of large nuclear arsenals; the Soviet military buildup is caused only by its fear and distrust of the U.S.; improved U.S. strategic arms will simply fuel the arms race; and nuclear war is unthinkable, so the main obstacle to arms agreements must be relieved by softening of verification standards and by unilateral actions such as cancellation of the B-1 bomber and the MX missle. The author states that the trust school now dominates national strategy but the Congress and public are increasingly supportive of the strength school. Comment: Pithy commentary on the issues by a representative of the strength school.

"The Strategic Forces Triad: End of the Road?" by Colin S. Gray of the Hudson Institute, Foreign Affairs, July, 1978. Theme: It would be a serious strategic failure if the U.S. triad of ICBMs, bombers, and SLBMs is cut back to a dyad of only bombers and SLBMs. By about 1983 the Soviets will have the capability of knocking out most of our ICBMs. Hence, the U.S. should deploy a survivable ICBM system based on the idea of multiple aim points (MAP). On civil defense, the author observes that if the S.U. can effectively neutralize our strategic deterrent and if their civil defense is half as effective as Leon Goure and T.K. Jones claim then it "takes a very talented friction writer to invent acute crisis for the 1980s wherein the U.S. would either choose to initiate nuclear employment, or could secure some political advantage from such employment". Comment: Gray considers that a drift into a dyad spells Soviet dominance. The alternative of a mutual reduction in land-based strategic weapons is not discussed.

CONCERNING THE CIA REPORT ON "SOVIET CIVIL DEFENSE"

BY

LEON GOURE

ON JULY 20, 1978, THE AMERICAN PRESS WIDELY PUBLISHED SUMMARIES OF AN UNCLASSIFIED CIA REPORT RELEASED BY ITS DIRECTOR, WHICH PURPORTED TO PRESENT THE BASIC FINDINGS OF THAT AGENCY ON THE CURRENT STATE, CAPABILITIES, EFFECTIVENESS AND IMPLICATIONS FOR THE STRATEGIC BALANCE OF THE SOVIET CIVIL DEFENSE PROGRAM. SAD TO SAY, THE REPORT, WHICH REPRESENTS A RECENT CRASH EFFORT ON THE PART OF INTELLIGENCE AGENCIES TO ASSESS SOVIET CIVIL DEFENSE AFTER NEARLY A DECADE OF TOTAL DISREGARD OF IT, ADDS MORE CONFUSION THAN CLARIFICATION ON THIS SUBJECT. THIS IS DUE IN PART TO THE FACT THAT THE REPORT BECAME "POLITICIZED" IN THE COURSE OF TRYING TO ACCOMMODATE THE OPINIONS OF STATE DEPARTMENT AND, IN PARTICULAR, ARMS CONTROL AND DISARMAMENT AGENCY REPRESENTATIVES ON THE COMMITTEE DRAFTING IT. AS A RESULT OF THIS, THE REPORT CONTAINS OBVIOUS INCONSISTENCIES, DUBIOUS CONCLUSIONS AND NUMEROUS CAVEATS, WHICH THE PRESS, AND THOSE OPPOSED TO A MEANINGFUL U.S. CIVIL DEFENSE EFFORT HAVE SIMPLY GLOSSED OVER. FURTHERMORE, IN THE PROTRACTED COURSE OF HAMMERING OUT A COMPROMISE AMONG THE AGENCIES INVOLVED IN THE STUDY, THE REPORT REPRESENTS THE LOWEST COMMON DOMINATOR OF THE FINDINGS WHICH, THEREFORE, DO NOT FULLY AND IN MANY INSTANCES ACCURATELY REFLECT THE ACTUAL STATE OF SOVIET CIVIL DEFENSE CAPABILITIES.

IN GENERAL TERMS, THE REPORT CORRECTLY NOTES THAT CIVIL DEFENSE IS AN INTEGRAL PART OF THE SOVIET MILITARY POSTURE AND STRATEGY, AND THAT "THE SOVIETS ALMOST CERTAINLY BELIEVE THEIR PRESENT CIVIL DEFENSE WOULD IMPROVE THEIR ABILITY TO CONDUCT MILITARY OPERATIONS AND WOULD ENHANCE THE USSR'S CHANCES FOR SURVIVAL FOLLOWING A NUCLEAR EXCHANGE." THE REPORT ALSO ACKNOWLEDGES THAT ITS FINDINGS ARE ONLY PRELIMINARY AND THAT "MORE EXTENSIVE ANALYSIS WOULD RESULT IN AN UPWARD...ADJUSTMENT" OF REPORTED SOVIET CIVIL DEFENSE CAPABILITIES, ESPECIALLY SHELTERS. NEVERTHELESS, THE REPORT MAKES THE UNWARRANTED ASSERTION THAT THE SOVIETS "CANNOT HAVE CONFIDENCE, HOWEVER, IN THE DEGREE OF PROTECTION THEIR CIVIL DEFENSE WOULD AFFORD THEM, GIVEN THE MANY UNCERTAINTIES ATTENDANT TO A NUCLEAR EXCHANGE," AND THAT PRESENT SOVIET CIVIL DEFENSE "WOULD NOT EMBOLDEN THEM DELIBERATELY TO EXPOSE THE USSR TO A HIGHER RISK OF A NUCLEAR ATTACK." YET, ACCORDING TO THE REPORT, SOVIET CIVIL DEFENSE ALONG WITH OTHER STRATEGIC DEFENSIVE AND OFFENSIVE MEASURES IS INTENDED ALSO "TO CONVINCE POTENTIAL ENEMIES THAT THEY CANNOT WIN A WAR WITH THE USSR," THEREBY REDUCING THE RISK THAT SOVIET AGGRESSIVE ACTIONS WOULD EXPOSE THE USSR TO THE THREAT OF A NUCLEAR ATTACK. FURTHERMORE, AMONG THE SCENARIOS DISCUSSED IN THE REPORT IT IS ESTIMATED THAT WITH A WEEK OF STRATEGIC WARNING TO IMPLEMENT CIVIL DEFENSE MEASURES, SOVIET POPULATION LOSSES FROM U.S. RETALIATORY STRIKES "COULD BE REDUCED TO THE LOW TENS OF MILLIONS, ABOUT HALF OF WHICH WOULD BE FATALITIES," I.E., ON THE ORDER OF SOVIET LOSSES IN WORLD WAR II. THIS SHOULD LEAD ONE TO CONCLUDE THAT THE SOVIET BELIEF THAT CIVIL DEFENSE "WOULD ENHANCE THE USSR'S CHANCES OF SURVIVAL" IN A NUCLEAR EXCHANGE IS INDEED WELL FOUNDED AND, CONSEQUENTLY, THAT THE SOVIETS COULD HAVE "CONFIDENCE" IN THE EFFECTIVENESS OF THEIR CIVIL DEFENSE PROGRAM.

ACCORDING TO THE REPORT THERE IS SUFFICIENT READY BLAST PROTECTION FOR "ALL LEADERSHIP ELEMENTS AT ALL LEVELS," BUT ONLY A "MINIMUM OF 10 TO 20 PERCENT OF THE TOTAL POPULATION IN URBAN AREAS COULD BE ACCOMMODATED AT PRESENT IN BLAST-RESISTANT SHELTERS," A FIGURE WHICH IS EXPECTED TO RISE TO 15 TO 30 PERCENT BY 1985. IT IS ACKNOWLEDGED, HOWEVER, THAT THIS ESTIMATE IS TOO LOW AND THAT FURTHER STUDIES WILL UNDOUBTEDLY SHOW THAT THERE IS A HIGHER READY SHELTER CAPABILITY. WHAT THE REPORT FAILS TO MAKE CLEAR IS THAT THESE "MINIMUM" SHELTER FIGURES APPLY ONLY TO IDENTIFIED BASEMENT AND DETACHED SHELTERS IN SELECTED SAMPLE CITIES AND DO NOT INCLUDE DUAL-PURPOSE SHELTER SYSTEMS WHICH, IF ADDED TO THE OTHERS, GREATLY INCREASE THE OVERALL SHELTER CAPACITY. FOR EXAMPLE, THE "DISCUSSION" SECTION OF THE REPORT NOTES THAT THE MOSCOW SUBWAY SYSTEM COULD SHELTER UP TO 34 PERCENT OF

THE CITY'S RESIDENTS. THUS, ACCORDING TO THE FIGURES CITED IN THE REPORT, THE TOTAL SHELTER CAPACITY IN MOSCOW IS ON THE ORDER OF 54 PERCENT, AND GIVEN THAT THIS ESTIMATE IS BELIEVED TO ERR ON THE LOW SIDE, IT IS MORE LIKELY THAT MOSCOW SHELTER CAN ACCOMMODATE 60 OR MORE PERCENT OF THE RESIDENTS, WHICH IS IN LINE WITH THE INFORMATION PROVIDED BY RECENT SOVIET EMIGRES WHOM I HAVE INTERVIEWED. THE SAME IS TRUE FOR OTHER LARGE TARGET CITIES WHICH HAVE SUBWAYS OR OTHER DUAL-PURPOSE SHELTER SYSTEMS. IT IS WORTH NOTING THAT IN 1973 THE CHIEF OF USSR CIVIL DEFENSE, ARMY GENERAL ALTUNIN, ANNOUNCED THAT A SUFFICIENT INVENTORY OF READY SHELTERS EXISTED TO ALLOW THE AUTHORITIES TO PLAN TO PROVIDE BLAST PROTECTION FOR THE "ENTIRE POPULATION" IN POTENTIAL TARGET AREAS AND THAT CONSEQUENTLY URBAN EVACUATION WAS NO LONGER THE PRIMARY METHOD TO PROTECT THE POPULATION.

THE REPORT'S ESTIMATE THAT 24 TO 48 PERCENT OF THE ON-DUTY WORKERS AT "KEY INDUSTRIAL INSTALLATIONS," (WHICH THE REPORT FAILS TO DEFINE OR IDENTIFY) COULD BE SHELTERED IN WARTIMES AT THEIR PLACE OF WORK IS WRONG. IT IS BASED ON THE ASSUMPTION THAT EACH WARTIME WORKSHIFT REPRESENTS ONE-HALF OF THE INSTALLATIONS' PEACETIME WORKFORCE. ACTUALLY, THE SIZE OF THE WARTIME WORKFORCE AT ANY PLANT IS CONSIDERABLY REDUCED BY THE MOBILIZATION OF RESERVISTS, THE DISPERSAL OF ADMINISTRATIVE PERSONNEL TO OUT-OF-TOWN LOCATIONS, AND THE EVACUATION OF EMPLOYEES TO OTHER LOCATIONS TO WHICH THEIR FAMILY MEMBERS MAY BE SENT. CONSEQUENTLY, IN MOST CASES THE ACTUAL SHELTER CAPACITY AT INDUSTRIAL INSTALLATIONS IS SUFFICIENT TO ACCOMMODATE THE ENTIRE WARTIME WORKSHIFTS, UNLESS THERE EXIST NEARBY OTHER SHELTER FACILITIES FOR THEIR USE.

FINALLY, THE REPORT CLAIMS TO HAVE FOUND LITTLE EVIDENCE OF EFFECTIVE SOVIET MEASURES TO PROTECT THE ECONOMY, ALTHOUGH THE SURVEY IS FAR FROM COMPLETE. YET, THERE ARE NUMEROUS REPORTS FROM SOVIET EMIGRES DESCRIBING PARTIAL OR FULLY UNDERGROUND FACTORIES, STORAGE FACILITIES, POWER AND PUMPING STATIONS, FUEL AND WATER RESERVOIRS, AND SO ON IN ALL PARTS OF THE USSR. ACCORDING TO OFFICIAL SOVIET STATEMENTS, OVER 60 PERCENT OF NEW PLANTS HAVE BEEN LOCATED SINCE THE MID-1960'S IN SMALL TOWNS AND NEW ECONOMIC REGIONS, ESPECIALLY IN SIBERIA, WHILE MANY OLDER PLANTS HAVE DEVELOPED SATELLITE FACILITIES SCATTERED IN SMALL TOWNS. ONE RESULT OF THIS IS TO CREATE NEW AIM POINTS FOR U.S. STRIKES WHILE THE SOVIETS EXPECT TO SHARPLY REDUCE THE NUMBER OF U.S. WARHEADS BY A FIRST COUNTERFORCE STRIKE, WHOSE PROSPECTS OF SUCCESS AS A RESULT OF IMPROVEMENTS IN SOVIET MISSILE ACCURACY, ACCORDING TO SECRETARY OF DEFENSE, HAROLD BROWN, ARE EXPECTED TO BE GREATLY ENHANCED IN THE NEXT FEW YEARS. FURTHERMORE, ACCORDING TO SOVIET STRATEGIC DOCTRINE, PRIORITY IN PROTECTION IS GIVEN NOT TO THE ECONOMY AS A WHOLE, BUT TO THAT ELEMENT WHICH IS BELIEVED TO BE ESSENTIAL TO SUSTAIN THE SOVIET WAR EFFORT AND INSURE SOVIET SUPERIORITY IN THE COURSE OF THE WAR AND AT ITS TERMINATION. FOR THE REST, THE SOVIETS APPEAR TO EXPECT THAT THEY WILL BE ABLE TO SUBSTITUTE SURVIVING INDUSTRIES IN EASTERN EUROPE AND THOSE CAPTURED IN WESTERN EUROPE FOR DESTROYED CAPABILITIES IN THE USSR.

FOR ALL OF ITS OBVIOUS SHORTCOMINGS, A CAREFUL READING OF THE CIA REPORT GIVES NO GROUND FOR OPTIMISM OR FOR DOWN PLAYING OF THE IMPLICATIONS OF SOVIET CIVIL DEFENSE FOR THE U.S.-SOVIET STRATEGIC BALANCE. THE REPORT NOTES THAT IN THE FORESEEABLE FUTURE THERE IS NO REASON TO EXPECT ANY CHANGES "IN THE SOVIET LEADERS' JUDGMENT THAT CIVIL DEFENSE CONTRIBUTES TO WAR-FIGHTING AND WAR-SURVIVAL CAPABILITIES." THE EXPECTED FURTHER IMPROVEMENTS IN SOVIET CIVIL DEFENSE MAY WELL REINFORCE THE SOVIET LEADERSHIPS' VIEWS THAT FOR ALL THE DAMAGE THE SOVIET UNION MAY SUFFER IN A NUCLEAR WAR IT WILL NOT ONLY SURVIVE BUT, AS THE REPORT STATES, "LEAVE THE USSR IN A STRONGER POSTWAR POSITION THAN ITS ADVERSARIES."

Appendix B

CIVIL DEFENSE IN SWEDEN*

Sweden has a population of 8 million people in an area about the size of California. A majority of the population resides in three regions (Figure B-1). Civil defense planning is based on the assumption that Sweden is not a main target for a strategic nuclear attack; therefore, the preparation is primarily for protection against conventional warfare. Protection against nuclear, biological, and chemical (NBC) warfare is also included when it can be achieved at little extra cost. For efficiency, the shelters are designed to perform a useful peacetime function, that is, as theaters, community centers, garages, shops, etc.

The civil defense effort consists of three programs: (1) population relocation, (2) shelters, and (3) rescue. An associated government activity is the stockpiling of critical supplies such as a year's supply of petroleum. Particular problems in the relocation program concerned transportation, accommodations, and protection against groundfighting where there are no shelters. This program received strong emphasis during the 1950s and 1960s.

In the shelter program, there are 5 million seats available; however, 13 million are needed. The number of seats exceeds the population because protection is needed both at work and at home. Additional shelters are most urgently needed in the central part of large cities and in single family houses. Shelters are compulsory in public buildings and the specifications call for protection from overpressures up to 12 psi and shielding from fragments. The government pays the cost of the shelter program and not many very large shelters have been constructed since the 1950s. Ventilation is by hand-driven fans analogous to the DCPA variety.

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*Based on remarks by Vilhelm Sjölin

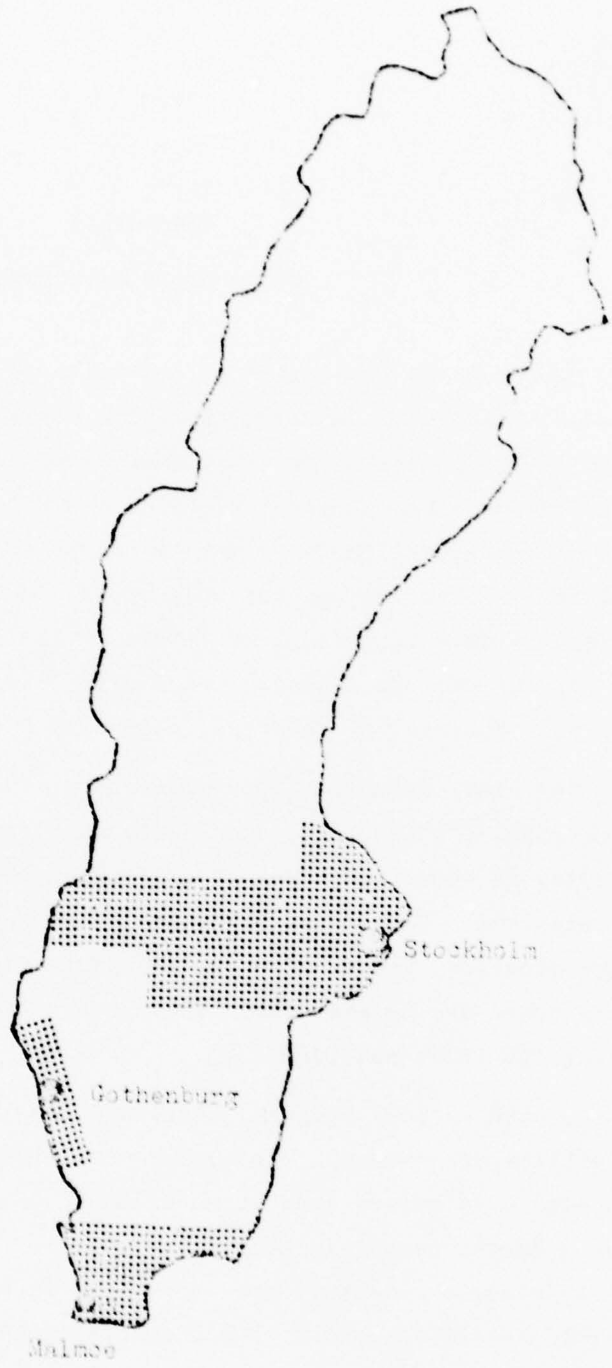

Figure B-1 WHERE PEOPLE LIVE IN SWEDEN

Only 15 per cent of the population live north of the heavely populated area stretching westwards from Stockholm. The three most populated areas deploy (from north to south) 2.5, 1.5 and 1.0 million inhabitants.

Rescue involves two groups: local and regional. Local forces consist of 280,000 men and women, many of them trained in peacetime for rescue work instead of the otherwise compulsory military service. In addition, there are 22 regional groups with equipment for dealing with larger problems.

Training proceeds on three levels: mass education, which includes 4 hours each of first aid and firefighting; general company training; and specialist training. Currently under consideration is an integration of the fire and civil defense organizations.

Research for civil defense purposes is performed by universities, private industries, and the National Defense Research Institute. Particular subjects of interest include fire, blast, human behavior, and NBC protection. Figure B-2 shows the emphasis in the fire research program; The rest of Appendix (B) describes the future research approach in more detail.

	Fire Location		
Phenomena	Buildings	Cities	Shelters
Ignition	●		
Fire spread	●	●	
Fire environment (heat, smoke, toxic products)			●
Fire suppression		●	

FIG. B-2 AREAS OF FIRE RESEARCH

FIRE RESEARCH MANAGEMENT IN SWEDEN

By Dr Vilhelm Sjölin, *The National Defense Research Institute*, Stockholm, Sweden, March 15, 1979

Scope of paper

The paper consists of two parts. The first one will briefly describe fire research in general in Sweden and then focus on the national fire research and development program. The second part of the paper will briefly discuss the process of selection of projects when matters of priority, funding, available resources, potential of progress etc will have to be considered.

PART ONE

Early fire research

Up to the late fifties, very litte fire research was conducted in Sweden. Once in a while, a project was carried out, but few projects involving in-depth studies were initiated. At this time only one research body, the National Institute for Materials Testing, was active in the field. Its projects, however, were entirely related to the fire behaviour of structural elements and the work was intended to produce fire test methods. Hardly any other kind of fire research was conducted in Sweden until around 1955.

An increased interest

The late fifties and the early sixties saw an improvement. Extensive projects came under way, particularly concerning the post-flashover phase of the fire and its impact on the structural loadbearing elements of a building.

Instrumental in sponsoring these undertakings was the National Building Research Council. The most extensive work was carried out at the Royal Institute of Technology in cooperation with the National Institute for Materials Testing. Gradually, more attention was paid to the fire itself rather than its influence on the building. The intention was to build up more knowledge as a background for understanding fires. Still, the efforts countrywide were scattered and no long term goals and fundings had been established. As responsibility for fire protection and control was split between a number of organizations, there was no central body capable of making a long term policy for fire research.

A council for fire research

In the late sixties, the first action was taken in order to establish a national council or board responsible for coordinated long term fire research. The Swedish Civil Defense Administration conducted a survey in cooperation with the National Defense Research Institute. The survey pinpointed the needs for fire research and proposed a joint venture in order to formulate and execute a national fire research and development program. As a modest beginning, attempts were made to establish a National Fire Research Council. These efforts failed, the lack of proper funding being the major obstacle.

In spite of this failure, successful fire research projects were carried out in Sweden. The Lund Institute of Technology was heavily involved in research on various aspects of fire growth and fire impact on structures. Mathematical methods to design structural fire protection were developed and accepted in the Swedish building code. During this time professor Ove Petterson and his associates established an international reputation primarely for their methods to calculate the time-temperature conditions during a fire. Other research groups made important contributions.

More and more, interest turned from the flame phase of a fire to the preflashover period. In this field, the Fire Research Group of the National Defense Research Institute conducted extensive work and also sponsored projects outside the Institute.

A National Fire R & D Program

Another attempt to establish a national program was made in 1976. The background was alarming. During a period of ten years, the national fire losses went up by some 100 per cent in fixed prices. A number of large fires occured with a fire loss in excess of 20 M $ per fire. Some exceptional fires took 20, 15 and 8 lives respectively, a so far unknown situation in Sweden. To add, the Swedish fire fighters complained about an increasing number of more intensive and unpredictable fires.

The Swedish government took quick action. A new training system for fire officers was prepared, a survey of life hazards due to fire was carried out in order to improve building codes and consumer acts and new efforts were made in order to establish a national fire research program. The National Board for Technical Development was ordered to survey the present fire research situation, estimate the needs for research and propose a national program. The task was handed over to the National Defense Research Institute. After extensive work over a period of 18 months, a proposal was presented and adopted.

The basic administrative concepts of the program is a joint funding between the government and private enterprises. On a 50-50 basis, funding has been provided for a program to be executed over a period of three years. A board of directors will be appointed with responsibility for the program. A small research administration group will be set up as a working tool for the board of directors. In order to avoid creating new agencies, the group will be housed by the Swedish Fire Protection Association. It will, however, take directives only from the program's board of directors.

Content of program

The new national fire research and development program consists of 26 projects under six headings. These headings indicate the nature or application of the projects. Ignition, growth of fire and fire environment represent the largest number of projects as well as some of the most extensive single projects. Fire effects on human beings cover projects on physiological, psychological and social impact of fires. Fire effects on materials, equipment and structures represent the traditional kind of fire research. These projects deal primarily with test methods and fire ratings. Fire fighting and safety engineering represents efforts in the field of detection, suppression and personnel protective equipment. System analysis evaluation includes projects concerning protective or operational systems on different levels of projects where aspects from various headings must be dealt with.

Finally, the last heading, basic and general support of fire research, represents administrative and evaluation functions, fire statistics, on-the-site investigations of fires and information projects. The important question where a specific project should be executed is still open. International cooperation will be considered.

PART TWO

Priorities

The process of selection of fire research projects are very complicated. In one way or the other, the first steps are normally based on some kind of problems or needs. These are normally described by the users, i e fire department staffs, safety engineers, building officials and code writers, with little knowledge of research. Quite often, the research needs or the problems are very unspecific. They have to be structured and evaluated before the transition in to a research project can begin. Unfortunately, priorities cannot be based on expressed needs only, however specific and urgent these needs may be. First, there are no easily available tools to rank problems or needs. Second, the ranking process will necessarily involve decisions that have to be taken on a very high level in our society. The ultimate long term goals must sometimes be set by the central government and might have to be based on parliament acts. These high level decisions are normally taken as part of a package involving also other kinds of safety aspects than fire. A good example of this kind is a consumer protection act.

Selection from the researcher's point of view

If we assume, that a ranking of needs and problems have been carried out, the next step could be to scrutinize the problems from executing point of view. A number of questions have to be answered.Can these problems be solved by a research project? Can they be solved by available scientific methods and resources? Will other problems have to be solved first? What is the time factor? It is obviously quite necessary to put these questions. If new scientific methods have to be developed and new resources established, the solution of the problem will not be available for many years. This does, however, not mean that this kind of projects should not be undertaken. It only means that these factors must be recognized in the selection process.

One way to meet these selection aspects, will be to develop a long term program. In order to do so, the funding aspect is of overwhelming importance. Only if the program can be funded for a substantial period of years, new resources in manpower, equipment and fire research management experience can be developed. Unfortunately, this long term funding is normally very difficult to obtain.

Contradictory measures

Very complex interactions might arise from purely technical or scientific conditions. These questions are quite often related to difficulties to estimate the benefit of one kind of fire protection measures when the very same measure creates a fire protection set-back from another point of view. Obviously, more chlorine in PVC reduces the ignition hazard. It will, however, create more hydrochlorine, when material decomposes due to a fire in the neighbourhood.

It will be considered up to the researchers and code writers to deal with these kind of problems. Quite often, however, contradictory interaction appears between properties of fire protection and other kinds of legitime properties. In these cases, other interests will have to take part in the selection process. No formal tools or organizations have been developed for this purpose within the selection process.

Outcome of project

Another important aspect is the potential for a successful outcome of the project. Obviously, the potential varies quite a lot between projects. The nature of estimation is different when a project deals with mathematical modelling of smoke movement compared with a project concerning development of a particular sprinkler head.

The extension of the potential of research success is the application of the results. This is even more difficult to predict.Hardware-oriented research projects are easy to apply. Projects involving complex systems and organization on high levels are quite difficult to introduce in to every day application. If legislative actions are necessary, the use of the results from the project may be many years delayed.

CONTENT OF THE SWEDISH NATIONAL FIRE R&D PROGRAM • PROJECTS

Ignition, growth of fire and fire environment

Ignition and explosion hazards within industry
Generation of smoke and toxic gases
Future fire hazards in housing and occupational environments
Spread of fire gases and smoke in multi-apartment buildings
Prediction of content of fire gases by computer programs
Origin and spread of explosive or toxic gas clouds within industry and transportation

Fire effects on human beings

Human behaviour at fires

Fire effects on materials, equipment and structures

Fire properties of fibre-reinforced plastics
Structural fire safety regulations in Sweden and other countries
Fire properties of linings
Accuracy of fire tests for building materials
Fire effects on light-weight structures
Fire safety requirements on upholstered furniture

Fire fighting and safety engineering

Use of aircrafts and helicopters for surveys of large fires
Technical requirements on oil-booms
Survey and proposal for R&D for fire departments
Cost-benefit analysis of fire suppression systems within industry
Gas and smoke ventilation with blowers

System analysis evaluation

Fire hazard identification, estimation and management
Reliability evaluation as a tool for hazard estimation in industry
Integrated systems for fire control in industrial plants
Impact on company and society from very large fires and cost/benefit analysis of protective measures

Basic and general support of fire research

Fire statistics
Fire investigations
Research program for industrial fire safety
Information activities

Appendix C

MODELING STRUCTURAL RESPONSES TO AIR BLAST LOADING

By

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Appendix C

MODELING STRUCTURAL RESPONSES TO AIR BLAST LOADING

In an earlier, preliminary assessment of blast and blast effects on fire, our attempts to develop techniques of experimentally modeling the phenomena culminated in delineation of the problem into two separate parts: Problem 1, the blast/structure interaction and Problem 2, blast/(collapsed) structure/fire interaction. The results of Problem 1 are expected to provide input conditions for Problem 2.

The pertinent literature contains some information relevant to Problem 1 and practically no information on Problem 2. Notable contribution to Problem 1 has been made by Wiehle and Bockholt[1] under the sponsorship of DCPA to develop an all-effects shelter survey system that evaluates the response of existing structures when subjected to air-blast loading.

Development of an experimental modeling technique requires formulation of the problem with the essential mechanistic details to arrive at the nondimensional variables that are ratios of the quantities exerting control over the behavior of the system and that therefore must be kept invariant between the model and prototype. Since the study objectives of Wiehle and Bockholt do not directly invoke deduction of these modeling laws, we have undertaken the analyses that follow.

Our current goal is to develop scaling laws relating a small-scale modeling experiment with a life-size prototype system that facilitates study of the blast structure interaction phenomenon. Development of scaling laws always entails minimization of variables in the problem by dimensional analysis and establishment of functional forms of the solutions. Specifically, the questions asked include: What is the time history of net pressure across the windowed wall of a chamber following the incidence

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of a blast wave? How long does it take to fill the room and hence to nullify the net loading on the wall? What sort of a flow pattern can be expected in the chamber before collapse? How does the threshold overpressure causing collapse depend on the room, window, and wall properties? For higher overpressures, how do the time, velocity, and acceleration of collapse depend on the properties of the system? These and other related questions are to be answered with a set of consistent nondimensional variables enabling scalable general predictions.

1. The Room Filling Process

Following Melichar's[2] work and Shapiro's[3] text on compressible flow, consideration of the mass and energy conservation for "steady" isentropic flow through a sharp-edged window orifice of area A in the wall (of area A_w, density ρ_w and thickness T_w) of a chamber of volume V_c, the chamber pressure P_c variation with time t is given by:

$$\frac{dP_c}{dt} = \frac{A}{V_c} f \quad , \tag{C-1}$$

where f is a function dominantly of the pressure difference across the wall $(P_e - P_c)$ and weakly (but highly nonlinearly) of γ, R, $T_{initial}$, and peak overpressure. Experience indicates[4] that f may be approximated (for air at about 25°C with overpressures not exceeding 150 psi) by

$$f = \Delta \, (P_e - P_c)^{1/2} \quad .$$

(Δ is approximately equal to 6700-ft psi$^{1/2}$ sec^{-1}.) Substituting this approximation in Eq. (C-1) and approximating the blast pressure decay by

$$(P_e - P_o) \approx (P_{so} - P_o)\,(1 - t/t_+) \quad ,$$

where $(P_{so} - P_o)$ is the peak overpressure and t_+ is the time of positive pressure phase duration, the problem at hand is:

$$\frac{d\pi}{d\tau} = -\left[\frac{1}{\tau_+} + 2\pi^{1/2}\right] \quad . \qquad \text{(C-2)}$$

$$\pi(0) = 1 \quad ,$$

where the scaled variables are defined as:

$$\pi \equiv \frac{P_e - P_c}{P_{so} - P_o} \quad \text{and} \quad \tau \equiv \frac{t}{\frac{2V_c}{A\Delta}\,(P_{so} - P_o)^{1/2}}$$

The solution of Eq. (C-2) is straightforward. It may be simplified, by noting from experience that $1/\tau_+$ is negligible, to

$$\pi \approx (1 - \tau)^2 \quad . \qquad \text{(C-3)}$$

The most important implications of Eq. (C-3) are two-fold: (1) the load on the wall due to the blast wave varies quadratically with time, and (2) the time to equilibrate the external and chamber pressures (i.e., to fill the chamber) is given by:

$$\tau_f \approx 1 \quad . \qquad \text{(C-4)}$$

This result is in concurrence with a multitude of experimental measurements, empirical rules, and computer calculations available in literature. In physical terms, Eq. (C-4) indicates that the time of filling t_f is

$$t_f \approx \frac{2V_c}{A\Delta} (P_{so} - P_o)^{1/2} \quad .$$

Consideration of the flow as incompressible also yields the same result as above, provided that the definition of Δ is altered in a minor fashion by a numerical coefficient.

2. Flow in the Room

As the flow emerges into the room through the window at a velocity dependent on the time-variant pressure differential, a well-defined jet may or may not be formed according to whether the ratio of room depth to the length of the jet's potential core is greater or less than unity. From considerations of the mixing flow and the jet diffusion constants available in Schlicting's[5] book on boundary layers, a jet is ensured if the room depth D is greater than $6.25A^{1/2}$. In buildings like some older factories and assembly plants and some modern residential structures, the windows are usually so large that a jet is not fully developed, and the shock traverses clear across the room to reflect off the internal wall. The blast effects on the internal wall consequently become of primary interest. In those architectural styles where the windows are relatively small, a well-defined jet and consequent recirculation flow are formed; the blast effects on interior walls are of secondary interest. The drag effects and resultant translational displacement of the room contents are, of course, drastically different in the two limiting cases discussed above.

We will not deal with the jet formation modeling in detail here because it is composed of an entirely separate, larger problem of fluid dynamics involving submerged bodies. Suffice it to say that the reference velocity is

$$C_d \left[\frac{2g}{\rho} (P_{so} - P_o)^{1/2} \right] \quad .$$

reference pressure differential is $(P_{so} - P_o)$, reference time is

$$2V_c\left(P_{so} - P_o\right)^{1/2}/A\Delta \quad ,$$

and reference length is $A^{1/2}$.

3. Collapse Dynamics

The response of a windowed wall on which the blast loading is exerted is described by the equation of motion, which expresses the balance between the applied (time variant) load, inertia of deflection, and elastic strain.

$$(A_w - A)(P_e - P_c) = (A_w - A)\,\frac{T_w \rho_w}{g}\,\ddot{y} + A_w q(y) \qquad \text{(C-5)}$$

The distributed loading, deflection, and resistance functions are, in real situations, very complicated functions of the wall material, support conditions, window geometry, and other properties. With these real functions Eq. (C-5) can only be solved numerically as done by Wiehle and Bockholt.[1] However, for illustrative purposes and for drawing the form of similarity rules, we assume below: (1) the loading and deflection distributions are independent of window geometry and location, and (2) the resistance function $q(y) = ay$ where a is the ratio of ultimate resistance to the corresponding ultimate deflection. The initial conditions for Eq. (C-5) are that the wall is at rest $\dot{y} = 0$ and flat $y = 0$ at time $t = 0$. Defining the scaled parameters,

$$\beta^2 = a\left(\frac{2V_c}{A\Delta}\right)^2 \frac{g}{\rho_w T_w}\,(P_{so} - P_o) \quad \text{and} \quad \Omega = \left(\frac{2V_c}{A\Delta}\right)^2 \frac{g}{\rho_w T_w^2}\,(P_{so} - P_o)^2 \qquad \text{(C-6)}$$

and nondimensional deflection and time

$$\eta = \frac{y}{T_w} \qquad \tau = \frac{t}{\dfrac{2V_c}{A\Delta}\,(P_{so} - P_o)^{1/2}}$$

the problem at hand reduces with Eq. (C-3), to

$$\left.\begin{aligned} &\ddot{\eta} + \beta^2\eta = \Omega(1-\tau)^2 \\ &\eta(0) = 0 \quad \dot{\eta}(0) = 0 \end{aligned}\right\} \qquad \text{(C-7)}$$

The solution involves a quadratic function of time upon which a harmonic oscillator is imposed.

$$\frac{\beta^2\eta}{\Omega} = \frac{(\beta^4 + 4)^{1/2}}{\beta^2} \text{Cos} \; (\beta\tau + C_2) + (1-\tau)^2 - \frac{2}{\beta^2} \qquad \text{(C-8)}$$

where the frequency constant $C_2 = \text{ArcCos}\left[\pm 2/(\beta^4 + 4)^{1/2}\right]$.

Differentiating Eq. (C-8) and eliminating τ, the magnitudes of deflection, velocity, and acceleration may be obtained. At collapse, set the criterion $\eta = 1$ to obtain time of collapse and velocity at collapse as functions of Ω and β.

Threshold conditions (*) of collapse are given by collapse with zero velocity so that $\Omega^* = \Omega^*(\beta)$ and $\tau^* = \tau^*(\beta)$. Noting from Eq. (C-6) that $\beta^2/\Omega^{\frac{1}{2}} \propto V_c/A$ and $\Omega/\beta^2 \propto (P_{so} - P_o)$, Figure C-1 shows the collapse threshold conditions thus predicted. For overpressures exceeding the threshold overpressure, the time of collapse will be shorter than τ^* and velocity at collapse will be larger than zero.

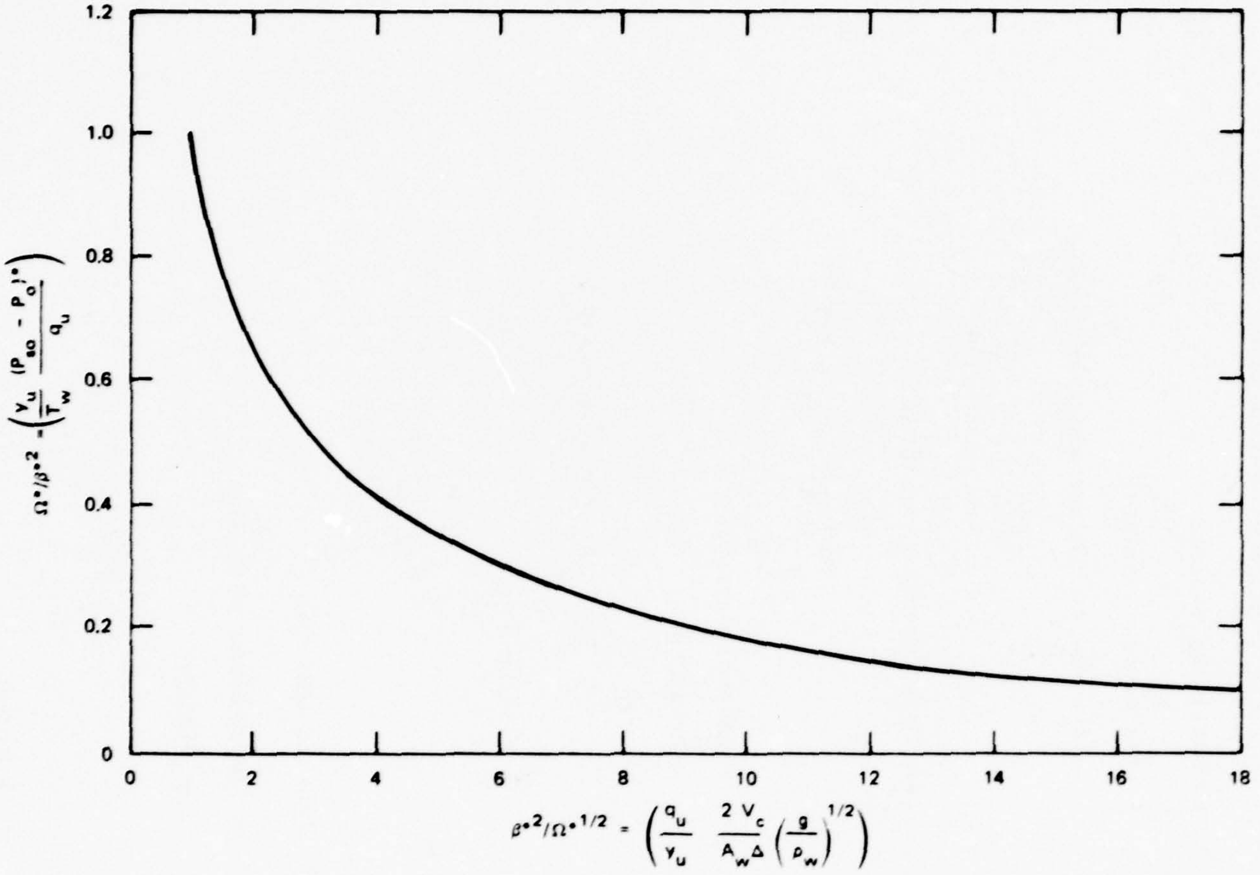

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FIGURE C-1 COLLAPSE OVERPRESSURE AS A FUNCTION OF CHAMBER PROPERTIES

4. Concluding Comments

The analyses described here successfully delineate the variables of the problem to arrive at the following scale variables:

(1) Room-filling process

- Independent variables
  - Elapsed time after shock incidence

$$\tau \equiv t \bigg/ \frac{2V_c}{A\Delta} (P_{so} - P_o)^{1/2}$$

  - Positive-phase duration

$$\tau_+ \equiv t_+ \bigg/ \frac{2V_c}{A\Delta} (P_{so} - P_o)^{1/2}$$

- Dependent variables
  - Pressure

$$\pi \equiv (P_e - P_c) \big/ (P_{so} - P_o)$$

  - Filling time

$$\tau_f \equiv t_f \bigg/ \frac{2V_c}{A\Delta} (P_{so} - P_o)^{1/2} .$$

(2) Flow in the room

- Independent variables
  - Distance

$$\xi \equiv \frac{64C'}{3} \frac{x}{w}$$

  - Radius

$$\Psi \equiv 2r/w$$

- Time

$$\tau \equiv t \Big/ \frac{2V_c}{A\Delta} (P_{so} - P_o)^{1/2}$$

- Dependent variables
  - Velocity

$$U \equiv u \Big/ C_d \left[\frac{2g}{\rho} \frac{\gamma}{\gamma - 1} (P_{so} - P_o) \right]^{1/2}$$

  - Entrainment

$$V \equiv v \Big/ C_d \left[\frac{2g}{\rho} \frac{\gamma}{\gamma - 1} (P_{so} - P_o) \right]^{1/2}$$

  - Potential core length

$$\xi_c \equiv \frac{64C'}{3} \frac{x_c}{w}$$

  - Potential core width

$$\psi_c \equiv 2r_c / w$$

  - Jet diameter

$$\psi_{max} \equiv 2\delta / w \quad .$$

(3) Collapse dynamics

- Independent variables
  - Time

$$\tau \equiv t \Big/ \frac{2V_c}{A\Delta} (P_{so} - P_o)^{1/2}$$

- Resistance-inertia ratio

$$\beta^2 \equiv a\left(\frac{2V_c}{A\Delta}\right)^2 \frac{g}{\rho_w T_w} (P_{so} - P_o)$$

- Total load, inertia ratio

$$\Omega \equiv \left(\frac{2V_c}{A\Delta}\right)^2 \frac{g}{\rho_w T_w^2} (P_{so} - P_o)^2 \quad .$$

- Dependent variables
  - Deflection

$$\eta \equiv \frac{y}{T_w}$$

  - Velocity

$$\dot{\eta} \equiv \frac{dy}{dt} \cdot \frac{2V_c}{A\Delta} (P_{so} - P_o)^{1/2} \cdot \frac{1}{T_w}$$

  - Acceleration

$$\ddot{\eta} \equiv \frac{d^2y}{dt^2} \left(\frac{2V_c}{A\Delta}\right)^2 (P_{so} - P_o) \cdot \frac{1}{T_w}$$

  - Collapse threshold values of

$$\Omega*, \ \beta*^2, \ \tau*, \ \ddot{\eta}*$$

  - Collapse τ, $\dot{\eta}$ and $\ddot{\eta}$.

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Appendix D

OUTLINE OF FIRE DEVELOPMENT MODELS AND THEIR STATUS

- Models
    - Field Equations
        - Torrance
            - Laminar, two-dimensional, axial symmetric, and rectangular
        - Battelle Northwest
            - Similar in intent, differed in detail
        - Notre Dame, UNDSAFE II
            - Two-dimensional, no radiation, algebraic viscosity
            - Two-dimensional, with two-flux radiation, algebraic viscosity
            - Three-dimensional, in process, differential viscosity
        - Baum Rehm
            - Two-dimensional, inviscid, acoustic wave suppressed
            - Vortex tracking, temporarily abandoned
            - Vortex tracking - potentially simple 3-dimensional
            - Vortex tracking - potentially simple 3-dimensional combustion
        - Spaulding - Pantankar
            - Proposed but not much used for two-dimensional transients
            - Spaulding contention - as finite element models (coupled phenomenia models) become more elaborate, they will become more complex than field equation models
            - Subscale modeling - viscosity an example - will be needed.
        - Coupled Phenomena
            - J. Rocket, 1968 state model with semiphysical rules for state transitions, considered whole building, highlighted geometric data needs.
        - Building pressurization
            - U.S. model derived from Canadian current version appears to have numerical problems

Japanese model considers two layers, technically most advanced

Russian model described as two layer

Berlin, N.F.P.A.

State transition - probability rules (data based) for transitions

Steady State

Parker

Balance of heat release and heat loss

Quintiere

Quasi-steady state, most complete current treatment of physics

Burning augmentation by radiation, flow limited or fuel limited, five control volumes (which interact), includes entrainment at door

Transient

IITRI

Numerical instability (in early versions) program controllable

Number of control volumes

Burning rates based on experimental fire burn

Well documented, looking at possibility of modeling furniture burns for more basic measurements being extended to include combustible walls by NBS.

Smith

Almost totally undocumented

Seems to be quite capable as used by Smith

NBS Jim Beyreis, guest scientist from U.L., trying to:

(a) Understand what the code is doing

(b) Test its ability to use other data sources--non-Smith apparatus test data

McArthur - Aircraft cabin orientation

Temperature of upper gas layer function of distance along cabin length

Detailed model of furnishings (and wall linings) fire growth

Harvard - Purports to be most ambitious in its treatment of fire physics

- Two-temperature gas model, no door mixing (entrainment)
- Burn rate based on experimental fire, computes changes in burning rate due to enclosure.
- Radiation treatment fairly detailed
- Highly modular structure
- Data structure still undergoing too many changes as subroutines are modified--suggests some poor structure
- Well documented but difficult to obtain machine readable "current version" (and "current" documentation)
- Tries to avoid adjustable parameters and succeeds fairly well.

C.I.T.

- Multiple - room - multivent
- Currently two rooms
- Three rooms being developed
- Vents can have variable reference ambient (effect of external wind)
- Fixed flow vents simulate HVAC
- Numerically somewhat tender; stable, but sometimes can't converge in required number of iterations, new version better.
- Claims to include empirical door mixing (based on experimental data) for hot gas flowing up from under a soffit, actually not in current version.
- Write-up very good - gives mixing expression for cold gas flowing in over a window sill, but this has not been implemented; note this mixing heats lower gas--three temperatures not two temperatures as Harvard and present C.I.T., and also vitiates the combustion air.

Where do we go from here?

- More phenomenological resolution
  - Wall/ceiling combustion
  - CO/CO_2 predictions
  - "Shooting" flows
  - Plume near field entrainment

- Door mixing--more physically based model
- Radiation blockage by upper gas

More spatial resolution

- Wall heating--Harvard lower walls absorb heat but don't change temperature
- Local "hot spot" for wall or corner fires
- Combustible wall ignition
- Variable ceiling layer temperature--with height
- Variable ceiling layer temperature--radial distance
- Combustion extending above thermal discontinuity
- Combustion extending under ceiling
- Effect on radiation field
- Effect on ceiling ignition
- Suppression (mission research/factory mutual/NBS scaling)

Comparison with data

- Many full and model scale tests
- Need to run model against these data (see J. Quintiere, PRC final report)

Find - sensitive parameters
- limits of reliability
- quality of predictions and reason for discrepancies
- data needs
    - Relation to test methods
    - Relation to what codes regulate

Graphics package

Appendix E

1979 DCPA Conference on Blast/Fire Research

SRI Fire Research Group

Fire Spread Models

1. Introduction: The 1978 Blast/Fire Conference recognized analytical methods for modeling fire behavior as a vital segment of the DCPA program. These methods should combine the description of the sustained ignition field and the description of the debris field into a vehicle for (1) predicting threats to facilities, machines, and people and (2) assessing the potential remedial benefits of countermeasures. Such modeling activities were a conspicuous part of the DCPA 5-City program during the 1960s and early 1970s but these efforts were terminated before all the problems were solved. Considering the current emphasis on a crisis relocation plan of Civil Defense, it appears desirable to examine the requirements for and the performance of fire spread models in this new role. In order to stimulate discussion in the predictive modeling workshop, we have contacted the fire spread community for information about the current status of models pertinent to the DCPA Program. Attachment (1) is a copy of the letter of inquiry. The responses to the letter are summarized here along with a little background information about the models developed for the 5-City Study.

2. Vital Facilities and Problem Boundaries: As indicated in Enclosure 1, under the crisis relocation plan, the emphasis on post attack recovery focuses attention on a small fraction of the structures in the average city; namely, part of the industrial area, some utilities and vital services. These vital components should be defined to facilitate discussions in both the modeling and countermeasures workshops. Enclosure (2) is a preliminary list that can serve as a starting point

for deciding which elements of our cities are essential for short term survival and long term recovery. Some thought should be applied to the relative survivability of these components to the blast/fire environment from a nuclear detonation. For example, a hospital loses its value when the building collapses, probably at an overpressure of 5 psi or less whereas a machine shop building may disappear completely at 10 psi with relatively little loss if heavy machinery inside survives. Such considerations of the blast/shock damage that can be tolerated will provide guidance to the blast/shock workshop in locating the debris field of interest with respect to ground zero. Once the interesting debris field is located, the initial fire distribution workshop will know where to concentrate their efforts in the spectrum of thermal radiation levels and overpressures. While formulating the list, it may also be desirable to consider the geographical location of the vital elements of our society. Some cities may have little to contribute to the post attack recovery. For example, Figure 1 shows the geographical location of machine tools in the United States. Sixty percent of the tools are located in the shaded area around the Great Lakes and in New England. Thoughts about fire threats should be compatible with the vital communities.

3. Fire Spread Models: Six responses were received to the letter of inquirey; however, they cannot all be intercompared because they do not all speak to the same problem Two of the replies, namely, Schmidt, and Gut are extensions of the IITRI fire spread model developed in conjunction with the Five-City Study; therefore, these approaches will be considered along with the other historical approaches, i.e., the URS and SSI models.

While it is trite to mention that "a practical reason for modeling is to reduce a problem to a level that can be handled both in terms of the effort and knowledge required to achieve a solution," this truism is amply illustrated by many of the approaches and assumptions involved in the fire spread models. We will start with the model that comes closest to reality in physical detail and retreat along the path of increasing simulation and synthesis.

Presumably, perfect adherence to reality would commence with an exact description of the fuel elements and their environment, i.e., each house, its contents, and environment would be described in detail sufficient to predict the detailed fire buildup and spread. Unfortunately, we cannot predict fire behavior precisely in such complex situations as burning houses; consequently, our limitation in knowledge forces an immediate abandonment of detailed perfection and we turn to average or a statistical distribution of fire behavior.

The SSI model came the closest to an exact description of the fuel elements. Survey teams measured the houses, their spacings, openings and contents in detail. Obviously, the labor involved in surveying one modest city exceeds the practical limit; e.g., the target would change before the survey was complete. Consequently, the SSI model is limited to a detailed sample section of the city.

Retreating to the next level of detail, the URS Model divides the city into areas of relatively uniform use factors, i.e., residential, industrial, commercial, public, and surveys a sampling of structures in each type of area to determine the potential for fire-spread along buildings in a typical block. The fire behavior throughout all areas of a particular type are based on the properties of the small sampling. The IITRI model follows a similar approach with some variations in the method of dividing and classifying the areas of the city into tracts. All tracts are square and equal in size. Each tract is assigned a type number based on the major occupancy, building sizes, spacings, types of construction, etc. Each type number corresponds to a different fire behavior but within a tract and in all tracts of the same type number, the fires exhibit the same behavior.

The SSI, URS, and IITRI models commence with a program to define the primary ignition field for a given nuclear detonation scenario, then follow the fire buildup and spread throughout the modeled city.

A large fraction of the input data and computation time is associated with the ignition field; therefore, Miercort developed a fast running version of the IITRI model that skips the ignition portion of the code. While much of the detailed building descriptions contribute to the calculations of the primary ignition distribution, the uncertainties regarding fire buildup and spread lead to stochastic procedures that forfeit much of the physical detail incorporated in the input data.

To provide a research tool for fire spread studies, Schmidt retreated from physical reality one step further and modified the Miercort model to make all the tracks equal and replaced the stochastic and deterministic features with probablistic spread coefficients. In the rectagular coordinate Monte Carlo version of the model, the computer plays a game of chance with either a single or a series of directionally dependent transition probabilities to arrive at a burn pattern.

Unfortunately, the Gut model is described in German and we have not had time to translate any subtleties that may be lurking behind the language barrier. Generally, the model follows our suppositions about the Miercort model. (We do not have a copy of the Miercort report; consequently, this comparison is second hand).

4. Limitations on the SSI, URS, and IITRI Fire Spread Models: Enclosure (3), the detachable summary from "Evaluation of Systems of Fire Development" points out several factors that limit the utility of these fire spread models. Probably the most severe restriction concerns blast damage to the structures. The experimental data, i.e., computations for fire spread by radiation and firebrands, are for the buildings as surveyed in the initial tract assignments. Consequently, the results do not apply to seriously damaged buildings, particularly when they are no longer standing. As illustrated in Figure (2) the IITRI model excludes the area of serious damage, contracturally set at the 6 psi overpressure line but probably a poor approximation for many structures in the 4 and 5 psi regions. Secondly, these models

make no provisions for mass fire phenomena i.e., the probabilities of fire spread by radiation and fire brands make no allowance for fire induced winds or a merger of individual flames into a single column.

5. Continuous Debris Field: In the regions of high blast overpressures, the structural debris field becomes fairly continuous and a third mechanism for fire spread becomes important, namely, continuous creep. Under these conditions, the fuel distribution becomes somewhat analogous to the wildland patterns encountered in forests. Consequently, several of the wildland fire spread models become of interest, e.g., Albini's "Spot Fire Distance from Burning Trees" and the MRC "Fireman Model" submitted by Pietrzak. One question that should be answered before extensive application of such models to the nuclear fire situation concerns the density of fire starts in the heavily damaged regions. In the absence of blast/shock extinguishment, the fire start density precludes the need for appreciable fire spread and the spread that occurs is filling in between the numerous starts. In contrast, the wildland fire spread models favor a fire front spread predominantly controlled by the wind and terrain.

6. The Facility Fire Vulnerability Rating: In the fire spread models examined so far, specific details are sacrificed to keep the labor effort at a practical level when dealing with a many structure target. In the crisis relocation plan only a small fraction e.g., less than 5% of the structures are directly concerned; therefore, a reverse procedure may be practical i.e., rate the fire vulnerability of the vital structures and ignore the rest of the buildings unless they obviously pose a threat to structures of interest. This rating approach was examined in the mid 1960s by T. Y. Lin and Associates in OCD and they developed a manual of Data Gathering Practice relative to the reusability of buildings after a war fire. Their procedure follows the general building code and insurance practices of evaluating the hazard due to fuel loading and the ameloriating influences of passive

fire protection measures. With critical resources such as machine tools, the rating process may even be simpler because these items are relatively insensitive to fire and should survive unless buried in hot coals for a long time. In metalworking shops, this juxtaposition of fuel, machines, and time is apt to occur only when combustible walls and roofs collapse and burn around the machines.

A four-step rating and analysis procedure should provide the estimate envisioned in Task 2 of Working Group 3:

(1) Classify buildings according to their fire hazard rating, which allows for both the fire potential and collapse potential of the structure.

(2) Determine the number of critical machines housed in structures of each fire hazard rating.

(3) Estimate the building area lost in each fire hazard category under a postulated nuclear attack. Compute the fraction of machine tools involved, assuming 100% loss in all collapsed combustible structures.

(4) Modify losses according to probability of sustained combustion, considering the potentials for primary and secondary ignition and fire spread from adjoining structures.

Table E-1 shows a matrix of structure categories suggested for Step 1. The five vertical headings correspond to the NFPA-type building classifications and the horizontal headings indicate various abilities to withstand the overpressure of the shockwave. Records from insurance companies and fire protection engineers, in conjunction with some surveys, would provide a distribution of machine shop floor areas in the 15 spots in the matrix. Average values of the overpressures to collapse the roofs would be obtained from Working Group 2 for the nine spots in the bottom three lines of the matrix. The two top lines can be neglected because these structures do not contain enough fuel to seriously damage the machines.

Machines in fire-resistive and noncombustible buildings may be destroyed by blast or flying missiles, but the fire should cause little problem. The fire hazard increases as the progression goes from heavy

Table E-1

FIRE HAZARD RATINGS ACCORDING TO STRUCTURAL CATEGORY
(Building Vulnerability Classification)

	Collapse Potential (overpressure in psi)		
NFPA Building Type	Load Bearing Walls	Weak Frame	Strong Frame
1 = Fire resistive	P_1	P_6	P_{11}
2 = Noncombustible	P_2	P_7	P_{12}
3 = Heavy timber	P_3	P_8	P_{13}
4 = Ordinary	P_4	P_9	P_{14}
5 = Wood frame	P_5	P_{10}	P_{15}

Fire Hazard Rating = Area (a)
Where Fires are Expected to Destroy Machines

Type	Load Bearing Walls	Weak Frame	Strong Frame
1	0	0	0
2	0	0	0
3	a_3	a_8	a_{13}
4	a_4	a_9	a_{14}
5	a_5	a_{10}	a_{15}

$a_i = \Pi R^2 K$, R_i = radius from ground zero where the overpressure from the nuclear burst equals the overpressure for structural collapse.

K = the probability of sustained combustion. In the simplest assumption, K = zero for building types 1 and 2 because there is no fuel and K = 1 for types 3, 4, and 5.

timber, which is difficult to ignite, to wood frame, which is the most combustible. Even in these combustible structures, the machine tools should survive as long as the roofs and walls burn most of the fuel in the standing position.

Step 3 involves estimating the fraction of collapsed combustible structures; therefore, some attack scenario is required to determine the areas that receive an overpressure in excess of the critical value for collapse. All degrees of sophistication can be introduced at this point, depending on the knowledge of enemy targeting plans. In the simplest case, assume N bombs of equal yield are detonated at the same altitude under identical atmospheric conditions over M cities of total area A containing Y machines equally dispersed throughout the cities in Z ft^2 of structures. If the structural collapse areas from the bombs do not overlap, the fraction of each of the nine vulnerable structures that collapse would be $\frac{Na_i}{A}$, where a_i is the overpressure area exceeding the critical value for collapse of structure classification i. Consequently, the total fraction of machines lost in this scenario becomes

$$f = \sum_{i=o}^{n} \frac{S_1 a_1 N}{A} + \frac{S_2 a_2 N}{A} + \dots \frac{S_n a_n N}{A}$$

where $S_i = \frac{\text{floor space of this particular type of structure}}{\text{total floor space for all 15 categories}}$

$$= \frac{Zn}{Z_1 + Z_2 + Z_3 \cdots Z_{15}} .$$

This scenario is severe because it assumes that all the collapsed structures burn and damage tools. The next degree of refinement, Step 4, allows for the vulnerability to sustained ignition from either primary or secondary causes. These sustained fire factors β enter the expression along with S, i.e., $\frac{S_i \beta_i a_i N}{A}$.

Obviously, if different sized bombs are employed along with variations in burst altitude, the summation must cover the individual bombed areas instead of the average, i.e., $a_i N$ is replaced by $a_{11} + a_{12} + a_{13} \cdots + a_{1n}$ where the second subscript refers to a specific bomb damaged area.

Incidentally, the specific nature of such rating procedures is particularly conducive to stimulating countermeasure concepts and to evaluating their effectiveness.

An alternative approach to rating according to a list of rules is to evaluate the fire behavior in the structure with an analytical model such as Berlin's "Building Fire Safety Model." Presumably, the model approach provides more flexibility if it can evaluate situations for which there are no rules. Conversely, the fire development and spread models can be used to establish rules for the traditional inspection evaluations. Since Berlin will be discussing the building fire safety model later in the Conference, I will leave further comments on this approach to that session.

7. Questions to be Answered and Decisions to be Made.

- Which approach, firespread scenario or fire vulnerability rating,is the most effective for a crisis relocation plan situation?
- How important are ignition field details in both approaches? e.g., Figure 2 suggests that about the same fraction of buildings burn per track irrespective of the density of ignitions.
- How should severe blast damage be handled if the fire spread scenario approach is pursued?
- How important are the so-called mass fire effects to both approaches? For example, how many layers of the surrounding buildings pose a threat to a vital facility and when can they be neglected?
- What are the problem boundaries in terms of vital structures and blast damage levels?
- Is it practical to use the existing fire spread models to predict the losses to be anticipated under a general nuclear attack or does the labor involved overwhelm the time, manpower, and support available?
- Where can and should models be employed?

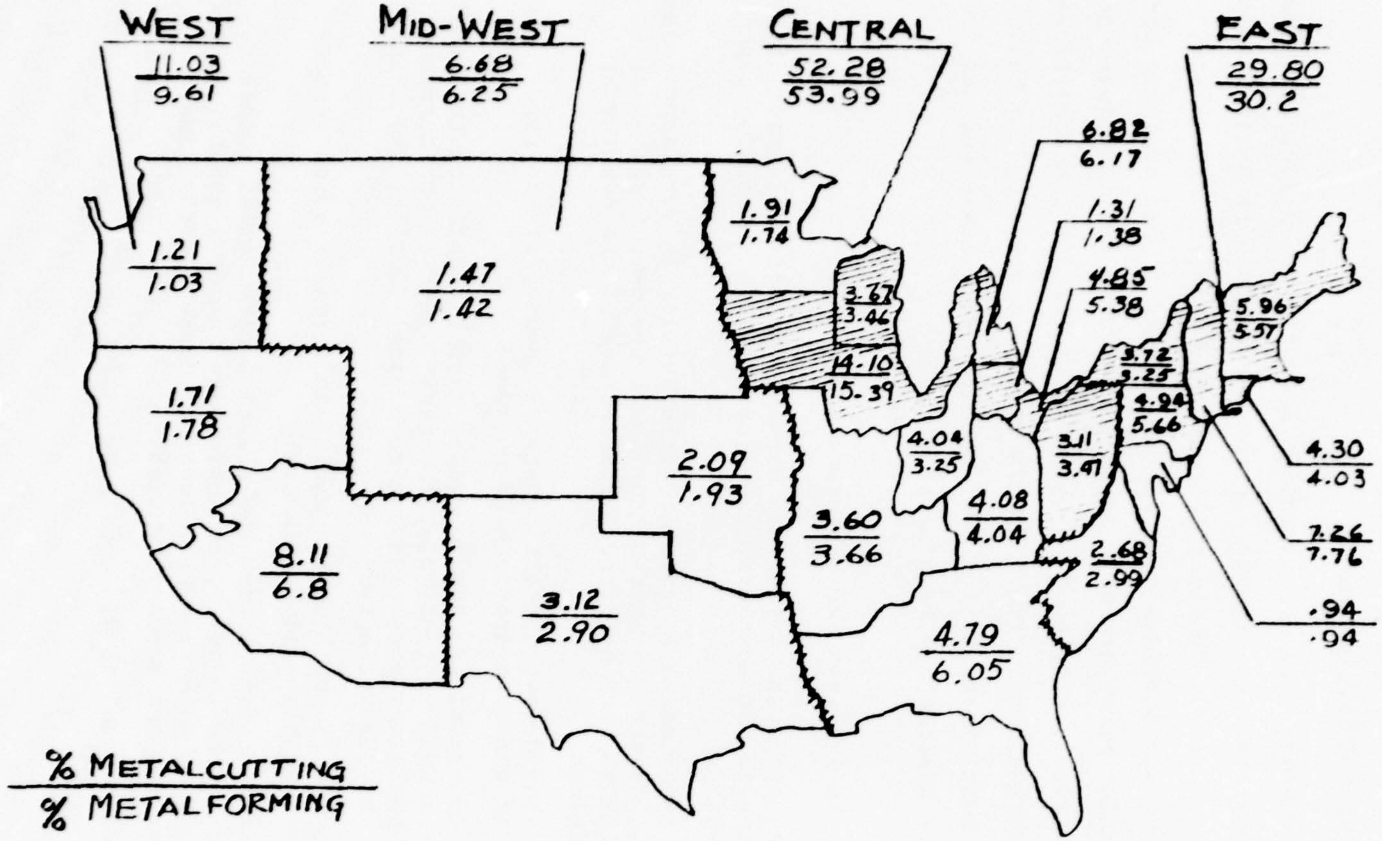
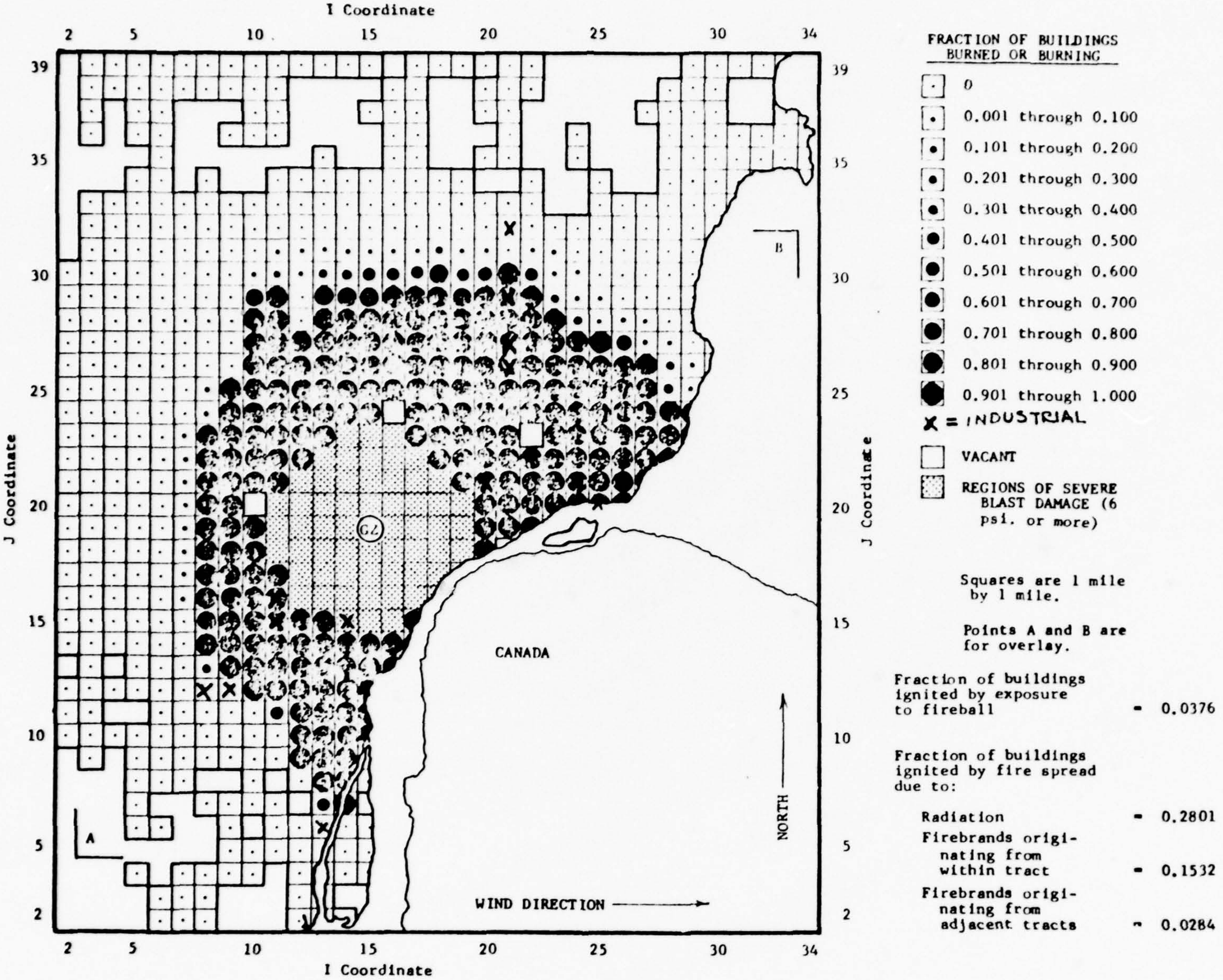


FIG. 1

GEOGRAPHIC LOCATION OF MACHINES

7914



Squares are 1 mile by 1 mile.

Points A and B are for overlay.

Fraction of buildings ignited by exposure to fireball = 0.0376

Fraction of buildings ignited by fire spread due to:

Radiation = 0.2801

Firebrands originating from within tract = 0.1532

Firebrands originating from adjacent tracts = 0.0284

Fig. 2 DAMAGE TO TRACTS OF DETROIT 28 HOURS FOLLOWING 5MT BURST ([illegible])

ENCLOSURE (1)

February 22, 1979

Dear

The 1978 Conference on Blast/Fire Interactions produced a set of requirements for predictive fire modeling and guidelines for structuring such models for DCPA use. A principal use of such models is to aid preparedness planning intended to maximize economic and societal recovery. Their purpose is to assess the additional damage and loss due to fire (i.e., over and above blast and other prompt weapon effects) and to evaluate the relative effectiveness of alternative countermeasures and mitigating actions. In the context of crisis relocation, however, emphasis is on resources and services that are essential to continued societal viability and postwar recovery, rather than population survival. I ask your help in providing DCPA with information to aid the making of decisions on how to proceed with model development for use in this context.

By way of review, several steps appear to be involved in arriving at suitable models, each involving a submodel:

- A blast-damage and debris-distribution submodel
- A fire-initiation submodel (predicts distribution of fires of both primary and secondary origin)
- A fire-spread submodel

Our focus here will be on the third step and approaches to fire spread modeling, but the other two must be kept in our peripheral vision since they provide the input target description for the third, while it, in turn, determines what detail the first two submodels will have to provide.

I have already noted that stress is to be given to fire vulnerability of critical resources. This includes the threats of fire to:

- Industrial plants and their hard-to-replace machine tools
- Personnel shelters for the segment of the population that has not relocated from the area prior to the attack (i.e.,

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in a successfully executed plan of crisis relocation, this would be mainly the key personnel who must remain to perform critical functions and to sustain essentiial operations, processes, and services).

- Such other critical resources as power plants, water supplies, communications, and transportation facilities.

Accordingly, whether or not most of the residences, commercial and office buildings, etc. burn is of concern only (1) if, as a neighboring structure, it directly threatens a critical structure while burning or (2) to whatever extent it may contribute to the development of a generally hostile fire environment. Thus, the model may justifiably neglect, perhaps, 90 percent of the buildings in a city, or treat them in broad-brush fashion only.

It is also important to recognize that the region of the urban target of main concern is within a roughly circular area including blast overpressures greater than about 1½ to 2 psi; that is, undamaged structures are of little concern to predictive modeling except in the presumably rare situation of a moving-front fire (e.g., a conflagration of the Tokyo-Yokohama sort). Therefore, in addition to treating fire spread by jumps between still-standing buildings, it is essential to include jumping spread between noncontiguous debris piles and creeping spread through more-or-less continuous fields of debris in which shells of the more blast-resistant buildings may still be left.

The character and detail of the output of any model that is acceptable for one application may be totally unacceptable or inappropriate for another. We perceive three levels:

(1) Minimum useful description--Extent of Burnout: a burn density map that provides an indication of whether or not a critical locale (e.g., specific resource, shelter, etc.) was at any time during the history of the fire directly threatened by fires in neighboring buildings. (Alternately, an assignment of the probability of destruction of a specific resource as a function of location, both in the city and relative to G.Z.)

(2) Better description--Time Phased States: a fire distribution map showing the number (or fraction) of critical structures in each of several states (e.g., no fire, burning, burned out), at different times following attack, from which the changing threat can be inferred. (Alternatively, an assignment of a probability-versus-time function that a specific resource is in a fire state, depending upon its location, both in the city and with respect to G.Z.)

(3) Best description--Dynamic Response and Threat: a (preferably nondiscrete) detailed description over time of the distribution and intensity of fire and associated threats, including interactions with the general fire environment and mitigating effects of active and passive countermeasures. This would be sufficiently detailed to permit determination of whether and when a specific resource is threatened by fire and, if so, its response to the threat in terms of percentage loss of function (or utility) over time. (Alternatively, its stochastic counterpart).

If you have (actually or conceptually) a fire-spread model that qualifies, (or are aware of one that might qualify) for DCPA's consideration, please describe it briefly and supply the following information:

1. Features of the model
   - Requirements for input data; detail required in the description of the fuel, the environment; basic parameters involved.
   - Basic assumptions employed; mechanisms treated, sensitivity to assumptions.
   - Mathematical formulation; sensitivity to empirical inputs.
   - Nature of the output.
2. Adaptability to DCPA applications
   - Which of the three levels of description outlined above (minimum useful, better, best) applies?
   - What appear to be advantages and disadvantages for these kinds of application?

This information will be required in time for the upcoming conference--March 18 through 22. Please respond if and as appropriate before March 9. Thanks for your attention to this.

Sincerely,

Stan Martin

Stanley B. Martin, Manager
Fire Research Department

Enclosure (2)

VITAL FACILITIES AND THEIR PRIORITY

(a) Life's Essentials (Short and Long Term)

- (1) Water Supply: Source, Purification Plant, Distribution System
- (2) Food Supply
  - (a) Source - Farm Equipment and Supplies
    - Seeds, fertilizers, chemicals, machinery
    - Animals, feeds, dairy
    - Fishing fleet
  - (b) Food Processing and Preserving
    - Canned food, cans, canneries
    - Frozen foods, freeze dried
    - Dried foods
    - Meat processers, packers
  - (c) Distribution
    - Trucks - roads, terminals
    - Trains roads, terminals
    - Boats, waterways, terminals
- (3) Shelter
  - (a) Energy to keep warm (avoid exposure)
  - (b) Sanitary system, sewer plant
  - (c) Hygiene supplies
  - (d) Garbage - trash removal
  - (e) Ultimately enclosures
- (4) Clothing
  - (a) Textiles plants
  - (b) Sewing machines
- (5) Law and Order, Protection of People, Possessions and Facilities
  - (a) Police, sheriff, highway patrol etc. assume martial law
  - (b) Fire departments
  - (c) Some public records

    (6) Medical Facilities e.g., Hospital, Drug Houses, Ambulance, Pharmacies

(b) Communication
    (1) Telephone
    (2) Radio
    (3) Mail

(c) People Transportation
    (1) Buses and Terminals and Repairs
    (2) Trains and Terminals and Repairs
    (3) Aircraft and Terminals and Repairs
    (4) Bicycles and Repairs
    (5) Autos and Repairs

(d) Energy for Economic Recover
    (1) Electrical Generating Stations and Distribution System
    (2) Natural Gas System and Distribution System
    (3) Petroleum Products, Refineries and Distribution System
    (4) Coal Products, Mines and Distribution System

(e) Industrial Plants - to Rebuild
    (1) SIC* #33 Primary Metals
    (2) SIC #34 Fabricated Metal Parts
    (3) SIC #35 Machinery Except Electric
    (4) SIC #36 Electrical Machinery
    (5) SIC #37 Transportation Equipment
    (6) SIC #38 Precision Instruments
    (7) SIC #39 Miscellaneous Manufacturing

(f) Material Inventory
    (1) Food Supplies (Short Term)
    (2) Metal Stock
    (3) Raw Materials
    (4) Chemical Supplies

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*SIC = Standard Industrial Classtion

ENCLOSURE (2) CON'T

BEST SHELTER
for
CRITICAL INDUSTRY WORKERS

FINAL REPORT • MAY 1975

Interagency Agreements No. AEC 40-31-64 and
DCPA 01-74-C-0227, Work Unit A 1637 B

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OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION • FOR THE U.S. ATOMIC ENERGY COMMISSION

2. DISCUSSION OF PROCEDURAL STEPS

a. Task A - Selection of Critical Industries

The selection of industries to be kept operating in an international crisis so serious as to trigger an evacuation can be a very difficult chore. The Soviet Civil Defense manual[2] gives the following instructions concerning operations during a crisis:

> "Stability of operation of national economic establishments during wartime is achieved by:
>
> 1. ensuring the reliability of power, gas, and water supplies; creating reserves of raw materials and fuel;
> 2. improving technological production processes, guaranteeing automatic shutdown when a plant, or facility is made inoperative;
> 3. constructing and equipping shelters in installations and plants for employees and workers, primarily according to the number of shifts, and preparing mine shafts and mines as shelters;
> 4. preparing bases in outer zones for the relocation of scientific-research, construction, and other establishments that are to be evacuated from large cities in order to continue operation in wartime;
> 5. creating protective structures for administrative units;
> 6. constantly preparing civil defense formations to carry out rescue and emergency restoration work with consideration of the special features of each plant;
> 7. performing organizational and engineering-technical work to prepare a plant for changeover to a basic work regimen, providing a series of defense measures for workers and employees, stockpiling material goods and special equipment, preparing to operate with

> emergency supplies of power and water, providing for fire prevention, and inaugurating other measures in accordance with the nature of production.
>
> "The principal measure to ensure the operational stability of establishments and plants in the event of enemy attack is the complete conversion of these sites to the 'basic operational system' for civil defense. The 'basic operational system' for an establishment or plant refers to the organization of plant operations under threat of attack (as ordered by civil defense signals) to ensure a reduction of losses, should the enemy employ weapons of mass destruction.
>
> "Converting these facilities to a 'basic operational system' expedites the reduction of plant activities to a range of attack (proclaimed by civil defense signals). The emergency measures are carried out including the prevention of fires, explosions, and other problems of a secondary nature (short circuits, destruction of the liquid fuel tanks, etc.). Thus, these plants which must continue certain of their operations, even after the air alert signal has been sounded, are converted to a reduced operating regimen. The workers and employees remaining in the plant take cover individually and make use of other protective measures. In case of radioactive, chemical, and biological contamination, workers and employees take the necessary protective measures. In addition to converting these units to a basic operating regime, technological measures must be taken to increase the operational stability of an enterprise and ensure the protection of workers and employees."

A more recent Russian Civil Defense publication[3] gives more clues:

> "An important place within the civil defense system is occupied by economic installations. The term installation in civil defense terminology is used to designate

> plants, factories, kolkhozes, sovkhozes, educational institutions, offices, and other establishments. Industrial and agricultural enterprises comprise the country's main economic potential. The principal productive force is employed at these enterprises -- the worker class and the kolkhoz peasantry. Therefore measures to provide protection against mass destruction weapons should be carried out on a priority basis at economic installations.
>
> "Civil defense headquarters are set up at all installations. Depending on the size of the installation, they are staffed either by full-time civil defense personnel or by employees who must also perform their regular duties."

The Russians use the phrase "national economic establishments" in all their civil defense literature, and the fact that civil defense headquarters are set up at all such installations leads us to the conclusion that only the industries considered important enough to be operated during an evacuation are included in the term "national economic establishment." The statement that these establishments "comprise the country's main economic potential" suggests that <u>most</u> industries would be kept in operation. Their military literature continually stresses the necessity for maintaining a strong, stable national economy as a base for military operation in the event of nuclear war.

DCPA has not yet established a priority list of critical industries for CRP, but an interim planning directive[4] says:

> "In general, activities recommended for consideration [as essential industries] include those essential for life-support of the population, for the national defense, and for maintenance of an austere level of economic activity (e.g., food, fuel, pharmaceuticals). Some of the more significant areas that should be considered include:
>
> Oil and gas production (under SIC* Code 13);

---

*SIC = Standard Industrial Classification.

ENCLOSURE (5)

Final Report
Detachable Summary

August 1970

EVALUATION OF SYSTEMS OF FIRE DEVELOPMENT

By: LEO W. WEISBECKER HONG LEE

Prepared for:

OFFICE OF CIVIL DEFENSE
OFFICE OF THE SECRETARY OF THE ARMY
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CONTRACT DAHC20-67-C-0116
OCD Work Unit 2619A

SRI Project EGU-6250

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For the purposes of assessing civil defense capabilities for nuclear attack situations and for evaluating and planning civil defense countermeasures, two distinct types of fire models are useful. They are (1) a model to provide information on the fire threat to the nation and (2) a model to provide information on the magnitude and characteristics of the fire threat at the local level. The first type of information is useful for damage assessment studies whereby not only the fire impact on national survival can be estimated but also through iterative studies a national policy can be established. The second type of information is useful for formulating and evaluating countermeasures against combined nuclear attack hazards including radiation exposure, as well as the fire threat at the local level. As such, it is important that this type of fire model estimate not only the extent of fire spread, but also the dynamics of fire spread, which include the rate, mechanics, and the associated hazards, as well as its behavior and response to countermeasures.

This study is limited to the evaluation of fire spread models developed by IITRI, URS, and SSI for the Office of Civil Defense. Criteria were developed against which the models were compared in terms of the vulnerability assessment and dynamic research information needs of civil defense. However, there is no adequate prototype experience or reference case calculation against which the models could be compared for realism. Accordingly their accuracy was evaluated in terms of a state of the art structuring of fire spread mechanisms according to submodels.

Fire spread model development was virtually limited to the radiation fire spread mechanisms, but both the IITRI and URS models included speculative treatments of fire spread by firebrands. The three radiation fire spread models all provided procedures for calculating fire spread given the inputs describing the urban configuration and the distribution of initial fires. The level of detail considered in the urban configuration model determines both the effort required in accumulating the data base and the computations. The modeling of urban configurations is an important and difficult task. It is important because the difference in fire spreads for each urban entity is due primarily to differences in the urban configuration. It is difficult because of the vast number of configuration combinations that exist. The IITRI procedure for modeling the inputs for urban configurations is the most complete, but the modeling treatment sacrificed too much accuracy for simplicity. The URS procedure gives a better account of urban configurations by considering the uniformities of street layouts and the uniformities of building orientations that are common among some tract types, but the procedure was not developed beyond that of a single-family residential row configuration tract. The SSI procedure used actual urban configuration measurements without modeling and, as such, it would be most realistic; however, because of the effort required in data accumulation and in computation, the procedure is prohibitively expensive except for small area sampling.

The modeling of the fire parameters is more limited in scope than the modeling of urban configuration. Nevertheless, ignition, burning, and radiating characteristics are associated with building type and occupancy characteristics, and a continuum of these characteristics exists. However, building and occupancy characteristics are more easily categorized into distinct groupings. All three models suffer from inadequate modeling of the fire parameters. The radiation fire spread properties are shown to be quite sensitive to the range of parameters used. Accordingly, the fire spread submodels were considered to be oversimplified, and the relationships among the submodels were not considered to be adequately developed.

The SSI model did not include any firebrand fire spread analysis. Although the URS report discussed firebrand fire spread and attempted to estimate its relative significance, only the IITRI model provided a firebrand fire spread model. However, the IITRI model is based upon empirical functions derived from inadequately documented data. As such, the parameters associated with the mechanics of firebrand fire spread were not modeled. The extrapolation of the limited data from two completely dissimilar events to firebrand fire spread in American cities without specification of the controlling effects and the differences among cities can only be considered to be speculative.

The development of a mass fire model was not included in any of the fire spread models, and yet this fire spread situation is particularly important in the formation of countermeasure concepts. None of the models included explicit modification of fire spread characteristics by fire fighting countermeasures. Nor was a fire spread model developed for blast-damaged configurations.

The SSI fire model for the assessment of national vulnerability was derived from their detailed fire spread model. This model simply equates total fire spread to the product of initial ignitions and a choice among a set of adjustment factors. The adjustment factors are a function of the initial ignitions for two types of tracts and for air and surface bursts. Since the validity of the detailed model has not been demonstrated, the validity of the derived model must remain questionable.

It is admitted that the criteria against which the models were compared were broader than the task specifications for which they were developed. Further, the criteria are broader than what is possible with the present state of the art understanding of fire spread phenomena. Nevertheless one of the objectives of this study was to recommend a model for further development for civil defense needs. Therefore, the models were tested against broad criteria to determine the full extent of their applicability. None of the models demonstrated a generality of approach and open-endedness of expression such that it could form a firm basis for further development. The URS approach seems to be in the right direction, but there would be no great advantage in building on it, since it did not get very far. Accordingly, it is recommended that a "reference" fire model formulation be constructed for evolutionary development. This model would represent the state of the art understanding of fire spread mechanisms and, as such, would utilize appropriate parts of the concepts and developments in all three models, and would indicate the research needs for upgrading the understanding of fire spread processes. By making appropriate simplifying assumptions, it would be possible to develop models of limited utility with predictable levels of detail, accuracy, confidence, and required operating effort.

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Appendix F

EXPERIMENTS ON BLAST EXTINCTION OF FIRES

1. Objectives

The objective is to establish complementary experimental and theoretical efforts leading to a basic predictive technology. An initial aim is to provide answers to fire/blast questions of immediate concern. The short-term objectives are to: (1) observe, under controlled and repeatable experimental conditions, the interactions of shock overpressures and blast-induced flows with combustion processes, (2) test postulated hypotheses (e.g., shearless displacement) for flame extinction, and (3) determine the critical pressure/flow conditions for extinction as they relate to fuel properties and perturbations due to geometry. The longer term objective is to establish the basic physics of the flame/shock interaction processes in order to formulate a generalized extrapolation and predictive model for interactions between air blast and fire.

2. Background

The radiation emitted by a thermonuclear explosion can cause ignition in a thermally thin combustible body with a high absorptivity and a good line of sight. Whether the blast wave that follows the radiative precursor enhances or retards flame spread is less certain. Appendix F describes (1) past experimental efforts to understand the blast/fire interactions and (2) the development of the DCPA Camp Parks shock tube that is the basis for this program.

3. Previous Experiments

Although it had been suspected earlier, the first evidence that low-peak-overpressures of an air blast could extinguish an incipient fire was set forth by Tramontine & Dahl (1953), who performed shock tube studies on kindling wood over a quarter-century ago. The most positive evidence to date remains work by Goodale (1970) on a full-scale furnished room in a shock tunnel. A 2.5 psi blast overpressure extinguished all flames in a test room, although up to 8 psi could not extinguish smoldering (rekindling occurred after time between minutes and an hour). There was a limited positive pressure phase and no independent control of the flow in these experiments; still, high-speed cinematography indicated that flame was swept off a burning surface by a "shearless displacement" upon arrival of the shocked air.

These experiments were conducted using different sized windows through which the blast wave passed; however, the findings were independent of window size. Since the flow field induced inside the enclosure is sensitive to window size, this independence of extinction threshold on window size suggests that the pressure discontinuity associated with the transmitted shock, rather than the character of the subsequent flow, is responsible for flame extinguishment. Indeed, motion pictures offer some evidence of this. In a few cases, the photographic images show flames displaced, without distortion, from the surface of the burning object. This displacement without boundary-layer shear may or may not be a practical extinguishment mechanism. Clearly, it has practical limitations; for example, this mechanism would fail to completely remove the flames over a fuel of greater length (along the direction of shock propagation) than the maximum possible shock-induced displacement. For a shock of given peak overpressure and yield, the duration may allow fairly large air and flame displacements, but in closed or constrained spaces, the shocks are reflected at barriers and often the flow stagnates after relatively short excursions. However, current understanding of transient boundary layer phenomena is insufficiently developed to permit establishing any scaling relationships.

Moreover, Goodale (1971 a,b) corrobated in another facility that a 9 psi overpressure still could not extinguish smoldering, even though a 2.5 psi overpressure could extinguish flame. It may be noted that some tested materials (a cushion filled with polyurethane foam and kapok) did not smolder at any pressure after flame blowout.

Wilton (1976) partially confirmed Goodale's work, since high flow-velocities (in a so-called long-duration-flow facility) did extinguish burning of *lightweight* objects at an *equivalent* of 2-4 psi overpressure. The fuel type, and its location in the room (i.e., its susceptibility to high-speed flow), influenced extinction. *Heavier* objects continued to smolder, and such objects rekindled to flame within a few minutes.

At the 500-ton high-explosive detonation of the MIXED COMPANY series in 1972, SRI attempted to validate results of the earlier URS shock tunnel simulations and to gain some preliminary scaling relationships for the extent of shearless displacement of flames. Horizontal trays of varying length (at grade) were filled with gravel saturated with kerosene. These trays were located at stations expected to experience peak overpressures ranging from 1 to 5 psi. The results of the experiment seemed to contradict the results of previous experiments. Not one of the fires was extinguished even at the 5 psi station, and shearless displacement consistently failed to occur. These seeming contradictions might be explained by the nonideal shock behavior near the ground in field tests of TNT explosions. Later, it was reported that the shock front was degraded near the ground. Because the fuel plots were flush with the ground surface, they could have experienced (1) a gradual pressure rise, rather than a shock discontinuity, and (2) a peak pressure less than the anticipated free-field value. On the other hand, the differences in effect could be the result of replacing solid fuels that require substantial heat to vaporize with a liquid fuel that has a significant vapor pressure and a low latent heat of vaporization.

Most recently, during the 120-ton detonation of a high explosive at MISERS BLUFF, Martin & Alger (1978) found that a 20-cal/cm^2 thermal load, followed 2 sec. later by a 7 psi shock, caused a vinyl-covered polyurethane foam cushion, situated well off the ground, to be subject to a sequence of fire initiation followed by extinction. Actually, the foam cushion was half covered with terrycloth, but both segments experienced quite similar fire behavior.

The duration, as well as the strength, of the overpressure enters into the question of whether the arrival of the blast wave can extinguish burning established by the radiant precursor; in fact, the blast/fire interaction appears to be a highly complicated interaction not related simply to overpressure alone.

Development of a Blast/Fire Test Facility

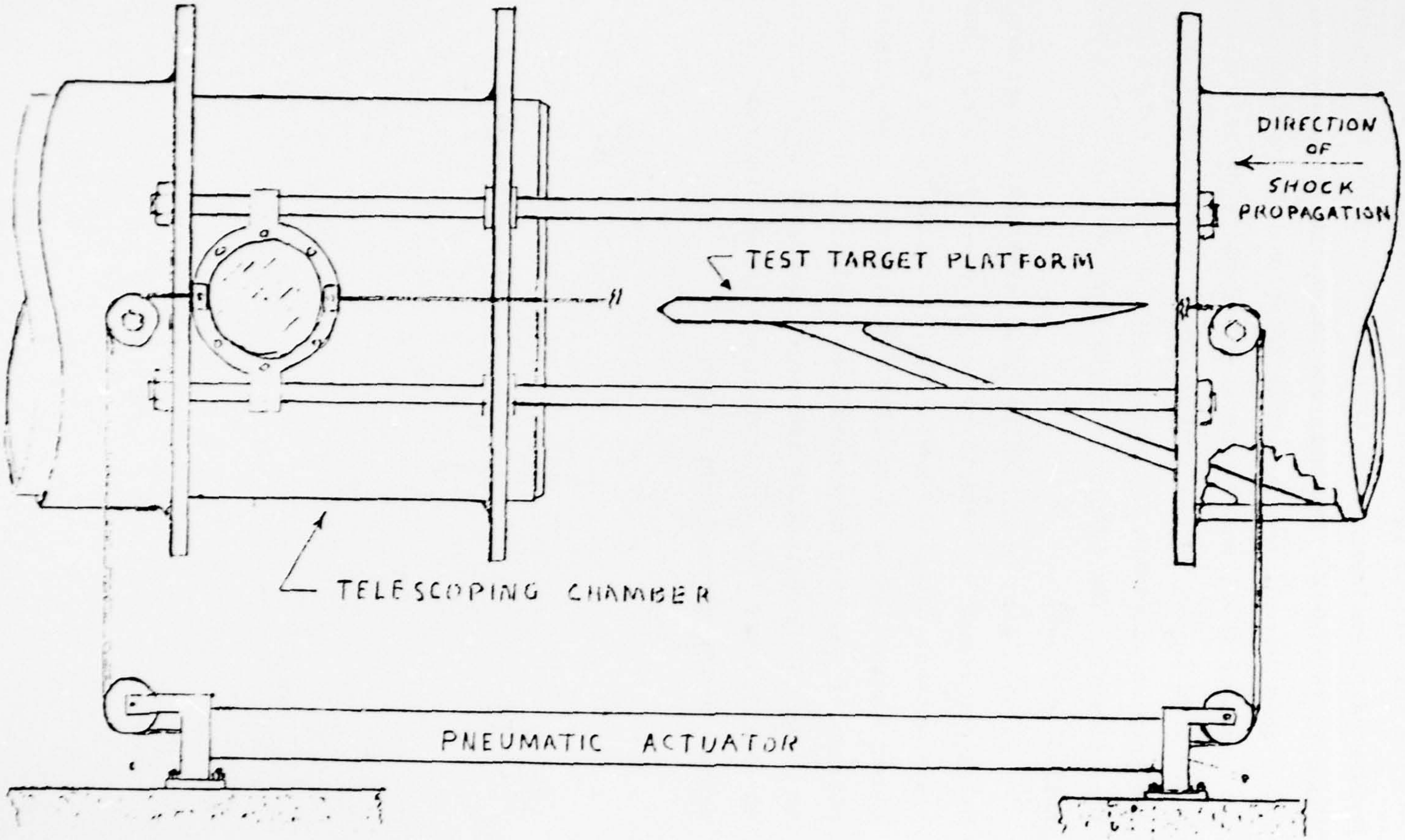
In 1972, DCPA funded the design and development of a shocktube facility specifically intended to provide a fundamental understanding of the physics of blast-fire interaction. The facility was not completed because of unexpected delays and insufficient funds. However, in early 1978, the Defense Nuclear Agency (DNA) provided funds to complete the facility. By December, 1978, the facility, which is located at USA Camp Parks in California, was operated successfully and is now available for experimental studies of blast-fire interactions.

The heart of the SRI-developed Blast-Fire Simulation Facility is a 30-inch diameter, air driven shocktube specifically designed for experiments in blast-fire interactions. This shocktube produces blast waves that simulate the characteristics of kiloton-to-megaton nuclear explosions in air. Peak overpressures and positive-phase durations, preselected and controlled by the operator, are subject to independent variation by relief of pressure from the plenum that drives the shocktube. The duration is controlled by a novel release mechanism external to the shocktube. The peak overpressure is governed by the initial plenum pressure. The facility is designed to provide peak overpressures up to 25 psi and positive-phase durations from fractions of a second to over 3 seconds. A system of orifices at both ends of the shocktube and a receiver tank at the exhaust end prevent the premature rarefaction of the test section by matching the outflow of the receiver tank (when it is fully pressurized) to the outflow of the plenum.

Although the facility is operable in its present form, several modifications need to be made before it is put into routine operation. Until now, the facility has been operated with the test section closed and without a fire target. The system was designed to have a telescoping test section that allows fires to become established, while burning in the open before being enclosed. The telescoping section is then closed just as the shock is initiated. For safe operation, this closure must occur automatically upon command from a remote location. We believe this closure can be performed with a remotely operated pneumatic drive. Firing of the shock would then follow automatically upon a signal from a microswitch interlock designed to eliminate any possibility of firing before positive test section closure. The interlock would also prevent firing if the test section failed to close.

It will also be necessary to provide test target supports that will be sturdy enough to hold large target ensembles steady under blast wave loads without interfering with the operation of the automatic test section closure mechanism or distorting the shockwave. Because the telescoping portion of the test section slides inside the adjacent downstream tube to allow for unrestricted movement, the test target support will have to be cantilevered from the nearest stationary upstream section as illustrated in the accompanying figure.

FIG. F-1 SHOCK TUBE TEST SECTION (ELEVATION VIEW)



4. Program of Research and Tasks

Idealized test targets (e.g., flat plates and spherical wicks of variable diameter) supplied with a variety of fuels representing a practical spectrum of flammability (e.g., gases, liquids and solids covering a wide range of B numbers*) will be ignited and subjected to shock waves of predetermined overpressure and positive-phase durations. Prior to shock initiation, the target will be allowed to burn in a fully ventilated, free-convection mode. Experimental conditions will be chosen to explore the dependence of response behavior on certain appropriate nondimensional parameters derived from theoretical considerations.

The course of this research is contingent on results that cannot be fully predicted in advance. We believe that the program will continue for several years and will need to be modified at several decision points as the work progresses. The activities of the first year, as outlined below, emphasize exploration and practical evaluation of the so-called mechanism of shearless displacement. A decision point is provided for the contingency that shearless displacement will be found to be unimportant.

Task 1--Use the blast/fire shock tube to explore the observable responses of ideal targets to blast waves of varying characteristics.

Task 2--Experimentally investigate the postulated phenomenon of shearless displacement and its dependence on fuel class and surface roughness. Observe transient boundary-layer development.

Task 3--Determine shearless displacement distances along flat fuel beds in the free-stream centerline of the blast/fire shocktube (i.e., idealized simulation of the MIXED COMPANY experiment). Seek a "scaling law" to relate displacement distance to blast wave characteristics; compare data from these experiments with the theoretical development being done in a separate Work Unit by TRW Systems.

Task 4--Using a rigid baffle erected on the fuel bed normal to the direction of shock propagation, explore effects of stagnated flow in front

---

*Ratio of gas-phase chemical exothermicity to endothermic requirement for gasification.

of a wall and other non-free-field perturbations behind the wall. Estimate threshold conditions for blowout when shearless displacement effects are not important.

Task 5--Review results of TRW theoretical study to identify key experimental tests of the validity of the theory; perform experiments that the remaining time and funds allow. Report the results of the year's work.

Tasks 1, 2, and 3 are planned to absorb most of the year's effort. However, if the results of Task 2 fail to confirm the practicality of the displacement, Task 3 will be inappropriate and the remainder of the year's effort will be given to Tasks 4 and 5.

5. Summary and Justification

At this point in time the *principal* uncertainty affecting the predictability of fire effects of nuclear attack is the nature of changes in the initial fire incidence/distribution caused by blast-wave interactions. As noted above, in regions of urban targets experiencing overpressures greater than about 2 1/2 psi; that is, the major part of the direct effects area, there are serious doubts about the validity of any estimates of the number and kinds of fires that persist following the passage of the blast wave. The lack of data and a theoretical understanding of the underlying physics precludes any worthwhile attempts to model fire behavior and evaluate the additional threat of fire to survival of the population and economic resources at risk. Early remedy of this deficiency through a program of careful experimental simulation and measurement, backed up by a coordinated effort to develop theories, is an urgent research requirement.

Appendix G

DEBRIS DISTRIBUTION

Introduction

As was emphasized by the May 1978 Conference on Blast/Fire Interactions, the major impediment to achievement of a fire behavior model pertinent to civil defense is the lack of understanding of the influence of blast waves on fire progress and development. A very wide range of interactions between the two inevitable concomitants of nuclear attack, namely blast and fire, must still be considered possible by theoreticians, and any model attempting to embrace all realistic alternatives would be essentially worthless.

Under DCPA sponsorship SRI International has already embarked upon an experimental program to study the blast/fire interaction itself. This work will contemplate abstract parameters, such as burning rates, blast overpressures and durations, fuel texture, and fuel density. Results of these idealizations will be invaluable to the final resolution of the civil defense problem.

But there is a need to approach the same problem from another viewpoint, namely, in what kind of environment will the blast/fire interaction take place? What kinds of fuels and nonfuels will be exposed to blast and fire? How will fuels and nonfuels be intermingled? If these aspects of the environment could be defined early enough, it might be possible to narrow the scope of the experimental blast/fire research.

It is the purpose of the research proposed here to begin the definition of the environment in which the blast/fire interaction occurs by calculating various possible distributions of wall debris imposed by the nature of the structure and of the blast wave. This work will differ from previous descriptions of debris distributions, which invariably made gross simplifying assumptions, by applying approximately but realistically known principles of wall collapse and aerodynamic translation of fragments. It is expected that this research will be the initial phase of a program which will later treat the combined debris from other structural elements than wall panels as well as debris from room contents.

Background

For more than 10 years SRI International has, under DCPA sponsorship, developed computational models of the response of building elements to airblast loading (Refs 1-5). Generally, these models contemplate an airblast incident head-on, side-on, or rear-on to a wall containing openings to an interior space, which gradually fills with air pressure (Ref 6). The erosion of the outside pressure and the buildup of the inside pressure are calculated, producing a history of net loading on wall or floor.

From the specified structural parameters, defining wall geometry materials and method of construction, a one-degree-of-freedom model of the structural element is constructed and the time response of the model to the load calculated by integration. If the wall reaches a point of collapse before the direction of its motion is reversed, the calculation terminates. "Collapse" is distinguished from "failure," which may mean merely complete cracking. A collapsed wall can no longer support any vertical load. These calculations have hitherto been made mainly in support of estimates of the shelter potential of specific buildings (Refs 7,8).

Sponsored by the Defense Nuclear Agency, SRI International is currently combining several of its computer programs for analysis of building elements story to make possible calculation of the simultaneous response of all walls on one story of a building (Ref 9). The purpose of the research for DNA is the development of damage functions relating structural damage to tactical weapon use. One of the advances made under DNA sponsorship has been the incorporation of procedures to handle oblique shock incidence on walls.

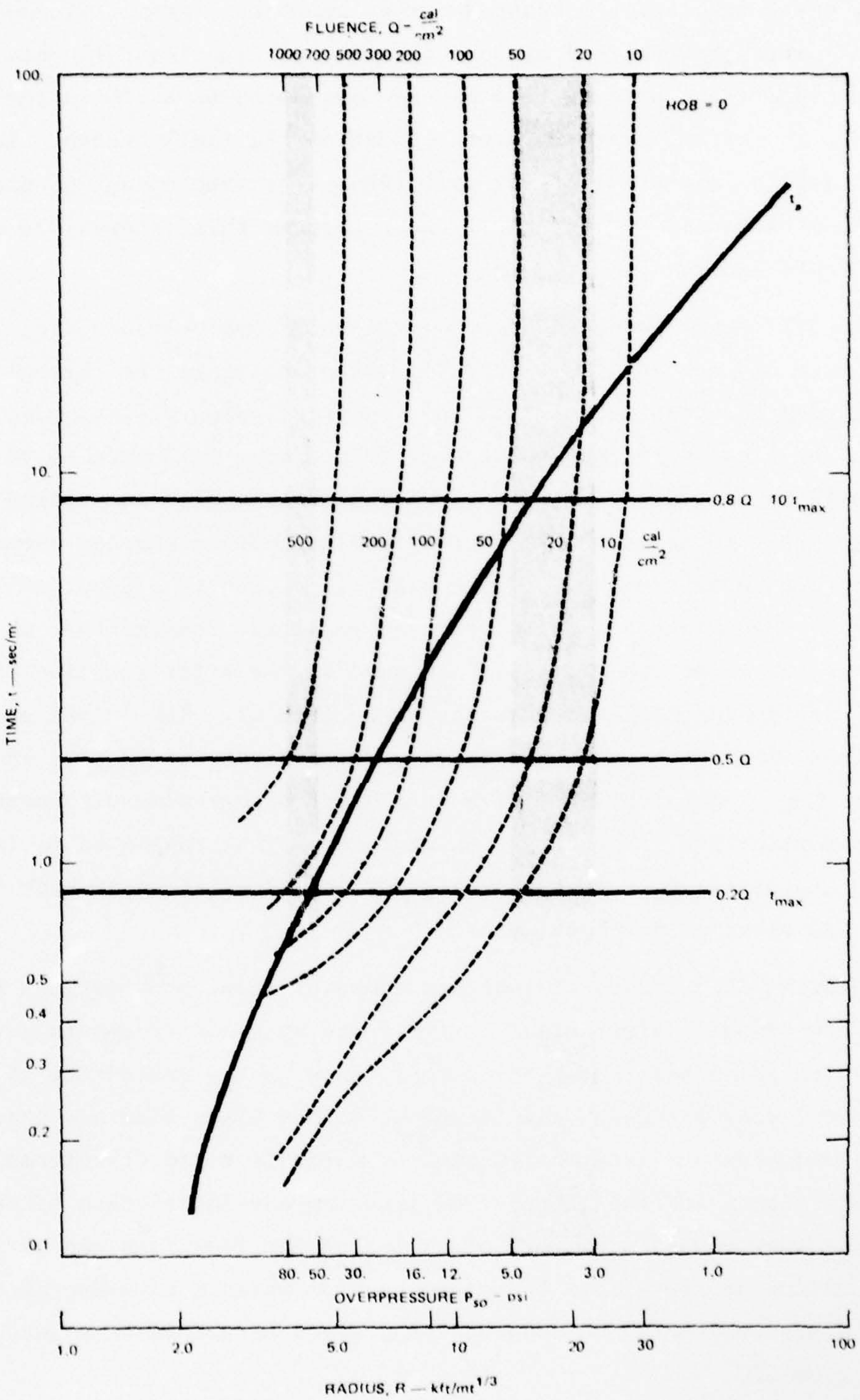
In 1973 SRI International turned its attention specifically to wall debris by modifying an IITRI 2-D program for calculating blast translation of the human body (Ref 10) to handle the motion of wall fragments in three dimensions. Initial conditions for the calculation are supplied by the SRI wall analysis code. Only a few test calculations have been made with this debris code as a part of a fire model study (Ref 11) (also for DCPA). Previous debris distribution studies have been concerned with assessing ease of ingress and egress and consequently were based on assumptions of uniform distribution of debris from failed structures.

Another component of the debris important to the potential for fire in a structure is that consisting of room contents, particularly the flammable contents. Some experimental work has been done to locate these materials during blast loading, chiefly work with models in shock tubes at BRL (Ref 14) and with near-full-scale walls at URS (Ref 15). Neither effort attempted to mix structural with content debris but examined floor effects within rigid structures. By applying the quasi-empirical theory of jets (Ref 16) it is possible to calculate with relatively simple procedures the important early motion of room furnishings located near exterior wall openings. As the flow continues, complex hydrocodes are necessary to follow the flow of air; however, it is likely that currents are weak at these later times and the final location of the major objects has been already determined by the simple jet flow.

The proposed research has the objective of determining those features of the distribution of debris that are important to fire spread and initiation

Method of Approach

Debris effects are felt by primary fires in two distinct ways: (a) in regions of high overpressure (30-50 psi), a major thermal pulse is delivered after the debris has been created and largely distributed; (b) in the low pressure regions (3-5 psi) debris appears only after primary fires have been started. The situation is illustrated in Figure G-1 where effects arising in a 1 mt surface burst are shown. The abscissa is distance R from GZ in kft; ordinate is time t in seconds after detonation. Thermal fluence as a function of range appears along the top ordinate. A partial scale has been provided on the abscissa to show overpressure. The solid curve represents time of arrival ta of the airblast front at



SOURCE: Effects of Nuclear Weapons, 1977

FIGURE 1 ARRIVAL TIMES OF BLAST AND THERMAL FLUENCE range R while the family of dashed curves shows the thermal fluence (cal/cm^2) which has arrived at R by the time t. The least fluence to start a significant primary fire may be considered to be 10 cal/cm^2, hence the 10 cal/cm^2 contour is the lowest of the family shown. (Creation of debris from a collapsing wall takes a certain amount of time after blast arrival, but for the present purpose this interval is short enough to be ignored.)

The differences between the two regions of overpressure are evident. In the more distant annulus (3-5 psi), essentially all the thermal pulse is delivered before blast arrival and, in fact, primary fires have an interval of 1 to 10 seconds to develop before that influence is felt. Blast here is most likely a perturbation to existing primary fires. In the high pressure range (30 to 50 psi), while quite dangerous amounts of thermal fluence arrive ahead of the blast (i.e., up to 150 cal/cm^2), the fire development interval is an order of magnitude shorter than at low pressures; moreover, the blast is followed by the major fraction of the thermal energy incident at these distances from GZ. (At 30 psi about two thirds of the thermal pulse appears after blast; at 50 psi, about four fifths.) Here, primary fire in a blast disturbed environment is a major possibility. The situation at intermediate ranges falls in between; there is opportunity for significant irradiation of both undisturbed and blast affected structures.

Existing SRI structural analysis computer codes provide both time to failure of wall (after blast arrival) and speed of fragments criterion. An existing SRI debris translation code computes the trajectory of a single wall fragment under the influence of the blast wind and gravity and approximates its interaction with essentially rigid structures such as intact floors and the ground. By ignoring any interaction between fragments themselves, a history of wall fragment locations can be found as a function of free-field overpressure from which a time-dependent debris distribution can be deduced for a given structure at a series of ranges from GZ.

Work Plan

Task 1 - Calibration of Analytical Model

Study film, pressure and deflection gage results and post shot inspection reports from the German house experiment at Operation Dice Throw (1976) to establish a history of wall deflection, fragmentation and translation to serve as a test case for the analytical debris model as applied to a single fragment. Any necessary modifications to improve realism of model will be made.

Duration:	3 months
Level of effort:	460 labor hours

Task 2 - Development of Unified Computer Program

Incorporate the analytical debris translation code into the building subsystems code for analysis of walls and floors of a single story of one building; test and debug the combined program.

Duration:	2 months
Level of Effort:	300 labor hours

Task 3 - Debris Distribution Near Incipient Collapse

Select one floor or a portion of a floor of a low-rise NSS building with predominantly masonry panels in a frame structure and apply the combined code developed in Task 2 to the exterior wall panels at three free-field overpressures: (1) incipient collapse overpressure of a facade struck head-on, P_c, (2) P_c + 0.5 psi and (3) P_c + 1.0 psi. Using the results of Task 2, describe the wall debris field in time.

Duration:	3 months
Level of effort:	520 labor hours

Task 4 - Fragment Interaction

Examine the results of Task 3 to assess the importance of the collisions among fragments. If the effort appears justified, develop an analytical means of taking collisions of this kind into account and recalculate distributions (2) and (3) of Task 3.

Duration:	1 month
Level of effort:	150 labor hours

Task 5 - Debris Distribution at High Overpressures

Attempt to repeat Task 3 at free-field overpressure equal to 30 psi. Assume building frame remains in place.

Duration:	1-1/2 months
Level of effort:	170 labor hours

Task 6 - Preliminary Study of Furniture as Debris

By means of the quasi-empirical theory of jets, attempt to determine typical trajectories of the simulated barrels used by BRL in their model basement studies (Ref 14) and compare results with reported observations.

Duration:	1-1/2 months
Level of effort:	230 labor hours

Project Responsibility

This project will be administered within the Quantitative Social Sciences Center of SRI's Urban and Health Systems Group. The project leader will be John R. Rempel, senior physicist, who will direct daily project coordination and technical operation and will be responsible for performing the project. Overall technical and financial performance will be reviewed by Vincent Lauricella, Manager of the Systems Development and Programs Department of the Quantitative Social Sciences Center. Other principal SRI staff members who will participate in this project are:

James E. Beck, senior research engineer
John Herndon, programmer
James Hewlett, programmer

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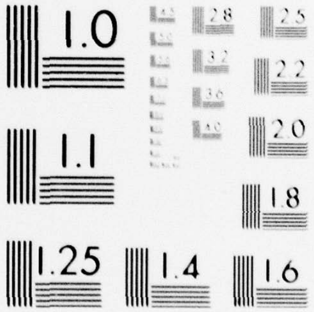

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Appendix H

PROGRAM STATEMENT FOR FIRE/BLAST INTERACTION

OBJECTIVE

The objective is to assess by analytic modeling the significance of a thermonuclear blast on the spread of fires initiated by the thermal radiation.

BACKGROUND

If the sudden arrival of rapidly translating shocked air can extinguish flames ignited by thermal radiation that arrived a few seconds to a minute earlier, then the fire threat of thermonuclear explosion is diminished appreciably; the weapon naturally engenders its own anti-fire countermeasure before significant fire damage can arise. The objective is to clarify, rapidly, inexpensively, and explicitly, the existing contradictory evidence from HE tests, shock tube and shock tunnel experiments, in which blast interaction with pre-existing fire has resulted in extinguishment on some occasions, and in no apparent influence on others.

The most perilous cases of spread of a fire entail propagation with the wind, because wind-aided flame spread typically occurs at rates orders of magnitude faster than flame spread against the wind. For example, spread up a wall is *far* faster than spread down a wall. While radiatively initiated fire may be spread with or against the flow experienced upon arrival of the higher-pressure, higher-temperature shocked air, attention here is confined to the more vigorous spread with the wind.

The only model of flame spread with the wind that couples gas and solid phases, that retains explicit temporal dependence, and that maintains mass (as well as thermal) budgets is presented by Carrier, Fendell and Feldman (1977). However, this model at present does not account for precursor radiation or finite-rate chemical kinetics, temporally and spatially varying pressure, or highly nonuniform flow. These generalizations are required if a model, originally designed for interpreting Steiner tunnel experiments (fire-test protocol ASTM E84), is to be extended to the thermonuclear-burst case.

PROBLEM

A feasible first two-spatial-dimensional problem, compatible in large part with simulation achievable in the SRI shock tube facility, is the following simplified situation. A horizontal long flat plate is taken to be known to undergo sublimation at a specified temperature, with specific (endothermic) heat of phase transition. At time zero, radiation is incident on the entire plate, with the most intense radiation occurring at one edge, henceforth alluded to as the leading edge. This radiation effects sublimation, with a portion of the outgassed vapor being combustible with oxygen in an exothermic gas-phase chemical reaction. Particularly if the specific heat of combustion significantly exceeds the specific heat of sublimation, the pyrolysis front and flame spreads across the surface.

The question to be answered is whether this flame spread rate is enhanced by the arrival of shocked (higher-temperature, higher-pressure) gas, taken to flow over the leading edge such that wind-aided flame spread ensues, or whether the high-speed flow leads to residence times for reactants too short relative to chemical-reaction-rate times, and extinction ensues.

APPROACH

In this study there is to be theoretical/experimental interchange, with additional and simultaneously executed shock tube testing: the aim is mutual advancement of experimental and theoretical work toward the goal of identifying parametric ranges in which blast/fire interaction enhances flame spread (presumably because of the augmented thermal loading from shocked air, increased pressure, and oxygen availability), and other parametric ranges in which blast/fire interaction suppresses flame spread (presumably because of temporally abrupt change in the environment, forced convective transport rate competitive with chemical and pyrolysis rates, and/or dispersal of the involved fuel into fragments individually unable to sustain burning). Blast/fire interactions need not entail blast waves generated by the same burst as that of the radiational precursor (e.g., an attack may involve multiple bursts), and indeed fire/blast interaction need not concern itself inextricably with the ignition mechanism of the fire interacting with the blast. The initial problem to be attacked is the relatively simple one-burst case: radiation from a thermonuclear burst ignites a fire, and this fire then interacts with the blast wave that arrives subsequently.

The proposed program of research is combined analytic and numerical modeling of fire/blast interaction. The aim is to retain all the essential physical phenomena, with a self-consistent level of approximation for simplified geometry and material properties and flow, such that rapid, inexpensive, and explicit solution displaying the variation in system behavior as a function of multiparameter dependence is attainable. Comparison of theory and experiment is then feasible, and extrapolation to a broader class of circumstances than those explicitly tested, either in the laboratory of in the field, is possible.

The inclusion of more sophisticated formulation, with respect to one class of phenomena is specious if other interaction phenomena are retained in only a simplistic manner. The requisite boundary and inertial conditions, corroborative measurement, and/or needed thermodynamic data are often unavailable, such that elaborate formulation assures greater expenditure, but may achieve no greater validity.

Thus, the interdisciplinary program of research emphasizes approximate but simultaneous inclusion of fluid dynamics, chemistry, radiative transfer, and phase transition in a manner that is aimed at current needs of DCPA.

NEED FOR SOLUTION

The question posed is answerable in mechanistic terms, by solution of statements of the conservation of mass, momentum, and energy, with appropriate boundary and initial conditions. There is a cause-and-effect relationship between the disturbance applied and the system response observed. Any stochastic discussion unprofitably would likely disregard the laws of physics and chemistry in favor of random responses according to somewhat arbitrarily chosen probabilistic parameters.

A particular need for solution is required because the synergistic nature of fire/blast interactions appears to be a basis for serious reappraisal of the threat from thermonuclear weapons. The conjecture that "shearless displacement" leads to blast blow-off of a diffusion flame from even a totally involved fuel slab, warrants scrutiny in the near future. Because the diffusive scales for mass, momentum and energy in most gaseous mixtures are typically comparable, it seems implausible that purely inviscid dynamics coexists with highly diffusive energetics. Thus important blast/fire phenomena are being interpreted in terms of physics of contestable validity.

In a more general context, one cannot characterize continuous and discontinuous fire spread without knowing the initial ignition sites. The initial ignition sites, in turn, are determined by the radiative-flux incidence, *as modified by blast-induced suppression*, for nuclear weapons. Thus, the question posed here was second to none in attention devoted to it by uncontrolled-fire specialists at the DCPA-sponsored meetings on the fire threat of thermonuclear weapons, held in March 1978 and in March 1979 at the Asilomar Conference Grounds, Pacific Grove, California.

CONCLUSIONS AND SUMMARY

The expenditure of time, money, and effort required for large-scale simulation of thermonuclear blast on an urban target limits these tests to a small number, executed at large intervals of time. The instrumentation is limited, and replication for corroboration quite impractical. Even the very partial simulation possible in the laboratory is highly costly, and few satisfactory facilities currently exist.

If one commits prodigious resources to install a civil-defense plan of preparation and countermeasures on the basis of stochastic game-playing alone, one may be deluding oneself *unjustifiably*, because much of the deterministic physics is known. The course deemed rational and cost-effective here is to devote a small amount of resources to fire/blast modeling, because this is a particularly critical, rather explicit question for which an answer in simplified circumstance is feasible. Speculative extrapolation to more intricate scenarios could better proceed from such a well-grounded answer.

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Appendix I

SHELTEREES FORCED OUT DUE TO FIRE

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This paper presents an analytical model for calculating the fraction of people assigned to shelters who will be forced out of those shelters by fire, and the fraction of those forced out who will become fatalities. The model can be used with any attack scenario, for any shelter class of known characteristics, in either a residential or built-up neighborhood. At the present time, values for some of the parameters can be only best estimates, due to lack of knowledge. These terms clearly indicate the areas where additional research is needed, and as better information develops, the values in the model can be improved.

Model for Fire Event Calculations

$FF_i = \sum_o (FF_i)_o$ = Fraction forced out of Shelter Class i by fire, in all overpressure regions (o) considered for class i.

o = 2-5 psi, 5-10 psi, 12-15 psi, > 15 psi

$(FF_i)_o = \sum_g (FF_i)_{og}$ = Fraction forced out of Shelter Class i in region o during all fire generations, g.

$1 \leq g \leq 4$

$FF_{iog} = a_{io} f_{og} C_g$ = Fraction forced out of Shelter Class i per fire generation g.

$$a_{io} = \frac{\text{\% of population in region } o}{\text{\% of population experiencing } <\text{(MLOP) for Class } i.}$$

f_{og} = Fraction of structures with sustained fires per fire generation g in region o

C_g = Countermeasures that are applied by trained/instructed population that reduce f_{og}

$F_i = \sum_o F_{io}$ = Fraction of fatalities among FF_i in all overpressure regions o considered for class i

$F_{io} = \sum_o F_{iog}$ = Fraction of Fatalities among FF_i in overpressure region o, for all gererations g.

F_{iog} = Fraction of fatalities among FF_i in overpressure region o, per generation g.

$F_{iog} = 0$ where $f_{og} \leq 0.02$

$= 0.204 f_{og} - 0.004$ where $f_{og} > 0.02$

$\sum_g f_{og}$ = $f_{o0}+f_{o1}+f_{o2}+f_{o3}+f_{o4}$

f_{o0} = Initial fires at 1/4 hr = $b_o+(c_o\ a_o)$ in region o

f_{o1} = First generation at 1 1/4 hr = $k_o\ e_o\ a_o$ in region o

f_{o2} = Second generation at 3 1/4 hr= $p_o(f_{o0}+f_{o1})$ in region o

f_{o3} = Third generation at 6 1/4 hr = $p_o f_{o2}$ in region o

f_{o4} = Fourth generation at 9 1/4 hr= $p_o f_{o3}$ in region o

Where: a_o = Fraction of primary fires in region o

b_o = Fraction of secondary fires in region o

c_o = Fraction of primary surviving fires in region o

k_o = Fraction of primary fires rekindled in region o

e_o = Fraction of primary fires extinguished in region o

p_o = Fraction of probability of fire spread in region o

$$T_{avg} = \text{average time of } (FF_i)_o = \frac{0.25f_{o0}+1.25f_{o1}+3.25f_{o2}+6.25f_{o3}+9.25f_{o4}}{\sum_g f_{og}}$$

The calculations that follow for strong basement shelters illustrate use of the model. The values of MLOP and MCOP are 10 and 7 psi, as indicated.- The Δ values increase the rated values to account for protective blast posture of shelterees.

Shelter Class 4 - Strong Basements (B/C) MLOP/MCOP = 10/7
ΔMLOP = 0.1 ΔMCOP = 0.3
Then MLOP/MCOP = 11/9.1

For this shelter class, three overpressure regions are considered, in each of which the consequences of the Fire Event would differ. The regions are: 2-5 psi; 5-9 psi; 9-11 psi. Strong basement shelters are usually found in the built-up commercial regions, although a few such shelters are found in buildings in residential areas, in apartment building, or stores in shopping centers. In general, fire incidence would be higher in commercial areas than in residential areas experiencing the same overpressures.

The fractions of sustained fires, per fire generation in the 2-5 overpressure region in the residential area, are assumed to be the same as those in the same region for Shelter Class 2, Home Basements. Similarly, the fractions of sustained fires, per fire generation in the 2-5 psi region in the built-up area are assumed to be the same as those in the "Heavy Residential" area of Shelter Class 1.

The "best" terms for the fractions of fires, per fire generation in residential areas in the two higher overpressure regions, were based on the following assumptions: (1) the average building height is about three stories (based on examination of the varied buildings listed in the class) for both regions; (2) in the 5-9 psi region, the probability of primary ignitions was taken as $p_p = 0.095$; (3) in the 9-11 psi region, the probability of primary ignitions was taken as $p_p = 0.3$; and the values of α in the model were then calculated: $\alpha = 1-(1-p_p)^3$; (4) in the 5-9 psi region, the fraction of surviving primary fires was taken as 0.1, the fraction of secondary fires as 0.03, one-half the primary fires extinguished were assumed rekindled, and the probability of fire spread was taken to be 0.1; (5) in the 9-11 psi region the fraction of surviving primary fires is also 0.1, the fraction of secondary fires is 0.04, half the extinguished primary fires were rekindled, and the probability of fire spread was taken as 0.2.

In the built-up areas the following assumptions were made for the "best" estimates based on review of the compilation of data in Refs. 1, 4, 11, and 13: (1) in the 5-9 psi region the fraction of primary fires was taken as 0.6, the fraction surviving as 0.10, the fraction of secondary fires as 0.05, 40% of the primary fires extinguished will rekindle, and the probability of fire spread is 0.2; (2) in the 9-11 psi region the fraction of primary fires was taken as 0.65, the fraction surviving as 0.15, the fraction of secondary fires as 0.1, 40% of the primary fires extinguished will rekindle, and the probability of fire spread is 0.2.

The "low" estimates include a lessening of thermal effects due to dampness and/or lack of wind, whereas the "high" estimates include a greater fire spread factor due to winds. According to Ref 1, such effects are probable if winds exceed 7 mph, and according to Refs 14 and 15, windspeeds of less than 7 mph could be expected in only 13% of the U.S. cities.

Calculations for the 2-5 psi and 5-9 psi regions in both areas are presented in tables, followed by the final results for this shelter class.

1. S. J. Wiersma and S.B. Martin, "The Nuclear Fire Threat to Urban Areas", DCPA Work Unit 2561A, Stanford Research Institute, Menlo Park, California (April 1975)

4. S. J. Wiersma and S. B. Martin, "Evaluation of the Nuclear Fire Threat to Urban Areas", DCPA Work Unit2651A, Annual Report, Project PYU 8150, Stanford Research Institute, Menlo Park,California (September 1973)

11. J. Rotz, J. Edmunds, and K. Kaplan, "Formation of Debris from Buildings, and Their Contents by Blast and Fire Effects of Nuclear Weapons", URS 651-4, URS Systems Corporation, Burlingame, California (April 1966).

13. B. Martin, S.B., "The Role of Fire in Nuclear Warfare", DNA2692F, URS Research Company (August 1974)

14. Statistical Abstract of the U.S., 1971, 92nd Annual Edition, U.S. Department of Commerce, Bureau of the Census

15. Work Almanac and Book of Facts, 1975 - Newspaper Enterprise Association, Inc., N.Y., Cleveland

Shelter Class 4 - Strong Basements: Built-Up Areas

Attack 6A a_{io}=0.35 TR-82 a_{io} = 0.42			2-5 psi				Attack 6A a_{io} = 0.43 TR-82 a_{io} = 0.23		5-9 psi		
					Best Estimate						
f_g	T(hr.)	Calculation	f_g	F_g	FF_o(6A)	FF_o(TR)	Calculation	f_g	F_g	FF_o(6A)	FF_o(TR)
f_ϕ	1/4	0.01+0.1(0.0956)	=0.0196	0			0.05+0.1(0.6)	=0.1100	0.0184		
f_1	1 1/4	0.5(0.9)(0.0956)	=0.0430	0.0048			0.4(0.9)(0.6)	=0.2160	0.0401		
f_2	3 1/4	0.5(0.01956+0.0430)	=0.0313	0.0024			0.2(0.11+0.216)	=0.0632	0.0089		
f_3	6 1/4	0.5(0.0313)	=0.0157	0			0.2(0.0632)	=0.0126	0		
f_4	9 1/4	0.5(0.0157)	=0.0079	0			0.2(0.0126)	=0.0025	0		
		$\sum_g$	=0.1175	0.0072	0.0411	0.0493	$\sum_g$	=0.4043	0.0674	0.1738	0.1172
		T_{avg} = 2.82 hr.					T_{avg} = 1.5 hr.				
					Low Estimate						
f_ϕ	1/4	0.002+0.1(0.02)	=0.0040	0			0.03+0.1(0.5)	=0.0800	0.0123		
f_1	1 1/4	0.1(0.9)(0.02)	=0.0018	0			0.3(0.9)(0.5)	=0.1350	0.0235		
f_2	3 1/4	0.25(0.004+0.0018)	=0.0015	0			0.2(0.08+0.135)	=0.0430	0.0048		
f_3	6 1/4	0.25 (0.0015)	=0.0004	0			0.2(0.0430)	=0.0086	0		
f_4	9 1/4	0.25(0.0004)	=0.0001	0			0.2(0.0086)	=0.0017	0		
		$\sum_g$	=0.0078	0	0.0026	0.0033	$\sum_g$	=0.2683	0.0406	0.1154	0.0778
		T_{avg} = 1.38 hr.					T_{avg} = 1.48				
					High Estimate						
f_ϕ		0.015+0.2(0.1403)	=0.0431	0.0048			0.08+0.15(0.65)	=0.1775	0.0322		
f_1		0.5(0.8)(0.1403)	=0.0561	0.0074			0.4(0.85)(0.65)	=0.2210	0.0411		
f_2		0.7(0.0431+0.0561)	=0.0694	0.0102			0.25(0.1775+0.2210)	=0.0996	0.0163		
f_3		0.7(0.0694)	=0.0486	0.0059			0.25.(0.0996)	=0.0249	0.0011		
f_4		0.7(0.0486)	=0.0340	0.0029			0.25(0.0249)	=0.0062	0		
		$\sum_g$	=0.2512	0.0312	0.0879	0.1055	$\sum_g$	=0.5182	.0907	0.2275	0.1535
		T_{avg} = 3.68 hr.					T_{avg} = 1.65 hr.				

Shelter Class 4, Strong Basements: Residential Area

Attack 6A a_{io} = 0.35
TR-82 a_{io} = 0.42 2-5 psi

Attack 6A a_{io} = 0.43
TR-82 a_{io} = 0.29 5-9 psi

Best Estimate

f_g	T(hr)	Calculation (2-5 psi)	f_g	F_g	FF_o(6A)	FF_o(TR)	Calculation (5-9 psi)	f_g	F_g	FF_o(6A)	FF_o(TR)
f_ϕ	1/4	0.01+0.1(0.01)	= 0.0110	0			0.03+0.1(0.26)	=0.0560	0.0074		
f_1	1 1/4	(0.5)(0.9)(0.01)	= 0.0045	0			(0.5)(0.9)(0.26)	=0.1170	0.0199		
f_2	3 1/4	0.1(0.011+0.0045)	= 0.0016	0			0.1(0.0560+0.1170)	=0.0173	0		
f_3	6 1/4	0.1(0.00155)	= 0.0002	0			0.1(0.0173)	=0.0017	0		
	9 1/4		0	0			0.1(0.0017)	=0.0002	0		
		Σ_g	= 0.0173	0	0.0060	0.0073	Σ_g	=0.1922	0.0273	0.0826	0.055

T_{avg} = 0.85 hr.

T_{avg} = 1.19 hr.

Low Estimate

f_g	T(hr)	Calculation (2-5 psi)	f_g	F_g	FF_o(6A)	FF_o(TR)	Calculation (5-9 psi)	f_g	F_g	FF_o(6A)	FF_o(TR)
f_ϕ	1/4		= 0.0020	0			0.02+0.1(0.18)	=0.0380	0.0038		
f_1	1 1/4	0.1(002)	= 0.0002	0			(0.3)(0.9)(0.18)	=0.0486	0.0059		
f_2	3 1/4	0.1(0.002+0.0002)	= 0.0002	0			0.1(0.038+0.0486)	=0.0087	0		
f_3	6 1/4		0	0			0.1(0.0087)	=0.0009	0		
f_4	9 1/4		0	0			0.1(0.0009)	= 0	0		
		Σ_g	= 0.0024	0	0.0009	0.0010	Σ_g	= 0.0962	0.0097	0.0413	0.027

T_{avg} = 0.6 hr.

T_{avg} = 1.08 hr.

High Estimate

f_g	T(hr)	Calculation (2-5 psi)	f_g	F_g	FF_o(6A)	FF_o(TR)	Calculation (5-9 psi)	f_g	F_g	FF_o(6A)	FF_o(TR)
f_ϕ	1/4	0.015+0.2(0.015)	= 0.0180	0			0.05+0.1(0.4)	=0.0900	0.0144		
f_1	1 1/4	0.8(0.8)(0.015)	= 0.0096	0			(0.5)(0.9)(0.4)	=0.1800	0.0327		
f_2	3 1/4	0.2(0.018+0.0096)	= 0.0055	0			0.2(0.09+0.18)	=0.0540	0.007		
f_3	6 1/4	0.2(0.0055)	= 0.0011	0			0.2(.054)	=0.0108	0		
f_4	9 1/4	0.2(0.0011)	= 0.0002	0			0.2(0.0108)	=0.0022	0		
		Σ_g	= 0.0344	0	0.0121	0.0145	Σ_g	=0.3370	0.0541	0.1449	0.09

T_{avg} = 1.2 hr.

T_{avg} = 1.52 hr.

Shelter Class 4 Fire Fractions

General Equations:

	LOW	BEST	HIGH
FF(6A)	0.0833R+0.1927B	0.1494R+0.3304B	0.2429R+0.4604B
FF(TR)	0.0587R+0.1325B	0.1406R+0.2453B	0.1709R+0.3568B
F	0.0343R+0.0952B	0.0695R+0.1690B	0.1187R+0.2387B

Where R = percent in Residential Area
B = percent in Built-up Area

For example, Let R = 20%, B = 80%
Then the fractions would be:

	LOW		BEST		HIGH	
	6A	TR	6A	TR	6A	TR
FF	0.1708	0.1177	0.2942	0.2172	0.4169	0.3196
F	0.0830		0.1491		0.2147	
FFS	0.9170		0.8509		0.7853	

Where FFS = Fraction of Those Forced Out Who Survive

Appendix J

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Investigation to Improve the Effectiveness of Water in the Suppression of Compartment Fires

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SUMMARY

Using a physically-based computer simulation of compartment fires, characteristics of the water spray from hose-nozzle systems used by the fire service are varied and the effect on fire knockdown performance compared. The objective is to improve hose-nozzle performance to achieve more effective fire control with smaller water usage and damage and with tolerable levels of high temperature steam over a wide-range of building and fire conditions.

A description of the computer simulation's theoretical and empirical basis is provided. The unique feature of the simulation is that it not only models fire growth from flashover through a free burning phase, but also follows the fire history through the period of water application to either knockdown of the fire or burnout.

It is then demonstrated how the computer simulation can be used to identify building and fire conditions most likely to stress the technology and also to estimate a preliminary set of near optimal water spray characteristic performance goals. These results then provide a basis for future hardware development and experimental testing.

INTRODUCTION

Despite the almost universal use by fire services of plain water dispersed by hydraulic nozzles there still remains considerable uncertainty in quantifying its effects as a suppressant in mobile fire fighting operations. One would like not only to estimate the total quantity of water and its application rate which would effectively suppress a given structural fire, but also one would like to identify

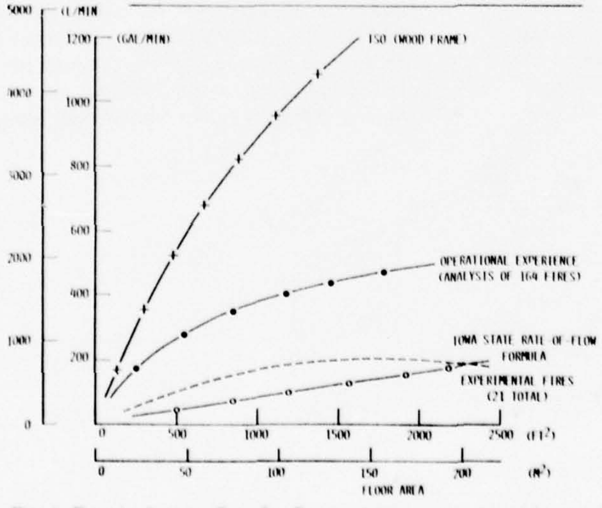

Fig. 1. Required water flow for fire service operations (residential fires).

and quantify the factors which influence suppression effectiveness. Operational experience supplemented, where necessary, by case-specific experimental tests has in the past provided empirical answers to these questions. Such results do not in many cases provide enough insight to forward the optimization of mobile fire suppression systems. This paper describes the use of a computer simulation which models the major physical interactions in the suppression of compartment fires and provides an estimate of water requirements and their functional dependence upon fire conditions and the characteristics of the suppression technology.

Figure 1 displays several generalized estimates of required water delivery rates for control of residential fires, plotted as a function of involved fire area, which illustrate present knowledge. The ISO (Insurance Services Office) curve, though based upon operational experience, is very conservative and probably represents worst cases [1]. An actual average is represented by the curve labelled operational experience [2]. By contrast the much lower water requirements obtained from experimental fires must reflect the absence of many of the difficulties and uncertainties of operational fire fighting [2]. The Iowa State formula is a simple theoretical estimate which demands a rate of water flow sufficient for cooling within 30 seconds, the heat generated by consumption of all the oxygen in the compartment volume [3]. The wide diversity of these estimates may reflect the inherent uncertainties in the problem, but it is also attributable to the coarseness of the description which attempts to relate required water flow to the single factor of involved floor area and which does not account for other factors which are known to affect water usage; *e.g.* fire growth with time, water to steam conversion efficiency (*i.e.* the difference between conventional and high pressure fog nozzles), building access as it relates to water stream dispersion efficiency, the firefighter who must contend with high gas and steam temperatures, and different fireground tactics, manning levels, etc.

SIMULATION APPLICATION

The function of the simulation which we have developed, called the fire demand (FD) model for short, is shown schematically in Fig. 2. The FD model is designed to relate the suppression effort via a simulation of the fire character to the suppression results. Fire character is determined by building and fuel parameters. This approach was developed to meet the objectives of a project aimed at identifying deficiencies in mobile fire suppression apparatus, identifying research areas of high potential, and of eventual improvement of equipment specifications.

From an early version of the FD model [4], the hose–nozzle emerged as a key item in the fire-fighting system. The characteristics of the water spray generated by a given hose–nozzle directly impacts fire control performance. For example, the smaller water drops (with corresponding high surface to volume ratios) generated by currently available high pressure fog nozzles operating at about 44.7 bars generally require lower water flow rates than conventional nozzles operating at a much lower 6.9 bars. On the other hand, because high pressure fog has higher water to steam conversion efficiencies, larger quantities of high tempera-

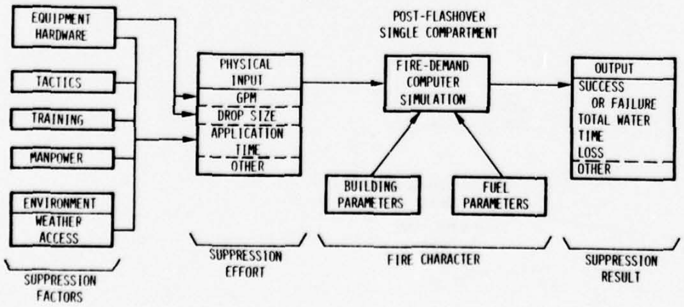

Fig. 2. Simulation applications.

ture steam may be generated and injure the firefighter.

An important question is then: are there alternative operating pressures, water flow rates and nozzle head configurations that might better utilize the delivered water and reduce the fraction wasted but without the potential injury problem? For example, *lower* water flow rates may be possible by setting reasonable standards on the range of drop sizes in the pattern to reduce the fraction blown away because the drops are too small, or the fraction that penetrates the fire without being fully evaporated because they are too large. By proper design and/or changes in operating pressure, one might achieve this *without* increasing the quantities of steam the firefighter must contend with or reducing fire knockdown effectiveness. In effect, one converts the same amount of water to steam, but by wasting less, the total water flow rate required is lower.

If these technological developments can be achieved the potential impact on fire fighting, in our view, would be significant and range from the pumper equipment itself to manning levels and tactics resulting from smaller hoses with lower weight, lower nozzle reactions, etc. These developments might also reduce water damage and enhance fire fighter safety by reducing water load on burning buildings that contribute to structural collapse.

For these reasons further development and application of the FD model focused on establishing requirements on water flow rate distribution densities (l/min m^2), drop size distributions and effective reach of the nozzle water pattern.

As demonstrated in subsequent paragraphs, the FD model is used to systematically vary a water spray characteristic (*e.g.* the shape and relative location of the drop size distribution curve) and to observe the effect on the desired end result (*e.g.* fire control). Input conditions that determine the operating environment are also varied to identify those most likely to stress the technology. In this way a preliminary set of *performance goals* and *critical operating conditions* for water spray are established.

These results provide a basis for hardware development and experimental testing. For example, further prototype development involves systematically changing the physical characteristics of the nozzle (*e.g.* head geometry and operating pressure) and measuring the water spray characteristics, as one proceeds, to see if the goals are being achieved. When completed, the prototype is then experimentally tested, but under the limited *critical* conditions identified previously.

In the future, we anticipate some cycling between computer simulation development, analysis, prototype development and experimentation to improve the estimates of each and to "fine tune" the final component design. In this approach, though, we believe costly hardware development and experimental testing work will be accomplished in a structured, controlled and focused way to assure maximum payoff.

SIMULATION DESCRIPTION

For the above applications the fully involved (post-flashover), single compartment fire was chosen as the fundamental model not only because it represents a stressful fire suppression situation, but also because previous investigators [5 - 7] have successfully modeled this fire in its freely burning phase without suppression. Their methods, which we follow, calculate the fire development in terms of lumped parameters describing the energy and mass balance of the compartment as a whole. The FD model adds to this work the effect of suppression efforts with applied water. The remainder of this section briefly highlights the structure, operational features, and general theory on which the simulation is based. A detailed description is given in ref. [8].

The level of detail of the model is determined by its practical objectives and the requirements of simplicity and computability. Figure 2 shows in general terms the principal inputs, outputs, and operating parameters of the FD model and suggests the relation of fire service operations to the physical inputs required to characterize the suppression effort. Table 1 is a summary of the major input and output parameters, and should provide an appreciation of the level of detail included in the FD model.

Figure 3 provides an overview of the physical effects and interactions incorporated in the model. Starting from assumed conditions at flashover, the FD model advances the fire

TABLE 1

Simulation input/output parameters

Situation descriptors (input)

Compartment:
area of ventilation opening
vertical height of ventilation opening
floor area
compartment height
wall/ceiling area
wall thickness
wall type (heat capacity and conductivity)

Fuel:
fuel load (weight/unit floor area)
fuel surface area
fuel surface exposed to water impact
effective heat of combustion

Water application:
water delivery rate
time of water application (after flashover)
cone angle of hose stream
sweep time of compartment coverage
volume median drop diameter of water

Results (output)

Primary:
knockdown/failure
total water used
total water vaporized
total water unvaporized
time to knockdown (if achieved)

Secondary:
fuel remaining
temperature history of compartment gas
temperature history of wall/ceiling surface
retained heat in structure

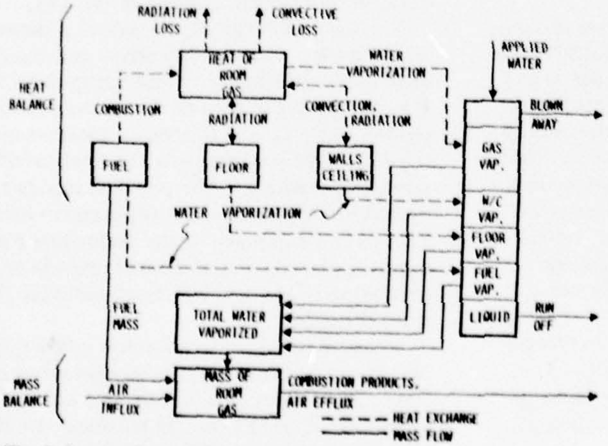

Fig. 3. Interactions of fire demand model.

in succession of time steps. Alteration of conditions with time is determined by preservation of a balance of heat transfer rates to the gas of the room and by preservation of mass balance of matter entering and leaving the compartment. In Fig. 3 heat exchange is indicated by broken lines and mass flow is indicates by solid lines.

The heat balance of the room gas accounts for heat sources (burning), heat losses (water vaporization) and heat exchange mechanisms (radiative, convective) with the other system components (ambient atmosphere, walls and ceilings, floors). The strong influence of the thermal properties of bounding surfaces for compartment fires requires subsidiary calculation of temperature profiles through the thickness of the walls and floor. Simple estimates for heat transfer rates are employed throughout.

The mass balance is an accounting of gas entering and leaving the compartment through ventilation openings and includes sources of mass due to burning fuel and vaporized water. The flow is assumed to be buoyancy driven through the ventilation openings by the temperature difference between the hot room gas and the ambient atmosphere. No further fluid dynamical detail is included.

Heat generation rate in the compartment depends upon ventilation (air influx) or fuel area. The model assumes cellulosic fuel and employs the empirical criterion developed by Harmathy [9] to estimate the burning rate based upon either ventilation controlled or fuel area controlled conditions. No account is taken of the decrease of fuel surface as burning proceeds but, as described later, a discontinuous reduction of fuel area can occur by extinguishment of a part of the glowing char. In addition an "effective" heat of combustion, less than the calorimetric value, is used to compensate approximately for the failure of all pyrolysis products to burn inside the compartment.

Prior to the time of first water application all the effects of water shown in Fig. 3 are inoperative. Subsequent to this time, water effects, the unique feature of the FD model, are included as shown. A portion of the applied water is vaporized in the compartment gas and cools it directly. Additional vaporization of liquid water occurs on the compartment interior surfaces whose cooling indirectly affects the temperature of compartment gases. The fraction of the total fuel surface area accessible to water impact may also vaporize liquid water and thereby reduce the rate of heat generation. Extinguishment of this fuel area is assumed to occur when the rate of heat extraction by water vaporization exceeds the heat generation rate by *charring combustion alone*. The total amount of water vapor produced from all sources must exit the compartment and therefore may reduce fire intensity by choking of ventilation openings.

Central to the estimation of water effects is the apportionment of the water volume into three parts: (1) a part which is blown away through failure to penetrate the updrafts in the compartment, (2) a part which is vaporized in the compartment gas, and (3) the remainder which impacts the fuel and interior surfaces in liquid form. This simplified submodel assumes a water drop of given initial diameter falls and evaporates in a compartment characterized by a *uniform* temperature and a *uniform* updraft velocity. The temperature is the gas temperature of the compartment and the updraft velocity is estimated from room geometry and air circulation rate in the compartment. The water drop is assumed to fall vertically from the ceiling at a terminal velocity (relative to the gas) determined by its instantaneous diameter. For given compartment conditions there are two critical drop diameters; the diameter of a drop whose terminal velocity equals the updraft velocity, and the diameter of a drop which will just reach the floor before its diameter has decreased by evaporation to a size small enough to be swept away by the updraft. Results for single drops are averaged over an assumed drop size distribution to produce a water partitioning as illustrated in Fig. 4. The model assumes a Rosin–Rammler [10] distribution of drop sizes which may be completely characterized by the volume median drop diameter, half of the water volume occurs in drops below this size and half above.* The fraction of water which is vapor-

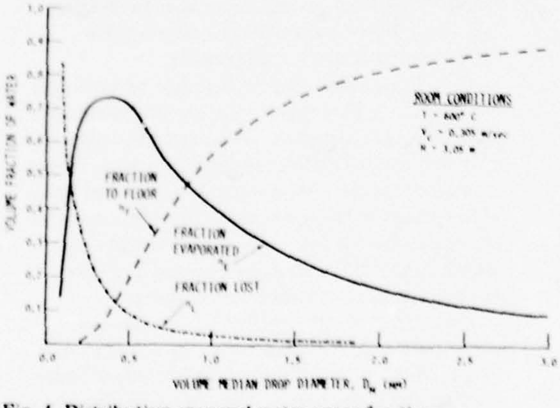

Fig. 4. Distribution averaged water usage fractions.

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*This distribution gives the volume fraction of water in the drop diameter range D to $D + dD$ by the formula:

$$P_v(D)dD = \frac{1.386}{D_m^2} D \exp(-0.693\, D^2/D_m^2)dD$$

where D_m is the volume median drop diameter.

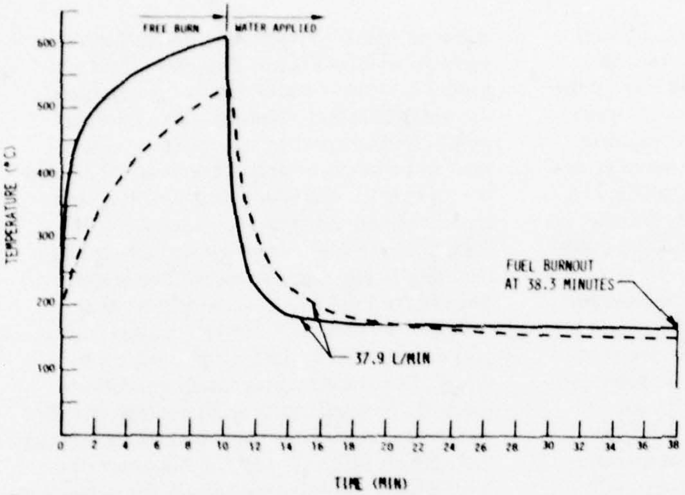

Fig. 5. Temperature history — knockdown failure.

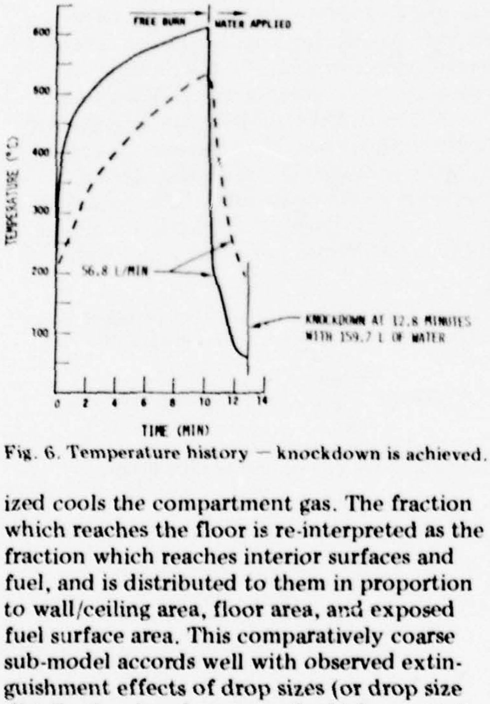

Fig. 6. Temperature history — knockdown is achieved.

ized cools the compartment gas. The fraction which reaches the floor is re-interpreted as the fraction which reaches interior surfaces and fuel, and is distributed to them in proportion to wall/ceiling area, floor area, and exposed fuel surface area. This comparatively coarse sub-model accords well with observed extinguishment effects of drop sizes (or drop size distributions) and captures the high sensitivity of cooling to this factor.

MODEL RESULTS AND SENSITIVITIES

Some example results of the FD model are shown in Figs. 5 and 6 which display the simulated temperature history for a post-flashover fire in a small compartment for the conditions listed in Table 2. The gas temperature is shown by a solid line and the temperature of the wall and ceiling surface is shown by a broken line. The fire burns freely for 10 min. Subsequent to this time water is applied at two different rates: 37.9 l/min (Fig. 5) and 56.8 l/min (Fig. 6). An application rate of 37.9 l/min produces a sharp temperature drop but the temperature stabilized at 170 °C and the fire continues until fuel burnout. By contrast an application rate of 56.8 l/min quickly reduces the gas temperature below 100 °C and the wall/ceiling temperature below 200 °C and knockdown is achieved. These two temperatures, which the model employs as knockdown criteria, are arbitrary and results are sensitive to them. Modification may be required based on future experimental testing but the present values yield conservative estimates of water requirements.

One finds in general that as the water application rate is increased, keeping all other conditions fixed, knockdown occurs abruptly above a certain critical application rate. Below this rate knockdown does not occur, but total water usage is large since the fire continues to burnout. Above this critical application rate water usage drops sharply because burning time after water application is short.

One can present simulation results and principal sensitivities in terms of a curve on a graph of water application rate *versus* volume median drop diameter. The curve divides the

TABLE 2

Conditions used in example

Compartment description:	
room height	2.44 m
floor area	11.11 m^2
area of walls and ceiling	42.85 m^2
window area	1.69 m^2
window height	1.12 m
wall thickness	0.15 m
wall type	light materials
Fuel description:	
fuel load	21.95 kg/m^2
fuel surface area	28.52 m^2
fuel surface area exposed to water	1.0 m^2
heat of combustion	2575 kcal/kg
Water application description:	
time of water application	10 min
cone angle of hose stream	60 degrees
sweep time to cover compartment	5 s
volume median water drop diameter	0.3 min
flow rate of water	37.9 l/min (10 gpm) Fig. 5 56.8 l/min (15 gpm) Fig. 6

a of the graph into two regions characterized by combinations of water delivery rate and volume median drop diameter which are successful or unsuccessful in knocking down the fire. The following demonstrates how charts of this nature can be used to help identify sensitive building and fire conditions likely to stress the fire suppression technology, as well as to identify near optimum nozzle water spray characteristics. The relative distribution of drop sizes in the spray is used as an example.

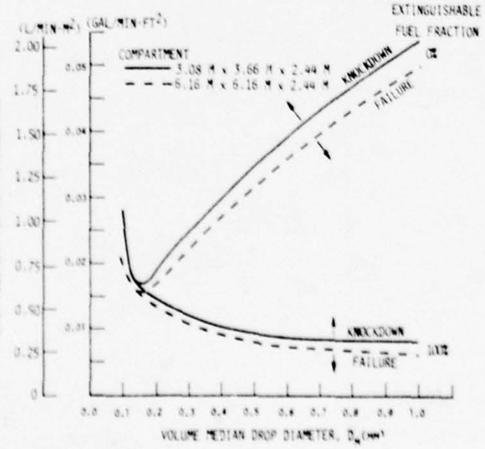

Fig. 7. Area scaling sensitivity. Opening factor, $F_0 = 0.033\ M^{1/2}$; post flash time = 10 min.

Figure 7 shows the sensitivity of the results to two compartment sizes as indicated by the solid line (small compartment) and broken line (larger compartment). There are two curves for each compartment size labelled by the extremes of possible fuel area accessible to direct extinguishment by water impact. This chart shows that if water application rate is scaled by total interior area of the compartment (*not* the total floor area) almost identical results are obtained for the two compartment sizes. However, the results are strongly sensitive to the fraction of fuel area which is reachable by water. Knockdown occurs by different mechanisms in the two cases. If no fuel can be directly extinguished knockdown must occur by cooling of compartment gas. The gaseous cooling which is a very sensitive function of drop size produces the sharp minimum of the curve at an optimum drop size. By contrast when a large fraction of the fuel area is accessible to direct water impact the critical water application rate for knockdown decreases as drop size increases. For these conditions knockdown is effected by a decrease of heat production rate consequent to extinguishment of burning surfaces. The larger drops are more effective since they penetrate better, lose less of their volume by evaporation, and carry more water to the burning surfaces. This strong sensitivity to extinguishable fuel area is also shown on subsequent graphs.

Figure 8 displays the sensitivity of results to the opening factor F_0 which we define as,

$$F_0 = A_w \sqrt{H/A_T}$$

where A_w is the area of ventilation openings, H their vertical height, and A_T the total interior surface area of the compartment. This factor, one of the prime descriptors of compartment conditions, roughly expresses the ratio of heat generation rate for ventilation controlled fires to the heat transfer rate to the bounding surfaces. Lower values of this factor produce lower temperatures and smaller circulation velocities in the compartment. The lower water application rates and the shift of optimum drop size to smaller values at smaller F_0 is consistent with the meaning of this parameter.

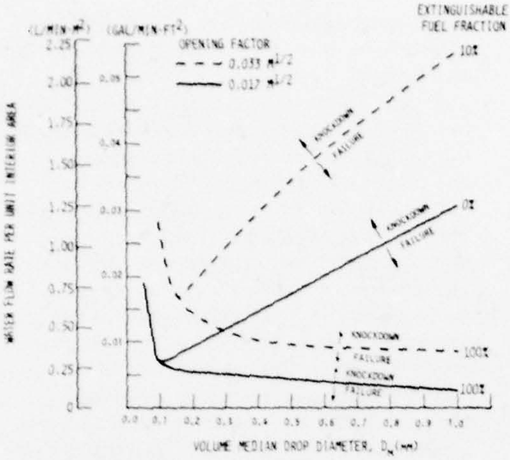

Fig. 8. Opening factor (F_0) sensitivity. Post flash time = 10 min.

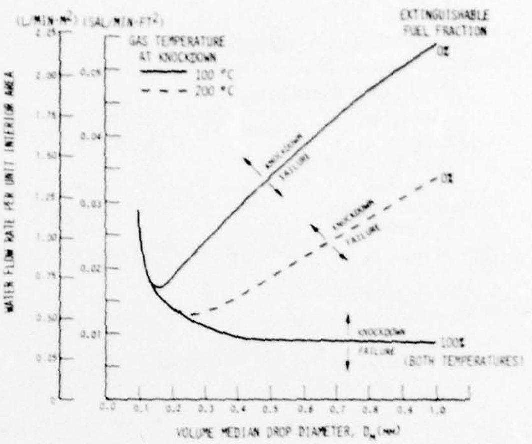

Fig. 9. Sensitivity to gas temperature at knockdown. Opening factor, $F_0 = 0.033\ M^{1/2}$. Post flash time = 10 min.

As mentioned earlier results of the simulation are sensitive to the knockdown criteria chosen. Figure 9 compares results obtained for two different gas temperatures selected to denote knockdown. In both cases knockdown requires a wall/ceiling surface temperature less than 200 °C. No effect is apparent when knockdown can be achieved by direct extinguishment of all fuel area. However, when control must occur by gaseous cooling, a higher gas temperature at knockdown lowers and broadens the minimum of the critical curve. Lowering of gas temperature the final 100 degrees from 200 ° to 100 °C puts a premium upon smaller drops.

For given conditions of compartment and fuel, simulation predictions of total water requirements can be epitomized on a fire demand chart as illustrated in Fig. 10. Total water volume per unit interior area required for knockdown is represented by contours in the region where knockdown is possible. Con-

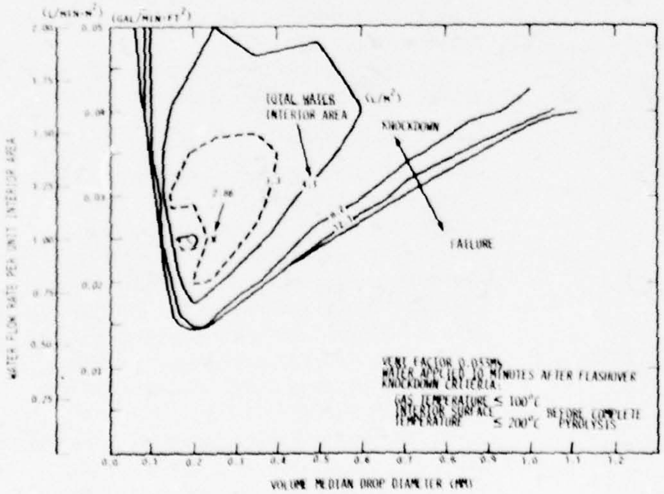

Fig. 10. Fire demand chart.

tours outside this region have little meaning since no knockdown occurs and water usage is determined by application rate and time to fuel burnout. It is worth noting that total fuel loading of the compartment, a conventional measure of possible fire severity, has no effect upon the simulation predictions of suppression effectiveness. It only determines the fire duration in the case of knockdown failure. On the fire demand chart a broad flat minimum of total water required occurs within the bight of the critical curve. Water delivery at the rates and drop sizes within this region achieve knockdown with minimum total water usage. The increase of total water requirements at higher application rates above this region is caused by the finite thermal diffusivity of the walls and ceiling. Their cooling requires a finite time regardless of the water application rate. Should knockdown *times* rather than total water be of interest these may also be plotted as contours on a similar chart.

EXPERIMENTAL

In Fig. 11 the predictions of the FD model are compared with some experimental results obtained by Salzberg *et al.* [11]. These data do not record the values of several parameters to which model results are sensitive so we have chosen reasonable values for the simulation. For example, we assume a volume median drop diameter of 0.3 mm which is perhaps typical of the spray nozzles used in the experiments.

The scatter of the experimental data is shown by the heavy dots and the curve is drawn through their average. The experiments found that a water application rate less than 25 l/min did not control the fire. The minimum application rate required for knockdown in the simulation is 34 l/min. In comparison with these experiments the FD model predictions are reasonable but somewhat conservative, an expected result deliberately built into the model. The too sharp rise of the total water requirements at high application rates shown by the simulation is a descrepancy which indicates that the model underestimates the rate of interior surface cooling.

In a series of post-flashover suppression experiments Fuchs [12] measured the quantities of water vaporized and remaining as runoff for fires occurring in a room similar in geometry, ventilation and fuel characteristics to that used by Salzberg *et al.* In his fires the water was applied 10 min after flashover and the rates varied between 25 and 50 l/min. Although Fuchs does not record drop size distributions it appears that both high pressure (~35 bars) and lower pressure fog nozzles were used. For these cases we assume that the volume median drop diameters would be of the order of 0.1 to 0.4 mm.

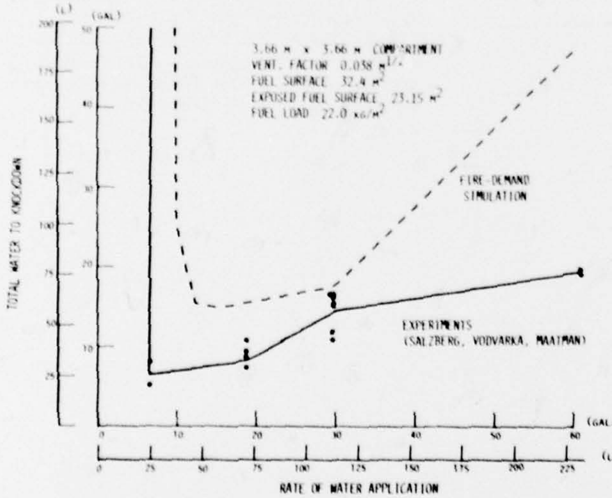

Fig. 11. Comparison with experiments.

A major conclusion of Fuchs' experiments is that approximately 100 l of water is vaporized during fire knockdown no matter which nozzle is used. This result is in good agreement with that predicted by the FD model. Although the *total* quantities required varies significantly, the model shows that for flow rates between 25 and 50 l/min and median drop diameters between 0.1 and 0.4 mm the water actually *vaporized* is fairly constant and of the order of 110 l.* The model results show that the difference between the total water applied and that vaporized is lost as runoff because the water droplets are too large or are blown away because the droplets fail to penetrate the updrafts in the compartment.

CONCLUSION

Development of the FD model is continuing and quantitative calibration by experimental testing is planned. The results to date, however, are sufficient to establish the utility of this modeling approach as a versatile tool for quantifying effectiveness of water to improve the technology used by fire services in the suppression of compartment fires.

ACKNOWLEDGEMENTS

The work reported here was supported by Contract No. NSF-C961 from the National Science Foundation (NSF) under its RANN program. Gratitude is expressed to Dr. David Seidman, the program manager at NSF, for his interest and encouragement.

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*The quantities vaporized tend to increase for spray characteristics *approaching* the knockdown failure line only.

Appendix K

Supplementary Papers to the Output Statements of Workshop 2

Topic 1

Task Description for Proposed Project: ANALYZE CITY COMPLEX (CRUDE CUT)

Objective

To describe the airblast-created debris field in a large U.S. city, as a function of time in relation to the thermal pulse, so that fuel arrays and environments can be known as necessary to improve understanding of primary and secondary firestarts and of firespread.

Scope

Perform the following subtasks:

1. Describe an exemplar city structurally
2. Select an attack that would provide a full range of damage (ground zero location, weapon yield and height of burst)
3. Using existing techniques augmented by considerable engineering judgment of blast effects researchers, predict in gross terms a probable range of debris field histories throughout the city
4. Identify the areas where further research in debris distribution and in structural evaluation of existing structures is likely to be the most rewarding in further understanding of fire damage and/or fire damage prediction/prevention.

Method

Subtask 1 may make use of previously collected material (e.g., Five-Cities Study, Sanborn maps, NFS data); it may benefit from special aerial and street level surveys, but it will require some detailed building examination. Not only will sizes and distributions of structures (as from aerial surveys) be required, but typical construction methods must be established by on-site inspection, examination of as-built construction drawings, and/or, possibly, consultation with architects and engineers well acquainted with the city.

Subtask 2 will quickly review extremes and a wide spectrum of attacks, in selecting the one attack to be studied (e.g., airbursts designed to maximize airblast damage, pinpoint attacks on limited targets within the city, and attacks on neighboring targets outside the city intended to produce collateral damage on the city itself.) For the first "crude cut" study, only a single-burst attack will be used.

Subtask 3 will make use of programs developed for analysis of structural elements (including frames) and for translation of fragments to set limits on likely debris distribution patterns at various times. Many assumptions will have to be made about airblast shielding, flow, fragmentation, and debris interactions (with other debris and with intact structural components). Limited parameter variation studies may be necessary to explore the effects of these assumptions, but this phase of research will seek to provide the debris distribution histories that are most likely in light of present knowledge.

Subtask 4, performed in consultation with fire researchers, will examine the predictions made in Subtask 3 as well as their bases, in order to assess the most needed improvements, in the overall crude debris distribution method used, and costs of the improvements.

By: Workshop 2 Member J. R. Rempel, with independent contributions by Chariman C. K. Wiehle and Members T. E. Kennedy and C. Wilton.

Topic 2

Analysis of Building Frames

Analysis performed over the past several years indicates that basements provide the best shelter space of all available options in buildings of an urban area. An exception is made for basements in flat plate buildings. These are expected to fail suddenly and at relatively low overpressures and therefore should be avoided. We feel that a further exception may be necessary. This refers to basements in tall framed buildings. High-rise buildings, especially those with strong walls, are expected to collapse due to the failure of the frame system at overpressures less than 10 psi. The number of stories that distinguishes low-rise from high-rise is not known at this time. When a high-rise building collapses, the interaction of the framing system with the basement, i.e., overhead slab, foundation, peripheral walls, etc., may be sufficient to damage these components. The result is that the basement loses its strength to resist overpressures. The interaction referred to is illustrated in Figure 4.

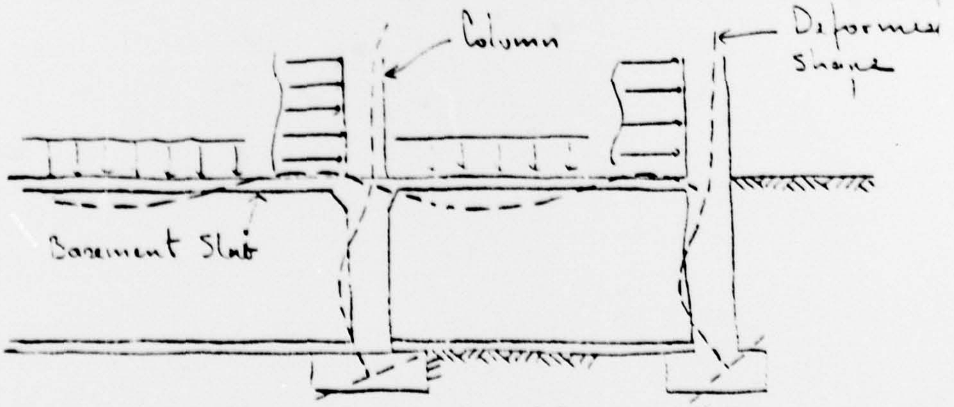

Fig. 4 Interaction of Basement Slab with Framing System

By: Workshop 2 Member A. Longinow

It is precisely this interaction that was neglected in previous analyses dealing with predicting the strength of basements. A study should be initiated to:

1. Define what categories of buildings will collapse when subject to blast overpressures. This should be done in terms of building height, plan area of the building, type of walls (arching, nonarching), percent apertures, type of framing system.

2. Determine to what extent and under what conditions the interaction of the framing system with the basement is important.

3. Develop simplified procedures for predicting the strength of basements taking into account the interaction with the framing system.

4. Develop procedures for expediently upgrading such basements.

The framing system/basement interaction phenomenon is especially important when dealing with hard upgraded basement shelters, i.e., greater than 30 psi. At high overpressures even buildings with weak walls may be expected to overturn or collapse. At the present time our information in this area is very limited.

Topic 3

Comments on Structural Loading/Response Current Work

Current investigations deal with both the loading and response of structures; the work can be categorized as follows:

I. Loading
   a. High resolution data on a specific structure
   b. Oblique angle studies
   c. Reentrant corner studies
   d. Internal loading from theory
   e. Blast shielding

II. Response
   a. Whole body response
   b. Structural response of wood elements

All of the above studies are active and will contribute in varying manners to the problem at hand. Consider initially the loading studies.

Item Ia deals with obtaining the complete loading on a house-like structure. The model is about 2 ft high, has a sloping roof and a basement. A large numbers of pressure gages both inside and outside provide wall loading data (differential pressures) for both normal and oblique angles of incidence. Data can be correlated with large-scale experiments in which wall failures were experienced. More significantly, the oblique angle experiements will be the first ones conducted where the angle selected will be that angle at which the maximum pressures will be developed. That pressure will be more transient, however, than that developed on the front face during a normal angle of incidence.

This loading data should be used as the input to a recognized and approved response code so that the loading change caused by the change in angle of incidence may be evaluated in terms of changes in structural response.

Item Ib is an oblique angle study that is aimed at the low pressure region ($\leq$ 2psi). The pressure increase caused by oblique angle intersection varies in pressure and duration as a function of the shock wave travel distance on the surface of interest. The variance is independent of the side edge effects. An equation for determining the waveform has been determined but is as yet unreported.

It is important that a procedure for accounting for this loading change be incorporated into the loading computation schemed and that the current experiments be extended to higher overpressure regions to complement D-prime scenarios.

Item Ic treats the increase in loading caused by shocks in reentrant corners. A reentrant corner is formed when the geometry of a target causes the shock wave to reflect and re-reflect while there is still substantial pressure. The re-reflections cause very high pressures to develop. They are, however, very localized, and their duration is quite short. The structural significance of these sharp increases must be assessed. Residential and commercial structures have geometries that can lead to the development of these very high pressures.

High interest targets should be assessed as to their likelihood of having a reentrant corner geometry that would make them more vulnerable than they are now believed to be. The expected short duration loads should be used as inputs to a response code to evaluate their importance in evaluating the blast resistance of specific structures.

Item Id deals with a computational technique for determining the shock loading within a structure. This use of acoustic theory, coupled with an existing scheme for determining the filling pressure history within a room (or structure) will allow one to determine the complete load history within a structure. This, coupled with a procedure for determining the exterior loads, will allow one to determine the differential loads on exterior walls. Large structures with nonfailing interior walls represent a special case that is not now being considered.

The current computational work should be checked by data from previously conducted experiment particularly against higher pressure experiments (10-20 psi).

Item Ie deals with the complex problem of shielding. Most blast/structure interaction problems consider classic cases where an undisturbed shock strikes a structure, when in fact in any city or industrial complex the shock wave will be continually redirected by its interaction with responding and nonresponding targets. Diffraction around one building will cause the shock wave to converge on the next building. The diffractive loads could be quite high in this case, but it follows, at least for some element of time, that the drag loading will be reduced. Little is known about the shielding problem and little is being done. Some data (not yet reported) from the 1978 Mighty Mach experiments were obtained in an elementary shielding experiment. Other more definitive tests will be conducted this year (FY 79). These experiments are being conducted with 1000-pound charges and models that are one meter high.

The shielding problem is an important one and experiments to solve it need not be done on such a large scale for the DCPA megaton scenario. Smaller models added to the FY 79 planned experiments could yield data on both the diffraction and drag loadings aspect of the problem. This leads to target response, the second part of the overall proposed work.

Item IIa deals with whole-body response, which received a large measure of effort during recent years. There are now many codes available to treat the problem, and there is ongoing work to refine the codes. Additional work on such codes is unwarranted.

Available codes should be tested against bench mark experiments, however. It is also worthwhile to consider large multistory structures as targets in response codes, which heretofore have been used only for tactical vehicle overturning problems. This should be a high priority task, which could be accomplished in the very near future because of the potential influence on the shelter and debris distribution problems.

Item IIb deals with obtaining the failure pressure of plywood sections under different boundary conditions. This work is ongoing on a small scale. Future plans call for testing sections up to about 6x6 ft.

This work should be compared to static loading data in order to properly assess the effect of dynamic loads on timber construction.

By: Workshop 2 Member W. J. Taylor

<u>Topic 4</u>

Blast Winds in Basement Areas

For the purpose of casualty prediction, there is a need to develop a procedure for predicting velocity fields in basement shelters. This casualty mechanism becomes important when closures are not provided or are collapsed by the blast. The problem we wish to solve is illustrated in Figure 5.

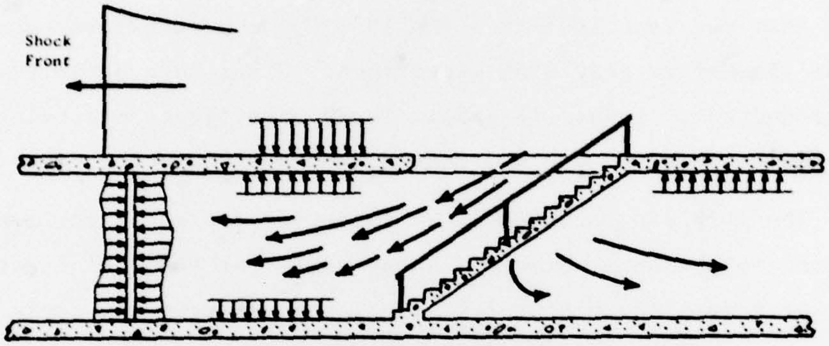

Figure 68. Blast Loading of Basement Areas

Figure 5 is a two-dimensional look at a three-dimensional problem. It illustrates that we are in need of simplified procedures for predicting basement velocity fields and time-dependent loadings on interior walls and partitions. Velocity fields would be used to predict the response of people and objects. Time-dependent pressures would be used to analyze the strength of walls, partitions and the overhead floor system. Partitions and walls are instrumental in holding up the overhead slab. When they fail, the strength of the slab is degraded.

We recommend that a study be initiated to develop a procedure for predicting:

1. Distribution of velocity fields in basements.
2. Distribution of pressure-time histories on vertical and horizontal, interior basement surfaces.

This needs to be a <u>simplified procedure</u> and may be developed based on results of currently existing hydrodynmaic codes.

By: Workshop 2 Member A. Longinow

Topic 5

Random and Systematic Uncertainties

For the most part, the analyses which are performed for DCPA on various of its research programs use deterministic models. Although uncertainties are discussed, and sometimes quantified, this is not done in any systematic manner. There is a need to account for uncertainties and to bound the results of our analyses. One approach to the problem is as follows. Consider a simple basement shelter whose response for a range of overpressures is illustrated in Figure 1.

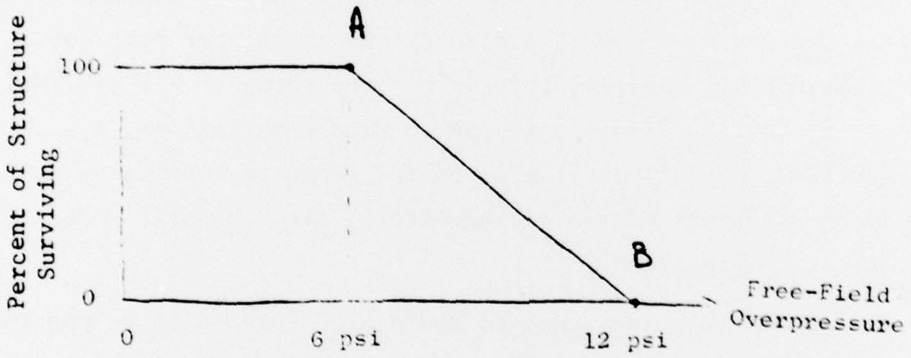

Fig. 1 Shelter Response

This shelter experiences yielding at 6 psi and total collapse at 12 psi. These results, however, represent one set of data and one weapon site, all of which are really random variables. The variations of these random variables should be considered when performing the response analysis. If this were done, then the cumulative distributions for points A (yielding of the shelter) and B (collapse of the shelter) may look as shown in Figure 2.

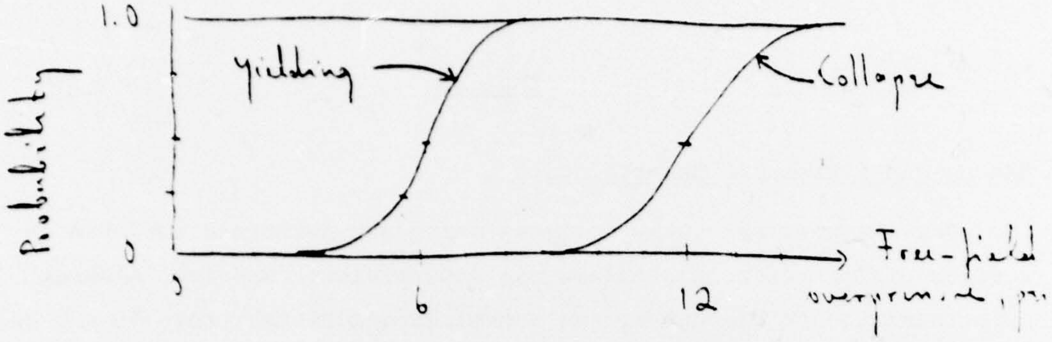

Fig. 2 Cumulative Density Functions for Points A and B of Fig. 1

This graph indicates that 25% of shelters of this type will yield at about 5.5 psi and 100% at about 8.5 psi. This provides us with more information than the graph of Fig. 1 and therefore allows for more confidence in our estimates. However, this is not yet enough. The variability in the functions shown in Figure 2 is due to random variations, i.e., material properties, deviations from specified geometry, workmanship, variations in overpressure due to aiming errors, etc. We still need to consider systematic variations.

Although random variations tend to average out over a large population of like objects, systematic errors do not. Systematic errors arise from the lack of precision in the analysis method such as used to generate the results shown in Figures 1 and 2. Thus, if the lack or precision of the given method is known, then this can be used to adjust the results. this, however, is seldom known and therefore, the most expedient approach may be to determine bounds on the results from the given analysis method, i.e., worst estimate and best estimate. The final result may be as shown in Figure 3.

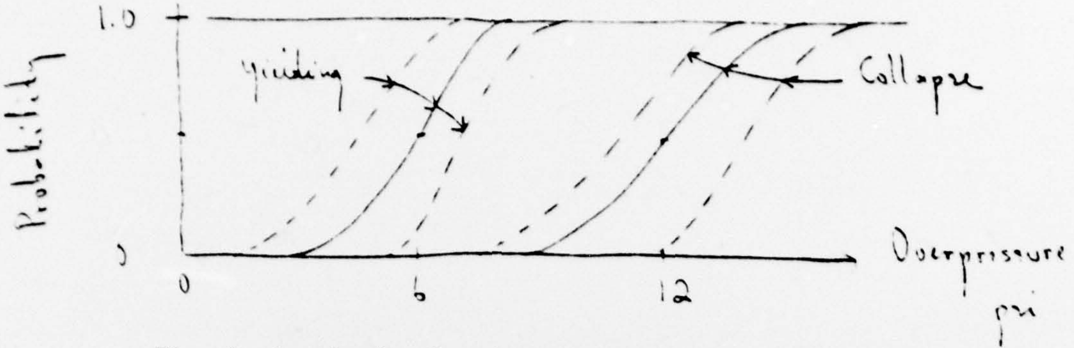

Fig. 3 Cumulative Density Functions for Points A and B of Fig. 1 with Bounds on Systematic Error

A beta distribution may be used to account for variations between these bounds.*

Other methods may be used to quantify variability in results, and the writer is not advocating this particular approach. The foregoing was written to illustrate the point that, due to the large number of uncertainties inherent in any given problem, we need to identify the degree of reliability in our calculations.

By: Workshop 2 Member A. Longinow

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*See Rowan, William H. et al., "Failure Analysis by Statistical Techniques (FAST)," Volume 1, User's Manual, TRW Systems Group, for Defense Nuclear Agency, Oct. 1974 (AD/A - 004 295).