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OPERATION CASTLE

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Summary Report of the Commander, Task Unit 13 Military Effects, Programs 1-9

Pacific Proving Grounds
March — May 1954

Headquarters Field Command
Armed Forces Special Weapons Project
Sandia Base, Albuquerque, New Mexico

January 30, 1959

NOTICE

This is an extract of WT-934, Operation CASTLE, Summary Report of the Commander, Task Unit 13, which remains classified SECRET/RESTRICTED DATA as of this date.

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

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

Operation Castle consisted of six nuclear detonations at the Eniwetok Proving Ground during the period 1 March to 14 May 1954. Two were surface or near-surface land shots: one on a natural island and the other on a man-made island at the end of a causeway. The other four shots were fired on barges: two anchored in reef craters from previous shots and the other two anchored in the lagoon proper.

The Department of Defense (DOD) military-effect program consisted of 37 projects divided among six planned programs and one program (biomedical) added in the field; in addition, one Los Alamos Scientific Laboratory (LASL) program (thermal radiation) was concerned with an area of military-effect interest.

In general, the principal objectives of the military-effect programs were realized. The numerous changes in shot schedules together with the repeated delays due to unfavorable weather forced many revisions and last-minute improvisations in many projects' plans. For some-notably those concerned with documenting fallout-much information was thereby lost; for other projects, such as those involving effects on aircraft, the repeated delays allowed completion of necessary maintenance between shots and resulted in almost 100-percent participation.

Despite uncertain yields and delays, the blast program obtained a considerable amount of worthwhile data and achieved its objectives. Wave forms from the surface gages were nonideal in shape for both overpressure and dynamic pressure and demonstrated that water is not an ideal surface-it sometimes had been presumed to be ideal. Precursors as such were not detected. The uncertainly of the free-air data did not permit any definite conclusions regarding the effects of a nonhomogeneous atmosphere on the blast wave. Data from a megaton burst over a shallow water layer indicated that except for the close-in region, underwater pressures are of comparable magnitude to the direct air-blast overpressures at the same range. In contrast to results from Operation Ivy, studies at Castle indicated that surface water waves do emanate from the central region of the detonation and that refraction and reflection against reefs and shores can significantly affect their destructive capability.

In the nuclear-radiation and fallout program, the unexpectedly high yield of Shot 1 caused destruction of much of the spare equipment on Site Tare, curtailing instrumentation on future shots; however, the important military significance of fallout over large areas beyond the blast- and thermal-damage envelopes was demonstrated dramatically. The realization that activity dissolved in sea water could be a measure of the fallout intensity provided the impetus for the water and aerial surveys that provided valuable data after Shots 5 and 6.

In the blast-effect program, the instrumented, rigid concrete cubicle was exposed to a blast intensity from Shot 3 of only about a tenth of that predicted. Although the specific objective of that particular project was not accomplished, an evaluation of the blast-loading data therefrom made by Sandia Corporation showed that two loading-prediction procedures were reasonably good. The documentation of air-blast effects on miscellaneous structures was an unplanned project of opportunity-one initiated because of the damaging, unexpectedly high yield of Shot 1.

Crater size data was obtained as planned, increasing considerably the reliability in predictions of craters produced by megaton weapons.

Despite unexpected deviations from predicted yields for Shots 1 and 3, breakage data and other results on damage to natural tree stands were obtained.

The underwater minefield-121 mines of various types set 180 feet deep and exposed to a 7.0 Mt surface detonation-gave data on the extent of neutralization of these mines by the detonation.

Extensive data was obtained in the biomedical study of the individuals acciently exposed to significant amounts of fallout radiation. Total gamma dosages up to 182 r were received and produced the physical effects expected.

The actual yield of Shot 1 was approximately 25 percent greater than the positioning yield used for the effects studies on aircraft in flight. An overpressure of 0.81 psi was recorded on the B-36; damage to the B-36 necessitated replacement of the bomb-bay doors, aft lower Plexiglas blisters, and the radar-antenna radome.

The specific techniques used during Castle to predict thermal inputs and responses were inadequate for accurate, close positioning of the aircraft. The procedures utilized to predict blast effects at overpressures less than 1.0 psi were satisfactory. In general, good correlation was obtained between measured and predicted values.

Results of contamination-decontamination studies with the two remote-controlled ships (YAG-39 and YAG-40) indicated that washdown effectiveness based upon the reduction of accumulated gamma dose averaged approximately 90 percent. Measured shielding factors on the YAG-40 were between 0.1 and 0.2 between the second and upper deck and varied from 0.03 and 0.05 between the upper deck and the hold.

Results of the Strategic Air Command's evaluation of interim indirect-bomb-damage assessment (IBDA) procedures indicated that current equipment and operating techniques were adequate. Scope photographs showed the typical horseshoe-shaped configuration during the early moments following time zero. The location of ground zero was established within an accuracy of 600 to 1,100 feet by determining the center of curvature for the horseshoe configuration. Computation of yields proved inaccurate.

In the studies of the effects on the ionosphere, it was observed at the Parry Island ionosphere recorder that severe absorption occurred for several hours following all megaton shots. It appears that the duration of the disturbances was related in some manner to the yield of the device and was about inversely proportional to the distance.

In the investigation of the problem of long-range detection of nuclear explosions, azimuthal errors with ± 3 degrees were experienced in locating the source by utilizing the electromagnetic effects. Reception and identification of detonation pulses when the time of detonation was known to a millisecond were relatively easy; however, to do the same thing on a 24-hour basis with the detonation time unknown would have been much more difficult. It was found that more information is needed on techniques of discrimination. There appeared to be an approximate relationship between yield and the frequency at which peak energy occurs.

The photography program obtained data that was more complete and accurate than any obtained on previous operations. Good measurements of cloud height and diameter over a 10-minute interval were compiled for the five shots photographed.

FOREWORD

This report has had classified material removed in order to make the information available on an unclassified, open publication basis, to any interested parties. This effort to declassify this report has been accomplished specifically to support the Department of Defense Nuclear Test Personnel Review (NTPR) Program. The objective is to facilitate studies of the low levels of radiation received by some individuals during the atmospheric nuclear test program by making as much information as possible available to all interested parties.

The material which has been deleted is all currently classified as Restricted Data or Formerly Restricted Data under the provision of the Atomic Energy Act of 1954, (as amended) or is National Security Information.

This report has been reproduced directly from available copies of the original material. The locations from which material has been deleted is generally obvious by the spacings and "holes" in the text. Thus the context of the material deleted is identified to assist the reader in the determination of whether the deleted information is germane to his study.

It is the belief of the individuals who have participated in preparing this report by deleting the classified material and of the Defense Nuclear Agency that the report accurately portrays the contents of the original and that the deleted material is of little or no significance to studies into the amounts or types of radiation received by any individuals during the atmospheric nuclear test program.

ABSTRACT

Operation Castle consisted of six nuclear detonations at the Eniewtok Proving Ground during the period 1 March to 14 May 1954. Two were surface or near-surface land shots: one on a natural island and the other on a man-made island at the end of a causeway. The other four shots were fired on barges: two anchored in reef craters from previous shots and the other two anchored in the lagoon proper.

The Department of Defense (DOD) military-effect program consisted of 37 projects divided among six planned programs and one program (biomedical) added in the field; in addition, one Los Alamos Scientific Laboratory (LASL) program (thermal radiation) was concerned with an area of military-effect interest.

Program 1, the blast program, was designed to document information on shock parameters in the propagation of the blast wave incident on and through the media of air, ground, and water for devices with yields in the megaton range.

Program 2, the nuclear-radiation program, had two primary objectives: documentation of the initial neutron and gamma radiation, and documentation of fallout from land-surface and water-surface bursts; both efforts were devoted to miltimegaton-yield devices.

Program 3, the blast-effect program, concentrated on (1) obtaining loading data for predicting structural response and damage from multimegaton air blast, (2) gathering data on the dimensions of apparent craters formed by multimegaton-yield shots for use in crater-size prediction, (3) studying blast damage to forested areas, and (4) determining the effects on a planted sea minefield from a water-surface detonation.

Program 4, the biomedical program, was organized immediately after the accidental exposure of human beings on Rongelap, Ailinginae, Rongerik, and Uterik to the fallout from Shot 1, in order to (1) evaluate the severity of the radiation injury to those exposed, (2) provide all necessary medical care, and (3) conduct a scientific study of radiation injuries to human beings.

Program 6 was a composite program covering tests of service equipment and techniques. The ultimate objective of the aircraft-participation projects was the establishment of operational and design criteria concerning nuclear-weapon delivery aircraft, both current and future; measurements of overpressures, gust loading, and thermal effects were made on aircraft in flight. In order to evaluate washdown countermeasures, two converted, remote-controlled Liberty ships were placed in multimegaton fallout patterns. In addition to simulating tactical conditions aboard a ship during and after fallout, these vessels were equipped to collect fallout on their weather surfaces for contamination-decontamination studies and housed instrumentation for studies of fallout material. Also, their weather surfaces served as a radiating surface for shielding studies. Lastly, one project studied effects on the ionosphere.

Program 7, the long-range-detection program, was concerned with the problem of detecting and locating the detonations and documenting them to the maximum extent possible.

Program 9 performed the photographic documentation function. In addition, a photo-

grammetry project determined nuclear-cloud parameters as a function of time and attempted to establish scaling relationships for yield.

Program 18, the thermal-radiation program, was administered by LASL. As a result, the DOD had no projects devoted exclusively to thermal-radiation measurements. Instead, to obtain thermal data of interest and avoid duplication of the Los Alamos efforts, the DOD provided funds for enlarging slightly the scope of Program 18.

In general, the principal objectives of the military-effect programs were realized. The numerous changes in shot schedules together with the repeated delays due to unfavorable weather forced many revisions and last-minute improvisations in many projects' plans. For some—notably those concerned with documenting fallout—much information was thereby lost; for other projects, such as those involving effects on aircraft, the repeated delays allowed completion of necessary maintenance between shots and resulted in almost 100-percent participation.

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PREFACE

This report is the final summary of the military-effect test program conducted during Operation Castle at the Eniwetok, then called the "Pacific," Proving Ground in the spring of 1954. It has been prepared by the Director, Test Division, and his staff of the Office of the Deputy Chief of Staff for Weapons Effects Tests[1], Field Command, AFSWP. Although a few military-effect project reports were not yet published when this summary was written, all had been submitted in draft form and were available for reference in preparing this summary report.

This report (WT-934) supersedes the preliminary summary (ITR-934), which was prepared a month after the last shot was fired on Operation Castle. That preliminary summary had been prepared by the Commander, Task Unit 13, and his staff, with the assistance of Dr. H. Scoville, Jr., then Technical Director, AFSWP.

Contributions to this final summary report were made by the following:

K. D. Coleman, Col, USAF, Director, Test Division
A. H. Higgs, CDR, USN, Deputy Director, Test Division
L. E. Killion, Maj, USAF, Technical Assistant, Test Division
H. T. Bingham, Maj, USAF, Director, Program 1
J. R. Kelso, Blast Branch, Headquarters, AFSWP
G. C. Facer, CDR, USN, Director, Program 2
J. A. Chiment, Maj, USA, Assistant Director, Program 2
V. A. J. Van Lint, Pfc, USA, Staff Assistant, Program 2
J. F. Clarke, LCDR, USN, Director, Program 3
C. W. Bankes, Lt Col, USA, Director, Program 4
F. E. O'Brien, Lt Col, USAF, Director, Program 5
S. G. Shilling, CRD, USN, Assistant Director, Program 5
H. Black, Lt Col, USA, Director, Program 6
W. C. Linton, Maj, USA, Director, Programs 7 and 8
J. G. James, Lt Col, USAF, Director, Program 9
W. M. Sheahan, Lt Col, USA, Assistant Director, Program 9
W. S. Isengard, Maj, USAF, Assistant Director, Program 9
G. P. Forsyth, Maj, USAF, Fiscal
P. W. Williams, CWO, USA, Administrative Officer, Test Division
W. J. Miller, Chief, Reports Branch
E. R. Jennings, Assistant Chief, Reports Branch
D. A. McNeill, ENS, USN, Analysis Officer, Reports Branch.

The preliminary summary report has been used as a point of departure in preparing this final summary; thus, much of the material herein is based directly on the preliminary version. The following had made significant contributions to that preliminary report:

H. K. Gilbert, Col, USAF, (DWET), Commander, Task Unit 13

[1] At the time of Operation Castle, this office was designated as the Directorate of Weapons Effects Tests (DWET).

N. E. Kingsley, Capt, USN, (AFSWP), Deputy Commander, Task Unit 13, and Director, Program 3

Dr. H. Scoville, Jr., Technical Director, AFSWP

W. L. Carlson, CDR, USN, (DWET), Director, Program 1

E. A. Martell, Lt Col, USA, (DWET), Director, Program 2

E. P. Cronkite, CDR, USN, (NMRI), Director, Program 4

D. I. Prickett, Lt Col, USAF, (DWET), Director, Programs 5 and 6

P. R. Wignall, Col, USAF, (AFOAT-1), Director, Program 7

J. G. James, Lt Col, USAF, (DWET), Director, Program 9

This final report is organized to present (1) a general summary of the background of military-effect participation on Castle in the first chapter, (2) a general discussion of the findings of each test program in subsequent chapters, and (3) a brief abstract of each project and bibliographical information on each project report in the Appendix.

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TABLES

FIGURES

Chapter 1
INTRODUCTION

The Armed Forces Special Weapons Project (AFSWP) was informed in April 1952 of plans of the U. S. Atomic Energy Commission (AEC) to conduct a developmental test of high-yield weapons at the Eniwetok Proving Ground (EPG) in the fall of 1953 (subsequently deferred to spring of 1954) under the code name Castle (Reference 1). Inasmuch as Operation Ivy — the first test involving high-yield weapons — was then being prepared for conduct in the fall of 1952, no immediate steps were taken by AFSWP to plan for Operation Castle. In August 1952, AFSWP requested the military services to submit project proposals for a military-effect test program for Castle (Reference 2). On the basis of the proposals submitted, AFSWP presented to the Committee on Atomic Energy of the Research and Development Board on 17 December 1952 an outline for a military-effect test program. After appropriate discussion (including additional hearings on the long-range-detection program, Program 7, and the shipboard-countermeasures project, Project 6.4), the Research and Development Board approved the program (Reference 3) and initiated release to AFSWP of research and development funds (see Section 1.3).

1.1 MILITARY-EFFECT PROGRAM

The military-effect program, as approved by the Research and Development Board, was of necessity couched in very general terms. Only preliminary data was as yet available from Operation Ivy, and a firm shot schedule for Castle had not yet been promulgated by the AEC. However, a tentative project list was framed in accordance with the following precepts: (1) Each project must be justified on the basis of a military requirement. (2) Each project must be such that its objectives cannot be attained except by a full-scale test, its objectives cannot be attained at the Nevada Test Site (NTS), and its objectives can be attained at the EPG without unreasonable support requirements. (3) Each project must conform to the shot schedule — yields, locations, burst heights — established for the developmental program of the AEC.

In early March 1953, representatives of AFSWP met at Los Alamos with staff members of the J-Division, Los Alamos Scientific Laboratory (LASL) to review compatibility of the desired Department of Defense (DOD) program with the AEC developmental program. Except for non-inclusion of an air burst by the AEC, the programs were generally compatible. As an outgrowth of this meeting, plans for a thermal program (Program 8) under DOD sponsorship were dropped, since LASL agreed to expand its Program 18 to include thermal measurements of particular interest to the DOD; also, a biomedical project involving the exposure of mice to neutron flux was eliminated.

During the detailed planning and preparation for the operation, many revisions of project plans were necessitated by changes in shot schedules, detailed analysis of Ivy data, and support considerations. However, there was no general revision of project objectives, with one exception: the objective of Project 3.2 was reduced from true crater measurement to apparent crater measurement, because the probability of meaningful data did not justify the support effort required. An additional project was approved at this time: Project 3.4, Minefield Clearance, under Navy sponsorship.

The possibility of expanding the objective of Project 1.4 to include underwater pressure-versus-time measurements from a surface burst over deep water was explored. Although LASL agreed to relocation of one of the barge shots to a position outside of the lagoon, with certain restrictions, the estimated yields of the devices then scheduled were too high to make a satisfactory test probable. In view of this and the additional support involved, the matter was dropped.

During the operational phase, the following projects were added to the military-effect test program:

Project 2.7 (Study of Radiation Fallout by Oceanographic Methods) was added to obtain

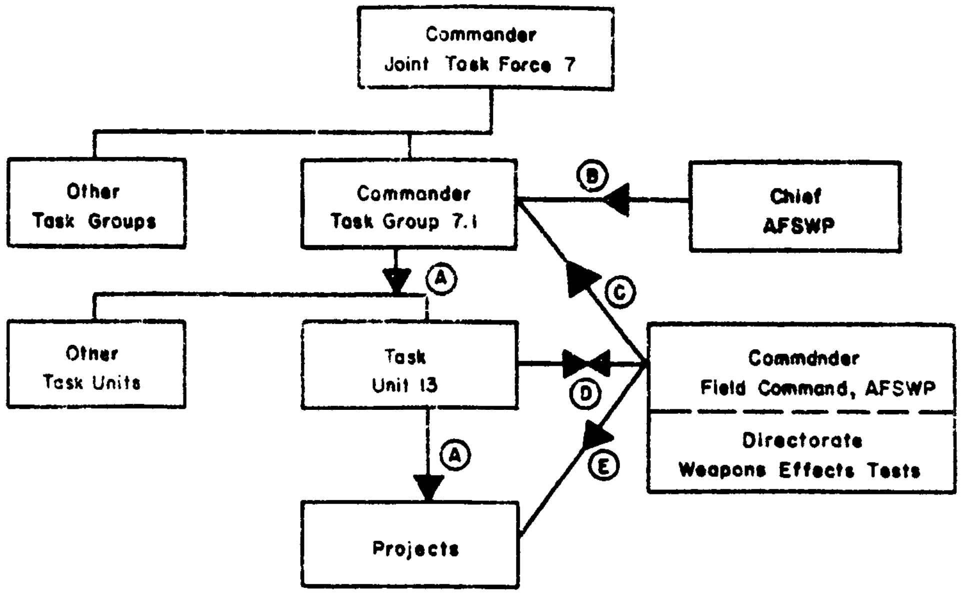


Figure 1.1 Organizational relationships.

additional fallout data by employment of water sampling and other techniques in free-ocean areas.

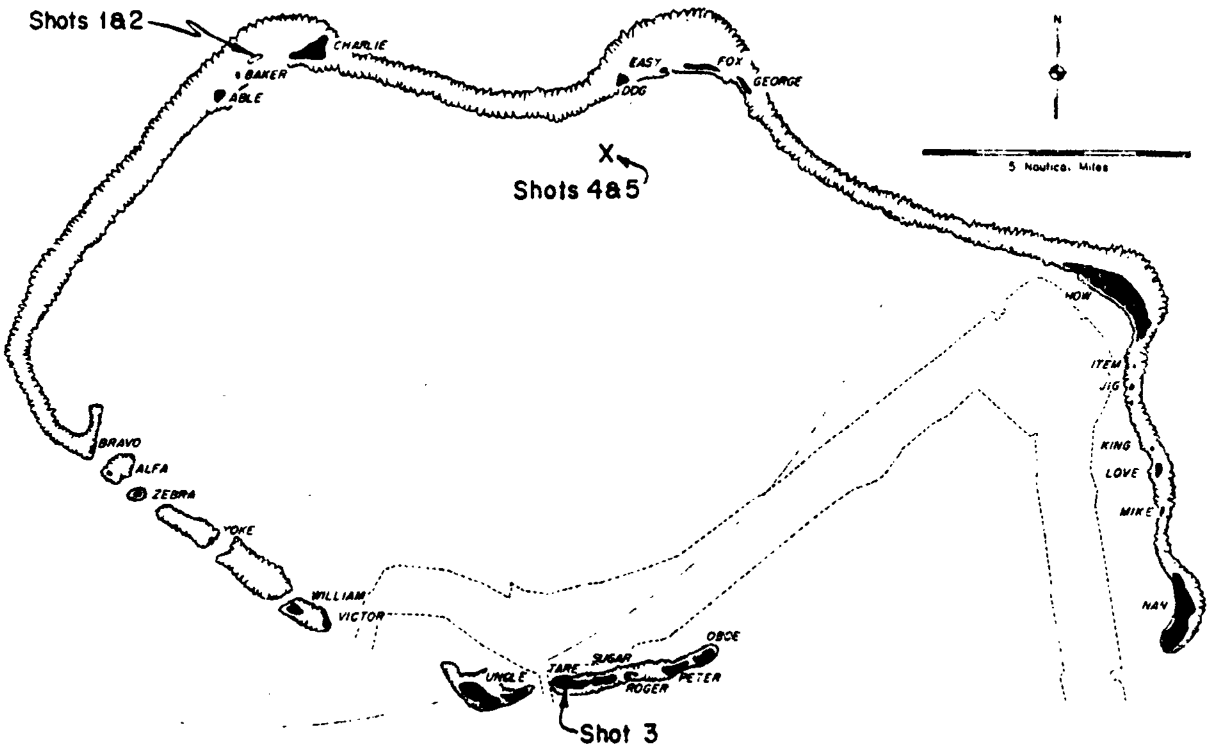
Project 3.5 (Blast Effects on Miscellaneous Structures) was added to document the damage to shore facilities arising from the unexpectedly high yield of Shot 1.

Project 4.1 (Study of Response of Human Beings Accidentally Exposed to Radiation Due to Fallout from High Yield Weapons) was added to document, incidental to medical treatment, observations of personnel evacuated from those atolls east of Bikini unexpectedly contaminated by fallout from Shot 1.

The physical damage and adverse radiological situation arising from Shot 1, coupled with repeated postponements of subsequent events because of weather, placed the military-effect participation in subsequent shots on a tentative basis. In particular, the adverse effects of the following factors were very real: (1) gradual loss of personnel as their total accumulative radiation dosage exceeded the maximum limit because of radiological contamination of Bikini Atoll land areas to which entry was mandatory for project purposes; (2) loss of equipment by Projects 2.2 and 2.5 by a secondary fire from Shot 1 on the Tare Island support facility; (3) conversion from land-based to ship-based operations at Bikini after Shot 1, with attendant difficulties of personnel transport, communications,

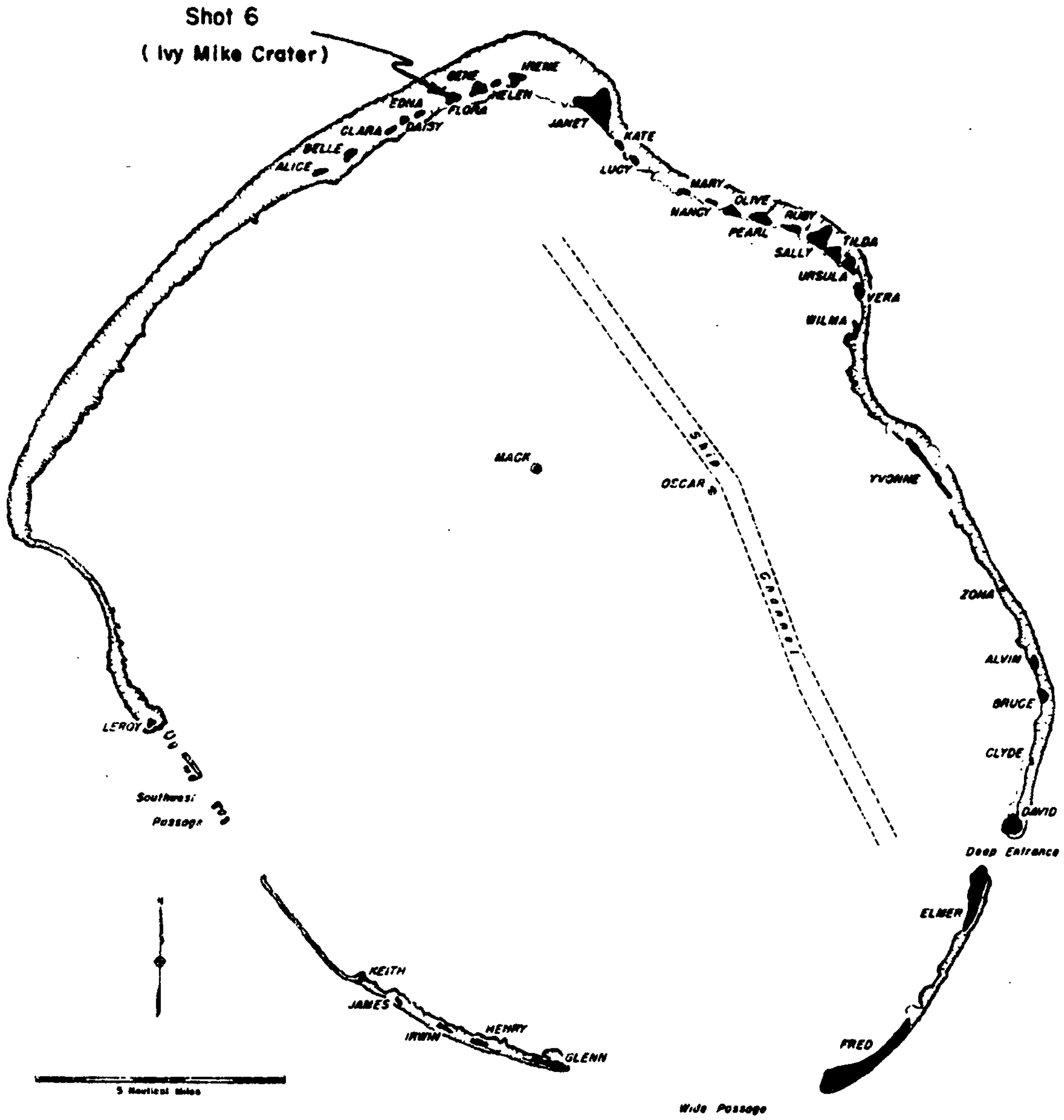
TABLE 1.1 SUMMARY OF SHOT DATA AND ENVIRONMENTAL CONDITIONS

	Shot 1	Shot 2	Shot 3	Shot 4	Shot 5	Shot 6
Date (EPG)	1 March 1954	27 March 1954	7 April 1954	26 April 1954	5 May 1954	14 May 1954
Time (EPG-WWV), not corrected for delay in transmission	0644:59.972 ± 0.010	0630:00.373 ± 0.001	0620:00.398 ± 0.001	0610:00.577 ± 0.001	0610:00.142 ± 0.001	0620:00.387 ± 0.002
Type	Land	Barge	Land	Barge	Barge	Barge
Location	Bikini, West of Charlie (Namu) on Reef	Bikini, Shot 1 Crater	Bikini, Tare (Eninman)	Bikini, on Barge at Intersection of Arcs with Radii of 6,900 ft from Dog (Yurochi) and 3 Statute Miles from Fox (Aomoen)		Eniwetok, Ivy Mike Crater, Flora (Elugelab)
Yield, Mt; Fission, Rad Chem Total	15.0 ± 0.7	11.0 ± 0.5	0.130 ± 0.012	7.0 ± 0.3	13.0 ± 1.0	1.7 ± 0.3
Code Name	Bravo	Romeo	Koon	Union	Yankee	Nectar
Device						
Holmes and Narver Coordinates	N 170,617.17 E 076,163.98	N 170,635.05 E 075,950.46	N 100,154.50 E 109,799.00	N 161,698.83 E 116,800.27	N 161,494.43 E 116,688.15	N 147,750.00 E 067,790.00
Station Number	20	90	50	30	40	10
Height of Center of Gravity of Device above Barge Deck or Foundation, ft	7	7	13.6	7	7	7
Height of Barge Deck above Water, ft	—	7.2	—	6.8	6.6	7.2
Foundation above Datum (6 inches below Mean Low Water Spring Tides), ft	10	—	8.0	—	—	—
Tide at Zero Time (Datum is 6 inches below Mean Low Water Spring Tides	2.72	3.22	5.92	2.91	5.70	2.35
Dew Point, F	72	72	75	76	75	75
Atmosphere Pressure, mb, at GZ	1006.1	1012.4	1009.7	1007.4	1010.8	1006.4
Surface Air Temperature, F	80	80	81	81	80.8	80
Surface Relative Humidity, pct	77	77	82	86	84	85
Surface Wind Direction at Shot Time	070	040	090	062	070	090
Velocity, knots	15	10	13	18	20	17
Atmospheric Transmission, total pct	GZ to George 10.6 GZ to Tare 12.0 GZ to Delta 58.0-65.0	SZ to Tare 22 SZ to Fox 8	GZ to How 0 GZ to Nan 5	SZ to Nan 26 SZ to How 28	SZ to Nan 1.1 SZ to How 1.6	SZ to Janet 67 SZ to Fred 0



Airukiiji	Oboe	Bokonfuaaku	Item	Ourukaen	Zebra
Airukiraru	Peter	Bokororyuru	Bravo	Reere	Sugar
Aomoen	George	Chieerete	William	Rochikarai	Love
Arriikan	Yoke	Eniairo	King	Romurikku	Fox
Bigiren	Roger	Eniirikku	Uncle	Rukoji	Victor
Bikini	How	Eninman	Tare	Uorikku	Easy
Bokoaetokutoku	Alfa	Enyu	Nan	Yomyaran	Jig
Bokobyaadaa	Able	Ionchebi	Mike	Yurochi	Dog
Bokonejien	Baker	Namu	Charley		

Figure 1.2 Bikini Atoll.



Aaraanbiru	Vera	Coral Heads	Mack, Oscar	Parry	Elmer
Aitsu	Olive	Eberiru	Ruby	Piiraai	Wilma
Aniyaanii	Bruce	Elugelab	Flora	Pokon	Irwin
Aomon	Sally	Engebi	Janet	Ribaion	James
Biijiri	Tilda	Eniwetok	Fred	Rigili	Leroy
Bogairikk	Helen	Giriinien	Keith	Rojoa	Ursula
Bogallua	Alice	Igurin	Glenn	Ruchi	Clara
Bogombogo	Belle	Japtan	David	Rujoru	Pearl
Bogon	Irene	Kirinian	Lucy	Runit	Yvonne
Bokonaarappu	Mary	"M"	Zona	Sandildefonso	Edna
Chinieero	Alvin	Mui	Henry	Teiteiripucchi	Gene
Chinimi	Clyde	Muzin	Kate	Yeiri	Nancy
Cochita	Daisy				

Figure 1.3 Eniwetok Atoll.

and equipment handling; (4) severe boating conditions at Bikini during delay periods, which restricted maintenance of test stations; (5) degeneration of test stations by salt spray, humidity, rain, and intense sun during the repeated postponements of shot days because of weather; (6) changes of shot sequence, sites, and predicted yields; (7) extreme variations in actual and predicted yields; and (8) cancellation of one shot (Echo) for which elaborate instrumentation had been prepared.

1.2 ORGANIZATION AND ADMINISTRATION

The solicitation, review, and coordination of project proposals was undertaken in accordance with the basic mission of the AFSWP. In April 1953, the Joint Chiefs of Staff augmented the mission of the AFSWP by directing the AFSWP ". . . to exercise technical direction of weapons effects phases of development tests or other tests of atomic weapons

TABLE 1.2 FUNDING AND COSTS, MILITARY-EFFECT TEST PROGRAM

Program	Title	Initial R&D Funding	R&D Costs to 1 October 1957
1	Blast and Shock Measurements	$2,200,000	$1,603,176
2	Nuclear Radiation Studies	1,400,000	963,891
3	Structures, Equipment and Material	700,000	367,218
4	Biomedical Studies	200,000	7,901
6	Service Equipment and Techniques	1,211,750	1,073,600
7	Long Range Detection	350,000	239,149
8	Thermal Radiation Measurements	300,000	20,000*
9	Supporting Measurements	1,000,000	132,210
Field Command, AFSWP		—	25,268
	TOTAL	$7,361,750	$4,432,413

* To Program 18, LASL, for thermal measurements.

within any task force organization for tests conducted outside the continental United States" (Reference 4). The mode of implementing this expanded mission for Castle was delineated in an agreement between the Commander, Joint Tast Force 7, and Chief, AFSWP (Reference 5). As a part of this agreement, AFSWP formed and manned Task Unit 13 (activated 1 June 1953) as a unit under Task Group 7.1 and exercised technical direction by direct communication with Commander, Task Unit 13, and as necessary with Commander, Task Group 7.1 (see Figure 1.1). At the request of AFSWP (Reference 6), personnel of project agencies were ordered by their respective services to report to the Commander, Task Group 7.1 through the Commander, Task Unit 13 for planning and coordination control during nonoperational phases and for full operational control during the on-site operational phase.

The Chief, AFSWP, supervised the preliminary work on the military-effect program, with the Weapons Test Division performing the detailed coordination. In March 1953, the Commanding General, Field Command AFSWP, was assigned the responsibility for the technical direction of the program. This responsibility was discharged through the Directorate of Weapons Effects Tests, Field Command AFSWP. During the operational phase, the responsibility for technical direction reverted to the Chief, AFSWP.

1.3 FUNDING

Research and development (R & D) funds were allotted directly to the participating project agencies by AFSWP (initially by Headquarters, but subsequently by the Field Command) to meet research and development costs (see Table 1.2) other than those for on-site construction and support. These latter costs were met by transfer of R&D funds from AFSWP to the Albuquerque Operations Office (then the Santa Fe Operations Office) of the AEC. Extra-military funds were budgeted and expended by Joint Task Force 7 as necessary to meet the extra-military costs of the participating project agencies.

1.4 SUMMARY DATA

Pertinent information for all Castle shots is summarized in Table 1.1; shot locations are noted on the maps of Bikini and Eniwetok presented as Figures 1.2 and 1.3. The yields listed were the latest and most reliable when this report was prepared. Minor discrepancies will be noted if these are compared with those listed in References 13 and 14; however, both of these reports were published within a year after the operation was completed. The slight revisions brought about by subsequent data analysis were supplied, upon request of Field Command, AFSWP, by the laboratories (References 15 and 16).

Chapter 2
BLAST AND SHOCK

The blast-and-shock program was designed to document information on shock parameters in the propagation of the blast wave incident on and through the media of air, ground, and water. The isolation of the EPG allowed experiments on the effects produced by test devices whose yields were in the megaton range. Only limited blast measurement at long ranges had been made for Ivy Mike, which was the first megaton device detonated by the United States. In a sense, the program was an extension of the Operation Ivy experiments; additional experiments were needed to confirm, explain, or supplement the Ivy data.

A considerable quantity of worthwhile data was obtained from Castle participation. Despite uncertain yields and shot delays, the program was able to adapt itself to these changing situations and achieve most of the objectives which were originally conceived.

2.1 OBJECTIVES

After Ivy, certain general objectives were defined for blast programs on future full-scale tests at the EPG; it was on these requirements that the Castle program was based. It was determined that free-air measurements should be made on devices with yields greater than 540 kt to check the basic free-air curve. Surface measurements were needed from high-yield detonations to validate the use of height-of-burst curves and the scaling relations in such yield ranges. Of great importance was the documentation of adequate dynamic-pressure measurements, to increase the knowledge of this parameter in itself as well as its relation to damage. More information was needed on the effects on the blast wave as it is propagated through a nonhomogeneous atmosphere. It was expected that refraction might also be noticed at distant ranges along the ground, because such effects had been observed for the Ivy Mike shot. Considerably more information was desired on blast effects over and through the water. Little data was available to define shock propagation in very-shallow water or describe the water shock produced by nuclear detonation over deep water. It was also hoped to obtain data on the transmission through the water via the sound fixing and ranging (SOFAR) channel as well as the outline and activity of the surface water waves.

The Castle shots were all developmental devices, so that the military-effect programs had to be fitted to available yields, heights-of-burst, and shot geometry. In all cases, the height-of-burst was essentially zero; that is, surface bursts on land, water, or the atoll rim.

From these general objectives, then, the following specific objectives were evolved: (1) determine air-blast overpressures as a function of altitude and time at relatively short distances above high-yield surface detonations; (2) obtain data on the occurrence of a precursor from high-yield surface detonations; (3) determine the time characteristics of air-blast overpressure as a function of distance from surface zero for high-yield weapons, in order to confirm the validity of scaling laws; (4) check the theoretical relationship between dynamic pressure and overpressure and evaluate dynamic pressure as a damage parameter; (5) obtain information on the pressure-time history of underwater shock in shallow water for high-yield surface detonations; (6) determine the transmission in water of acoustic pressure signals generated by high-yield detonations; (7) determine water-wave phenomena in shallow water from high-yield surface detonations; and (8) determine ground accelerations at distances relatively close to surface zero for high-yield detonations.

2.2 SCALE FACTORS

Air-pressure data were reduced to standard conditions—equivalent to a 1-kt burst at sea-level ambient pressure and to 20 C ambient temperature. The standard Sachs corrections were applied:

$$\text{Pressure } S_p = \frac{14.7}{P_o}$$

$$\text{Distance } S_d = \left(\frac{P_o}{14.7}\right)^{1/3}\left(\frac{1}{W}\right)^{1/3}$$

$$\text{Time } S_t = \left(\frac{T_o + 273}{293}\right)^{1/2}\left(\frac{P_o}{14.7}\right)^{1/3}\left(\frac{1}{W}\right)^{1/3}$$

Where: W = yield of the device, kt

P_o = ambient pressure at burst elevation, psi

T_o = ambient temperature at burst elevation, C

Table 2.1 presents the pertinent scaling factors used in converting the data to standard conditions.

2.3 SURFACE MEASUREMENTS

The significant factor affecting measurements of the blast wave along the surface was that all shots in the scheduled Castle series were surface bursts, either on atoll islands or lagoon barges, with yields in the megaton range. Considerable interest had been maintained in surface bursts; it was obvious that more-complete data was necessary to improve the state of the knowledge. Safety consideration restricted full-scale tests of even kiloton-range devices on the surface at the Nevada Test Site. It was hoped that Castle would supply answers to questions on large-yield surface bursts.

Upshot-Knothole had confirmed the existence of the precursor, and while its fundamental mechanism was not fully understood, its effect on the various blast parameters was quite evident. However, these were precursors from aboveground bursts. The surface-burst intercepts of the height-of-burst curves were based on Jangle surface and the Ivy Mike events as well as the Greenhouse and Sandstone tower shots. Castle offered an opportunity to check these data, as well as to investigate the possibilities of a precursor forming from surface bursts, even though it was recognized that Nevada precursors might not be duplicated under the EPG conditions of atmosphere and ground surface.

Upshot-Knothole also showed the fallacy of assuming side-on overpressure in the precursor region as a basic damage parameter to drag-sensitive targets. It was found that overpressure and dynamic pressure were not affected in the same manner by the precursor: dynamic pressures were not only considerably greater than those calculated from measured overpressure but were even greater by factors of two to three over those calculated from the ideal curve. It was also possible that dynamic pressure might assume added significance with the high-yield devices because of the increased positive-phase duration.

2.3.1 Overpressure. A fact of major significance noted on the records of both overpressure and dynamic pressure was the non-ideal shape of the wave forms. It had been thought—the possibility of precursor notwithstanding—that considering the long distances of water travel inherent in the instrumentation of long blast lines at the proving ground, most wave shapes would appear nearly as the ideal: a fast rise followed by a

TABLE 2.1 SCALING FACTORS

Shot and Environment	1 (Surface, Reef)	2 (Surface, Crater)	3 (Surface, Land)	4 (Surface, Lagoon)	5 (Surface, Lagoon)	6 (Surface, Crater)
Yield, Mt	15.0	11.0	0.130	7.0	13.0	1.7
P_0, mb	1006.1	1012.4	1009.7	1007.4	1010.8	1006.4
P_0, psi	14.58	14.67	14.63	14.60	14.65	14.58
T_0, F	80.0	80.0	81.0	81.0	80.8	79.9
T_0, C	26.66	26.66	27.22	27.22	27.12	26.61
S_p	1.0078	1.0016	1.0046	1.0068	1.0035	1.0078
S_d	0.0405	1.0450	0.1973	0.0522	0.0425	0.0836
S_t	0.0409	0.0456	0.1997	0.0528	0.0430	0.0845
S_l	0.0412	0.0456	0.2006	0.0531	0.0431	0.0854

smooth decay. This was not observed. A typical series of overpressure records is shown in Figure 2.1. The low-pressure records, after an initial sharp rise, exhibit a continuing slower rise to peak before the decay—a hump-back appearance. In the higher-pressure regions, this second rise is not prominent; however, the front is rounded and peak pressures are smaller than would be obtained by extrapolating the decay back to the arrival time. The cause appears to be associated with the water-laden medium through which the blast wave was propagated: specifically, the water cloud picked up by passage of the shock over the water surface. Shock photography along the surface showed what appears to be spray behind the shock fronts, particularly on Shots 2 and 4. It may be concluded that water does not constitute or approximate the ideal surface—it sometimes had been assumed as ideal.

Precursors that could be identified as such were not observed on any of the records. Two shots on which this phenomenon might have been detected were modified: one was cancelled entirely and the other experienced a much-lower yield than planned and instrumented for.

2.3.2 Dynamic Pressure Free-Field Measurements. Various types of gages were selected for those measurements, recording either dynamic pressure, q, directly or some related parameter—density, temperature, total pressures—that would aid in the interpretation of results. All gages were placed 6 feet aboveground, a compromise to eliminate interference effects from the ground yet allowing a strong enough mount to withstand the high dynamic pressures. Gages were placed on each shot to span the 10-to-40-psi range of overpressure. Self-recording gages mounted 3 feet above ground level were also located in this pressure range.

Participation on Shots 1 and 2 was a minimum effort, and the low yield of Shot 3 precluded effective results. Shots 4 and 5 gave dynamic pressures higher than those computed from the measured overpressure. As in the overpressure records, the wave forms were quite distorted and non-ideal in character, as shown in Figure 2.2. All of these gage stations were located near the edge of the water, except for the measurement on Shot 6 which was preceded by some 800 feet of blast travel over an island surface; the latter record showed only a slightly rounded wave form with a peak dynamic pressure in good agreement with that value computed from the measured overpressure. For those dynamic pressures measured near the edge of the water, it was assumed that the blast wave picked up water droplets which contributed to the disturbed appearance of the wave form and that water is not an ideal surface.

The primary objective in taking dynamic-pressure measurements was a study of the pressure-time records to check the theoretical relation between dynamic pressure and

TABLE 2.2 COMPARISON OF MEASURED AND CALCULATED VALUES OF DYNAMIC PRESSURE

Shot	Type of Gage	Measured Δp	Calculated q	Measured q	Ratio of Measured q to Calculated q
		psi	psi	psi	
6	S/R* Pitot static	122.0	166.0	138.0	0.83
6	S/R* Pitot static	22.5	19.6	23.5	1.20
5	S/R* Pitot static	24.3	11.7	11.7	1.00
6	Diff pres q	23.3	10.7	13.0†	1.21
5	Drag q	23.3	10.7	13.3†	1.24
6	S/R* Pitot static	22.4	10.1	10.1	1.00
6	Pitot static	21.0	8.9	8.5	0.96
4	S/R* Pitot static	20.0	8.17	9.20	1.13
6	S/R* Pitot static	19.0	7.5	8.8	1.17
6	S/R* Pitot static	16.8	5.95	5.5	0.92
4	Diff pres q	14.6	4.3	7.0†	1.63
4	Drag q	14.6	4.3	7.5†	1.74
3	S/R* Pitot static	7.60	1.31	1.1	0.84
3	S/R* Pitot static	4.43	0.46	0.77	1.67
3	S/R* Pitot static	3.80	0.34	0.47	1.38
3	S/R* Pitot static	3.26	0.25	0.50	2.00

* S/R refers to self-recording mechanical gages of Project 1.2b (BRL). All other gages are electronic gages employed by Project 1.3 (SC).

† Maximum value of q which is indicated here occurred at a later time than maximum value of Δp.

overpressure. From a somewhat-limited quantity of data, it was found that the relation did not hold where the path of the blast wave approaching the gage station was over a water surface. Table 2.2 shows a comparison of measured and calculated values of dynamic pressure.

2.3.3 Dynamic Pressure as a Damage Parameter. Jeeps were used as representative models to investigate further the role of dynamic pressure as the damage parameter to consider for drag-sensitive targets. Participation was planned for two shots, one of which was cancelled; actual participation was accomplished on Shots 3 and 6. The low yield of Shot 3 gave low dynamic pressures and consequent light damage to vehicles. Satisfactory damage—light to severe—was attained on Shot 6.

The limited data obtained were not conclusive enough to permit an evaluation of dynamic pressure as a damage parameter to be applied to the jeep as a drag-sensitive target. The response of such a target depends on the loading, which is a function of both dynamic pressure and duration. The results obtained did not allow a separation of the effect of the one damage parameter from that of the other.

Furthermore, it was not possible to determine specific levels of dynamic pressure for different degrees of damage. Consequently, it was difficult to justify the cube-root

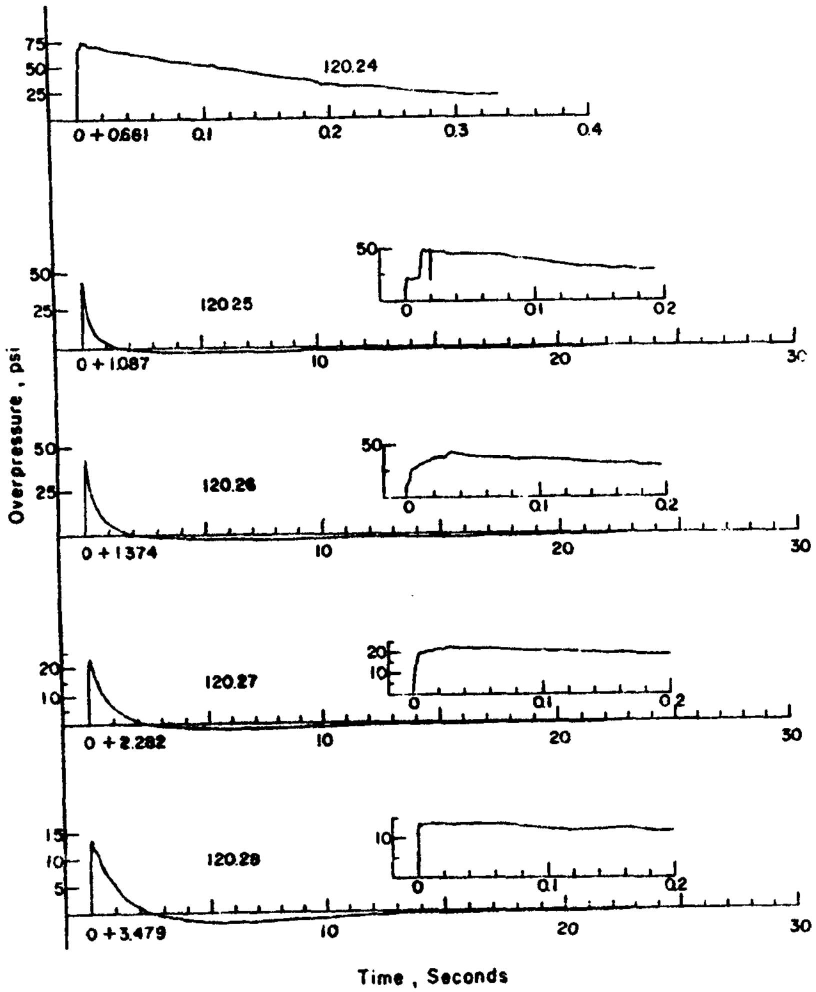


Figure 2.1 Overpressure versus time, Shot 6.

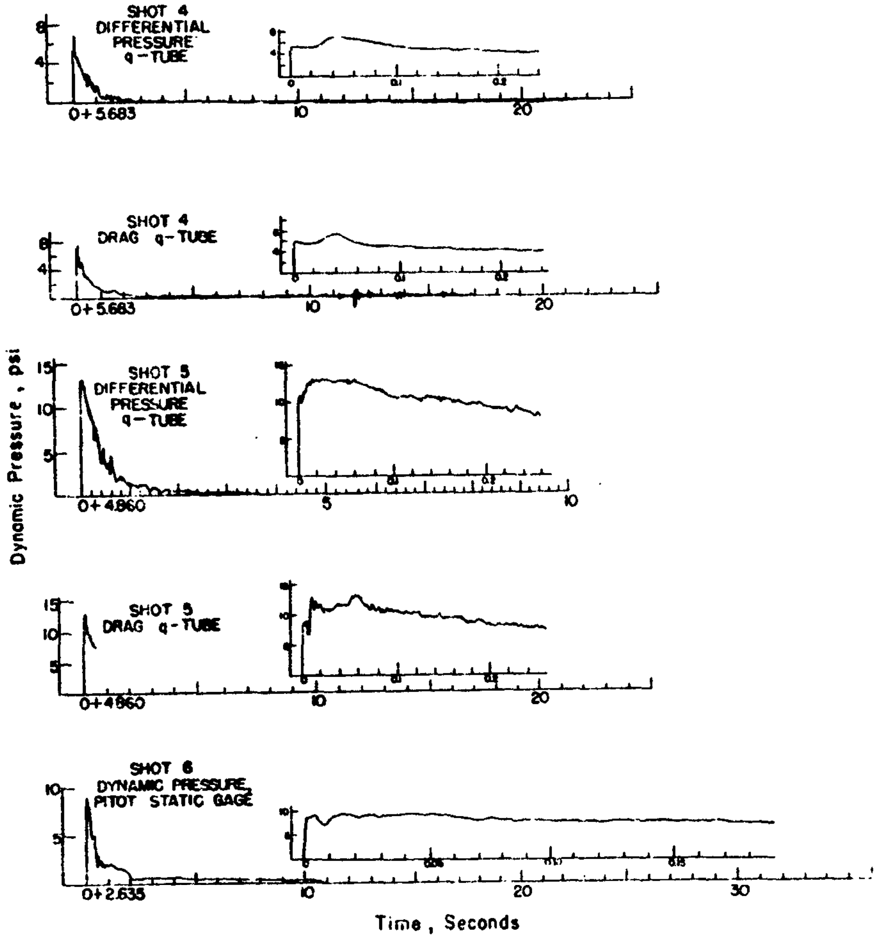


Figure 2.2 Dynamic pressure versus time, Shots 4, 5, and 6.

scaling for vehicle damage proposed by Project 1.8, since this attached importance only to dynamic pressure. Castle data was utilized in the preparation of a composite AFSWP report (Reference 12), which showed that $W^{0.4}$ scaling is the most-appropriate method for predicting damage to military field equipment.

2.3.4 Effects of Rain. Ground zero of Shot 3 and most of the Tare complex to the east were covered by heavy clouds with accompanying shower activity at zero time, a situation well documented by radar, photography, and transmissivity measurements. Although the low yield of this shot failed to satisfy many of the program's objectives, very inter-

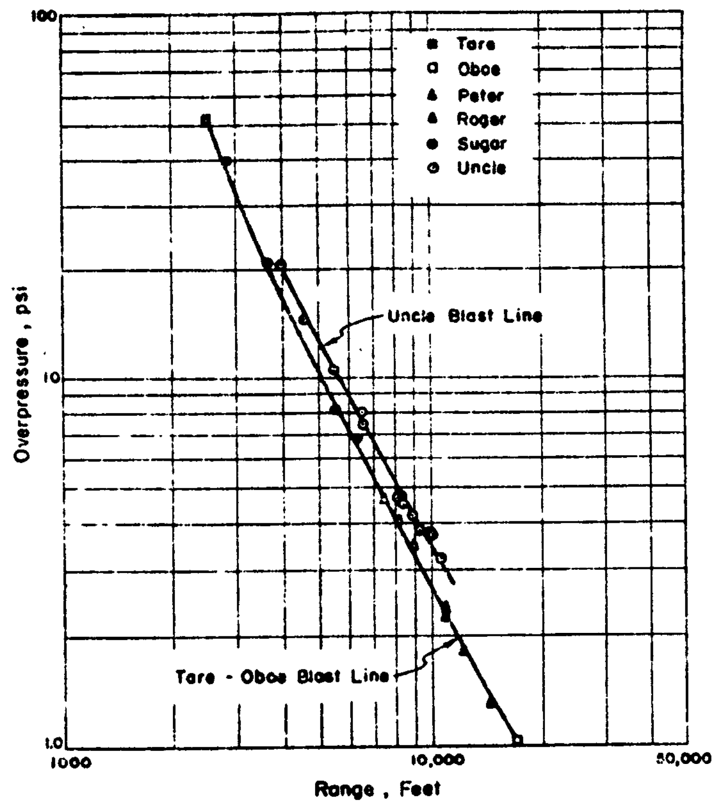


Figure 2.3 Overpressure versus ground range, as measured for Shot 3.

esting data was obtained that appears to be directly associated with the presence of high moisture content in the air.

Two instrumented blast lines had been established on bearings approximately 180 degrees apart—along the Tare complex eastward to Oboe Island and westward through Uncle Island. When the data had been reduced and plotted, it became obvious that an anomaly existed: pressures obtained from the Tare line were somewhat lower than those recorded by the Uncle gages.

Possible correlation of this effect with low clouds or rain was suspected when the radar-scope photography disclosed that Uncle and that area immediately to the west of ground zero was relatively clear, while a solid return over the Tare complex indicated heavy clouds and, possibly, actual rain.

Figure 2.3 shows a plot of pressure data from both lines. Project 1.2b instrumented the east and west lines with self-recording gages, while Project 1.2a covered only the

Tare complex with electronic gages. There was a definite and consistent variation in the data between the two lines.

It is recognized that a moisture-laden air will attenuate pressures in the blast wave, simply because blast energy will be lost by an amount proportional to that which is necessary to evaporate the suspended water droplets or rain in the path of the shock. Studies on the problem by the two projects concerned indicated that a moderate shower could contribute sufficient water content to the air to account for the deviation in the pressure-distance curves of the two blast lines (described in the Project 1.2a and 1.2b reports, see Appendix).

2.3.5 Comparison with the 2W Theory. It was anticipated that sufficient data would be obtained from Castle to allow a quantitative comparison to be made, for surface bursts, with the ideal case. Theoretically, such a burst over a perfectly reflecting plane should act like one of twice its yield in free air. Data from previous surface bursts, Jangle Surface and Ivy Mike, did not entirely confirm this theory. The question was the value of the reflection factor — of necessity between 1 and 2. From Castle data, it appeared to be certainly less than 2 — probably between 1.6 and 2.

The difficulty, and the reason a more-definite figure cannot be assigned, lies with the determination of yield of the multi-stage devices; fireball and time-of-arrival methods used to estimate yield involve the 2W assumption. A method independent of this assumption is necessary. Unfortunately, only radiochemical analysis, which determines only the fission yield of a device, satisfies this restriction.

Figure 2.4 shows a pressure-distance plot of all the surface overpressures scaled to 1 kt at standard sea-level conditions, along with similar data from Jangle Surface and Ivy Mike, compared to the 1W and 2W free-air composite curves. All measured data were scaled to 1 kt at sea-level conditions. The solid line represents a composite pressure-distance curve for a 1-kt surface burst based primarily on Castle measurements. Yields used for data reduction were based on a radius-time history of the fireball (involving the 2W assumption)[1]. All arrival-time data are compared in Figure 2.5 on a similar basis.

There were no apparent effects due to refraction observed during Operation Castle. In fact, Figure 2.4 indicates that overpressures at long ranges fall closer to the 2W free-air curve than do overpressures at closer ranges.

2.4 ABOVE-SURFACE MEASUREMENTS

The results of Ivy King confirmed the scaling laws for free-air pressures up to a yield of 540 kt. Data obtained from the Mike event, however, were confined to the low-pressure region. There was reason to suspect that for high yields, an altitude correction must be made for propagation vertically through a nonhomogeneous atmosphere. Castle, then, presented an opportunity to document pressures in the air above megaton-yield surface shots. These phenomena include a definition or delineation of the shock from a surface burst as it propagates through the low levels of the atmosphere out to long ranges.

2.4.1 Pressures. The smoke-rocket and direct-shock photography techniques were used for pressure-distance determination in the air and along the surface. In general,

[1] On Redwing, considerable data was obtained from two land-surface bursts, one a kiloton burst of medium yield determined by radiochemical analysis. A composite land-surface burst curve was drawn from the data — it scaled about 1.6W.

results were satisfactory. However, cloud cover, usually present at low altitudes over the EPG, made it difficult to obtain photography to the desired degree of success. However, this lack of data was supplemented by the use of less-accurate data from photographic film from another source. No film was usable from Shot 3 because of the low yield of the device and the poor visibility at the time of the shot.

Pressure-distance data vertically above the shot were obtained only on Shot 2. Beyond the fireball, data was measured in the region from 10,000 to 15,000 feet. Two wave fronts were also observed at very-high altitudes (~ 265,000 to ~ 335,000 feet). The first wave probably was the blast wave; the second was presumed to be an acoustic wave. The low-altitude (10,000 to 15,000 feet) data are plotted in Figure 2.6; these data are compared

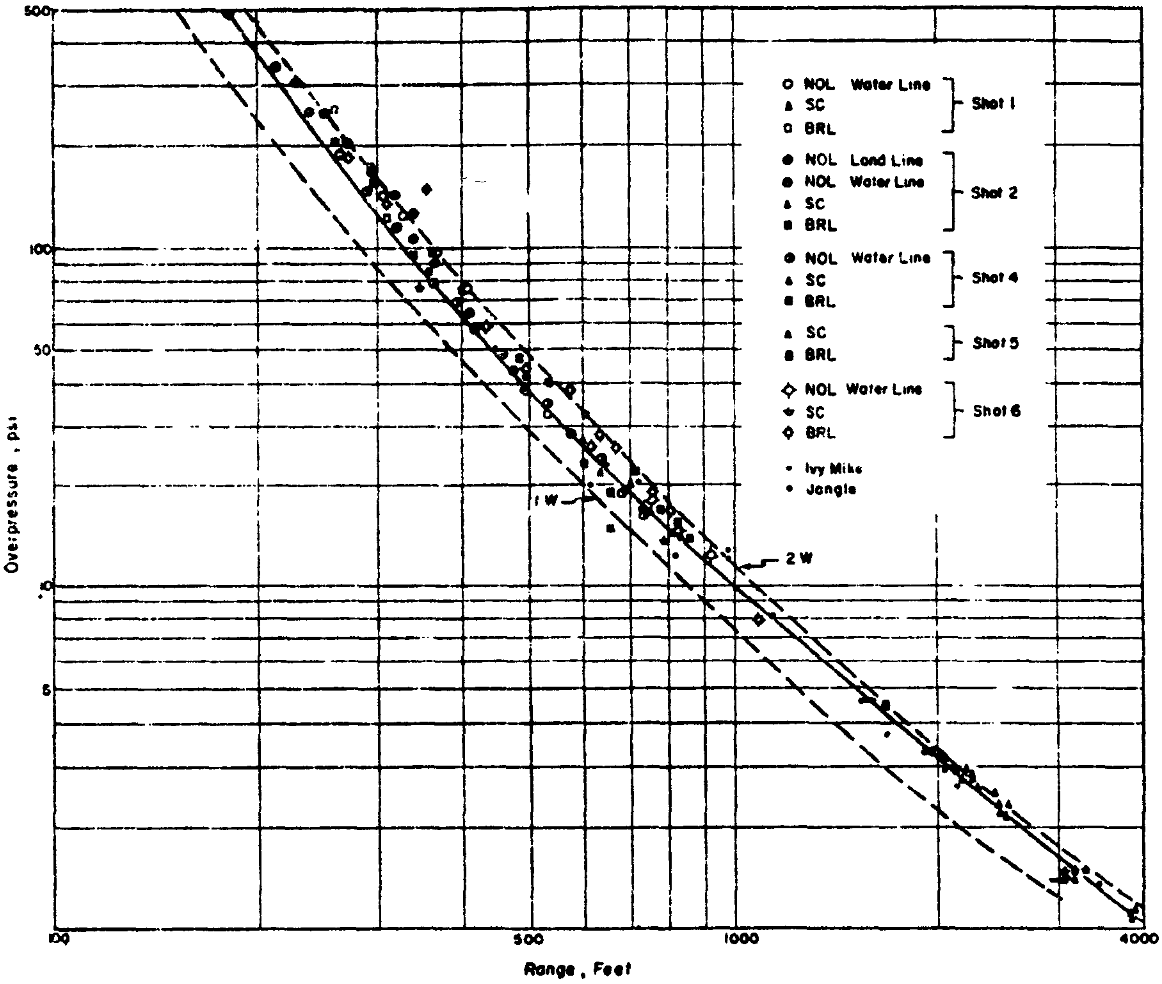


Figure 2.4 Composite overpressure versus scaled ground range, Shots 1 through 6.

to theoretical pressure-distance curves which were constructed using the Theilheimer-Rudlin Naval Ordnance Laboratory (NOL) method for considering the variation of the pressure-distance relation with altitude, which involves the determination of an equivalent TNT charge radius. The upper theoretical curve for Shot 2 in Figure 2.6 is based on an average change radii of 404 feet for the surface-level data obtained by Project 1.2a with electronic gages. The lower theoretical wave is based on an average charge radii of 349 feet for the surface-level data obtained by Project 1.1a with rocket-trail photo-

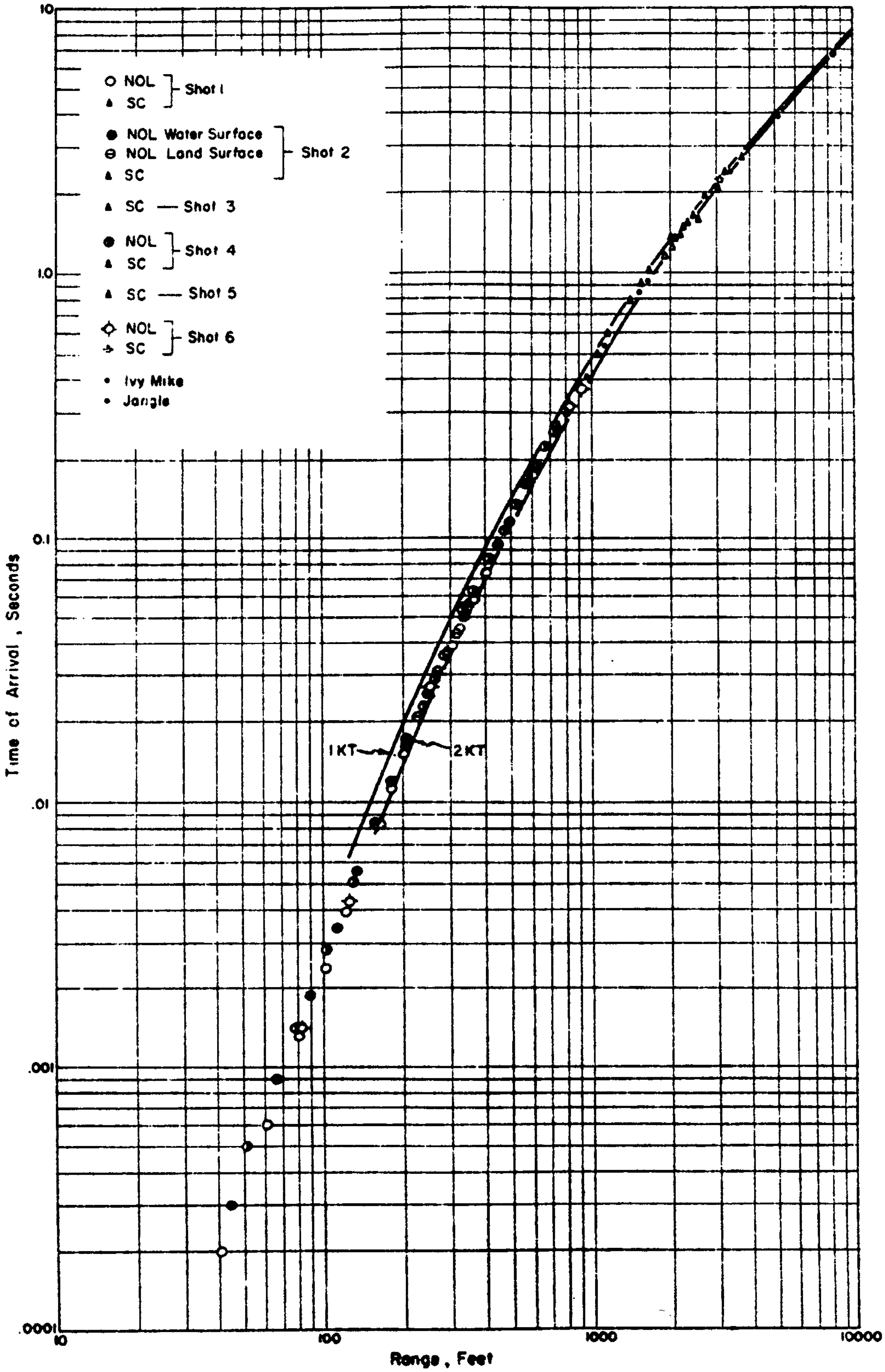


Figure 2.5 Composite scaled time of arrival versus scaled ground range, Shots 1 through 6.

graphy. Consequently, an average charge radii of 376 feet were used, which compares favorably with the average charge radii of 387 feet computed for the Ivy Mike surface-level data obtained with electronic gages. The pressure-distance curve for these equivalent TNT charge radii was then scaled vertically by the NOL method for comparison with measured data, using the observed ambient conditions at altitude. The uncertainty of the measured data was such that it was not possible to correlate the vertical peak overpressures with the theoretical curves derived from the surface-level peak overpressures in this manner. Consequently, it was not possible to determine the best method of making an altitude correction to account for blast propagation through a nonhomogeneous atmosphere for high-yield bursts.

Those pressure data measured along the surface, obtained on Shots 1, 2, 4, and 6 by using smoke-rocket and direct shock photography, are plotted in Figure 2.7. Gage data from Jangle Surface and Ivy Mike have been included for comparison and correlation. The data were normalized by scaling to 1 kt at standard sea-level conditions, so that the composite free-air data scaled to 1 and 2 kt could be shown. A comparison to the 1- or 2-kt free-air curve for the purpose of determining a reflection factor for surface bursts was not strictly valid, since the hydrodynamic determination of yield for these shots involved an assumption of the factor of two. (Discussion of the surface-burst reflection factor was presented in Section 2.3.5.) Figure 2.8 shows scaled arrival-time data obtained by smoke-rocket and direct shock photography, with the 1- and 2-kt composite free-air curve. Scaled data for both pressure and arrival time appear self-consistent, as well as comparing favorably with Jangle and Ivy gage data. It seems justified to conclude, then, that cube-root scaling of blast data from events in this yield range is valid.

Part of the objective of the direct shock photography was to observe the formation and growth of any precursor which might occur. At this time there was some doubt that the precursor would form on a surface shot. Actually, no precursor as such was noted; however, anomalous wave forms were recorded by the pressure-time gages. Observations made of the film exposed on Shots 4 and 5 disclosed a dense water cloud following immediately behind the shock front. This cloud implies water droplets contained in the shock front and may explain the anomaly.

2.4.2 Base Surge. Early planning provided for the determination of the characteristics of the base-surge phenomenon for each of the shots. It was hoped that from such a study, scaling laws could be formulated to predict base-surge effects of surface shots with yields different from those of Castle. The base surge becomes of military significance when it acts as a carrier of radioactive contamination to regions beyond normal fallo. The extent to which this could occur from surface bursts, as well as the general dynamics of the phenomenon and the determination of scaling laws, were the objectives of this study.

The experiment was almost entirely unsuccessful, since the primary analytical tool, photography, was rendered useless when it was decided to schedule the shots before sunrise. A minimum photographic effort was maintained throughout the series, from which it was determined that a base surge probably did form on Shots 1 and 2. This limited material prevented any detailed study anticipated in the early objectives.

2.5 CLOSE-IN GROUND ACCELERATIONS

Study of ground motion produced by multimegaton devices detonated on the ground surface was planned for Castle to extend and supplement those data obtained from Ivy Mike.

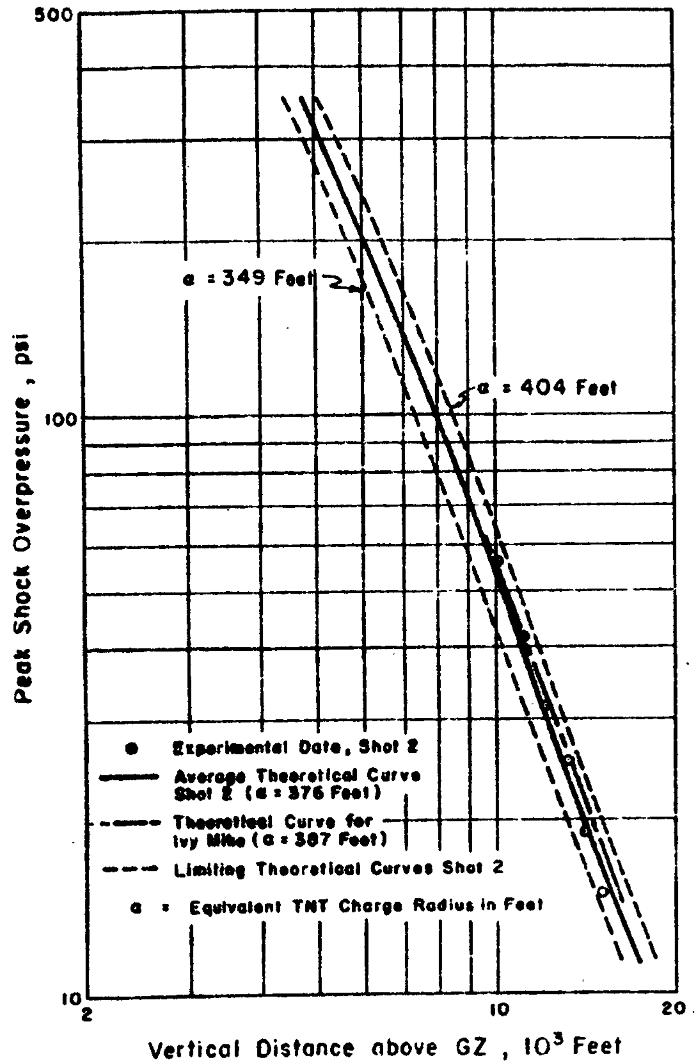


Figure 2.6 Vertical pressure-distance data, Shot 2, with curves derived from NOL theory.

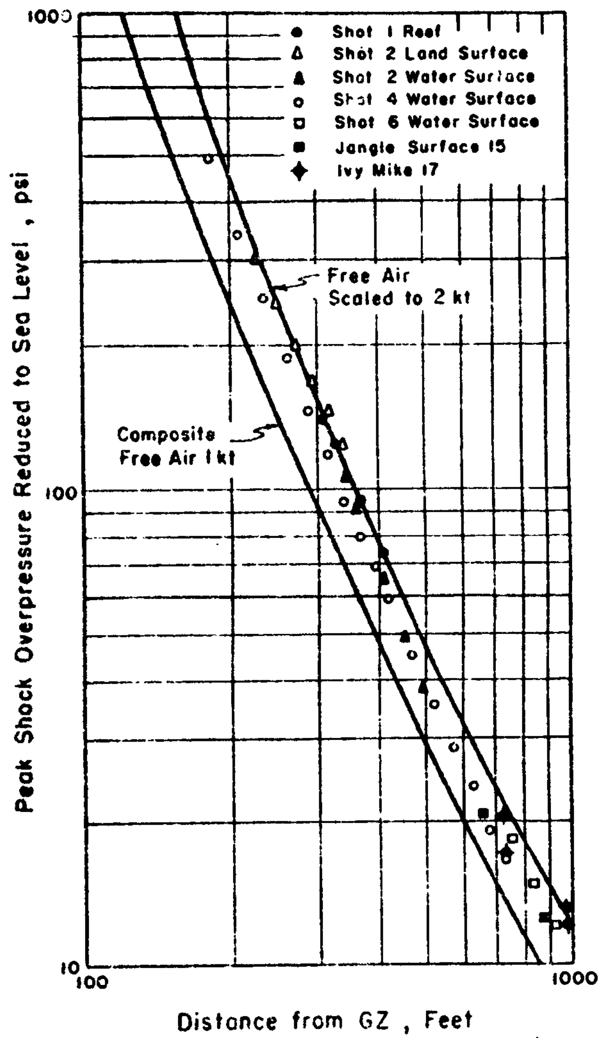


Figure 2.7 Surface pressure-distance data scaled to 1 kt at sea level.

The primary interest was in motion closer to ground zero than previously instrumented.

Participation was planned for two shots, both to be detonated on atoll islands: one at Bikini, one at Eniwetok. Measurements were obtained on Shot 3; however, the unexpected low yield of that event (Morgenstern) forced cancellation of the other shot (Echo) for which measurements had been planned.

The instrumentation layout for Shot 3 consisted of vertical, radial, and tangential components of acceleration in the ground below the water table at ranges corresponding to 200-, 100-, and 36-psi peak air overpressure predicted for a 1-Mt yield. As a result of the low actual yield, set ranges for the gages were too high, recording a very-low signal amplitude. With such a low signal-to-noise ratio, the identification of phase arrivals, frequencies, and amplitudes was uncertain. The results are given in Table 2.3. The curve of arrival time versus range is shown in Figure 2.9. The air-induced signal propagated with a velocity of the air blast wave, decreasing with increasing ground range. The ground-transmitted shock propagated with a velocity of about 8,700 ft/sec.

TABLE 2.3 ACCELERATION DATA

Station Number	Ground Range	Set Range	Component	Acceleration: Ground-Transmitted: Arrival Time	Ground-Transmitted: Maximum Positive	Ground-Transmitted: Maximum Negative	Ground-Transmitted: Frequency	Air-Shock Induced: Arrival Time	Air-Shock Induced: Maximum Positive	Air-Shock Induced: Maximum Negative	Air-Shock Induced: Frequency
	ft	g		sec	g	g	cps	sec	g	g	cps
170.01	2,596	33	V	No Record							
		33	R	0.31	0.96	0.47	42	0.63	3.44	4.10	90
		33	T	0.31	1.50	1.27	45	0.66	2.20	4.67	100
170.03	3,650	24	V	0.39	0.37	0.25	—	1.24	0.23	0.55	45
		24	R	0.40	0.13	0.35	—	1.23	0.62	0.29	—
		8	T	0.42	0.11	0.19	—	1.24	0.24	0.18	—
170.02	5,599	9	V	0.61	0.17	0.15	38	2.63	0.15	0.51	—
		9	R	0.61	0.13	0.12	—	2.56	0.51	0.25	—
		3	T	0.61	0.10	0.10	—	2.61	0.16	0.25	—

The determination of velocities and displacements by means of integration of the acceleration traces was not attempted because the quality of the data was too poor to support such analysis. Also, the ground motion was too small to produce significant structural damage.

2.6 UNDERWATER MEASUREMENTS

Propagation of shock waves in shallow water was not well understood. Crossroads Baker and Ivy Mike had been instrumented with underwater measurements. Baker results did not define the underwater pressure-time history with any degree of accuracy, but they did establish the order of magnitude of the pressure decay as a function of range. No significant data were obtained from Mike. Castle offered the first opportunity to document the underwater pressure-time history from a nuclear device detonated on the surface of the water. Actually, the geometry of ground zero for the Castle series of shots — represented by the lagoon bottom and the atoll rim — was quite complicated, involving a condition not well understood. However, such geometry did represent conditions of practical military significance: (1) air attack against a submarine in shallow water, (2) an attack against ships in harbors as well as the harbor facilities, and (3) attacks against dams or mines.

The specific objectives of this project included measurement of underwater pressure as functions of time, distance, and depth for large-yield weapons detonated at the sur-

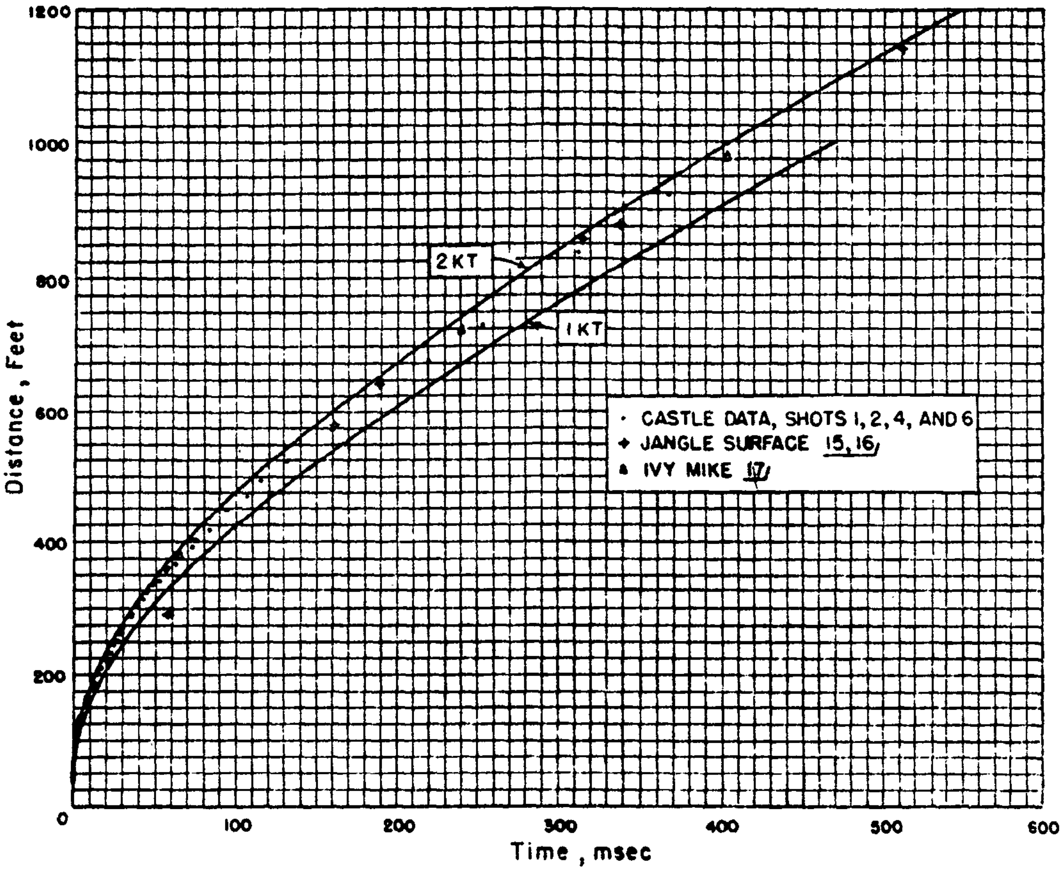


Figure 2.8 Surface arrival-time data scaled to 1 kt at sea level.

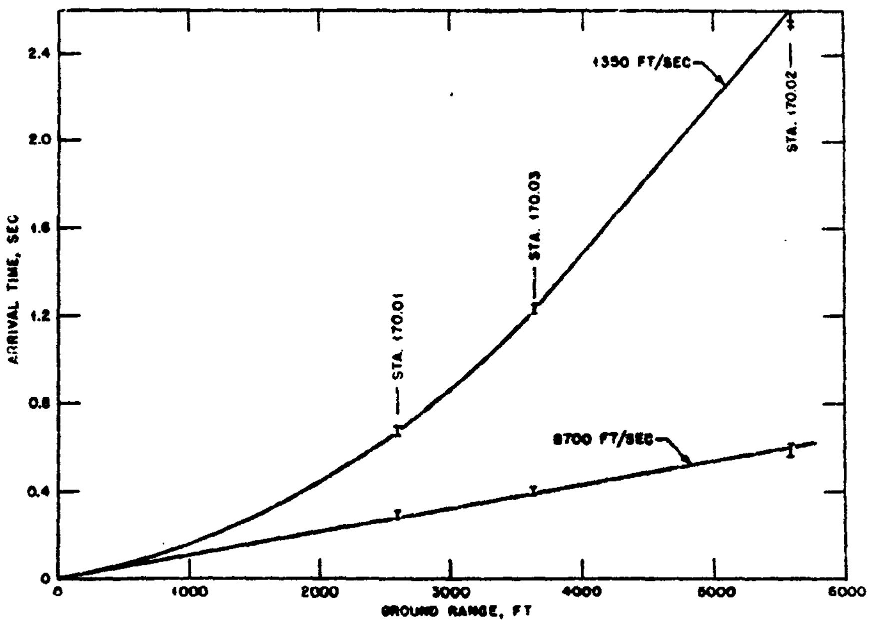


Figure 2.9 Earth-acceleration arrival times versus ground range for Shot 3.

face in shallow water. In addition these data were to provide for comparisons with a shallow underwater burst (Crossroads) and a deep underwater burst (Wigwam). At the same time, this operation provided an opportunity to check out instrumentation and obtain experience in making underwater measurements that proved valuable in preparing for Operation Wigwam.

2.6.1 Underwater Pressures. Three laboratories jointly participated in this project, under the sponsorship of the Office of Naval Research. Some difficulty with instrumentation due to repeated delays was experienced by each agency during the operational phase; as a result, a lesser amount of reliable data was obtained than originally anticipated. However, sufficient measurements were recorded from the five events to allow some conclusions to be drawn.

The major result of the recorded data indicated that except for the close-in region, the maximum, or peak, underwater pressures were of the same magnitude as the air-blast peak overpressures at the same range. The maximum underwater pressures recorded were probably not due to the air-coupled shock alone, but included some of the seismic and the direct water-borne shocks as well. However, this comparison breaks down for the region close in to surface zero. The exact range where the dissimilarity of pressures becomes significant appears to be a rather-involved function of yield, water depth, and relative depth of the target.

Figure 2.10 reproduces typical pressure-time records. All records of this type followed a similar pattern: an initial disturbance followed by several positive and negative pulses, followed by a slow-rising signal caused by the air-blast wave passing over the surface. This latter arrival was confirmed by air shock-arrival times. The initial positive disturbance, with its succeeding pulses, travelled with average velocities faster than might be expected for transmission of underwater shock, and it is believed they were transmitted through the ground and reflected from various subsurface strata. The values of pressure and time after zero were measured at each point labeled A, B, C, etc., and entered in Table 2.4.

Figure 2.11 shows a plot of data obtained with two types of gages: the ball-crusher (BC) and the pressure-time (P_t). These data are a composite of measurements made on all shots and at various depths, and have been normalized to 1 kt. The included curve is the 2-kt composite free-air pressure-distance function, approximating a surface burst of 1-kt yield. The measured (scaled) data show a fair fit to the free-air curve.

It was concluded that a nuclear device detonated on the surface of a relatively shallow water layer produces underwater pressures which are probably of small military significance, because: (1) although they are of comparable magnitude to the air-blast pressures, typical underwater targets are, by their very nature, of such strength that they require pressures which are at least one order of magnitude larger than air pressures normally considered as damaging; and (2) they are insignificant compared to pressures produced by underwater bursts such as Crossroads Baker or Wigwam.

These conclusions must be qualified, however, since they are based on results obtained under the specific environment as experienced in the Bikini and Eniwetok Lagoons. Different conditions will probably produce different results.

2.6.2 Acoustic Pressure Signals in Water (SOFAR). The presence of a low-velocity sound channel at a depth of 700 fathoms in the Atlantic and at 350 fathoms in the Pacific is well known. Low-frequency sound channeling into this layer will travel great distances. It is also possible for sound to travel long ranges through the water by reflecting successivley from top to bottom of the ocean—both boundaries being excellent reflectors

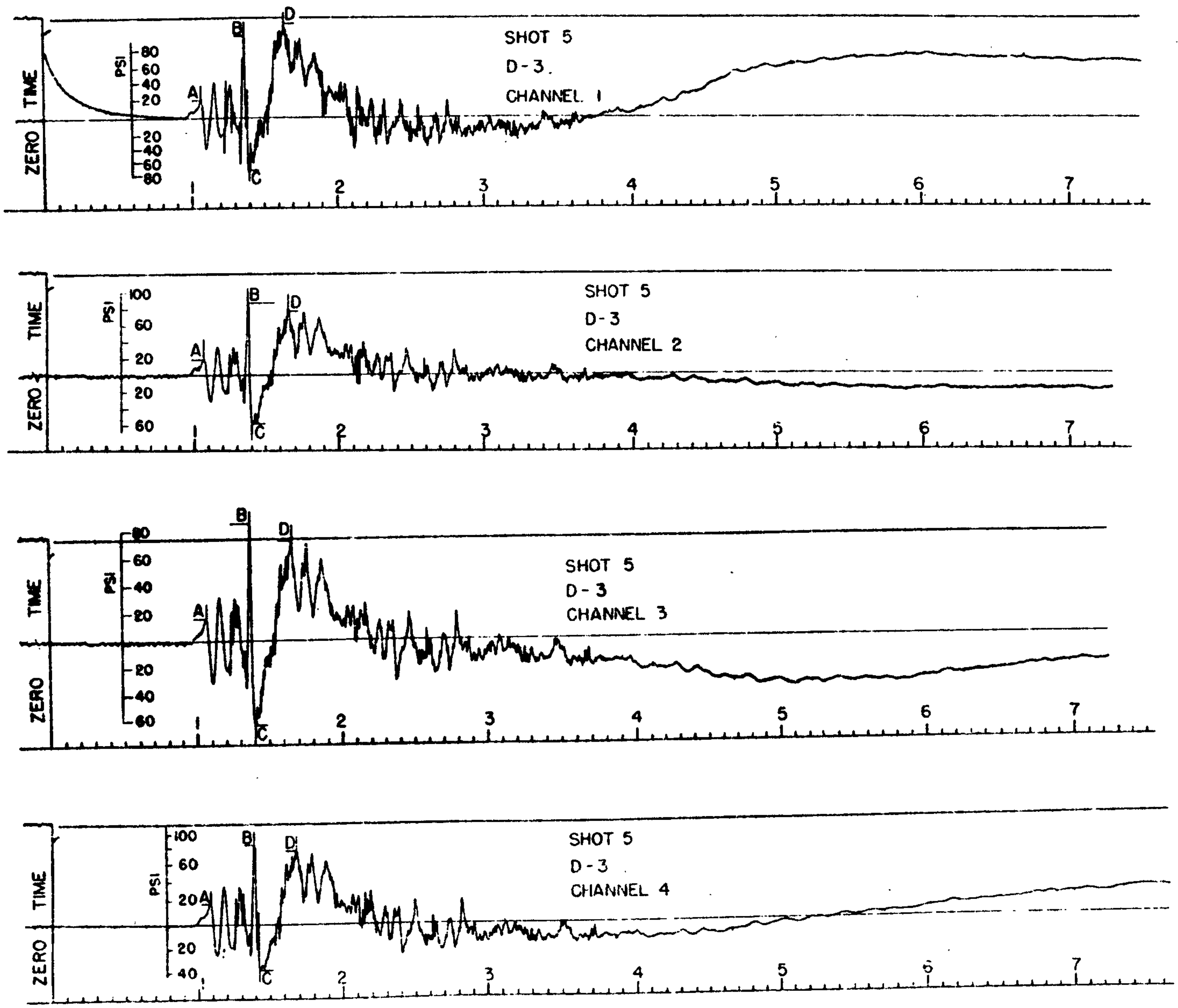


Figure 2.10 Pressure-time records, Shot 5.

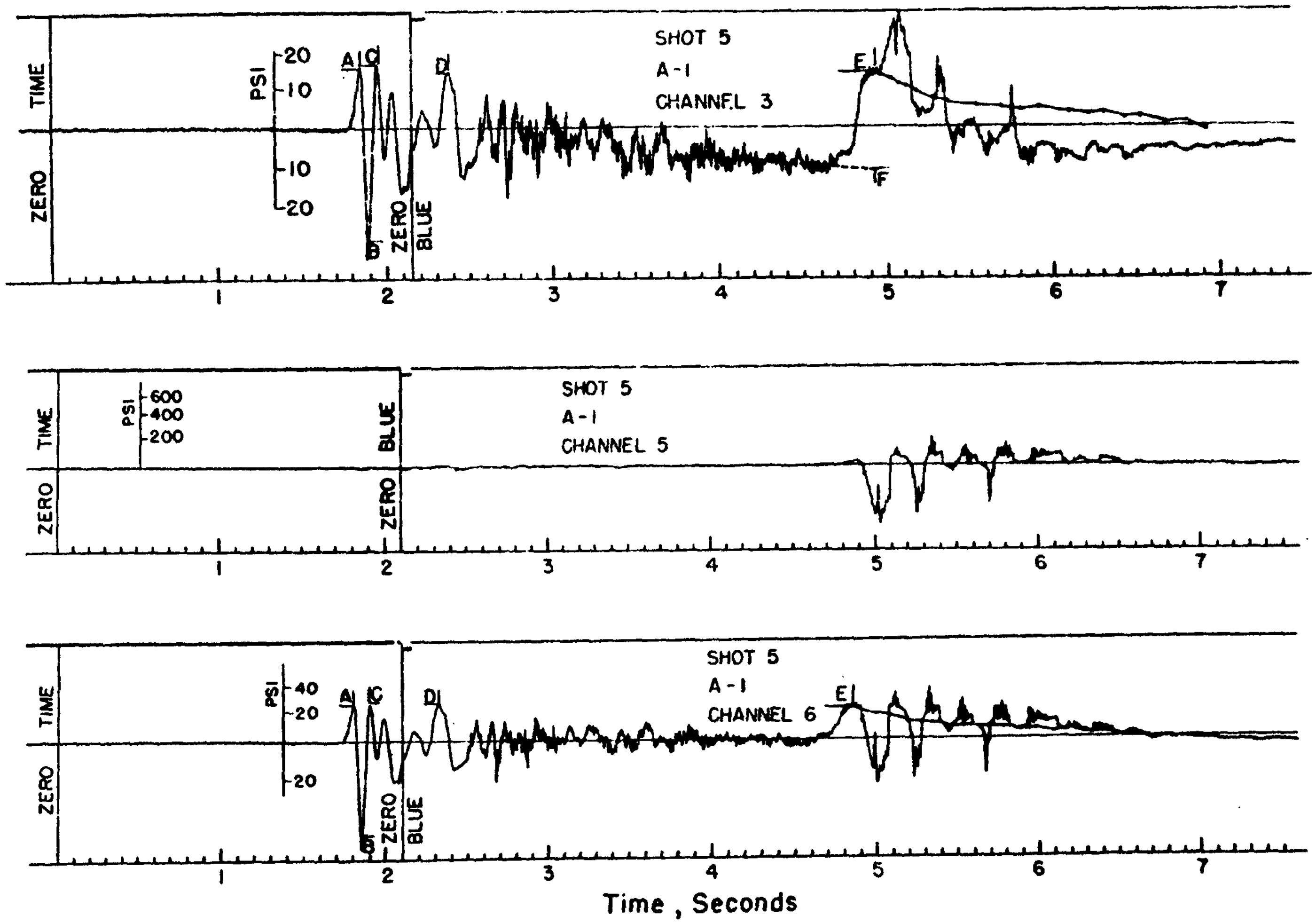


Figure 2.10 Continued

for low-frequency sound waves. Some success had been achieved during both Greenhouse and Ivy in detecting SOFAR signals transmitted through the water. Relative yields were fairly well established from signals received during Greenhouse at one of the detecting stations. It was planned to again activate these remote stations for Castle to make special observations of acoustic pressure signals of the SOFAR type, to add to the knowledge of underwater sound propagation, and to investigate the possibility of determining yields.

Shots 2, 4, 5, and 6 were monitored by detecting stations located on the California coast and at Bermuda. No clear-cut signals were recorded which could be attributed to

TABLE 2.4 SUMMARY OF PRESSURE-TIME DATA, SHOT 5

	Buoy D3, 9,300-ft Distance				Buoy A1, 16,100-ft Distance		
Depth, ft:	50	100	100	100	40	40	75
Channel:	1	2	3	4	3	5	6
Blue Box from Zero	0	0	0	0	2.14	—	2.08
Pressure Arrival Time, sec	0.97	0.97	0.96	0.96	1.77	—	1.67
Pressure A, psi	19.27	18.2	16.3	17.25	17.4	—	24.2
Time, sec	1.06	1.06	1.05	1.06	1.85	—	1.78
Pressure B, psi	82.7	84.3	84.5	84.5	−28.9	—	−35.6
Time, sec	1.36	1.37	1.36	1.36	1.89	—	1.83
Pressure C, psi	−74.7	−56.6	−62	−36.6	18.5	—	24.2
Time, sec	1.40	1.40	1.39	1.40	1.94	—	1.89
Pressure D, psi	88.4	75	72.2	76.1	15.75	—	25.3
Time, sec	1.64*	1.65*	1.64*	1.64*	2.37	—	2.30
Pressure E, psi	—	—	—	—	32	—	20
Time, sec	—	—	—	—	4.90*	—	4.81*
Gage	PE	PE	PE	PE	PE	Wiancko‡	Wiancko
Amplifier	log	lin	lin†	log†	log	—	—

* Air blast, based on arrival time.
† Same gage.
‡ Equipment inoperative.

sources at either Bikini or Eniwetok. It is concluded that the position of the shots inside the lagoon and on the atoll rim was such as to preclude coupling of energy into the SOFAR channel in the frequency range for which instruments were available. Another factor which might have prevented reception at the California stations was the presence of shoal areas between the Bikini atoll and the coast along the most likely path of travel.

2.7 SURFACE WATER WAVES

The effects of water waves resulting from megaton-yield detonations at the surface could have military significance for (1) generation of waves in harbors causing damage to secured vessels, docks, shore installations, etc. and (2) long-range propagation of tsunami-like waves from a source over deep water, which could produce serious damage over extensive coastal areas.

The only previous full-scale data on water waves generated from a megaton surface burst had been obtained from Ivy Mike. No measurable waves were produced in the central region of the detonation, yet waves which were of measurable amplitude were observed at a range greater than four miles. These waves increased in height out to a distance of approximately 28 miles and arrived as though generated close to ground zero, having travelled across the lagoon at the velocity of shallow water waves. Since Ivy Mike was an island shot, it was not wholly surprising that it did not generate waves in a manner analogous to high explosives detonated on water. Although the Mike shot did reach into the lagoon, the generation and collapse of the cavity was not considered to be identical to that from a burst on water. Therefore, it was believed that the shot environment cancelled out most of the direct generation region.

In contrast to the Mike results, Castle data indicated that the recorded waves did emanate from the central region of the detonation. The first arrival was a short-period, highly damped series of ground- or water-transmitted shocks. Following these, the

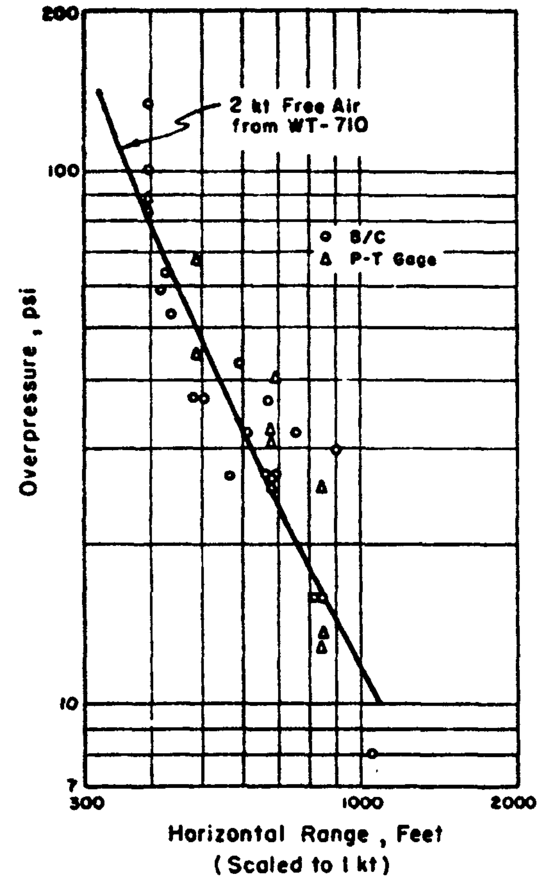


Figure 2.11 Averaged pressure-distance data.

records clearly showed the arrival of the air-transmitted shock wave. Next, preceding the direct water wave, a slow rise in pressure (water) occurred that was postulated to be caused by large quantities of water and coral debris falling back to the water surface. This was abruptly lost in the arrival of the direct water wave—the first arrival in all cases being a crest followed by a trough. These appeared to act as oscillatory waves, the time of arrival of the first crest showing a propagation velocity fitting the relation $V = (gh)^{1/2}$, where h is an average depth of 170 feet assumed for the Bikini Lagoon.

Refraction and reflection against a reef or shore line may significantly reduce or amplify the destructive capabilities of water waves at termination. At Bikini, How Island is an example of a protected shore, while Nan is an example of one highly susceptible to amplified inundation. Where focusing effects and the reflection-refraction potential of the adjacent lagoon topography are a minimum, the heaviest inundation and potential damage occurs with the first crest.

Unfortunately, these results were highly unique: they were obtained under particular conditions of geometry, in a region of relatively shallow depth. The conclusions are applicable to conditions which depart only slightly from these under which the data were obtained.

Waves were also recorded at a few distant islands. However, the results were meager and inconclusive, and a better interpretation can probably be made if held for a synergistic inclusion with the results of the distant-island phase of the Redwing studies.

Chapter 3

NUCLEAR-RADIATION MEASUREMENTS AND FALLOUT STUDIES

The nuclear-radiation program had two major objectives: (1) the documentation of the initial radiation, neutron and gamma, from megaton-range nuclear detonations and (2) the documentation of fallout from land-surface and water-surface bursts of multimegaton devices.

The unexpectedly high yield of Shot 1 had two influences on the execution of the program: First, much of the spare equipment was destroyed on Site Tare, and instrumentation for subsequent shots was curtailed. Second, the importance of fallout in terms of effects of military significance over large areas beyond the blast- and thermal-damage envelopes was demonstrated dramatically. This realization, together with the observation that activity dissolved in sea water could be a measure of the fallout intensity, provided the impetus for the water and aerial surveys that yielded valuable data after Shots 5 and 6.

Prior to Operation Castle, only one multimegaton detonation had provided data on nuclear-radiation effects—Shot Mike of Operation Ivy. The initial-radiation data consisted of records of initial gamma versus time at two stations, total initial-gamma exposure at a number of distances, and a few neutron-flux measurements using Au, and I activation detectors. There had been an extensive array of fallout-documentation stations along the islands and in the lagoon of Eniwetok Atoll; however, these collected data on the crosswind and upwind fallout only, since the more-extensive downwind fallout occurred on the ocean toward the north.

The fallout from the few kiloton-range surface and underground shots prior to Castle had also been documented. Measurements of initial radiation from fission devices up to 500 kt had been performed extensively. The initial-radiation data were not adequate prior to Castle because (1) the scaling laws are not simple and do not lend themselves to extrapolation from kiloton-range to multimegaton yields and (2) the neutron dose from neutrons in the energy band above thermal but below 3 Mev had not been measured due to the lack of detectors with thresholds in this region. The objectives of the Castle nuclear-radiation experiments were aimed at obtaining data to eliminate the deficiencies mentioned above. In particular, the objectives were to document for multimegaton land-surface and water-surface detonations (1) distribution of fallout; (2) physical, chemical, and radiochemical nature of fallout; (3) rate of delivery and total initial-gamma radiation at various distances; (4) energy spectrum of and dosage from neutrons at various distances; and (5) the applicability of fission threshold neutron detectors and germanium neutron-dose detectors.

3.1 INITIAL-GAMMA RADIATION

The total exposure from initial-gamma radiation was detected at a number of locations using film-badge and chemical-dosimeter systems. Only a part of the anticipated data was obtained because of extensive destruction of stations and supplies during Shot 1.

The measurements, including two points calculated by integrating gamma-rate records from Shot 4, are presented in Figure 3.1. Prediction curves (from Reference 7) and measurements during Greenhouse and Ivy (References 8 and 9) are also presented for comparison.

One record of initial-gamma rate versus time up to shock-arrival time (0.9 seconds) was recovered after Shot 1. Two complete records (illustrated in Figure 3.2) were recovered after Shot 4. The shock-arrival times interpolated from Project 1.1 data are

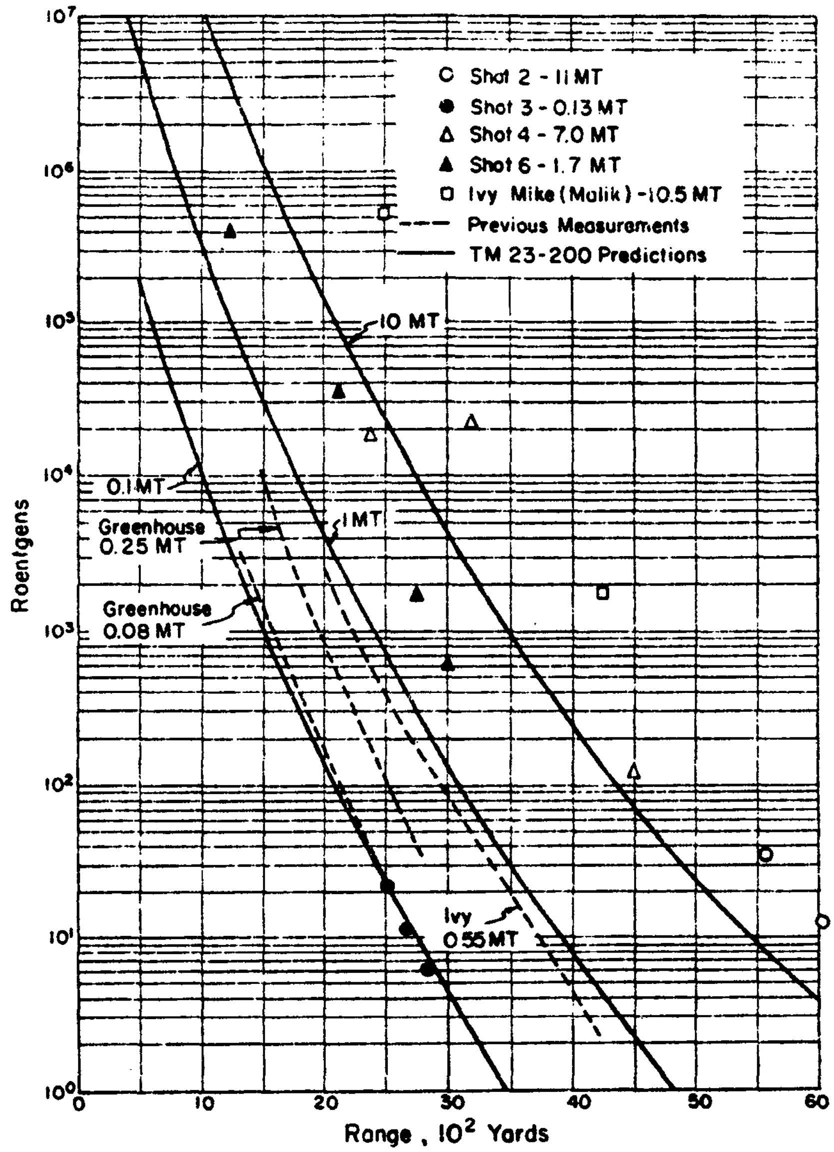


Figure 3.1 Initial gamma exposure versus distance.

indicated on the figures. Apparently, this time is associated with the break in the slope of the gamma-rate curve. The integration of these curves indicates that the exposure at the 7,171-foot station was 1,000 r before shock arrival and 16,800 r after arrival. The corresponding exposures at the 13,501-foot station were 14 r and 109 r. Therefore,

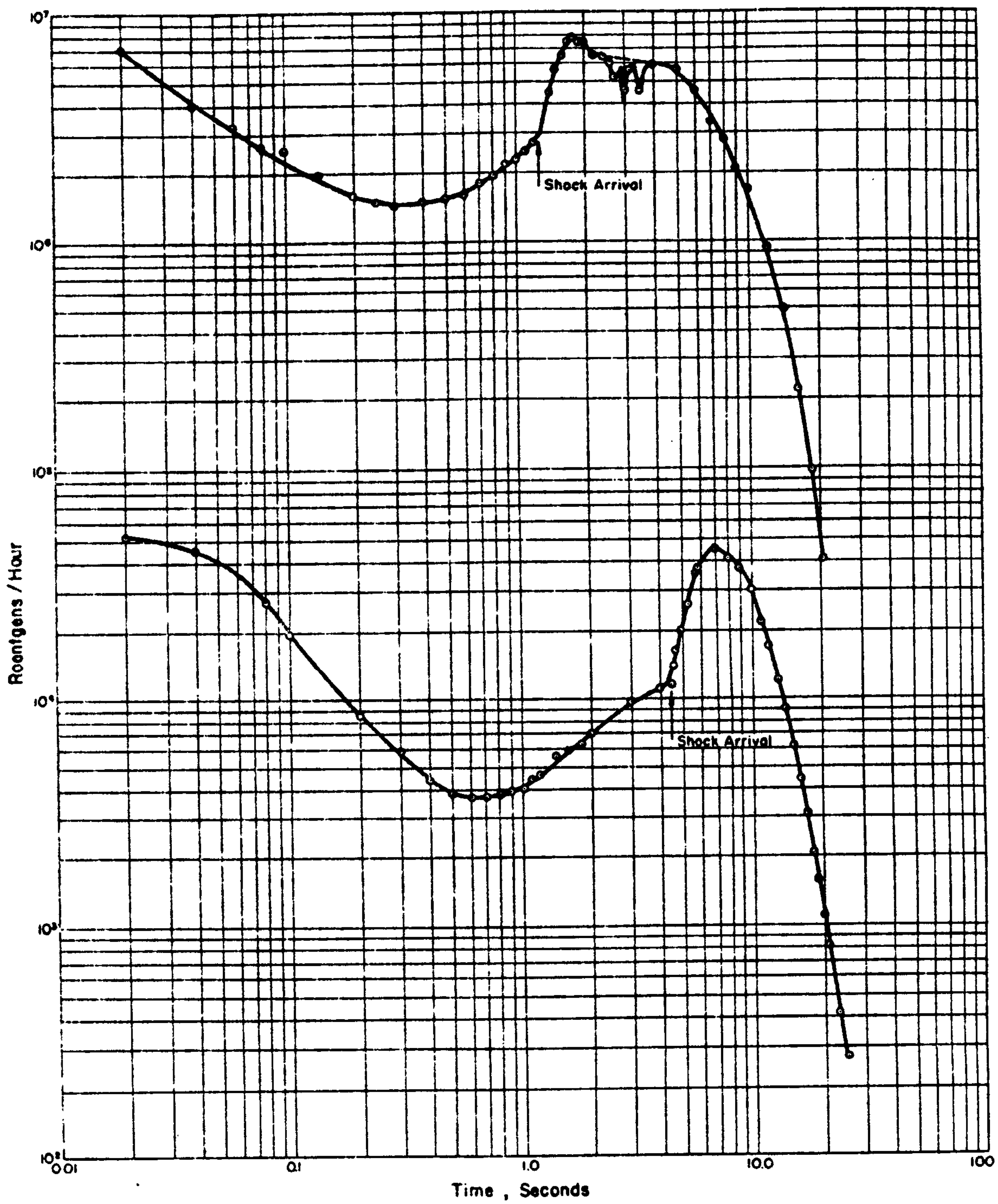


Figure 3.2 Initial gamma-exposure rates, Shot 4.

only 6.4 percent and 11 percent of the total exposures were delivered before shock arrival at these two stations.

3.2 NEUTRON RADIATION

The basic neutron-flux measurements were made with activation detectors whose indicated effective threshold energies were:

Detector:	Au, Au-Cd	Ta, Ta-Cd	S
Threshold:	< 1 ev	< 1 ev	> 3 Mev

Additional measurements were made with fission detectors and germanium crystals, primarily to test their usefulness. The fission detectors were used in two ways: counting fission fragments in a photographic emulsion and counting gamma activity from fission products after recovery of the samples. The fission detectors used and their effective threshold energies were:

Detector:	U^{238}	Np^{237}	Th^{232}	Pu^{239}
Threshold:	1.5 Mev	0.64 Mev	1.5 Mev	200-1,000 ev[1]

The Shot 1 data from the activation and fission detectors are summarized in Figure 3.3; the fission detector data from Shot 2 are illustrated in Figure 3.4. The germanium crystal (Ge) dose data agree in order of magnitude with the threshold detector data. There was a large scatter in the Ge data, indicating that the detectors were not reliable in the form used.

3.3 FALLOUT DISTRIBUTION

3.3.1 Instrumentation. The following procedures were used to furnish information on the distribution of fallout activity after each of the Castle shots (some of the collectors also provided samples for chemical, physical, and radiochemical studies of the fallout material):

1. Survey readings were taken by project personnel and the Rad-Safe organization at island stations at various times after the shots.
2. Readings of total residual-gamma exposure at island stations were taken from film badge and chemical dosimeters.
3. The activity of samples from total fallout collectors was related to the infinite-field exposure rate by normalization at island stations. Total collectors of the funnel-and-bottle or gummed-paper type were placed at island stations, on rafts anchored in the lagoons, and on free-floating buoys placed north of Bikini Atoll during the last few days before shot time.
4. Gamma-exposure-rate recorders were placed at some island stations to provide data on the time of arrival, rate of arrival, peak activity, and decay of fallout.
5. Incremental fallout collectors were used to collect samples during 5- to 30-minute intervals and to provide data on time and rate of arrival of fallout.
6. After Shots 5 and 6, surface and aerial surveys of the ocean fallout area were performed to measure the activity in the surface layer of the ocean and its depth of penetration. The existence of a mixed layer in the ocean down to the thermocline, with little mixing below, enabled these measurements to be related to the total activity deposited.

[1] Depending on amount of B^{10} shielding around sample.

3.3.2 Shot 1. The data gathered by the Bikini Atoll surveys and collectors were supplemented by surveys performed on the atolls that were unexpectedly contaminated. The major portion of the pattern, which occurred over the open ocean, was not documented. However, an analysis of the wind structure during the fallout period was performed; this

TABLE 3.1 AREAS OF AVERAGE RESIDUAL GAMMA ACTIVITY

Shot 1 Area	Average Residual Gamma Activity*
mi^2	r/hr at H + 1 hr
2,040	3,000
2,880	2,500
3,860	1,500
6,030	750
12,900	300

*See WT-915, Appendix F.

analysis, combined with the available data points, produced the pattern exhibited in Figure 3.5.

The time of arrival of fallout at the Bikini Atoll stations was between 15 and 45 minutes after detonation. Statements from persons accidentally exposed on downwind atolls indicated an arrival time of 8 hours on Rongerik Atoll (at a distance of 126 nautical miles) and of about 18 hours at Uterik Atoll (300 nautical miles). The data from two measure-

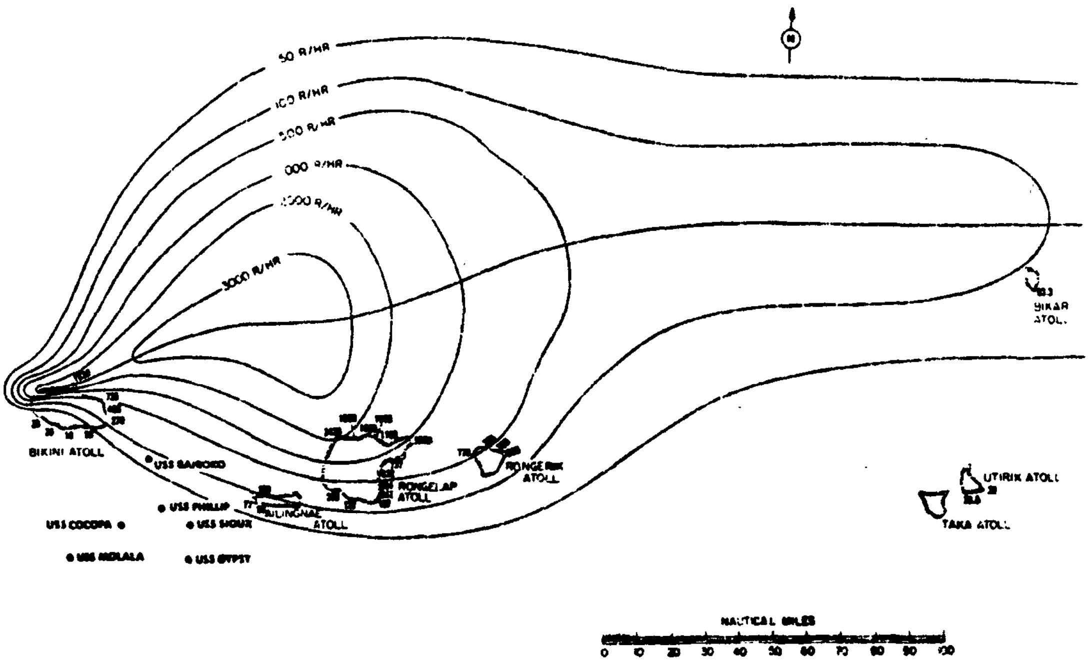


Figure 3.5 Reconstructed complete fallout pattern, Shot 1, (r/hr at H + 1 hour).

ments of residual gamma versus time at nearby stations are presented in Figure 3.6. The decay exponents estimated from these graphs are between 1.1 and 1.4 for Station 220.12, and 0.81 for Station 220.08. (Decay exponent is defined as x in the relation for exposure rate $I = I_1 t^{-x}$, where t is the time.)

Table 3.1 presents the data on contour areas. From this, a rough activity-balance

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calculation indicated that about 50 percent of the activity was accounted for in the fallout pattern.

3.3.3 Shot 2. Bikini Atoll was not heavily contaminated after Shot 2, since the winds carried most of the activity toward the northwest. Some data were available from the free-floating buoys, but they were not sufficient to produce reliable contours. The maximum reading observed at 35 miles from ground zero corresponded to a land reading of

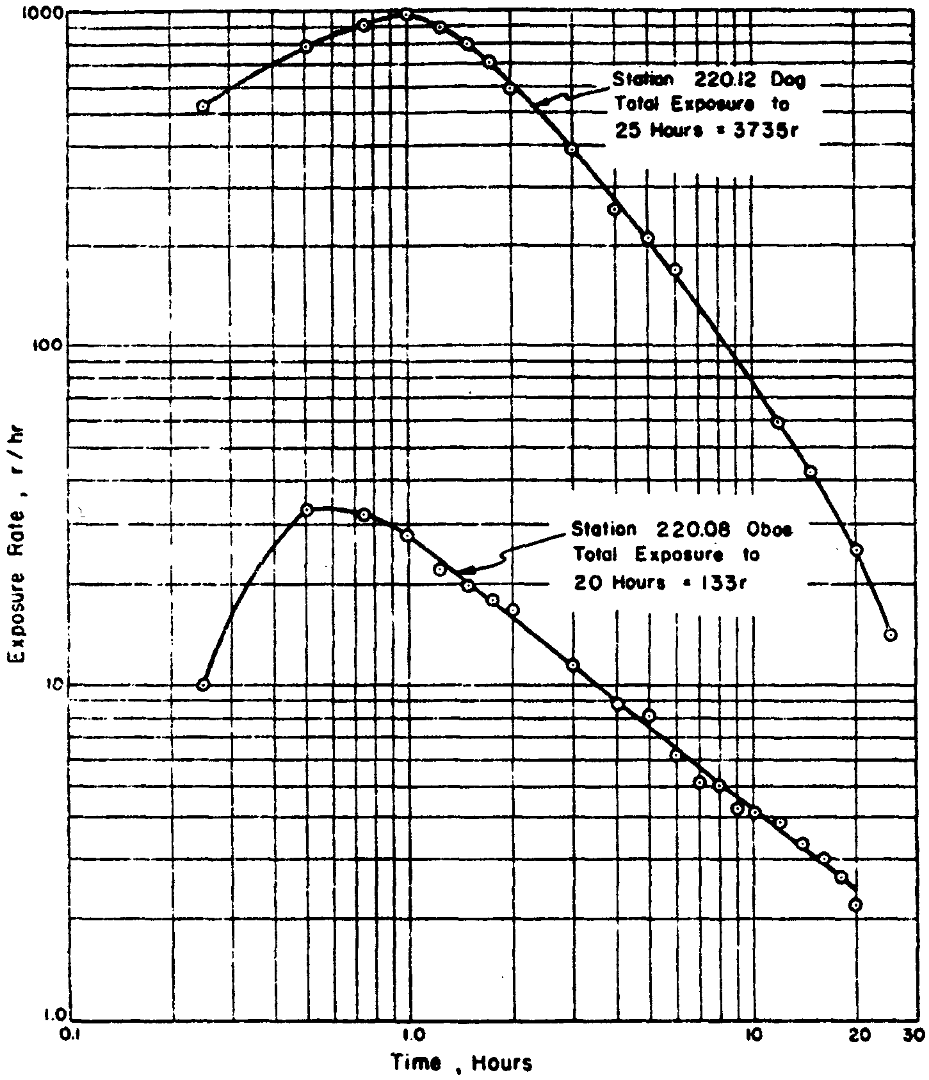

Figure 3.6 Residual gamma rate versus time, Shot 1. Upper curve: Station 220.12 on Dog, 41,372 feet to ground zero. Lower curve: Station 220.08 on Oboe, 83,762 feet to ground zero.

435 r/hr extrapolated to H + 1 hour. Rad-Safe readings on Sites Able and Charlie near ground zero indicated readings of 4,700 r/hr and 1,100 r/hr, extrapolated to H + 1 hour. The other islands received exposure rates of less than 25 r/hr at H + 1 hour.

3.3.4 Shot 3. The fallout pattern from Shot 3 was ideally located with respect to the measurement stations. The shot was located on Site Tare, on the south edge of the atoll, and the fallout was directed northward, intercepting the anchored lagoon stations and the northern islands. The close-in fallout pattern is illustrated by the data points and estimated contours in Figure 3.7. Since the yield of the detonation was only 130 kt, this pattern represents a large fraction of the total fallout.

One gamma-rate record was obtained from Site Dog, indicating a decay exponent of residual radiation between 1.1 and 1.25. The fallout arrived at about H + 20 minutes, and a maximum exposure rate of 23 r/hr was observed at H + 40 minutes. The integrated exposure till H + 15 hours was 51 r.

3.3.5 Shot 4. Most of the Bikini Atoll stations did not receive appreciable fallout during Shot 4. The shot location and the winds localized the radiation levels of military significance to the northeastern portion of the atoll. Land readings and contours derived from sample counting and Rad-Safe surveys are illustrated in Figure 3.8 for the atoll area only.

A gamma-rate record from Site George, about three miles from ground zero, indicated a time of arrival of 20 minutes, a peak exposure rate of 670 r/hr at H + 40 minutes, and a decay exponent of 1.4.

3.3.6 Shot 5. The only close-in data available for Shot 5 are from Rad-Safe surveys. The extensive downwind fallout pattern was documented for the first time by a combined water-surface survey, aerial survey, and water-sampling operation. The results of these surveys are represented in the contours of Figure 3.9, in which the dashed contours near the atoll have been drawn by interpolating between the survey results and the Rad-Safe data.

3.3.7 Shot 6. The pattern on the northern end of Eniwetok Atoll was documented by counting fallout samples from land and raft stations, and by Rad-Safe surveys on land. The aerial survey operated north of the atoll to determine contours, and two tugs gathered water samples throughout the fallout area. Analysis of the water samples, combined with an estimate of the depth of mixing, served to determine the land-equivalent exposure rate at a number of points; the aerial survey served to fill in the contours. The results are illustrated in Figure 3.10.

3.4 PHYSICAL AND CHEMICAL CHARACTERISTICS OF FALLOUT

Samples from the land-surface Shots 1 and 3 generally contained both solid and liquid components, although the liquid could have been due in part to rain and ocean spray. The solid component consisted mostly of white, opaque, irregularly shaped particles. The water-surface Shots 2, 4, and 6 produced predominantly liquid fallout, with some solid particulate observed after Shot 6. An appreciable part of the activity from water-surface bursts was probably in the form of an aerosol, which produced high activity levels on identification flags of the floating stations after Shot 2.

The particle-size distribution of solid fallout during Shot 1 at Bikini Atoll and at the distant atolls is summarized in the form of integral distributions on a log-probit plot in Figure 3.11. The data appear to fit long-normal distributions with different mean sizes and standard deviations for the different downwind distances.

Between 92 and 98 percent of the activity from land-surface—burst fallout was associated with solid material, but only 25 to 40 percent of the activity from the barge shots was not in solution. The pH of the land-surface—burst fallout was between 9.0 and 12.3,

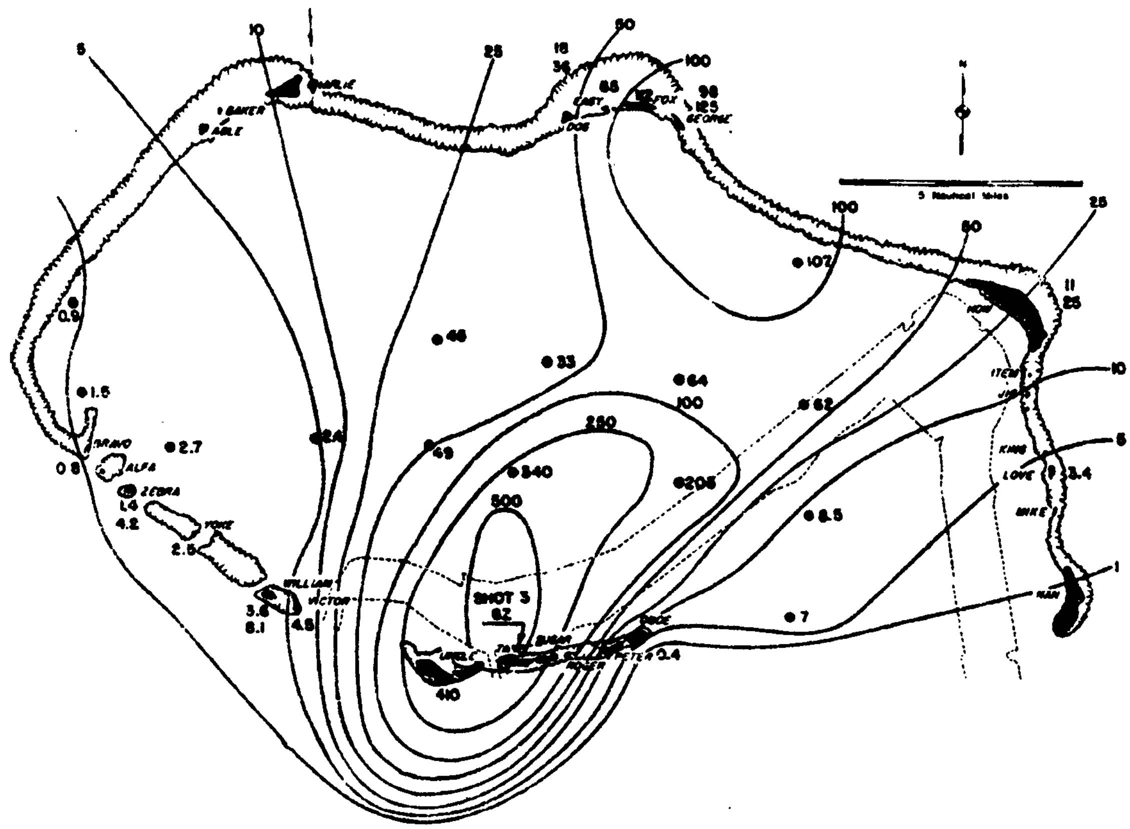

Figure 3.7 Close-in gamma fallout pattern, Shot 3, (r/hr at H + 1 hour).

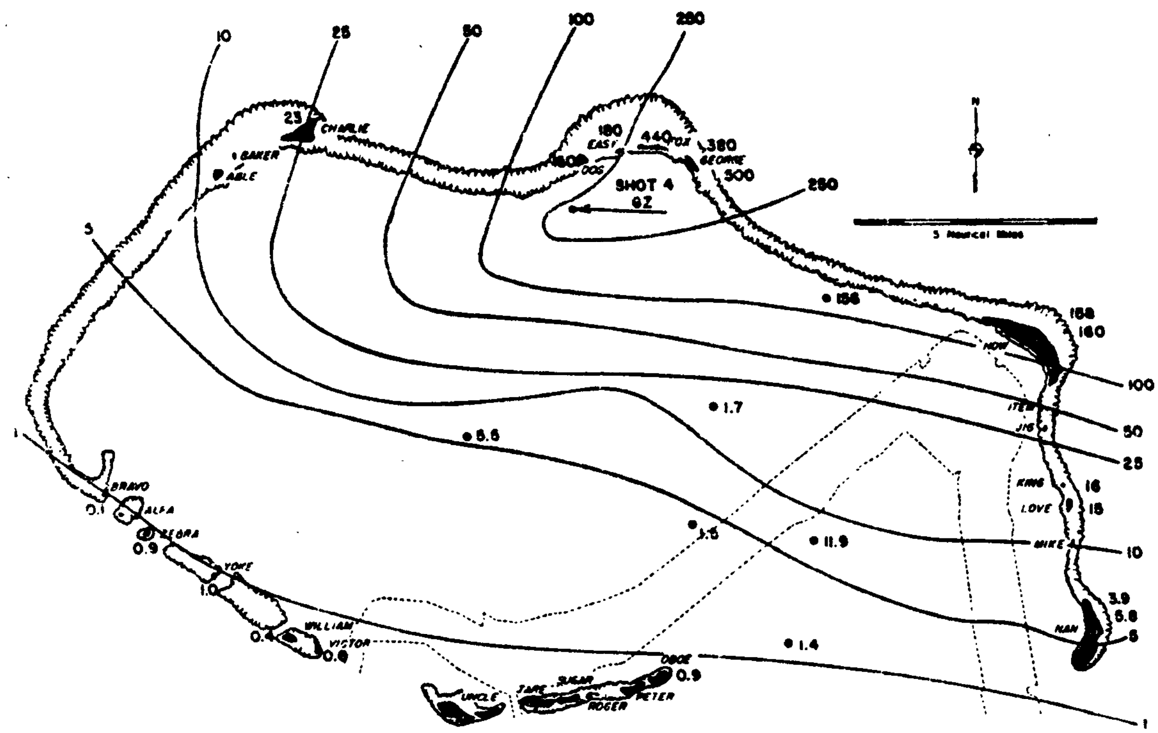

Figure 3.8 Close-in gamma fallout pattern, Shot 4, (r/hr at H + 1 hour).

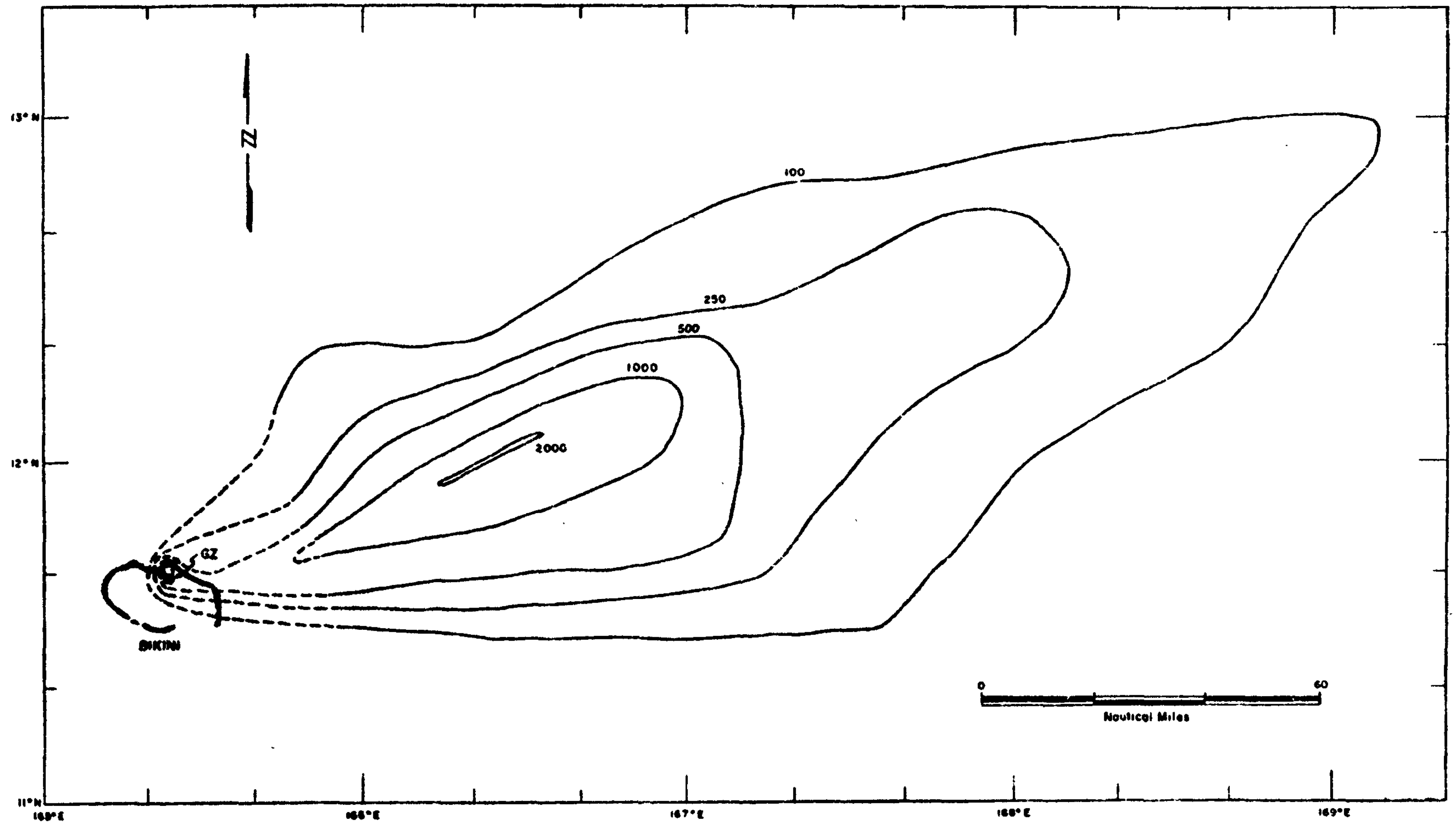

Figure 3.9 Exposure-rate contours, Shot 5, (r/hr at H + 1 hour).

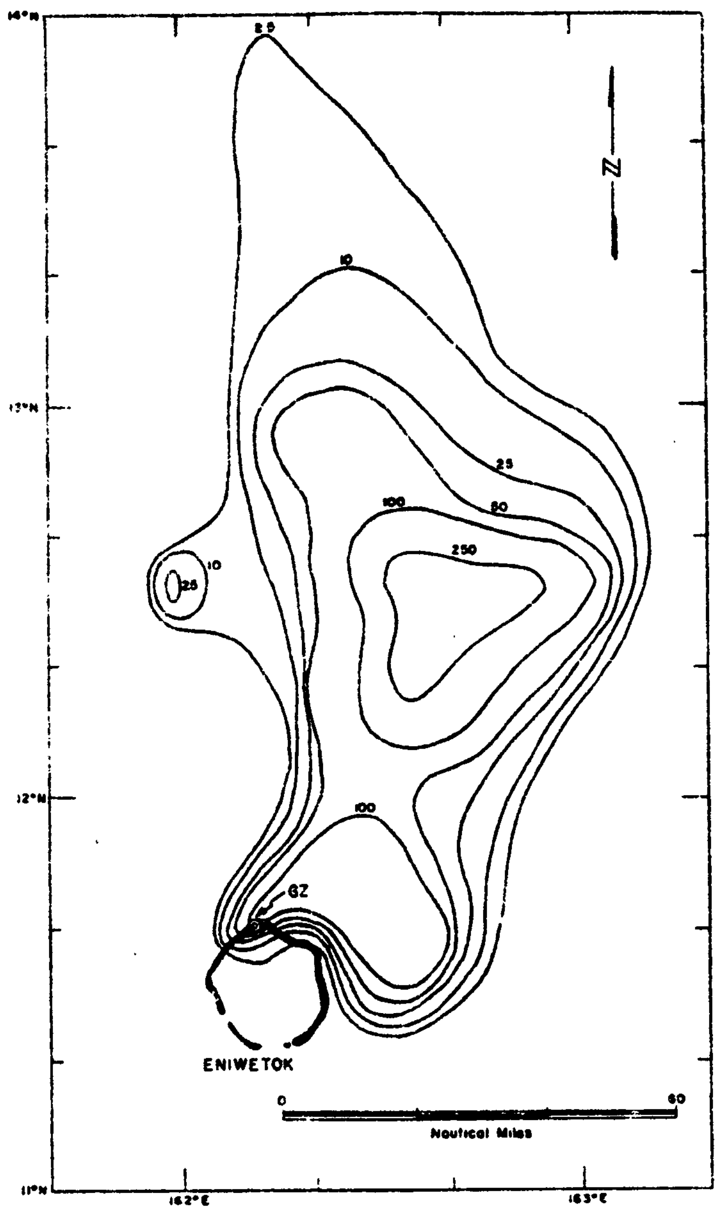

Figure 3.10 Exposure-rate contours, Shot 6, (r/hr at H + 1 hour).

characteristic of the alkaline solution of $Ca(OH)_2$, but the pH of the water-surface-burst fallout was about the same as ocean water, 7.5 to 7.7.

Approximately 25 percent of the particulate matter was not radioactive. The evaluation of this number is uncertain due to the possible introduction of dust into collector trays. One sample from Site How indicated that 33 percent of the activity was associated with particles greater than 225 microns in diameter. A large fraction of the activity was also found to be associated with very-small particles, but these could have been the result of particle break-up in the sizing procedure. Radioautographs of particles revealed

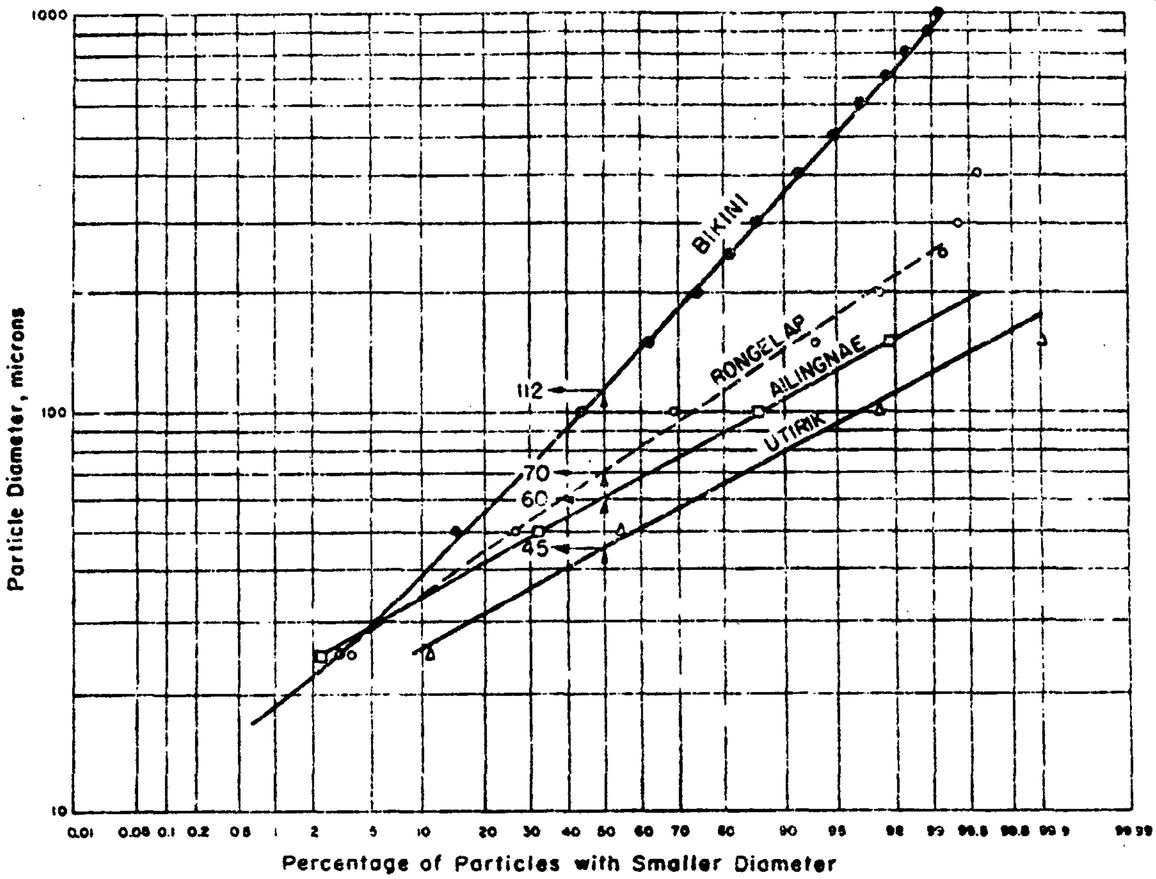

Figure 3.11 Cumulative particle-size distribution.

some with activity only on the surface, others with activity irregularly distributed, and still others that were radioactive throughout. The angular-shaped particles usually had the activity on the surface, whereas the uniformly radioactive particles had a spheroidal shape. The average particle density was 2.4 gm/cm^3.

Samples collected on aerosol filters after Shot 1 revealed the same types of particulate: angular with surface activity and spheroidal with a volume-distributed activity. A water leaching only removed 24 percent of the activity, whereas about 96 percent was removed by weak acetic acid. Aerosol samples were collected aboard the ships (YAG's) stationed in the fallout zone during Shots 2 and 4. The activity appears to have arrived principally in water droplets.

Chemical analysis of the samples was used to separate the fallout composition into coral, sea-water, and device contributions by evaluating the Ca, Na, and Fe content of the samples. In general, the land-surface shots deposited more coral than the water-surface shots, and the inverse relationship applied to sea water. There was rough correlation between fraction of the device and the fallout radiation level at the station.

3.5 RADIOCHEMICAL CHARACTERISTICS OF FALLOUT

Decay of the fallout activity was observed by measuring three separate activities: beta disintegrations per minute, gamma photons, and gamma ionization. The measured data are summarized in Figures 3.12, 3.13, and 3.14. The beta-decay curve was also

calculated by adding contributions from fission products and activities induced in device components (Figure 3.15). These curves were used to extrapolate activity measurements to a common time.

Radiochemical studies of the samples have yielded data on capture-to-fission ratios and R-values. (R-values are an indication of the relative abundance of a particular nuclide as compared to its normal abundance in fission products from slow-neutron fission of U^{235}.)

The most-important neutron-capture activities were due to Np^{239}, U^{237}, and U^{240}.

The R-values were measured for Sr^{89}, Ag^{111}, Cd^{115}, Ba^{140}, Ce^{144}, Nd^{147}, Sm^{153}, Eu^{156}, Gd^{159}, and Tb^{161}, using Mo^{99} as a reference nuclide.

The measured capture-to-fission ratios are summarized in Table 3.2. Usually, the R-values for the cloud and fallout samples were consistent. The R-values for the rare earths Ag^{111} and Cd^{115} were usually greater than unity, indicating an enrichment of these isotopes compared to slow-neutron fission products of U^{235}. The R-values for Sr^{89} were usually less than unity. Detailed results are reported in the final reports of Projects 2.6a and 2.6b (see Appendix).

Two methods of performing material-balance calculations were used: (1) the fraction of the device was computed using a radiochemical Mo^{99} determination as a tracer for the number of fissions contributing to the sample and (2) the absolute beta count of a sample was related to a calculation of beta activity of fission products and induced activities resulting from fission of a certain number of atoms at various times, as in Figure 3.15.

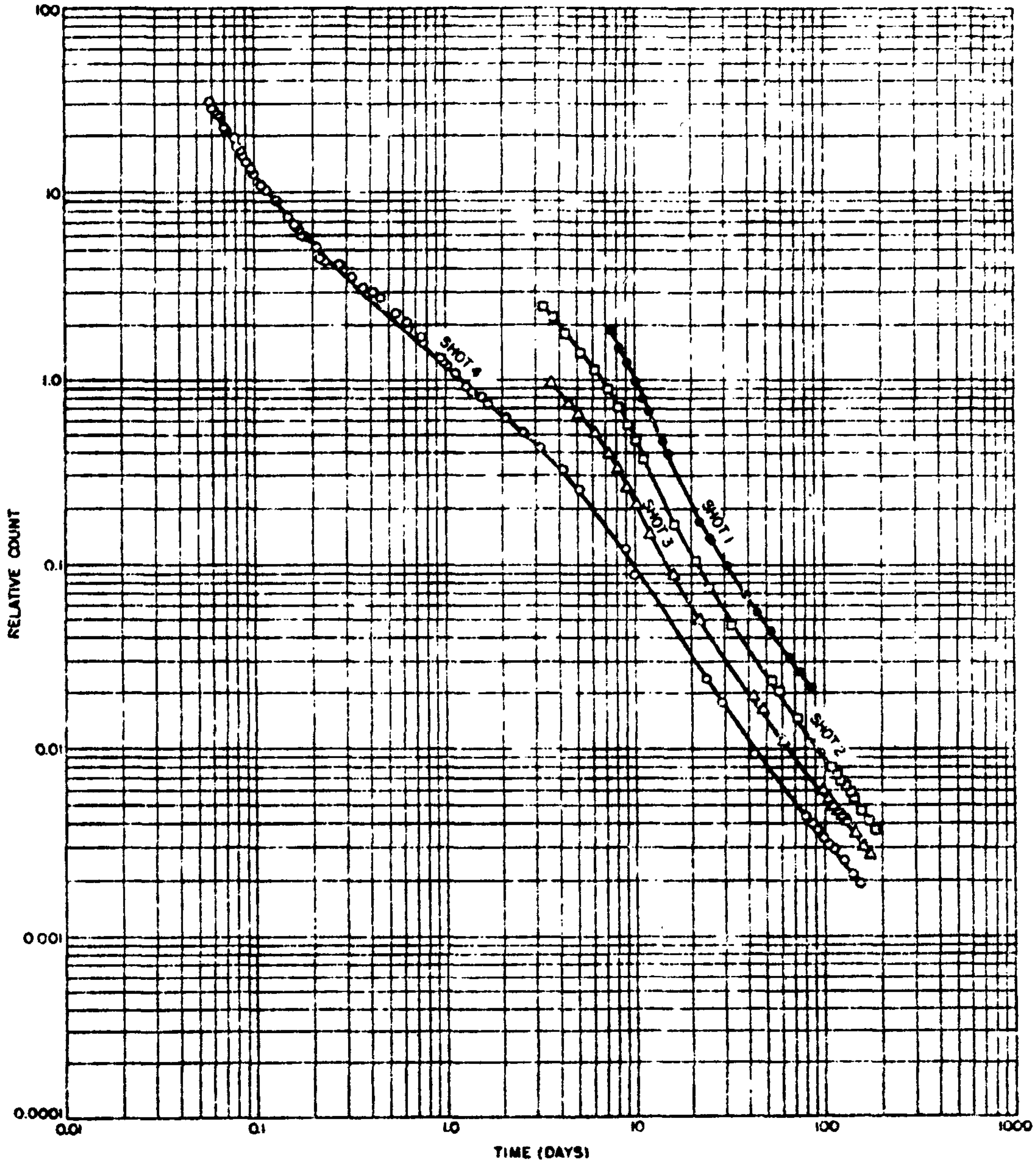

Figure 3.12 Gross beta decay of fallout samples from Shots 1, 2, 3, and 4.

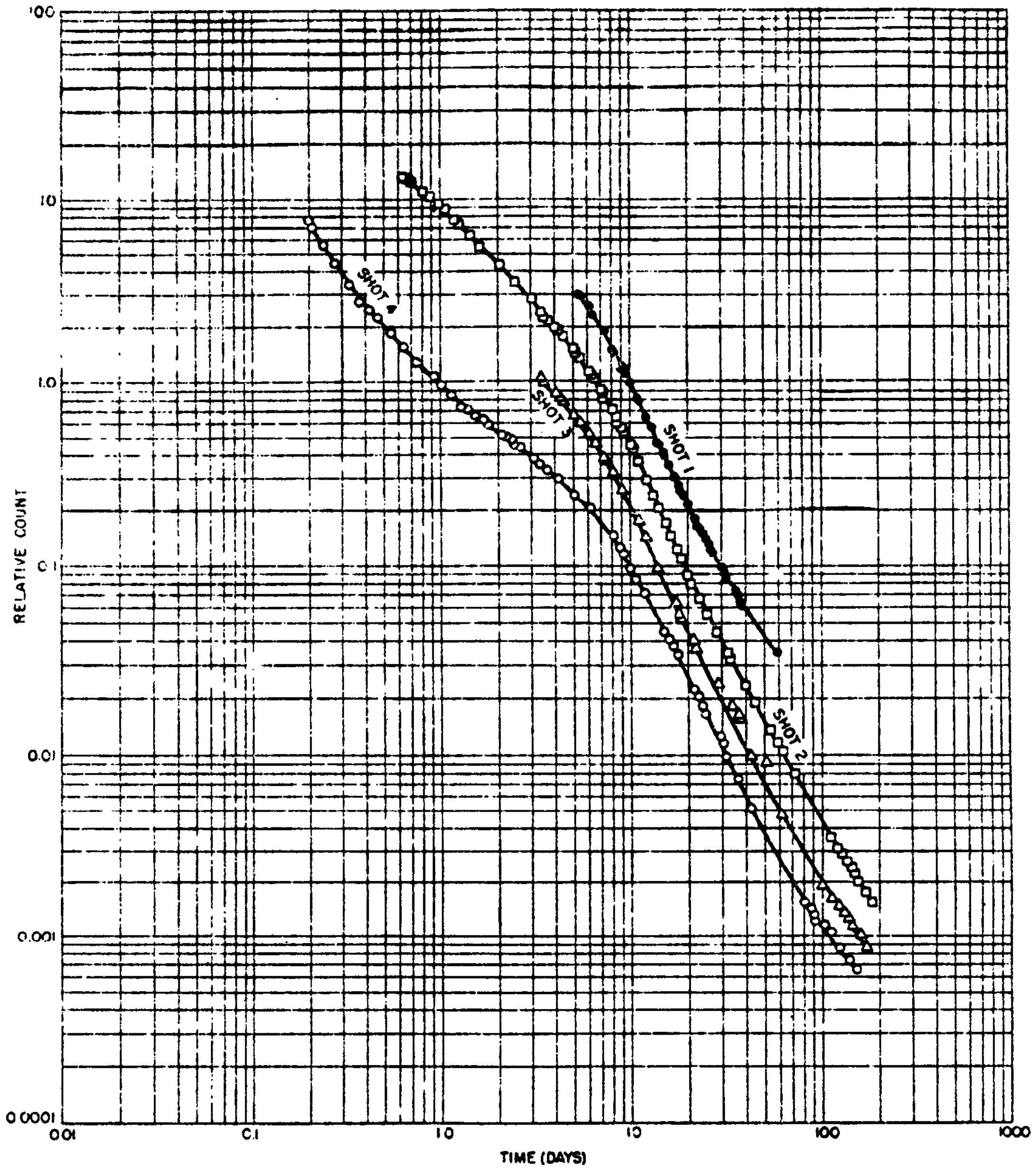

Figure 3.13 Gross gamma decay of fallout samples from Shots 1, 2, 3, and 4.

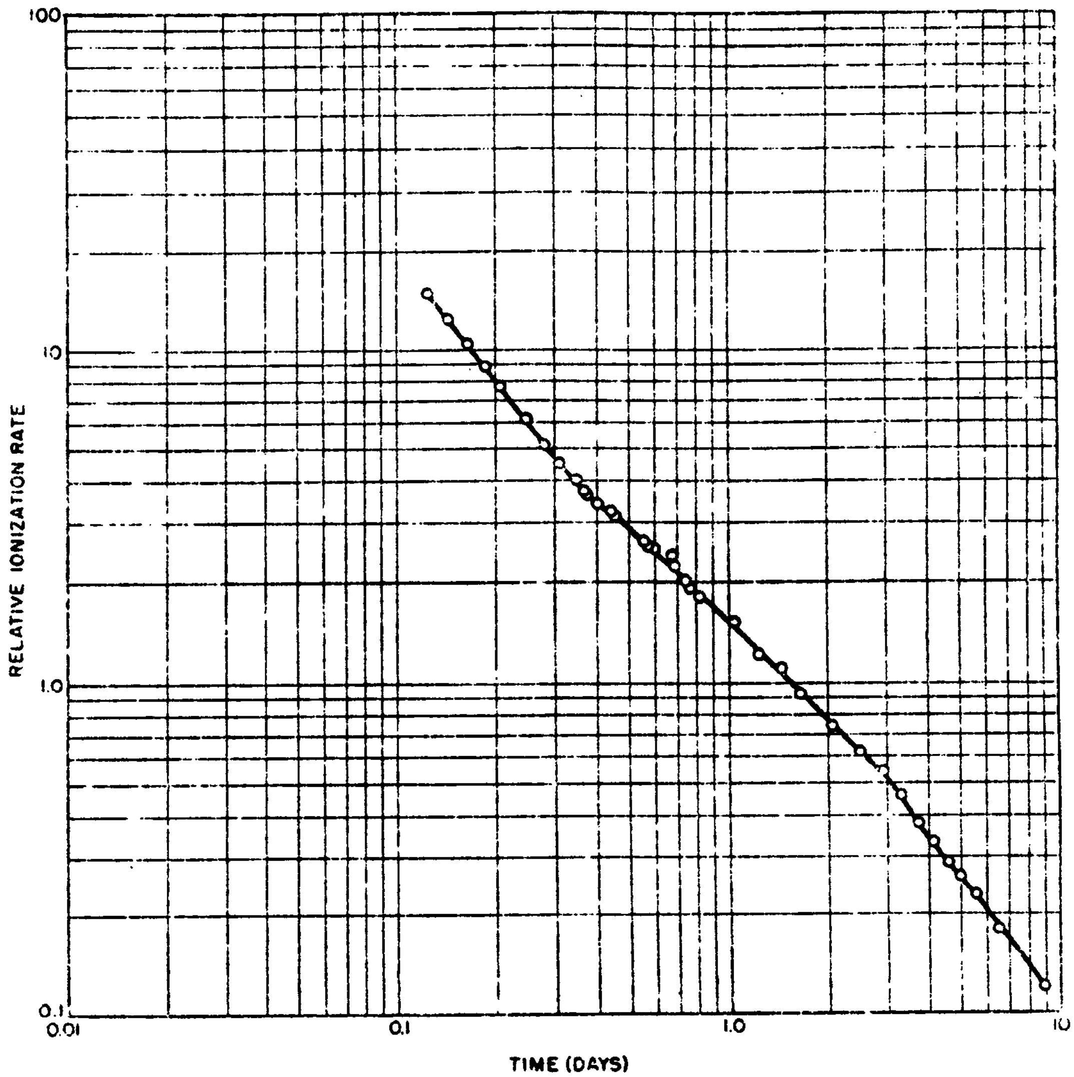

Figure 3.14 Gamma ionization decay as a function of relative ionization rate, Shot 4.

Using an estimate of the beta-to-gamma ratio and the average gamma energy, the gamma-rate contours were also related to the device fraction.

The Shot 1 contour data, when reduced according to an assumed fission yield of beta-to-gamma ratio of 0.45, and an average photon energy of 0.344 Mev at D + 8 days, accounted for 57 percent of the activity of the shot. Another calculation that normalizes the data using the Mo^{99} device fraction and the measured gamma field at the Site How station accounted for approximately 30 percent of the activity in the pattern.

For Shots 5 and 6, the beta counts of the water samples were used to normalize the contours constructed from the surface and aerial surveys. These calculations accounted for only 10 percent and 8.5 percent of the activity of Shots 5 and 6, respectively, in the

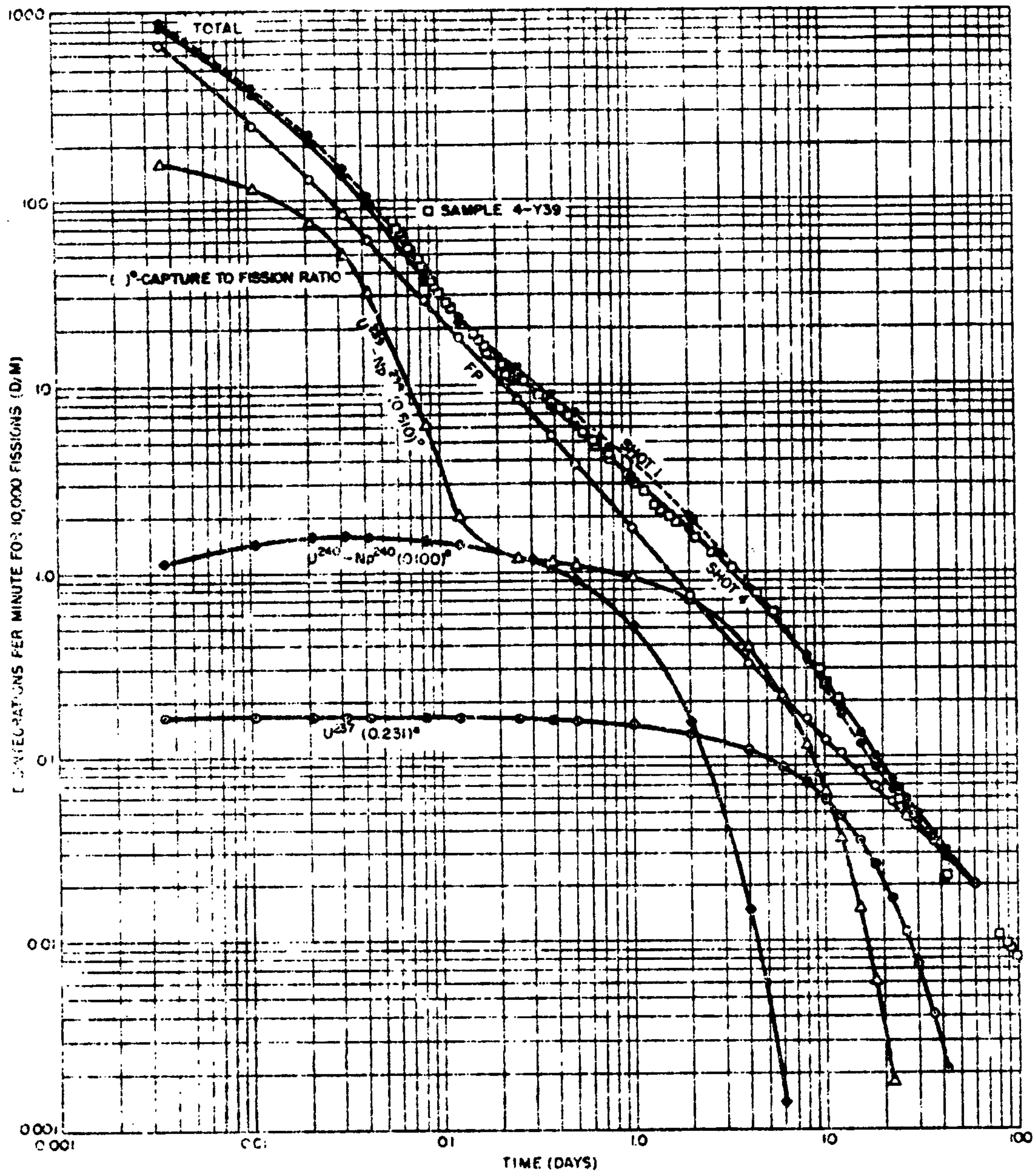

Figure 3.15 Calculated beta decay.

surveyed part of the patterns. These values do not include the fallout deposited near the atoll and are considered to be lower limits.

3.6 UPTAKE OF FISSION PRODUCTS BY ZOOPLANKTON

A small subsidiary project was undertaken during the Shot 5 water survey, consisting of collecting a few samples of zooplankton. These were sent back to the Scripps Institution of Oceanography for classification and counting and to the Naval Radiological Defense Laboratory for radiochemical analysis. The results of these experiments indicated that (1) the feeding mechanism of the organism affected the amount of activity assimilated, (2) the solid phases were concentrated in preference to non-particulate matter, and (3) there was no evidence of fractionation of isotopes in the assimilated material.

Chapter 4
BLAST EFFECTS

The blast-effect program consisted of five projects under the categories of structures, crater survey, tree-stand studies, and minefield clearance. Within these categories, the principal planned objectives of Program 3 were to:

1. Obtain further data on structural loading under air-blast conditions, for the purpose of developing prediction techniques applicable to the calculation of structural response and consequent damage from high-yield nuclear devices (Project 3.1).
2. Determine the dimensions of the apparent craters formed by Shots 1, 3, and 4, in order to assist in the prediction of the crater produced by a high-yield nuclear weapon. The two situations of particular interest on Castle were a surface burst on land and a surface burst in relatively shallow water (Project 3.2).
3. Obtain data on the blast effects on three natural tree stands in support of studies on blast-damage prediction to forested areas. These were to provide a method of damage assessment to material and personnel, knowledge of the amount of cover a forest affords, and the impediment to troop movements through or out of a forested area after a forest-damaging detonation (Project 3.3).
4. Determine the effects of a surface-detonated nuclear device on a planted sea minefield (Project 3.4).

An additional objective was added during Castle to provide for the documentation of damage inflicted upon miscellaneous structures from the unexpectedly high yield of Shot 1 (Project 3.5).

4.1 STRUCTURES PROGRAM

The structures program consisted of a planned Project 3.1, in which a 6-by-6-by-12-foot rigid concrete cubicle was instrumented for blast loading, and an unplanned Project 3.5, which consisted of documentation of unexpected damage to structures from Shot 1.

Until late in the planning stage, it had been intended to reinstrument a test structure remaining from Operation Greenhouse—a multistory building 26 feet in height, 196 feet in width, and 52 feet in length, sectionalized into various types of construction (Army Tests Structure 3.1.1). It was planned to perform limited rehabilitation of the structure, to augment the existing gage mounts with mounts to obtain more corner and edge loading detail, and to make limited use of displacement gages. A change in detonation sites made it necessary to abandon this plan, and adopt instead a different approach (see Appendix).

Both the original and final plans for Project 3.1 were modest in scope, since construction costs in the EPG were very high, all construction was difficult, and land area suitable for a structures program was very limited. In addition, no extensive structures program could be justified until the extensive data obtained at Upshot-Knothole had been analyzed, a task which was just being initiated when decisions on the Castle program had to be made.

Accordingly, Castle Project 3.1 was designed to provide blast-loading data only on the rigid concrete cubicle (Figure 4.1). The cubicle size and gage locations were determined by previous loading experiments on a similar-size structure in Upshot-Knothole Project 3.1 and high explosive tests by Sandia Corporation at the Coyote Canyon site, Sandia Base. Gages were placed in pairs at various locations on the front, top, and back of this structure; the pairing allowed determination of how closely two independent gages of the Wianko type would agree under air blast.

As it developed, the Castle Project 3.1 structure was exposed to a blast from Shot 3, which had a yield (130 kt) of only about a tenth of that predicted. Thus the peak overpressure was only about 3.5 psi instead of the 12 to 15 psi predicted. Although the specific objective of the project was therefore not accomplished, it was believed that much useful information could still be obtained from the data subsequent to the shot. Two blast-loading methods had been developed which could possibly be checked by this data. The blast-loading method in AFSWP-226 had been developed by Sandia Corporation based

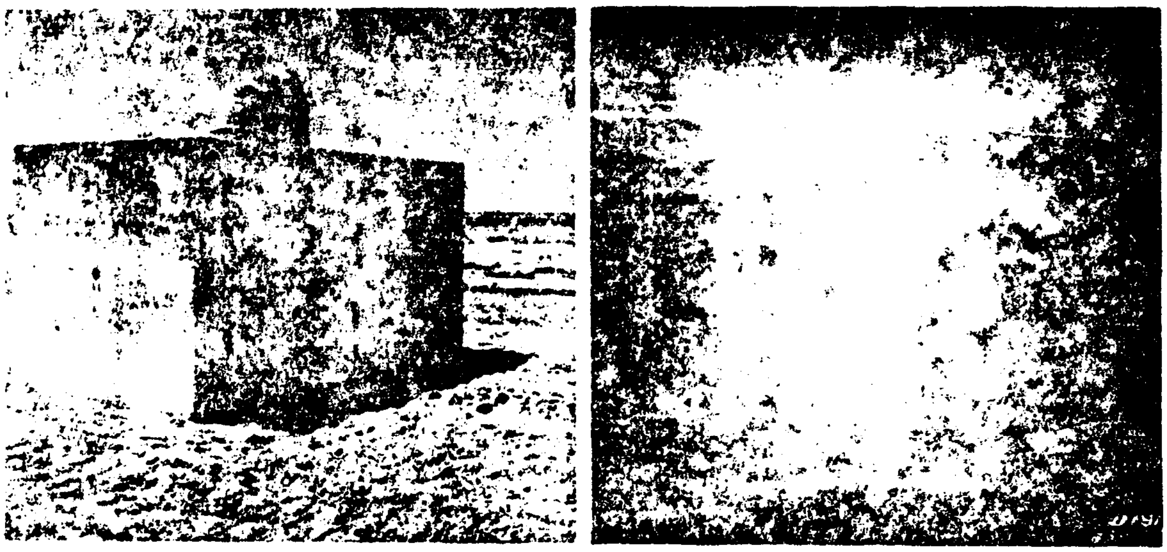

Figure 4.1 Test cubicle, Project 3.1. Left: front view. Right: rear view.

on high explosive, shock-tube, and full-scale data; the Armour Research Foundation (ARF) method was a blast-loading procedure developed by the ARF based on shock-tube and full-scale data. Consequently, an evaluation of the blast-loading data from this project was undertaken by Sandia Corporation to (1) make a comparison of the blast loading on the two Upshot-Knothole and Castle structures (which were of approximately the same dimensions) when subjected to blast waves having the same peak incident overpressure but different positive-phase duration; (2) evaluate the accuracy of both the so-called AFSWP-226 and ARF loading-prediction procedures against the pressure loading indicated by the centerline gages of Castle Structure 3.1 — since the procedure set forth in AFSWP-226 is predominantly applicable to two-dimensional structures, the gages at the center line of the structure were expected to give the best agreement; and (3) assess the reproducibility of Wianko gage measurements from the records of gage pairs on Castle Structure 3.1.

The results of this evaluation by Sandia Corporation indicated the following. The AFSWP-226 loading-prediction procedure gave reasonably good results. Also, the agreement of both AFSWP-226 and ARF predictions (within the diffractive phase) with the centerline gage records of the two full-scale tests was reasonably good. The net-loading curves produced with both the AFSWP-226 and ARF prediction procedures (within the diffractive phase) correlated reasonably well with the early drag phase of loading (out to about 50 msec). Actually, for the Castle Structure 3.1 in which the target width was twice the length, the ARF net-loading prediction was not quite as good an approximation to the experimental data curve as was the AFSWP-226 prediction. However, the ARF method of computing the net blast load on a closed, diffractive-type structure stipulates that the target length must be ". . . greater than the height or half width, whichever is smaller." For this reason, the net-loading comparison may not have presented the ARF method in its best light.

On the basis of the record provided by eleven pairs of gages on Structure 3.1, the reproducibility of the Wianko gage measurements was good. The probable error from the mean of the impulse ratios of each gage pair was only about 9 percent, while the probable error of the arithmetic mean itself was only about 3 percent.

In view of the failure of Project 3.1 to meet its original specific objectives, the question arises as to whether even a modest structure program should be included in any future developmental test series at the EPG. A comparison of the planned shot schedule (estimated yield and intended shot sites) with the actual shot schedule reveals that there was no feasible location either at Bikini or Eniwetok Atoll at which the test structure could have been placed to be in the desired 15-psi overpressure zone. Certainly, these facts emphasize that the inclusion of a structures program in an EPG developmental test series must be considered in the light of yield uncertainties, possible changes in detonation sites, and the restrictions imposed by small land areas. In addition, possible water-wave damage and the radiation hazard imposed upon the existing land masses by prior detonations in a series as well as the shot in which participation is desired, must be carefully considered in planning.

The documentation made by Project 3.5 (see Appendix) was not planned, but rather an opportunity initiated because Shot 1 gave a higher yield than originally predicted. The objective of this project was to determine the effects of air blast from a high-yield device on miscellaneous structures. The unexpected high yield of Shot 1 (approximately 15 Mt instead of 5 Mt) caused damage to certain structures at ranges where no damage had been expected. It was considered highly desirable to obtain all the data possible about this unexpected blast damage, since such knowledge could assist in establishing design criteria for blast protection.

That part of Project 3.5 which documented damage to a camp and facilities on Tare (Figure 4.2) and Peter Islands, some 14 to 16 miles from Shot 1, presented a picture of conditions to be expected in the fringe zone between no damage and light damage for metropolitan targets. Analytical prediction of such damage on the basis of overpressures and positive-phase duration would be difficult if not impossible. Therefore, documentation of such damage was probably of just as great value as data obtained from a project specifically designed to obtain such damage data.

At the location of the camp installations on Tare and Peter Islands, the estimated peak overpressure was about 1.4 psi, with a positive-phase duration of about 13.4 seconds. Damage to light wood-frame structures varied from light to severe damage. For a given design, the larger structures received greater damage than the smaller structures. Light knee bracing or truss work was effective in preventing collapse of rafters and walls of small buildings. The structures oriented parallel to the direction of the blast suffered less damage than those oriented normal to the direction of burst. Generally, the sides of the buildings facing toward ground zero were caved in, usually by bending fractures of the studs. Also, the roof rafters on the burst side were usually broken. The damage to the side and roof away from the burst direction varied widely: some were completely blown out, others partially damaged, and some received no visible damage. The buildings end-on to the direction of the blast were damaged less severely than those side on. Buildings which were closed tightly received more damage than those which were left open.

The damage to two heavily reinforced concrete shelters on Able and Charlie Islands was also documented by Project 3.5 (Figure 4.3). The damage inflicted upon these two massive instrument shelters, which were in the high-pressure region of approximately 130-psi peak overpressure (estimated 170-psi peak dynamic pressure), is significant background material for the design of maximum-protection shelters for either personnel or equipment. These shelters maintained their structural integrity, but failed functionally because of detail failure. Failure of the reinforced concrete, by either shear or tension, was predominantly around walls supporting doors and special windows and other structural discontinuities. The value of earth cover over structures, where practicable, was also indicated by the reduced damage to one of the two massive concrete structures, which was exposed to approximately the same 130-psi peak overpressure. Primary failures in the latter shelter were in ripping of portions of the concrete parapet and retaining walls at the rear of the shelter structure, which were torn off by the blast. A study of these failures may suggest corrective design improvement. Some of these improvements are appropriate for inclusion in future test-operation instrument shelters and other utilitarian structures.

4.2 CRATER SURVEY

The immediate objective of Project 3.2 was to determine the dimensions of the apparent craters formed by Shots 1, 3, and 4 (Figure 4.4). The long-range objective of the work was to obtain data to assist in the prediction of the crater produced by any high-yield nuclear weapon. Two situations were of particular interest in this regard in Operation Castle: surface burst on land and surface burst in relatively shallow water.

The major military interest in craters stems from the observation that the limiting distance of important damage to well-constructed underground fortifications lies only a relatively short distance outside the crater. For the prediction of such damage, the shape of the crater near the rim is more important than its shape or depth near the center.

Although of somewhat less military interest, the crater produced by the surface shot in shallow water—determining the limiting distance of damage to tunnels and the possibility of damming a harbor by the formation of a crater with a shallow or above-water lip—was also of some concern.

In planning for Castle, it was found that previous crater studies utilizing full-scale-nuclear, high-explosive, and theoretical data had reached the point where additional full-scale-nuclear data was required. The interest was actually not in water or atoll detonations, but there was no prospect of obtaining full-scale test data for surface or underground shots in continental tests. As a result, the participation in Castle represented a compromise measure.

A second compromise was necessary: one between what was desired (measurement of true craters) and what was operationally and financially feasible (measurement of apparent craters only). This compromise was also based on the lack of detailed information of the geologic structure at the detonation sites. Deep drilling and coring operations at Eniwetok Atoll in connection with Ivy indicated the presence of extensive sand lenses and other geologic nonhomogeneities, which made it uncertain that the demarcation line between the true and apparent craters could be readily ascertained by any means. In addition, the time interval between Shots 1 and 4 and the ready date for the shots follow-

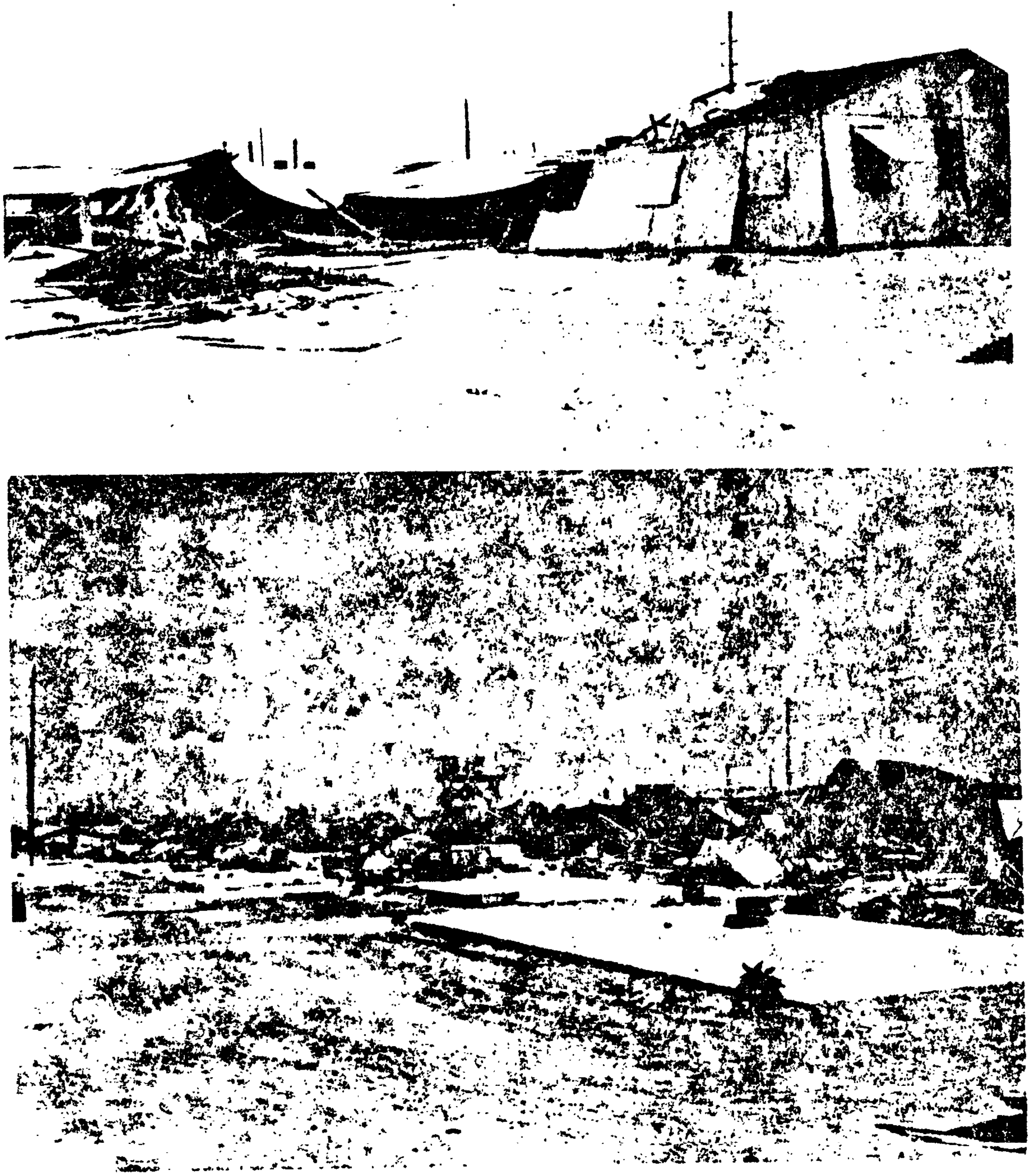

Figure 4.2 Tare Island facilities after Shot 1. Above: mess hall. Below: camp area.

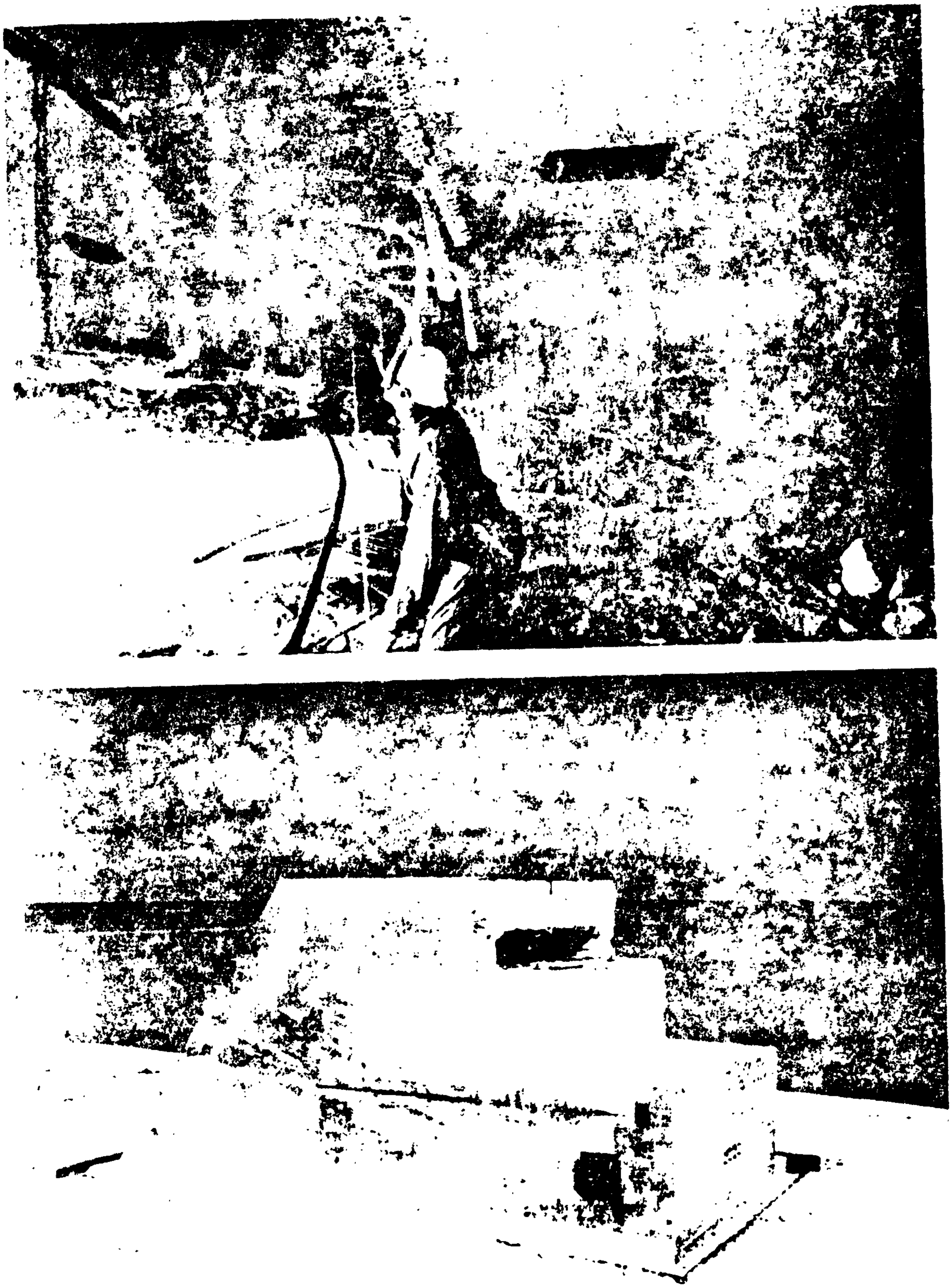

Figure 4.3 Close-in instrument shelters after Shot 1. Above: the upper aperture of the shelter in the lower photograph.

Figure 4.4 Aerial view of crater formed by Shot 1.

ing them at the same sites would have severely limited any effort to measure true craters by coring and drilling. In the case of the crater from Shot 3, any such extensive operation would have been long deferred because of radiological safety considerations.

In determining the depth of craters, both sonic fathometer and lead-line sounding measurements were utilized. It is pertinent that the fathometer survey of the Shot 1 crater showed a uniform flat bottom at a depth of 170 feet; however, this flat bottom undoubtedly represented the upper surface layer of mud and suspended sand which was settling in the crater. By contrast, lead-line soundings taken at approximately the same

TABLE 4.1 CRATER SURVEY DATA

All results are based on fathometer, lead line soundings, and aerial surveys. There was branching of the reef to the lagoon side for Shots 1 and 3.

Shot	Location	Yield	Days after Shot: Aerial Survey	Days after Shot: Fathometer Survey	Height of C.G. of Device	Preshot Water Depth at Site Zero	Crater Diameter	Crater Depth	Lip Formation
					ft	ft	ft	ft	
1	Coral Reef	15.0 Mt	0	7	15.4 above water	0	6,000	240	None
3	Island	130 kt	1	24	13.6 above ground 16.2 above water 20 above MLWS*	0	800	75	§
4	Water (barge)	7.0 Mt	1	6	17 above water	160	3,000	250† 90‡	None apparent

* Mean low water springs.
† Below water surface.
‡ Below original lagoon bottom.
§ The Shot 3 crater formed a "U" in the island with the open end on the lagoon side. There was no lip apparent at the time of survey in the shallow water of the open face of the "U." On the land around the crater, lip formation was fragmentary and had one peak extending 30 feet above the original ground level. In general, the lip was less than 16 feet above the original ground level; however, the water wave from Shot 4 had completely inundated the lip before the lip survey was made.

time recorded a depth of 240 feet, which is considered to be the Shot 1 depth of crater. This emphasizes that when there is suspended material in the water, the use of the sonic fathometer is unreliable and not recommended.

Table 4.1 indicates the general results of this crater-survey project.

One of the most significant aspects of Project 3.2 was that the crater-survey results caused serious questions to be raised (in the project report, WT-920) regarding the validity of the usually accepted cube-root scaling for prediction of nuclear-crater radii. This point stimulated considerable study, evaluation, and differences of opinion prior and subsequent to the publication of WT-920.

However, after considerable additional study of existing high-explosive and nuclear crater data, an AFSWP report was published (Reference 10) which clarified the prior differences of opinion by carefully cataloged conclusions in favor of the continued use of the cube-root scaling procedure for predicting crater radii. Significant conclusions of Reference 10 regarding crater predictions were: (1) For a given energy release, the cratering effectiveness of an explosive charge will in general decrease with increasing energy density. (2) A common soil factor of 1.8 to 2.0 should be used in conjunction with TM 23-200 (Reference 7, Figure 32, crater-radius prediction curve for dry soil) as the ratio between scaled crater radii at the EPG (washed soil crater) and the Nevada Test Site (dry soil crater) for both high-explosive and nuclear-device craters. (3) The cube-root scaling law can be used for prediction of crater radii, whereas the scaling relationship for crater depth may approach the fourth root; this conforms with the crater-prediction curves in Reference 7 (Figures 32, 33, 34, and 35).

Thus, especially based on the conclusions derived in Reference 10, (made partially possible by the data of Castle Project 3.2) considerable increase in reliability has resulted with respect to predictions of craters produced by megaton detonations.

4.3 TREE-STAND STUDIES

Operation Castle presented an opportunity to make measurements on natural tree stands several times larger than the Operation Upshot-Knothole experimental tree stand. Even though the natural stands were composed of tropical trees found at the EPG, breakage data was considered desirable, since continental tests in forested areas were not planned.

During Upshot-Knothole, an artificial stand of trees 320 feet long by 160 feet wide composed of 145 Ponderosa pine trees averaging 51 feet in height, had been exposed at a 4.5-psi peak static overpressure. The stand was instrumented along its length and across its width with ground-level static-overpressure gages, as well as dynamic-pressure gages at three elevations located 250 feet from the front of the stand. Ground-level pressure measurements had showed no significant attenuation in peak static overpressure or increase in rise times.

Upshot-Knothole results had also indicated that the prediction system for isolated trees was conservative when applied to small coniferous tree stands. However, in view of the unknown degree of attenuation for large stands and the tenuous nature of military-damage criteria for trees, damage predictions for isolated trees were assumed representative for tree stands. Thus, from all available data, a general breakage-prediction system had been developed that represented various levels of breakage probability for tree stands. The prediction system could be applied to idealized tree stands to determine damage by various-yield weapons, using height-of-burst curves modified to include wave form, where damage criteria were based on length of stem down per acre. For three general tree-stand types, isodamage curves giving light and heavy damage had been prepared for inclusion in TM 23-200 (Reference 7).

Sample plots were selected on three small, naturally forested islands of Bikini Atoll—Uncle, Victor, and William. These islands spanned a desirable predicted-overpressure region for the expected yield from Shot 3 ranging from heavy damage to light or no damage. It was essential that a substantial portion of the trees remain intact as a group, giving a graded series of damage to correlate with the previously developed tree-breakage prediction system.

In spite of the unexpected low yield of Shot 3, Project 3.3 achieved basic damage data. The unexpectedly large yield of Shot 1—blast incident from the opposite direction of Shot 3—caused heavy damage to the tree stands on William and Victor Islands and light damage to the upper portion of the stand on Uncle Island. Shot 2—blast incident from the same direction as Shot 1—caused no additional damage. The Shot 1-Shot 3 situation proved to be very fortunate. Because of the opposite directions of blast incidence and extreme yield difference, heavy damage from Shot 3 only extended to just beyond the light damage region of Shot 1. Thus, two sets of graded damage data were secured instead of one: from a high-yield device with long positive-phase duration (15.0 Mt, 2.5-psi peak static overpressure, 10-second positive-phase duration) and from a medium-yield device with shorter positive-phase duration (130 kt, 4.5-psi peak static overpressure, 1.2-second positive-phase duration).

The principal tree growth on the three islands selected consisted of five main components: the coconut palm (Figure 4.6), the Pisonia tree (Figure 4.5), and three species of large shrub. The Pisonia is a broad-leaf tree, numerous clumps of which averaged some 50 feet in height and 24 inches in diameter at the base. The Pisonia tree clumps bore a marked resemblance to the branching system and leaf size of an American Beech forest. Also, examination showed the root system to be similar. It became increasingly apparent that this similarity would make the Pisonia portions of the stands the most useful for verification of the breakage-prediction system developed. Palm, on the other hand, is unlike either the coniferous or broadleaf trees which comprise the bulk of the earth's temperate vegetational area and was thus of lesser value for this experiment.

The following general conclusions were reached:

1. Ground-level pressure measurements, made 2,000 feet into the tree stand, substantiated Upshot-Knothole conclusions of no attenuation in peak static overpressure;

TABLE 4.2 SUMMARY OF EFFECTS ON MINES, SHOT 4

L denotes Laid; N denotes Neutralized.

Mine Types	Row 1 2,000 ft to GZ Number		Row 2 3,440 ft to GZ Number		Row 3 4,800 ft to GZ Number		Row 4 7,000 ft to GZ Number		Row 5 11,100 ft to GZ Number		Row 6 12,800 ft to GZ Number		Row 7 13,800 ft to GZ Number	
	L	N	L	N	L	N	L	N	L	N	L	N	L	N
Mk 6-0														
Surface	–	–	–	–	–	–	2	0	–	–	–	–	–	–
30 ft case depth	–	–	–	–	3	3	2	2	4	0	3	0	–	–
125 ft case depth	–	–	–	–	4	4	4	4	4	0	3	0	–	–
Mk 10-9														
60 ft case depth	–	–	–	–	4	4	3	3	4	0	3	0	–	–
Mk 18-0	4	4	3	3	4	2	–	–	–	–	–	–	4	0
Mk 25-0	4	4	3	3	4	4	–	–	–	–	–	–	4	0
Mk 36-2	–	–	3	3	4	1	4	1	4	0	–	–	–	–
Mk 36-2	–	–	3	3	4	2	4	0	4	0	–	–	–	–
Mk 39-0	4	4	3	2	4	1	–	–	–	–	–	–	4	0
USSR R-1A	1	1	1	1	1	0	–	–	–	–	–	–	–	–
Percentage of all mines neutralized at each location	100		93.8		65.6		52.6		0		0		0	

therefore, for this purpose, further measurements of overpressure in tree stands should not be necessary.

2. It was not possible to assess the stand influence by observation of damage, because of non-uniformity of stand composition; nor was it possible to determine the peak-dynamic-pressure attenuation, because the three gages in or near the stands showed large, unexplained variations.

3. Observed damage from two devices of different yields compared favorably with the TM 23-200 isodamage curves (Reference 7) prepared for broadleaf tree stands.

4. Damage in broadleaf stands will be principally limb breakage and defoliation, with occasional breakage or uprooting of the main stem.

5. Snubber-wire arrangement for measurement of maximum deflection of tree stem is not feasible in a forested area composed of broadleaf trees and brush species where limb breakage is the principal form of damage.

4.4 MINEFIELD CLEARANCE

Project 3.4 had the objective of determining the effects of a megaton-range surface detonation on an underwater naval minefield. Inert versions of the following US and

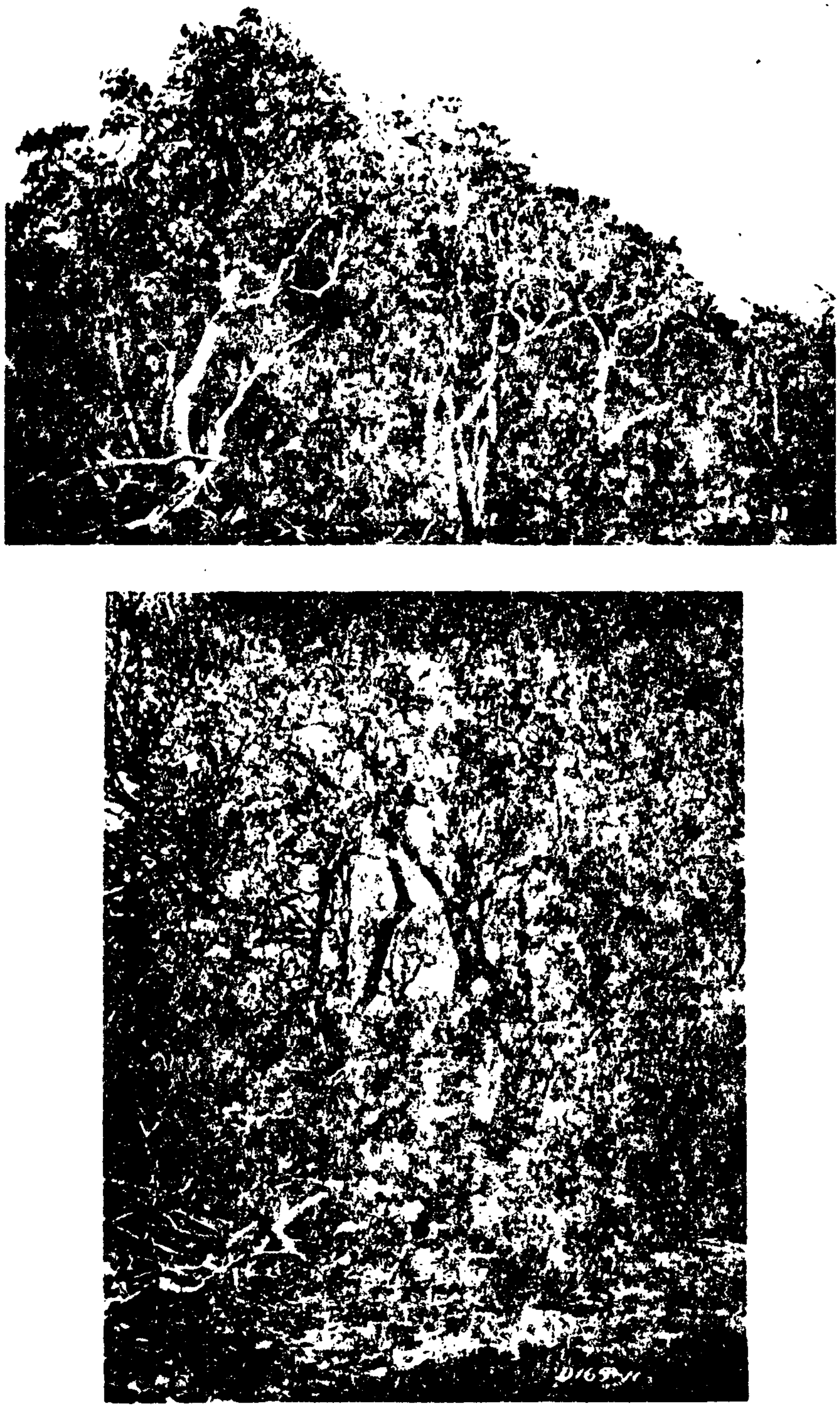

Figure 4.5 Sample Pisonia Plot D, Uncle Island, looking toward ground zero. Ground range, 75,400 feet; peak overpressure, 1.7 psi. Above: before Shot 1. Below: after Shot 1.

Figure 4.6 Sample Palm Plot B, Uncle Island. Ground range, 8,610 feet; peak overpressure, 4.4 psi. Above: before Shot 3. Below: after Shot 3.

USSR naval mines were exposed to the underwater effects of Shot 4: Mk 6-0, Mk 10-9, Mk 18-0, Mk 25-0, Mk 36-2, Mk 36-3, Mk 39-0, and USSR R-1A.

The statistical validity of the results may be questionable, since only 121 mines of all types were exposed. These results indicated a 95-percent probability that a surface-detonated 7.0-Mt weapon will neutralize 70 to 93 percent of all Mk 18-0, Mk 25-0, Mk 36-2, Mk 36-3, and USSR R-1A mines within a radius of 4,500 feet from site zero, if the mines are in water approximately 180 feet deep. With identical conditions of yield, height-of-burst, and water depth, results also indicated a 95-percent probability that 72 to 96 percent of all Mk 6-0 and Mk 10-9 mines within a radius of 7 000 feet will be neutralized. For Mk 39-0 mines laid in 180 feet of water, an approximate range of 2,800 feet was established as the maximum distance from a 7.0-Mt surface detonation at which lethal damage will occur. Table 4.2 presents a summary of the blast effects of Shot 4 on the minefield.

The radii of destruction obtained with the 7.0-Mt yield of Shot 4 are impressive; however, for a 20-kt weapon, assuming that cube-root scaling is valid to a first approximation, these radii would be only one seventh as large. The limited clearance ranges so obtained indicate that use of surface-detonated nuclear weapons for naval-minefield clearance is not feasible.

Chapter 5

ACCIDENTAL EXPOSURE OF HUMAN BEINGS TO FALLOUT

Immediately after the accidental exposure of human beings on Rongelap, Ailinginae, Rongerik, and Uterik to the fallout from Shot 1, Project 4.1 was organized to (1) evaluate the severity of the radiation injury to the human beings exposed, (2) provide for all necessary medical care, and (3) conduct a scientific study of radiation injuries to human beings. This project represented the first observations by Americans on human beings exposed to excessive doses of radiation from fallout (mixed fission products). The groups of exposed individuals were sufficiently large to provide good statistics. Although no pre-exposure clinical studies or blood counts were available, it was possible to study Marshallese and American control groups that matched and exposed population closely with regard to age, sex, and background.

The exposures involved far exceeded the normal permissible dosage. Calculations indicated that 28 Americans on Rongerik Atoll received a total gamma dosage of 86 r, 64 Marshallese on Rongelap Atoll 182 r, 18 Marshallese in the neighborhood of Ailinginae 81 r, and 157 Marshallese on Uterik Atoll 13 r. The external gamma dosage was delivered primarily by radiation energies of 100, 700, and 1,500 kev. The beta dosage was delivered by beta radiation with maximum energies of 0.3 and 1.8 Mev. The exposures occurred between 4 and 78 hours after the detonation, and the fallout was of about 12-hour duration. The internal dosage was due mostly to ingested material rather than inhaled material.

The physical effects of the radiation on individuals were typical of those normally expected. A significant number of individuals on Rongelap suffered from mild nausea, and one or two individuals vomited on the day of exposure. With the exception of nausea in one Ailinginae individual, there were no other definite gastrointestinal symptoms in the other Marshallese or the Americans. The Marshallese on Rongelap and Ailinginae and the Americans experienced, to a varying degree, burning of the eyes and itching of the skin for from 1 to 3 days. Later signs of radiation injury included definite loss of hair (epilation) in the Rongelap and Ailinginae groups, and the development of spotty, superficial, hyperpigmented skin lesions that peeled off (desquamated) from the center of the lesions outwards. In some cases the skin damage was sufficient to result in raw weeping lesions. There was no full-thickness destruction (necrosis) of the skin. The Americans developed only minor skin lesions without ulceration; there were no skin lesions in the Uterik natives. All lesions healed rapidly, with no further breakdown of the skin noted during the period of observation. Microscopic examination of biopsies of the lesions showed changes usually associated with radiation injury. Fully clothed individuals and those remaining inside of buildings or huts were protected to various degrees from development of lesions.

Hematologic changes were definite in the Rongelap, Ailinginae, and American groups. Lymphopenia appeared promptly and persisted for a prolonged period of time. Neutropenia occurred in all the individuals, with initial minimum values occurring around the 11th day followed by an increase in the counts and a secondary minimum around the 40th to 45th day. The most consistent hematologic change was the depression in the platelet counts. Platelets were below normal when first counted on the 10th day after exposure and progressively decreased, attaining a minimum between the 25th and 30th day. Although recovery commenced following this minimum, the platelet count had not returned to normal by completion of the initial study on the 76th day after exposure. The incidence of various respiratory and skin (cutaneous) infections was identical in all exposed groups and had no relationship to the hematologic changes.

Urinary excretions of radio-isotopes were studied. Beta activity in the urine of these exposed human beings indicated significant internal contamination. The body burden of the group of human beings with the greatest contamination was of the order of the maximum permissible concentrations for the individual radionuclides. The contribution of the effects of internal contamination to the total radiation response observed appears to have been small. Few of the fission products present in the environment were readily absorbed by the blood stream from the lungs and the gastrointestinal tract. Most of those radio-elements that gained entry into the body had short radiological and biological lives, and thus, the level of activity in the tissues of the body was relatively low.

At the end of six months, follow-up medical examinations were made of the Marshallese inhabitants of Rongelap. In general, the individuals appeared healthy and normally active, and no deaths had occurred in the interim period. Three babies had been born since exposure, none of whom displayed detectable abnormalities. One miscarriage at 3 months occurred during the interim period; no specimen was available for study. The skin lesions previously prominent had healed completely, and only occasional hyperpigmentation of depigmented scars was seen in a few individuals who had severe early skin damage. Regrowth of hair had commenced during the third month following exposure and was essentially complete at the six-month examination. Residual discoloration of the fingernails was found in three individuals.

No additional physical-examination findings could be ascribed to radiation exposure, and most individuals had gained weight during the interim period. An epidemic of measles was in progress during the examinations. The severity of the disease in the Rongelap people was no greater than in a control, unexposed population, and the incidence was no higher. Chest X-rays of all individuals revealed no abnormalities ascribable to the fallout radiation. Analysis of hematological data obtained failed to demonstrate a significant effect of measles on the peripheral blood count. Neutrophile, lymphocyte, and platelet counts were not significantly different from counts taken on the 74th post-exposure day, and none of these values had returned to control levels. Studies of bone marrow specimens obtained on 20 adult individuals revealed no significant abnormalities. Minimal amounts of residual radioactivity were detectable in the urine of approximately one third of the exposed individuals.

Chapter 6

TEST OF SERVICE EQUIPMENT AND TECHNIQUES

6.1 EFFECTS ON AIRCRAFT IN FLIGHT

During Castle, Wright Air Development Center (WADC) continued their studies of the overpressures, gust loading, and thermal effects on aircraft in flight. A B-36D, previously used on Ivy and Upshot-Knothole but with additional instrumentation and a white-painted underside, was flown in close proximity to all Castle shots. A B-47, previously utilized on Ivy and also additionally instrumented, participated in all shots but Shot 5.

The ultimate objective of the program was the establishment of operational and design criteria concerning nuclear-weapon effects on delivery aircraft, both current and future. Data on both thermal and blast responses at input levels that were to approach the design limits of the aircraft were to be obtained for the B-36. The B-47 project had as its particular objective the determination of the effects of a megaton-yield-range nuclear device upon a B-47B positioned to receive the predicted-maximum thermal radiation.

The important characteristics of a nuclear detonation, with respect to aircraft, are nuclear and thermal radiation and the air-blast wave. At ranges critical for a B-36 with regard to thermal and blast effects of weapons in the megaton-yield category, it had been previously shown that nuclear radiation effects due to proximity, envelopment in the cloud, or fallout were negligible.

The irradiance from the fireball varies with time and is characterized by a fast rise to a peak followed by a relatively slow decrease to zero. Radiant exposure for the B-36 in the Castle tests was expressed as:

$$Q = C \frac{W}{D^2} e^{-KD} = 36 \frac{W}{D^2} e^{-0.008D} \qquad (6.1)$$

Where: Q = radiant exposure on a surface normal to the radiation, cal/cm^2

W = total yield of source, kt

K = atmospheric attenuation coefficient, $(10^3 \text{ feet})^{-1}$

D = distance between source and receiver, 10^3 feet

C = a constant based upon thermal yield and attenuation measurements

The relationship between the temperature rise of the thin skin (commonly used in aircraft) and radiant exposure was given by:

$$\Delta T = \frac{Q \alpha L \cos i}{\rho C_p t} \qquad (6.2)$$

Where: ΔT = change in temperature, F

α = absorptivity coefficient

i = incident angle: the angle between the source-target line and a line normal to the skin surface

L = heat-loss factor

ρ = density, lb/ft^3

C_p = specific heat, Btu/lb-F

t = skin thickness, feet

Similar relationships were established for the B-47 tests. In addition to the theoretical calculations above, thermal effects on certain critical panels were determined by experimental furnace testing. The limiting thermal response for the B-36 was a 400 F rise in the 0.020-inch magnesium hat panels of the elevator. For the B-47, the critical thermal response was a 370 F rise in the 0.020-inch aluminum skin of the ailerons.

The characteristics of the blast wave in free air include a sharp rise to its peak positive pressure (the shock front), followed by a relatively slow decrease through the initial ambient value to a minimum of approximately a third of the peak positive value and a slow return to initial ambient pressure. The difference between the peak-positive-transient and initial-ambient values is the overpressure. For the B-36 in Castle, this was expressed empirically as:

$$\Delta P = 31.3 \frac{W^{1/3}}{R} \left[\log_{10} \left(\frac{R}{W^{1/3}} \right) - 0.88 \right]^{1/2} \qquad (6.3)$$

Where: ΔP = peak overpressure, psi

W = yield, lbs TNT equivalent

$$R = \frac{\text{Slant range, ft}}{\left(\frac{\rho_h a_h}{\rho_b a_b} \right)^{1/2}}$$

ρ = air density, slugs/ft^3

a = speed of sound, ft/sec

h = altitude of the measurement

b = burst altitude

Equation 6.3 was used only for overpressures less than 2 psi. Both equations 6.1 and 6.3 were derived from limited test data from previous operations.

The second important property of the blast wave is the material, or gust, velocity — the air movement behind the shock front. The equation used to predict material velocity was:

$$u = 1.89 a_h \frac{\Delta P}{P_h} \left(7 + 6 \frac{\Delta P}{P_h} \right)^{-1/2} \qquad (6.4)$$

Where: u = material velocity, ft/sec

a_h = speed of sound at measurement altitude, ft/sec

ΔP = peak overpressure, psi

P_h = initial ambient pressure at measurement altitude, psi

The principal blast effects are crushing due to overpressure and the change in steady state aerodynamic conditions due to the material velocity. The latter is similar in nature to the sharp-edged gusts encountered in the normal atmosphere. These changes are influenced by bending of the structure and displacement of the entire aircraft.

For Castle, analytical and experimental investigation established the critical overpressure of the B-36 as 0.8 psi, and of the B-47 as 1.0 psi. The analysis of gust loading established the B-36 horizontal stabilizer as the critical component. Since the B-47 experiment was primarily designed to investigate thermal effects, the gust-load investigation was performed only to establish the safety of the aircraft for the thermal input to be obtained.

Two basic problems were involved in the operation of the aircraft: the flying of the aircraft to a point in space at a given time, and the accurate determination of the actual

TABLE 6.1 DESIRED AND ACTUAL POSITIONS AT TIME ZERO AND TIME OF SHOCK ARRIVAL

Shot 3 data unusable because of low yield. All B-36 data calculated from radar scope photos except for Shot 6, which is Raydist data. B-47 data obtained from ship's instrumentation for Shots 4 and 6 and from Raydist data for Shots 1 and 2. Ranges in thousands of feet.

Shot	Horizontal Ranges				Shock-Arrival Position	
	At Time-zero		At Shock-arrival		Slant	Actual
	Desired	Actual	Desired	Actual	Range	Altitude
1: B-36	50.0	50.8	75.7	71.5	78.8	33.0
B-47	48.0	50.9	121 0	137.5	141.9	35.0
2: B-36	50.0	51.7	78.5	77.9	86.2	37.0
B-47	50.0	75.8	132.0	192.5	195.7	35.0
4: B-36	50.0	50.5	78.5	81.6	89.6	37.1
B-47	48.2	54 2	119.4	140.0	144.3	35.0
5. B-36	39.5	40.6	65.5	69.7	80.4	40.0
B-47*	—	—	—	—	—	—
6: B-36	121.4	122.0	90.3	86.0	92.1	33.0
B-47	31.8	29.5	84.6	84.0	91.0	35.0

* B-47 aborted Shot 5 because of fuel leak.

flight path during the thermal and blast phases of the detonation. Positioning was in general performed by aircraft instrumentation, and tracking by a combination of aircraft instrumentation and a Raydist Radio Navigation System. For safety reasons, positioning was based on the predicted maximum-possible yield of the device.

For both experiments, danger-region diagrams were plotted in terms of horizontal range and altitude, upon which the effects parameters discussed previously were plotted simultaneously in order to show the boundaries of regions within which aircraft damage would result. These diagrams were used on each shot under a given set of conditions of yield, aircraft velocity, and aircraft configuration, to establish a position in space which would give the desired input without endangering the aircraft. Positioning data is summarized in Table 6.1.

Thermal instrumentation was installed to define radiant exposure, irradiance, and the temperature rise on wing, fuselage, stablizer, and elevator. In addition, strain-gage bridges were installed in the left wing and stablizer of the B-47 to obtain information on the mechanical effects of the thermal input. Free-stream overpressure and pressures on the underside of various surfaces were measured. Blast-response data were in terms of strain-gage measurements of the wing, fuselage, and stabilizer; linear and angular accelerations; and elevator and wing deflections. Photography and temp-tape measurements of peak temperatures were also utilized.

The principal results of the experiments are summarized in Table 6.2 and 6.3.

The Shot 1 yield of about 15 Mt (approximately 25 percent in excess of the positioning yield) provided the highest peak overpressure, 0.81 psi, recorded on the B-36. The damage to the aircraft necessitated replacement of the bomb-bay doors, the aft lower Plexiglas blisters, and the radar-antenna radome. Superficial damage was encountered on the B-36 on Shots 2, 4, and 5. On Shot 5, the yield was predicted (12 Mt) with less conservatism compared to previous shot estimates; the fact that the actual yield was 13 Mt resulted in the largest temperature rise and stabilizer bending moment (for the B-36) obtained during the tests. The radiant exposure at the aircraft during Shot 5 was less than that for Shot 1, but the incident angle was smaller, resulting in more thermal energy being absorbed. This was apparent from the extent of the thermal damage suffered during Shot 5. The elevator skin was permanently buckled at four places, and a large percentage of the paint on the stabilizer and elevator was blistered and peeled.

A haze layer higher than 35,000 feet was reported by the B-47 crew on Shot 6. This layer provided a reflecting surface for irradiation and induced a noticeable amount of thermal irradiation on the upper surface of the aircraft. This was the only shot in which this crew noticed any significant heating of the crew compartment.

Only on Shot 5 was any nuclear radiation observed on board the aircraft. The maximum value was 20 mr recorded in the B-36 crew compartment, with radiation detected over a period of about 20 seconds. After the return of the aircraft to the continental U. S., some residual radiation was detected that emanated from microscopic particles imbedded in the paint and lodged in the joints of the aircraft skin.

The data obtained from the projects can be used to evaluate three related studies: (1) the correlation of inputs measured at the position of the aircraft with those inputs predicted by theory for such given parameters as yield, slant range, and altitude; (2) the verification of predicted effects of a nuclear detonation upon an aircraft; and (3) the prediction of the nuclear-delivery capability of the aircraft involved.

A postshot comparison between predicted and measured inputs and responses for the B-36 is tabulated in Table 6.4. The predicted figures were calculated using actual yield and aircraft range for each shot, therefore establishing a basis for evaluating the prediction methods, both for inputs and responses.

A similar comparison is shown in Table 6.5 for the B-47 thermal data. The first tabulation of input data corrects the measured inputs to zero time i.e. to a point in space, in order to make a valid comparison with the calculated single-point values. Although comparisons are shown for values obtained with both radiometers and calorimeters, the calorimeter values are considered more reliable.

Table 6.6 compares thermocouple and other temperature-indicating measurements to the predicted maximum temperature rise in panels having different thicknesses. Measured values were greater than calculated values in thin skins and smaller in thick skins.

The attempt to evaluate the magnitude of temperature-induced strains in panels involved a complex stress analysis and was further complicated by the influence of temperature on the strain gages. For this reason, the data was not immediately available, but was considered in planning for Operation Redwing.

The specific techniques used during Castle to predict thermal inputs and responses were inadequate for accurate, close positioning of the aircraft. Factors which contributed to the discrepancies were insufficient information on attenuation, absorptivity, and the cooling coefficient. As a result, it is apparent that a need still existed for continual

TABLE 6.2 DATA SUMMARY, B-36

Shot	1	2	4	5	6*
Radient Exposure, cal/cm²†	47.5	35.2	17.4	45.9	—
Max Irradiance, cal/cm²-sec†	6.2	5.2	3.7	7.2	—
Max Temperature Rise of Elevator Skin at Station 144.5, percent of 400 F limit	52‡	45	37	64	—
Max Overpressure, psi	0.81	0.56	0.42	0.60	0.22
Max Pressure, psi, on underside of:					
Wing	0.90	0.62	0.48	0.68	0.27
Fuselage	0.92	0.64	0.48	0.67	0.23
Stabilizer	1.20	0.83	0.60	0.85	0.25
Max Positive Bending Moments,§ percent of limit¶:					
Stabilizer, Station 62	59	60	37	76	27
Fuselage, Station 1476	50 to 70	47 to 67	22 to 42	67 to 87	4 to 20
Wing, Station 1062	50	50	44	53	49

* Head-on orientation.
† Average of multiple instrumentation.
‡ Temp-tape data.
§ Max positive bending moments are the peak incremental bending plus dead weight and in-flight conditions.
¶ Bending moment limits are defined as two thirds the static test ultimate.

TABLE 6.3 DATA SUMMARY, B-47

Shot 3 data unusable because of low yield. No participation in Shot 5.

Shot	1	2	4	6
Radiant Exposure,* cal/cm²	32.1	17.5	16.3	11.8
Max Irradiance,* cal/cm²-sec	5.27	2.67	4.10	5.33
Time to Peak Irradiance, seconds	3.81	3.24	2.41	1.33
Duration of Irradiance, seconds	48	46	33	12
Peak Temperature Right Stabilizer, F	134	44	81	99
Time to Peak Right Stabilizer Temperature, seconds	9.0	10.0	7.0	5.0
Time to Shock Arrival (Station 1217), seconds	110.5	159.1	116.9	73.66
Peak Overpressure, psi	0.31	0.22	0.26	0.25
Peak c.g. Acceleration, g's	0.38	0.32	0.28	—

* Corrected to zero incident angle.

TABLE 6.4 - COMPARISON OF MAXIMUM THEORETICAL AND MEASURED INPUTS AND RESPONSES, B-36

Shot	1	2	4	5	6
Radiant Exposure, cal/cm²					
Theoretical	50.8	33.4	22.8	53.8	—
Measured	47.5	35.2	17.4	45.9	—
Overpressure, psi					
Theoretical	0.78	0.56	0.44	0.61	0.26
Measured	0.81	0.56	0.42	0.60	0.22
Temperature Rise; percent of critical rise of elevator skin, 0.020-inches mag.					
Theoretical	98	76	58	119	—
Measured	52*	45	37	64†	—
Bending Moment, percent of critical moment of stabilizer at Station 62					
Theoretical	60	49	40	69	27
Measured	59	60	37	76	27

* Temp-tape data.
† For Station 144.5. At Station 312 where the paint was missing, the percent of critical temperature rise was 81.

TABLE 6.5 COMPARISON OF MEASURED DATA WITH EXTRAPOLATIONS TO ZERO-TIME POSITIONS, B-47

Measured: data as measured on the aircraft. Zero-time: values of measured data extrapolated to zero-time position.

Shot	1	2	4	6
Average Energy				
Radiometers:				
Measured, cal/cm²	28.8	18.2	19.8	13.8
Zero-time, cal/cm²	33.7	19.7	21.3	14.7
Measurement duration, seconds	25	25	15	10
Calorimeters:				
Measured, cal/cm²	29.6	16.3	15.7	11.7
Zero-time, cal/cm²	35.2	18.4	16.6	11.8
Measurement duration, seconds	25	25	15	10
Peak Irradiance, cal/cm²-sec				
Radiometers:				
Measured	5.3	2.7	4.1	5.4
Zero-time	5.7	2.9	4.2	5.6
Calorimeters:				
Measured	4.8	2.8	3.6	4.7
Zero-time	5.1	3.1	3.8	5.2
Time to Second Maximum, seconds				
Radiometers:				
Measured	3.81	3.25	2.40	1.33
Zero-time	3.85	3.29	2.42	1.35
Calorimeters:				
Measured	3.80	3.22	2.40	1.37
Zero-time	3.95	2.97	2.60	1.35

improvement in the techniques used in predicting thermal effects. However, the data obtained should assist in revising the procedures used to calculate thermal effects and, thus, result in more accurate predictions. The formulas and procedures utilized to predict blast effects at overpressures less than 1.0 psi were satisfactory; in general, good correlation was obtained between measured and predicted values.

As a result of the experiments, sufficient data are available to determine the responses of the B-36 aircraft to nuclear detonations and to define with reasonable accuracy the maximum delivery capabilities of the aircraft. Furthermore, the data and experience obtain-

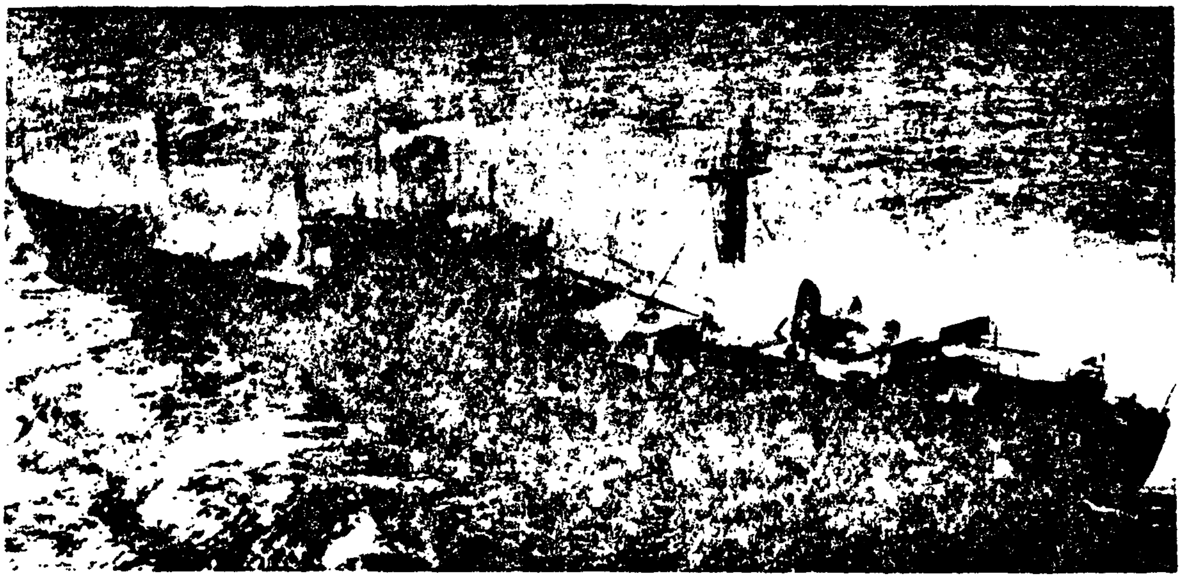

Figure 6.1 The YAG-39 with the washdown system operating.

ed from both experiments will be useful to assist in the establishment of general methods for the determination of nuclear effects as related to weapon-delivery capability, structural vulnerability, and lethality problems.

6.2 CONTAMINATION AND DECONTAMINATION STUDIES

The basic vehicles exposed to the fallout from the Castle detonations were two converted Liberty ships: the USS Granville S. Hall (YAG-39) and the USS George Eastman (YAG-40). In addition to simulating conditions aboard ship during and after fallout, these vessels served to mount devices to collect fallout on their weather surfaces for contamination-decontamination studies and to house instrumentation for studies of fallout material. Their weather surfaces served as a radiating source for various shielding studies.

The basic difference between the two ships was the installation and operation of a washdown system aboard the YAG-39 only. It was planned to have the two ships experience the same magnitude of fallout and thereby evaluate the effect of washdown. Figure 6.1 is a photograph of YAG-39 with the washdown system operating.

The ships were instrumented extensively for the measurement of gamma dose and dose rate at a total of 137 stations. Each instrument consisted of four ion chambers which provided for covering a dose-rate range from 0.1 mr/hr to 10,000 r/hr. The detector-recorder system recorded dose increments in the ion chambers as deflections on the chart of a pen-and-ink recorder. The data from the numerous records were reduced to plots of both dose rate versus time and dose versus time by an electronic reading-computing-plotting device.

Each ship transported a Navy F4U fighter aircraft which was exposed to fallout. After exposure, the aircraft were transferred to a land decontamination area upon return of the ships to Eniwetok Atoll and were subjected to decontamination studies. A similar procedure was followed for a frame supporting panels of paving, wall, and roofing materials to be studied by an Army Chemical Corps project. These panels were exposed aboard a barge anchored in Eniwetok Lagoon during Shot 6.

Studies of the phenomena aboard a ship during and after radioactive fallout were made utilizing the gamma-dose-rate detectors in addition to aerosol filters, gummed-paper

TABLE 6.6 COMPARISON OF MEASURED AND CALCULATED PEAK TEMPERATURE RISE, B-47

Deviation: Percentage deviation of calculated value from measured value.

Shot	1	2	4	6
Peak Temperature Rise, 0.020-inch Skin:				
Measured, F	—	—	180*	205*
Calculated, F	211	92.5	126	159
Deviation, percent	—	—	−30	−22
Peak Temperature Rise, 0.040-inch Skin:				
Measured, F	134	44	81	91
Calculated, F	110	47	68	86
Deviation, percent	−16	+7	−16	−5
Peak Temperature Rise, 0.064-inch Skin:				
Measured, F	89	32	54	65
Calculated, F	110	52	65	69
Deviation, percent	+24	+61	+21	+6
Peak Temperature Rise, 0.188-inch Skin:				
Measured, F	39	10	19	22
Calculated, F	36	13	20	24
Deviation, percent	−9	+32	+3	+9

* Temp-tape values.

collectors, and airborne-activity monitors distributed weatherside and in the ventilating system of the ship. Test cubicles were provided aboard the YAG-40 with different ventilating systems to evaluate the effect of different air-flow rates, and with filters or an electrostatic precipitator in the system.

The contamination alighting on the ships' weather surfaces provided conditions for two sets of experiments: (1) The gamma radiation was detected at various locations below decks and within various thicknesses of shields to evaluate the effective absorption of the radiation by steel. (2) After return of the ships to Eniwetok Atoll, the weather surfaces were subjected to various decontamination procedures to evaluate their effectiveness and speed; inclusion of a section of wooden flight deck aboard the ships yielded data for extrapolation to aircraft carriers.

Both ships participated in Shots 1, 2, 4, and 5 and were equipped for remote control operation. During the first two shots, both ships were vacated during the night before the shot and were operated from a P2V-5 aircraft, with a secondary control party aboard the USS Bairoko (CVE-115). During Shots 4 and 5, both ships were controlled by a crew stationed in a shielded section aboard the washdown-equipped YAG-39. This provision ensured closer control of the ships and enabled them to be located closer together and to experience similar fallout. After the shot, the unmanned radioactive ships were towed back to Eniwetok Lagoon by the ATF-106, and decontamination was initiated subsequently.

6.2.1 Operational Results. The location of the ships during Shot 1 was determined by lower-level, preshot wind forecasts. Changes in the wind structure and the unpredicted

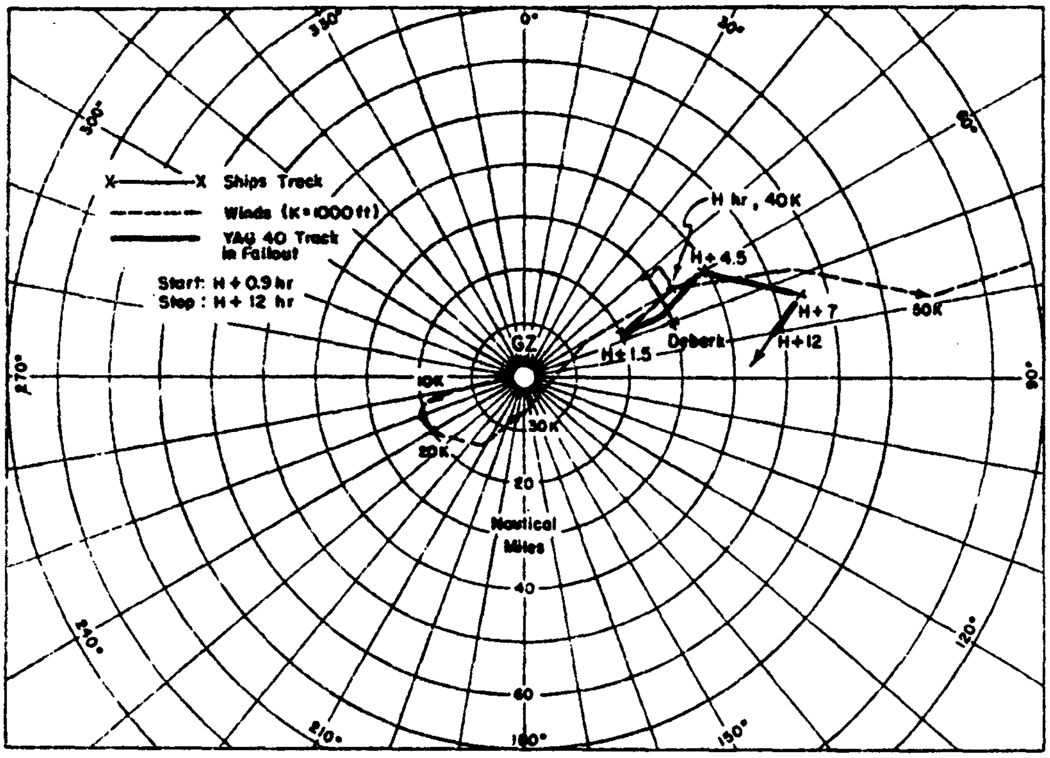

Figure 6.2 Ship's course, Shot 5.

height to which the radioactive material was carried caused the fallout to occur east of Bikini Atoll, while the ships were west of Bikini. The resultant low contamination levels denied the acquisition of useful data. The ships were more-favorably located during Shot 2, but a control failure caused the YAG-39 to stop before fallout ceased, and the two ships did not experience comparable events. The results from Shots 4 and 5, during which the YAG-39 was manned, were more satisfactory, with the highest doses being experienced during Shot 5. Figure 6.2 presents the ship's tracks during Shot 5, together with a hodograph of the wind structure.

In spite of the close operation of the two ships during Shots 4 and 5, appreciable differences in fallout were observed: the dose that would have been observed aboard YAG-39, had it not been washed down, varied (with time) between 25 and 100 percent higher than that actually observed aboard YAG-40. Operation of a single ship with part of the deck washed was recommended to eliminate this problem at future operations.

6.2.2 Washdown System Evaluation. The washdown system aboard the YAG-39 operated successfully at a rate of approximately 2,000 gal/min. The only difficulty was a stoppage in the boat-deck drain during Shots 4 and 5, which impeded the removal of contaminated water from this area. The coverage was adequate except when the wind was abeam. Installation of nozzles along the sides of the ship or maneuvering the ship would have alleviated this difficulty.

The washdown effectiveness based upon the reduction of accumulated gamma dose averaged approximately 90 percent. The effectiveness based on gamma dose rate after the cessation of fallout averaged approximately 94 percent. In general, this system was found to be more effective than any subsequent decontamination effort performed on the non-washdown ship, the YAG-40.

The washdown effectiveness based on dose and dose-rate measurements in the interior of the ship decreased in the areas more remote from the deck. This fact indicates that sources of radiation other than the washed-down deck become important at the more-remote locations.

The data from the building-material panels placed aboard the ships after Shot 2, when corrected for an estimated difference in fallout of a factor of ten, indicated a washdown effectiveness of greater than 95 percent based on dose rate. The effectiveness measured on the aircraft was comparable to that measured on the ships' decks.

The only material damage noted on the aircraft from exposure to salt-water washdown was manifested as excessive magneto drop-off, some minor rusting of unpainted ferrous metals, and the presence of excessive water where the lead goes into the spark plug.

6.2.3 Ship-Shielding Studies. The detectors placed within cylindrical steel shields yielded data on the effective absorption coefficient as a function of time. The data can be fitted with a function of the form:

$$I = I_0 e^{-\mu x} \qquad (6.5)$$

Where: I = observed dose rate

x = steel thickness

μ = effective absorption coefficient (to be determined)

I_0 = source dose rate

The average values of μ are plotted in Figure 6.3 versus the time since the detonation. Observations below decks indicate that for relatively lightly shielded locations, the measured values of μ can be utilized in a formula for the radiation from a plane-source distribution to calculate the shielding factors. In more heavily shielded location (e.g., in the concrete-covered recorder room), the actual shielding is not as effective as the calculated shielding, presumably because the sources of radiation other than the contaminated decks become important. The measured shielding factors on the YAG-40 were between 0.1 and 0.2 between the second and upper deck, and between 0.03 and 0.05 in the hold. The corresponding YAG-39 values were 50 to 100 percent larger than these. In the superstructures compartments on both ships, the shielding factors ranged from 0.1 to 0.6.

6.2.4 Airborne-Activity Studies. Airborne activities were measured above decks and in ventilation and boiler air ducts during fallout, and above decks during decontamination operations. These measurements provided data on a fallout-detection system, inhalation hazard to crews above and below decks, activity-removal efficiency of various ventilation systems, and inhalation hazard to decontamination crews.

Peak airborne beta activities aboard ship were measured to be of the order of 0.6 mc/m^3. A similar detector placed on Parry Island detected peak levels of 0.15 and 0.003

mc/m^3 at 12 hours after Shots 2 and 3, respectively. The instrument used was sensitive to 10^{-3} mc/m^3 if the background gamma field was less than 0.5 r/hr.

Weatherside filter samples counted at 10 days after the shot yielded values of about 2×10^3 counts/min/ft^3 of air drawn through them. This value represents an average over the time from the start of fallout till shutdown of the filters approximately 19 hours after detonation.

The standard ventilating system operating at 1,000 ft^3/min resulted in an activity concentration in the cubicle which was a factor of 1×10^{-4} to 2×10^{-4} lower than that above

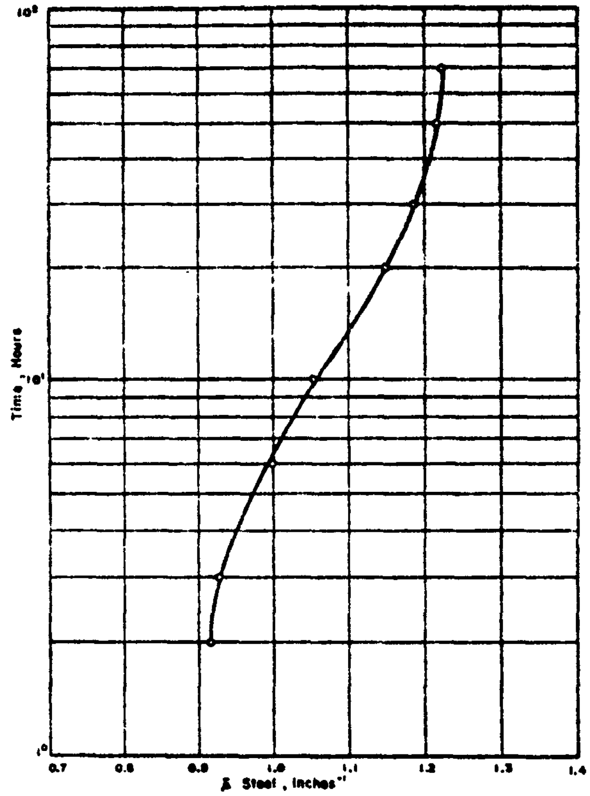

Figure 6.3 Apparent absorption coefficient μ as a function of time.

decks. Changing the flow rate had no appreciable effect, but the Naval Research Laboratory (NRL) preciprotron or Army Chemical Center (ACC) paper filters were approximately 95-percent effective in further reducing the activity.

During recovery and decontamination operations, the airborne activity concentration was almost always less than 0.1 mc/m^3. Respirators were worn by personnel operating a Tennant resurfacing machine principally for protection from flying chips.

6.2.5 Radiation Surveys. The radiation condition aboard an unmanned ship was first estimated from data telemetered from a fixed gamma-detector station. A second order-of-magnitude estimate was derived by multiplying a reading made from aboard the recovery tug by a calculated factor. For purpose of scientific experiments and personnel-dosage prediction, more-accurate surveys were utilized. The ships were marked at approximately 900 points on the interior and exterior. The surveys were performed at these locations by groups of previously inexperienced Navy enlisted men. Surveys included readings of gamma dose rate at 3 feet, beta surface readings, directional gamma-detector readings (of limited use because of unwieldiness of the detector probe), and wipe samples. These readings gave separate estimates of the contamination on an extended area, the local contamination, and the loose contaminant. The resultant data, when weighted and averaged, provided the basis for evaluation of decontamination procedures as well as studies of environmental influences on contamination. The results of a typical survey are presented in Figures 6.4 and 6.5.

6.2.6 Decontamination Studies. The decontamination studies were performed on many different surfaces, including ships' steel decks, wooden flight decking, aircraft skin, and numerous common building materials. In general, the decontamination was performed in sequence with less-effective procedures being applied first.

The procedures used on shipboard were firehosing (FH), hot-liquid-jet cleaning (HLJ), hand scrubbing (HS), surface removal (SR), and paint stripping (PS). The basic tactical sequences evaluated were as follows:

Procedure S: FH, HLJ, HS, FH
Procedure A: HLJ, HS, FH
Procedure B: HLJ, HS, HLJ
Procedure C: FH, HS, FH
Procedure D: HLJ, FH

Figure 6.6 illustrates the effectiveness of each procedure together with the man hours consumed. Procedure C can be performed with equipment commonly aboard Navy ships and represents a useful interim decontamination procedure.

Resurfacing of a wooden deck with the Tennant machine subsequent to nondestructive decontamina ion resulted in a net decontamination effectiveness of 70 percent in gamma radiation and 90 percent in beta radiation.

Application of a water emulsion paint (Formula 980) and its removal subsequent to contamination resulted in a decontamination effectiveness of approximately 80 percent. The basic technique was sound, but further development was needed to make the paint more-easily applied, more durable, and more-easily removable.

The aircraft exposed aboard the ships were subjected to decontamination procedures and regular material-damage inspections. The results of the decontamination procedures were classified into three groups depending on the previous history: Condition A, only slight washing by rain; Condition B, washing by heavy rainstorms; and Condition C, subjected to washdown. Figure 6.7 demonstrates the effort required to reduce the contamination to a given fractional level. The procedures consisted of repeated firehosing, hot-liquid-jet washing, and eventually scrubbing with detergent and Gunk solutions. The aircraft received in Condition C were immediately firehosed and then scrubbed with detergent.

The results of the decontamination procedures applied to building-material panels after Shot 2 are summarized in Figure 6.8. The panels were exposed in normal orientations: pavement horizontal, walls vertical, and roofing on a slant. The variation in the gamma radiation before decontamination was principally due to orientation, with the vertical panels approximately three times as active as the horizontal ones. The same effect was observed after Shots 4 and 6, but by a factor of less than two. Wind impacting the fallout material on the surfaces possibly was the explanation. Surface-removal studies indicated that the activity penetrated to a maximum depth of 200 microns in painted wood. Studies performed at the Army Chemical Center indicated that the active material was

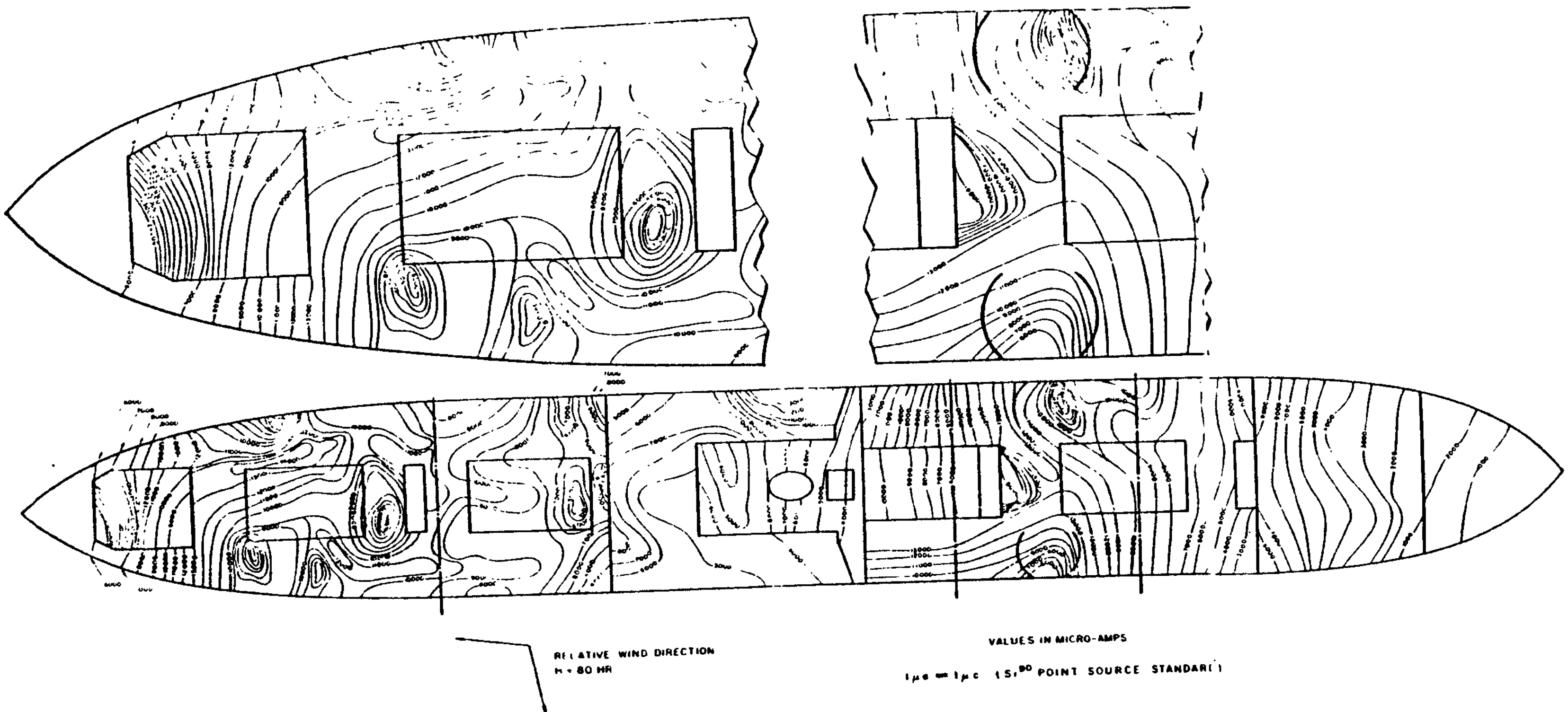

Figure 6.4 Radiation contours from original beta survey on the YAG-40 after Shot 5, 8 May 1954.

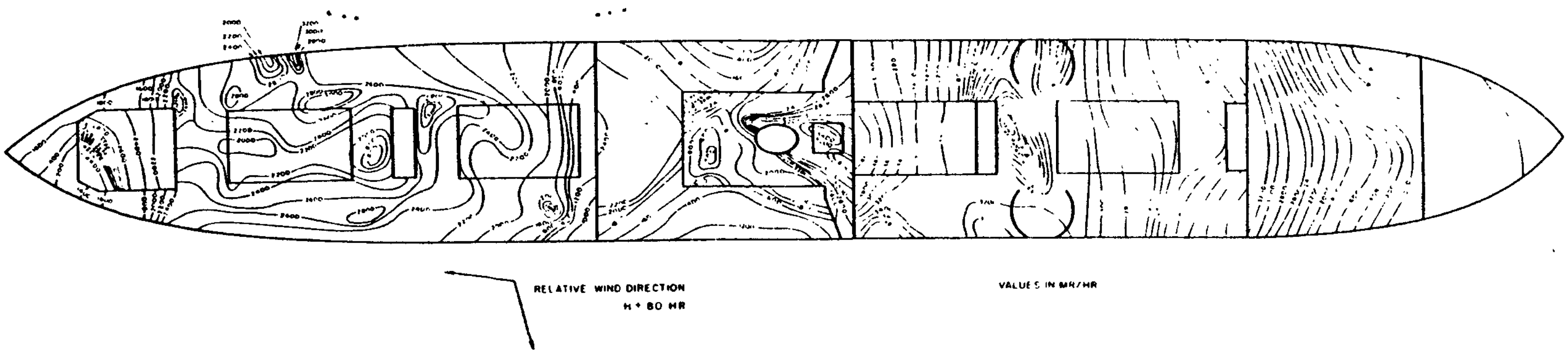

Figure 6.5 Radiation contours from original gamma survey on the YAG-40 after Shot 5 8 May 1954

principally ionic rather than particulate. Detergents and ion-exchange carriers were effective in removing some remaining activity.

6.2.7 Protection of Personnel in Radiation Fields. Since the operation of the ships and their subsequent decontamination involved the exposure of a large number of personnel to radiation, a number of studies were performed on personnel protection and dosimetry. In general, mission planning and survey readings were effective in limiting dosages to

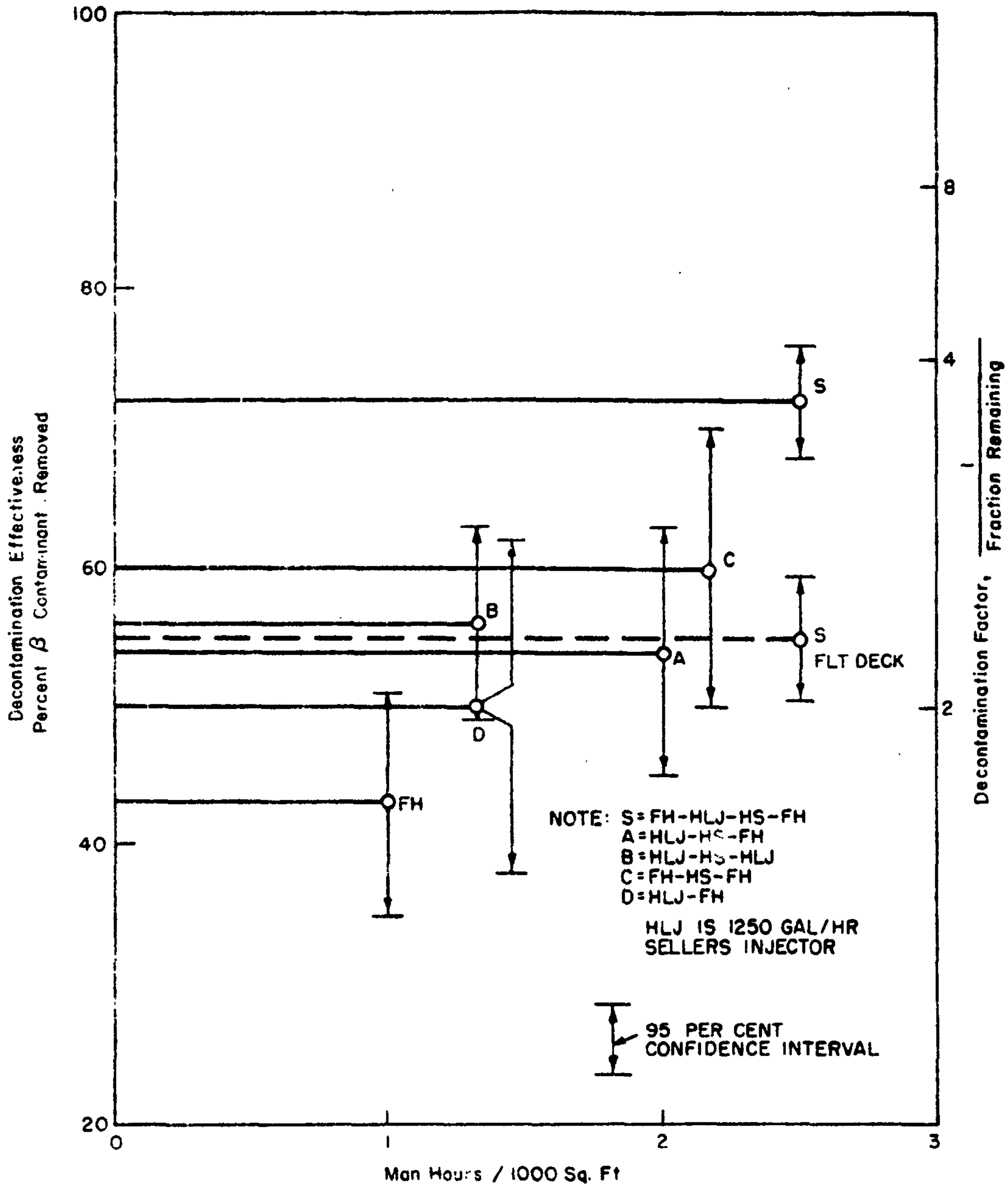

Figure 6.6 Evaluation of experimental decontamination procedures, YAG-40, Shot 2.

safe amounts. A system of zoning, with check points and provisions for clothing changes between, prevented the spread of contamination. A study of a special multiple-shield film-badge holder revealed that combination beta-gamma dosimetry was valuable, but that there were discrepancies in gamma dose between the tested badge and the standard Task Unit 7 badge.

6.3 OPERATIONAL EVALUATION OF INDIRECT-BOMB-DAMAGE ASSESSMENT

In project 6.1, the Strategic Air Command continued evaluation of interim indirect-bomb-damage-assessment (IBDA) procedures and indoctrination of air crews in these procedures. The interim IBDA capability used airborne navigation-bombing radar and camera systems to obtain radar-scope photographs of the detonations, from which IBDA data could be extracted.

Three B-50D aircraft were involved on six shots—a total of 18 missions. Excellent radar-scope photographs were obtained on all except two of the missions, and equipment

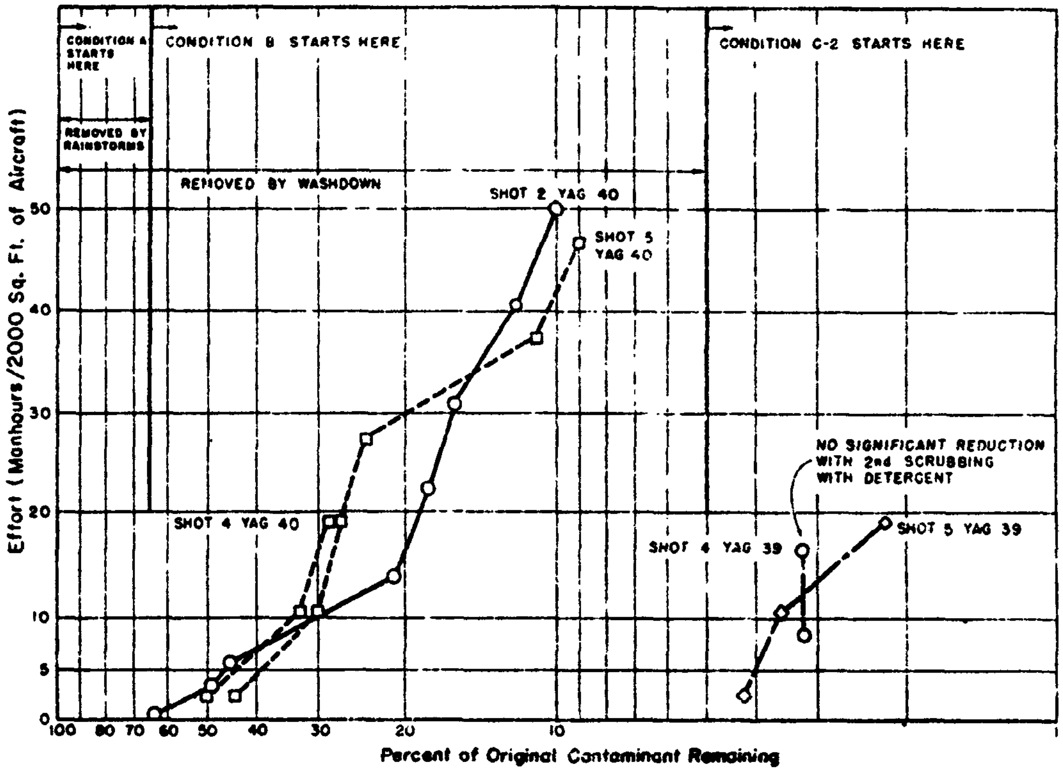

Figure 6.7 Percent of original contaminant remaining versus manpower.

and operating techniques were adequate. Because there were no air drops, information on techniques for radar-scope photography with the equipment on a strike aircraft was not obtained.

Table 6.7 presents aircraft positions relative to site zero for the various shots. One aircraft aborted on Shot 4 and another on Shot 5, resulting in 16 successful missions for IBDA purposes. In addition to the IBDA missions, one B-50 recorded radar returns in the vicinity of site zero for 10 to 15 minutes after shot time for Project 1.1c.

Examples of the photographs obtained are shown in Figures 6.9 and 6.10. For a surface detonation, the burst clearly shows as a horseshoe-shaped configuration during the

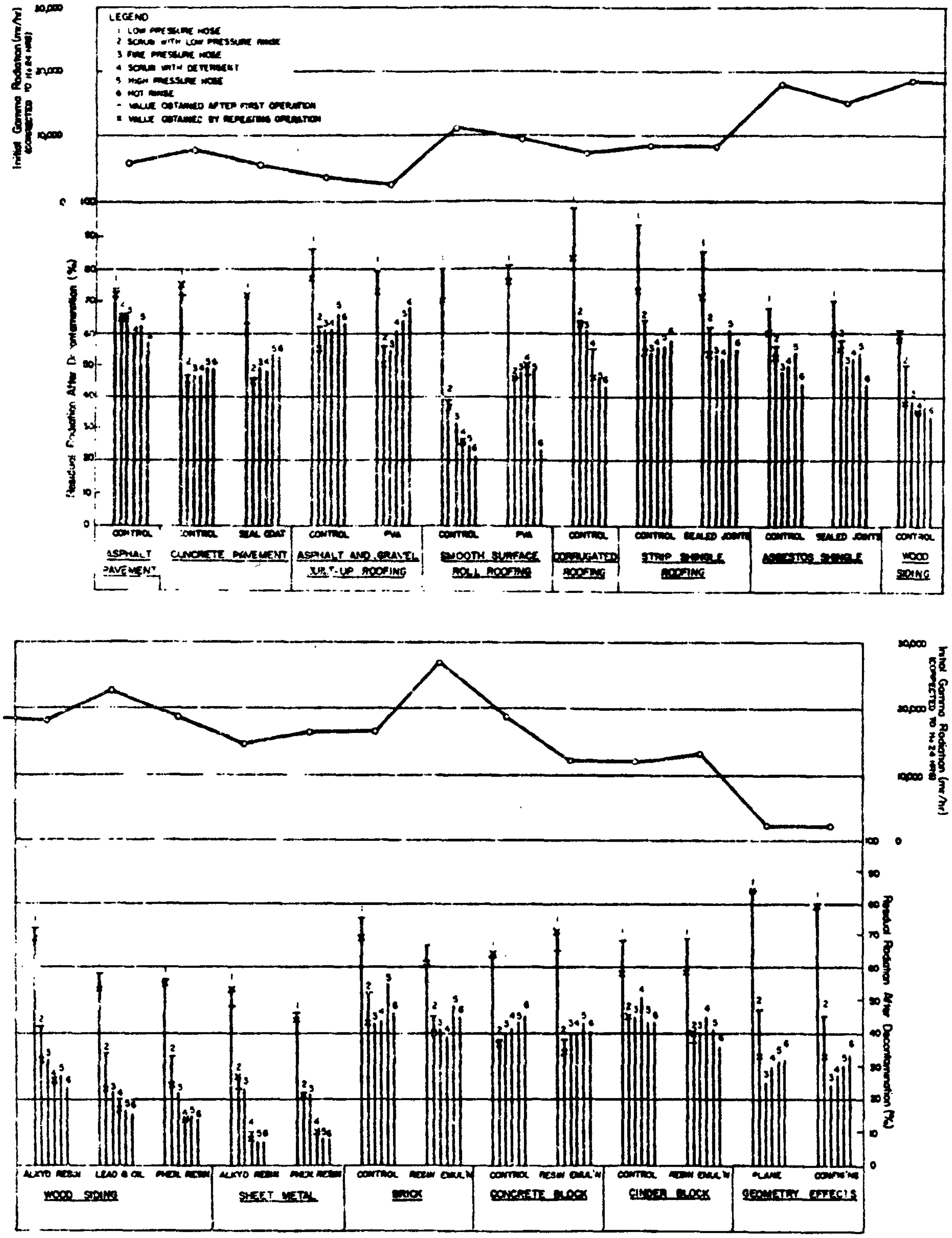

Figure 6.8 Initial gamma contamination and residual percentages after decontamination operations, Shot 2.

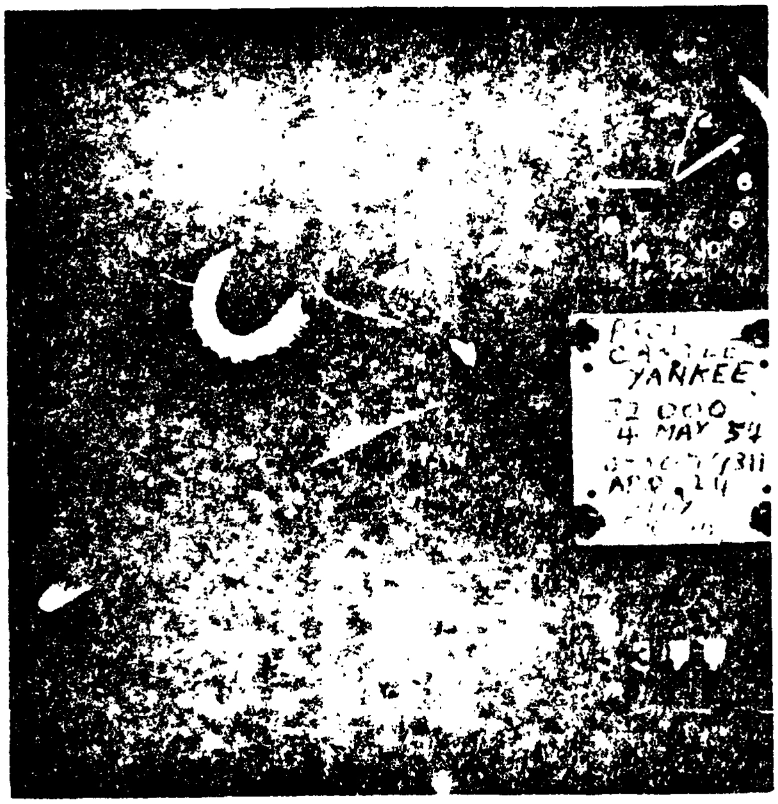

Figure 6.9 Third picture after H-hour at about H + 4 seconds. Recorded by B-50 No. 1.

Figure 6.10 Progress of shock front at H + 22 seconds. How, Uncle, and Victor Islands are visible. Recorded by B-50 No. 1.

early moments subsequent to time zero. Later pictures show the shock wave along the water surface as it progressed outward from site zero.

To extract IBDA data from the photographs, large-scale graphics were prepared to achieve greater accuracy in interpretation. Site zero was established within an accuracy of 600 to 1,100 feet from the actual location by determining the center of curvature for the horseshoe configuration. Interpreters attempted to obtain yield data from the photographs by utilizing time-distance curves that indicate the progress of the shock wave

TABLE 6.7 AIRCRAFT POSITIONS

Shot	1	2	3	4	5	6
B-50 No. 1						
Altitude, ft	34,000	32,000	32,000	—	32,000	32,000
Distance, naut mi	15	15	12	—	15	12
B-50 No. 2						
Altitude, ft	31,000	31,000	31,000	31,000	—	31,000
Distance, naut mi	23	23	20	23	—	20
B-50 No. 3						
Altitude, ft	30,000	30,000	30,000	30,000	30,000	30,000
Distance, naut mi	30	30	27	30	30	27

outward from ground zero for various yields. Computations of yield by this method proved inaccurate. Since participation was limited to surface bursts, no attempt was made to obtain height-of-burst information.

6.4 IONOSPHERE STUDIES

Project 6.6 was conducted to study the effects of megaton-yield-range detonations on the ionosphere Following Shot Mike of Operation Ivy, it was noted that the virtual height of the F-2 layer greatly increased. The project desired to corroborate this phenomenon and to study the cause-and-effect relationships associated with it. It was also desired to obtain data on effects at large distances from the detonation to ascertain the possibility of using such effects as a means of long-range detection.

For collection of data, two ionosphere recorders were operated in the Marshall Islands: one at Parry Island 200 miles west of Bikini and the other at Rongerik Atoll 150 miles east of Bikini. In addition, normal data from existing stations at Maui and Adak and special data from existing stations at Guam and Okinawa were studied to determine effects at distances of 1,400 to 3,000 miles.

At Parry Island, severe absorption occurred for several hours following all megaton-yield shots. This phenomenon was attributed to ionization resulting from radioactive particles carried to the west by fast winds at altitudes of 60,000 to 120,000 feet. Turbulence in the E-region after megaton-yield shots was manifested by sporadic E-returns detected at Rongerik. In the F2 layer, an effect similar to that observed during Ivy was noted, but its nature varied from shot to shot. Apparently the movement of electrons in this layer was far more complex than originally assumed, but was still attributable to a large-scale convection resulting from the conversion of blast-wave energy into heat in the upper atmosphere.

Data from the distant stations indicated that ionospheric disturbances were propagated up to 2,600 miles from the points of detonation at velocities between 8 and 16 km/min. It appeared that the duration of the disturbances was related in some manner to the yield of the device and was about inversely proportional to the distance.

Chapter 7

LONG-RANGE DETECTION

Program 7 consisted of three projects to investigate the problem of long-range detection of nuclear explosions. The problem divided itself essentially into two major parts: (1) detecting and locating the explosion and (2) documenting it to the maximum extent possible with regard to type (i.e., fission, fusion, or composite), yield, design, etc. Each project attacked the problem from a different aspect and with certain inherent limitations and capabilities. Project 7.1 investigated the electromagnetic radiations, Project 7.2 investigated airborne low-frequency sound, and Project 7.4 investigated solid, liquid, and gaseous debris resulting from nuclear explosions. A discussion of the findings of these projects follows; details on their test procedures are summarized in the Appendix.

7.1 ELECTROMAGNETIC EFFECTS

Experimental measurements of the electromagnetic pulse emitted by a nuclear detonation had been made during each series of nuclear tests beginning with Buster-Jangle. From those experiments, the following conclusions had been drawn:

1. There is an electromagnetic pulse less than 100 μsec long emitted at the time of a nuclear detonation; at a distance of 20 km from the generating source, its field strength may be a few hundred volts per meter. A general relationship exists between kiloton yield and the electromagnetic energy emitted.

2. The emitted frequency spectrum extends from about two kilocycles or below up to a few megacycles, but the main components are in the region of about 6 to 50 kc, with an approximate inverse relationship between yield and predominant frequency.

3. Pulses received close-in—approximately 20 km—exhibit very-short rise times of less than a microsecond in a negative direction (i.e., the electric field vector is downward). The pulse is predominantly vertically polarized.

4. Even low-yield devices can produce a pulse receivable at distances in excess of 1,000 km. Close-in reception indicates that certain nuclear-device characteristics can be determined from pulse fine structure.

5. The ground wave is generally not detectable beyond about 1,500 km from the source because the ionospheric sky wave predominates Close-in fine structure disappears during sky-wave propagation to distances.

6. A fix of the source of the pulse can be obtained with direction-finding equipment. Observed azimuthal errors using equipment tuned to 10 kc are between 0 and 9 degrees; most errors are less than 3 degrees.

7. At distances, the pulse is extended to approximately ten times its close-in length, the result of multiple arrivals by various paths each characterized by one or more ionospheric reflection.

To further this work, Castle Project 7.1 had the following objectives: (1) determination of pulse character before changes due to propagation became apparent; (2) determination of pulse character as a function of external parameters such as distance, time of day, and ionospheric conditions; (3) measurement of field strength; (4) explanation of the causes of the electromagnetic phenomena observed; (5) determination of the relation of pulse occurrence to sequence of events during the detonation; (6) correlation of device characteristics and pulse characteristics, both close-in and, as far as possible, at distances; (7) experimentation with prototype surveillance equipment; (8) measurement of azimuthal errors in direction-finding equipment; and (9) determination of times of pulse reception to within 1 msec in world time.

In order to achieve these objectives, two fundamental problems first had to be solved: (1) the discrimination of nuclear-device pulses from natural atmospherics and (2) the determination of the maximum information on the source itself and external conditions at detonation time from the characteristics of this electromagnetic pulse.

7.1.1 Pulse Identification. One means of identifying a nuclear-detonation pulse with an experimental system (when recording at distances from the detonation point) is by knowledge of the time of detonation. To aid pulse identification during Castle, local timing signals were referred to world time. Both timing signals and pulse signals were corrected for propagation, giving an accuracy of 1 msec for world time and less than 1 msec for the pulse. Reception and identification of such pulses when time of detonation was known to millisecond accuracy was relatively easy; doing the same thing on a 24-hour basis if the detonation time had not been known would have been much more difficult. More information was found to be needed on techniques of discrimination, much of which could be learned by studying naturally occurring atmospherics.

In locating the pulse source, azimuthal errors were generally within the error ordinarily experienced with the location equipment used: ±3 degrees.

7.1.2 Pulse Characteristics. All close-in records showed the characteristic first negative-going pulse; wherever the effect of the second stage was apparent (except Shot 3) the first portion of the secondary pulse went positive. Wave forms were recorded at distances up to 12,000 km; however, beyond about 2,000 to 4,000 km, close-in detail disappeared. The changes in wave form caused by the filtering effects of the ionosphere (decreased reflection of the higher-frequency components) and interference between different sky-wave modes was quite apparent as the broad-band pulse was recorded at greater distances: the pulse lost character and presented a damped-sine-wave appearance. The broad-band wave forms at the far stations, in general, covered about 6 to 100 kc, which encompassed the greatest portion of the energy available.

7.1.3 Field Strength. Data from Guam, Shemya, and Point Barrow were generally low. The reasons were not definitely known, and these anomalies are being investigated. Contributing causes may have been interference between sky-wave modes, ionospheric absorption, ground constants, and in the case of Point Barrow, attenuation due to auroral absorption. In addition, it was believed that the Shemya results may have been low because of local conditions at the receiving site.

There was apparently considerable variation from day to day and during the day. Day-and-night variation in signal strength was generally more pronounced on the north-south path than the east-west. The magnitude of diminution in signal from dark-to-daylight path was apparently greater when the auroral zone was penetrated. Field strengths were lower during magnetically disturbed periods (i.e., 24 March 1954) than during relatively quiet magnetic periods.

7.1.4 Yield Determinations. Field strength, especially at distant points, was only a very-approximate measure of yield; however, the vagaries of propagation were only imperfectly known—yield is also more properly a function of total energy emitted. For an operational system, a rough estimate of yield within about an order of magnitude may be obtained from broad-band field-strength measurements with proper correction for path, terrain, ionospheric conditions, time of day, etc. However, the corrections to be made were imperfectly known. Frequency analysis of wave forms, together with other characteristics, may offer some assistance. Field strengths were measured at various places, but variations with presumably identical equipment at the different locations were not all explainable.

There appeared to be an approximate relationship between yield and the frequency at which peak energy occurs, with some theoretical justification for this relationship.

7.1.6 Ionosphere Data. The arrival times of the first sky wave gave an ionospheric layer height of about 90 km. Some records showed as many as five sky waves, but of course with less energy for each reflection; they also indicated a layer height of about 90 km.

7.1.7 Peripheral Lightning. Fast-frame moving-picture photography (3,000 or more frames per second) of Ivy Mike had shown what appeared to be lightning flashes between the natural cloud cover and the sea on the periphery of the fireball. This phenomenon started at about 5 msec after the beginning of the nuclear reaction and continued for about 75 msec or more. These visible flashes were also in evidence on Castle high-speed photographic film. No signals attributable to the discharges were noted.

7.2 AIRBORNE LOW-FREQUENCY SOUND

Acoustic measurements from remote stations had been made, prior to Castle, on all nuclear tests except Trinity.

The purpose of the experiments carried out during Crossroads, Sandstone, and Greenhouse had been to establish the feasibility of detecting nuclear explosions of moderate yield at ranges in excess of 4,000 km by acoustic means—felt to be the minimum range at which a suitable acoustic system for detecting foreign explosions could be established. Results from Crossroads and Sandstone had indicated positive detection to a range of only 1,900 km. With improved equipment and better techniques, detection had been accomplished out to 4,500 km during Greenhouse.

Additional experiments had been carried out during Buster-Jangle, Tumbler-Snapper, and Upshot-Knothole to delineate the capabilities and limitations of acoustic-detection techniques for a wide range of yields of air, surface, and shallow-underground detonations during different seasons of the year. Results from these tests indicated a limited, but usable, detection range for low-yield explosions—even for shallow underground detonations. Seasonal shift in propagation, which had originally been noted during tests conducted with small TNT charges, were confirmed. It had been found that amplitudes varied considerably with propagation conditions and that any correlation between signal period and yield was quite variable.

Results from experiments carried out on Ivy had indicated that acoustic signals from high-yield kiloton and megaton explosions were detectable at longer ranges and showed generally increased amplitudes, longer periods, and generally longer durations. In addition, the megaton explosions had been characterized by a dispersive train of acoustic waves similar to those produced by the great Siberian meteor and not previously observed from man-made explosions.

Operation Castle presented an opportunity to study a wide range of yields, offering a possibility of establishing a lower limit of yield required to generate dispersive waves in the atmosphere.

For Castle, the primary objectives were to (1) record and analyze the airborne acoustic waves generated by thermonuclear explosions, in order to provide calibration data for use in the interpretation of the acoustic signal from foreign explosions and (2) delineate the capabilities and limitations of standard detection equipment and study the relation of various signal characteristics to the total energy released in the explosion.

A secondary objective was to collect data on the propagation of dispersive waves from a very-large atmospheric pressure pulse, with a hope of eventual interpretation in terms of the temperature and wind structure in the upper atmosphere.

7.2.1 Detection Ranges. Each shot (1, 2, 4, 5, 6) in the megaton range was detected with standard equipment at very-great distances: (1) Every operative station detected the direct wave[1] from the megaton-range shots. (2) Four of the nine operational stations on Shot 1 detected the wave via the antipodes[2], seven of eleven on Shot 2, four of eleven on Shot 4, eight of eleven on Shot 5, and two of eleven on Shot 6. (3) Four stations detected the second passage of the direct wave on Shot 1, three on Shot 2, two on Shot 4, two on Shot 5, and none on Shot 6. (4) One station detected possible second antipodes arrival from Shots 4 and 5.

Maximum detection ranges with standard equipment were 51,470 km for Shot 1, 46,940 km for Shot 2, 75,200 km for Shots 4 and 5, and 32,080 km for Shot 6.

Only four standard-equipment stations detected the direct wave from Shot 3, and the maximum detection range was 11,470 km. None of the stations to the west of the explosion detected the acoustic waves from Shot 3, although three stations were arrayed between 3,960 and 4,860 km from the explosion.

Detection ranges for very-low-frequency (VLF) equipment were generally less than for the standard equipment because of the greater noise recorded on the VLF equipment. Nevertheless, every operational VLF station detected the direct wave from the four highest-yield shots (1, 2, 4, and 5); most detected Shot 6, but only one detected Shot 3. Maximum detection ranges were 31,890 km for Shot 1; 25,140 km for Shots 2, 4, and 5; 4,040 km for Shot 3; and 18,100 km for Shot 6.

These results confirmed those obtained from Ivy and previous nuclear detonations regarding the range of detection. With standard equipment, it was possible to detect megaton shots at very-great distances (usually at least 25,000 km). Ranges for VLF equipment, while still considerable, were generally appreciably less than for standard equipment. Range for Shot 3 was greatly reduced, but was greater than the 4,000 km normally considered desirable for effective detection-net operations.

7 2.2 Signal Characteristics. All VLF recordings from megaton shots showed the dispersive train of waves. However, each shot produced significant differences in the variations in period and amplitude with time. Significant changes in the dispersive train

[1] The direct wave refers to the signal arriving by the most direct great-circle path from the explosion site.

[2] The antipodes wave refers to the arrival via the antipodes of the explosion site.

with distance and direction were also noted. Most recordings on standard equipment also showed definite evidence of at least a portion of the dispersive train for the four largest shots although the amplitudes were greatly reduced by lack of low-frequency response. Antipodes and second direct arrivals on VLF equipment also showed marked evidence of the dispersive train in cases of high signal-to-noise ratio.

Horizontal-phase velocities were slightly lower than the normal velocity of sound at ground level (about 335 m/sec) and were nearly equal to the travel speeds for first arrivals at the same locations. Theoretical studies predicted phase velocities equal to the speed of sound at ground-level, i.e., vertical, wave fronts.

Horizontal-phase velocities obtained from standard equipment at stations where the microphone spacing was, in general, small compared to the wave length of the acoustic signal showed a considerable range of values. However, practically every first-wave signal gave phase velocities covering some portion of the range from 318 to 360 m/sec.

Signal amplitudes received were approximately as expected. A detailed study of the amplitudes recorded by VLF equipment was undertaken.

Detectable signals for direct-wave arrivals on standard equipment persisted for a minimum of 8 minutes and a maximum of 369 minutes, the average being 74. Antipodes and later arrivals persisted for a minimum of 3, a maximum of 530, and an average of 140 minutes. For VLF equipment, the direct-wave signals persisted for a minimum of 9, a maximum of 240, and an average of 79 minutes. Antipodes and later arrivals gave a minimum of 83, a maximum of 339, and an average of 192 minutes.

In general, signals from the megaton shots started with an increase of pressure, followed by a larger negative pulse. The first measurable periods generally ranged from 200 to 450 seconds and were followed by decreasing periods at later time, at least for the first 30 minutes. Short-period arrivals characteristic of waves trapped by temperature and wind gradients in the first few thousand feet of the atmosphere were observed at the beginning of some recordings at stations within 5,000 km of the explosion. Such waves had occasionally been observed at stations within 1,000 km of previous U. S. nuclear detonations, but never at such long ranges. Periods in these arrivals were of the order of 3 to 5 seconds and persisted for as long as 5 minutes.

The characteristics of acoustic signals from the Castle detonations were similar to those observed for previous tests. All megaton shots showed dispersive waves while the kiloton shot did not; horizontal-phase velocities showed considerable spread, but covered the same range of values previously observed. Amplitudes ranged from a tenth to several hundred dynes per square centimeter, depending on the equipment, yield of the shot, distance from source, and noise level. Signals persisted for a very-long time, and signal periods spread over more than 8 octaves, from 3 to 450 seconds.

Castle data definitely proved that dispersive waves may be generated by shots having a yield as low as 1.7 Mt. These dispersive waves seemed to be modified by the atmospheric structure along the path from the source to the station.

7.2.3 Travel Speeds. Travel speeds recorded by standard equipment were generally within a few meters per second of each other at all stations; however, there was a general trend shown toward decreasing speeds eastward and increasing speeds westward as the Castle series progressed from 28 February to 13 May.

The average travel speed for first arrivals from the direct wave on VLF equipment ranged somewhat higher than speeds obtained from standard recordings. These higher speeds were due to the earlier arrival of the long period dispersive train recorded on VLF equipment.

Greatest travel speeds were normally observed for the long-period dispersive waves, but in a few instances much shorter-period waves were propagated over a few thousand kilometers at these same speeds. The maximum speed of travel, 335 m/sec, was roughly equal to the speed of sound at ground level.

Travel speeds for direct waves on standard equipment showed somewhat greater variability than did the speeds for Ivy.

7.2.4 Azimuth Errors. For distances less than 12,000 km from the explosion site, the maximum observed azimuth error was 11.5 degrees, and the average error was 3.2 degrees. At longer distances much-larger errors were reported. No consistent pattern of azimuth errors was observed that could be related to the direction the acoustic wave travels from the source.

Azimuth errors observed for Castle were consistent with those observed on previous tests. Errors in the azimuths computed for the dispersive train were roughly the same as the errors for later portions of the wave train.

7.2.5 Yield. Attempts have been made to relate various characteristics of acoustic signals at great distances to the total energy released by the nuclear explosion. Critical dependence of signal amplitude on the variable temperature and wind structure in the upper atmosphere, coupled with difficulties in the accurate measurement of amplitude led to a search for more-reliable indicators of yield. A possible connection between signal frequency and yield involving a cube-law relationship based upon general scaling considerations was postulated. This cube-law relationship between the duration of the first negative pulse and yield was verified for acoustic records at ranges of 7 to 600 miles from explosions at the Nevada Test Site.

A critical examination of a great many acoustic recordings at distances greater than 1,000 km from explosions in the yield range of from 1 to 500 kt led to the use of the visually observed signal periods in the vicinity of maximum amplitude for standard recordings as the best indicator of yield. For each shot, periods from selected stations were averaged and the averages were plotted. Similar periods were selected from standard recordings of the direct wave from the megaton shots of Ivy and Castle. A best power-law curve was computed by the method of least squares for data up to and including yields of 500 kt. This curve indicated the yield to be equal to a constant multiplied by the period raised to roughly the third power.

Data for yields above about 100 kt fell along a curve of different slope from that for lower yields. The best curve in this region indicated that for megaton shots the yield would be equal to a constant multiplied by the period (at maximum amplitude, for standard equipment) raised to roughly the fourth power.

The method of measuring the period was somewhat subjective and the relationship between yield and period very inaccurate. In addition, the method requires measurements at a number of stations for each shot in order to achieve even the semiquantitative results noted here.

Very-large errors are inherent in this method of determining yield from acoustic measurements. For yields up to about 100 kt, three standard errors of estimate cover yields as small as a fifth and as large as five times the correct value. Errors at yields above roughly 100 kt seem slightly smaller, although a correction for the small sample has been applied. Three standard errors cover yields as small as a third and as large as three times the correct value at these higher yields.

Studies of the accuracy of yield determinations from the VLF recordings were being made, with effort centered on measurement of amplitude for these recordings.

Many other general indicators of yield were apparent: the existence of a dispersive train was apparent on graphic records only for shots with yields of 1.7 Mt and greater; also, the greater detection ranges, the larger numbers of stations recording, and the generally higher amplitude all were indicative of larger shots.

7.2.6 Directional Effects. The shift noted in travel speeds (speeds toward the east greater than that toward the west in March shifting to the opposite in May) were consistent with previous observations. This indicates that April was the change-over month for stratosphere winds.

7.2.7 Equipment. Standard equipment was superior to VLF equipment for detection purposes and provided a convenient, though inaccurate, means of estimating yield. In addition, most standard recordings showed some evidence of the dispersive train, though with greatly reduced amplitude at the longer periods. It remains to be seen whether VLF recordings of the longer periods will give an accurate estimate of yield.

7.3 ANALYSIS OF NUCLEAR-DEVICE DEBRIS

7.3.2 Petrographic Analysis. All shots resulted in the formation of micro spheres: these particles represented the non-crystalline constituents and presumably included compounds from the device, fission products, device casing, and device support. All shots except Shot 6 resulted in collection of one or more of the following crystalline compounds: oxide, hydroxide, and carbonate of calcium, megnesium oxide, and sodium chloride. Shots 1 and 3 showed only calcium compounds, indicating that little if any sea water was vaporized. Shots 2 and 4 showed principally sodium chloride and magnesium oxide from sea water, although Shot 4 showed some calcium compounds, indicating that a small percentage of island material was vaporized in this shot. It is interesting to note that sodium and calcium compounds were absent as major constituents of the debris from Shots 5 and 6. It is significant, perhaps, that rain was recorded subsequent to both tests, which may have resulted in the leaching of these compounds.

7.3.3 Specific Beta Activity. From a plot of the number of particles per unit logarithmic interval of disintegrations per minute divided by the cube of the particle diameter in microns, a modal value for specific beta activity can be obtained from the apparent normal distribution curve. The modal values for the Castle shots were only rough estimates, since the observed frequency distributions covered a broad spectrum of specific activity with no pronounced peaks. Modal values for the barge shots were much greater than those from island shots.

7.3.4 Operation of the Squeegee Sampler. Castle included the first full-scale operational test of the small size, high-pressure squeegee, although sufficient experimentation had been accomplished during Upshot-Knothole to indicate its suitability. For ease of sample removal from contaminated aircraft and handling enroute to processing laboratories, this method proved ideal. During Castle, the main malfunctions of the system consisted of high-pressure leaks from fittings and connections, compressor difficulties, or faulty check-valve operation due to freeze-up at high altitudes, all of which caused either loss of sample or no collection. These defects were corrected, as Castle progressed, with improved operational procedures and maintenance. Of all squeegee flights during Castle, 68 percent resulted in successful missions and 18 percent were only partially successful in sample collection; 14 percent of the missions failed. The size of most good samples collected was adequate for assay.

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Chapter 8
THERMAL-RADIATION MEASUREMENTS

The DOD had no projects exclusively concerned with thermal-radiation measurement and only one, Project 6.2, which was incidentally concerned with such measurements (see Section 1.1). This omission was deliberate, to avoid duplicating the effort planned by Harold Stewart of the Optics Division of the Naval Research Laboratory (NRL) and Herman Hoerlin of LASL-sponsored Program 18. In lieu of such duplication, the DOD provided funds for a slight enlargement in scope of Program 18.

Final reports of the thermal-radiation measurements made by Program 18 were being written at the time of publication of this report; they were not in a suitably finalized state to warrant quoting information therefrom with any degree of certainty that such information would remain unchanged when the final reports were published.

For these reasons, no final data is reported in this chapter. The Program 18 final (WT) reports may be consulted when they are available. A brief description of these projects is given in the Appendix.

Chapter 9

CLOUD PHOTOGRAPHY

Following the Ivy-Mike test in 1952, there was considerable controversy as to the rate of rise and stabilization time of the Mike cloud. Concern was expressed by the aircraft-delivery group that strike and supporting aircraft might be faced with a critical escape problem from high-yield weapons. In view of this, the Air Force presented a requirement for a photogrammetry project which would determine the various parameters of nuclear clouds as a function of time and attempt to establish approximate scaling (yield) relationships.

First in importance was determination of the initial rate of rise of the cloud and height at time of stabilization. Second in importance was determination of the lateral dimensions and drift as functions of time after the cloud had reached its maximum altitude. It was further suggested that should aerial photography prove successful on this project, analysis of the negatives would most likely provide valuable information pertaining to fallout-distribution, long-range-detection, and meteorological studies. In July 1953, the requirement was incorporated into the Castle program and given project status. Participating agencies were Edgerton, Germeshausen & Grier, Inc. (EG&G) and Lookout Mountain Laboratory. EG&G was assigned responsibility for the analysis and reporting of the data and as a technical advisor to the Program Director and Lookout Mountain personnel. Lookout Mountain performed all aspects of the project relating to the taking and processing of the pictures, scheduling of aircraft, training of crews, and the procurement and modification of cameras and camera mounts. Back-up terrestrial photography from ground stations was supplied by EG&G under Project 13.2.

The project involved the participation of four aircraft: One RB-36 operated at an altitude of 35,000 to 40,000 feet and conducted photography through H + 10 minutes; three C-54's operated from H-hour through the time required for cloud dispersal. Aircraft position ranges from ground zero at H-hour varied from 50 to 75 nautical miles, depending on expected yields. All aircraft were identically equipped with a K-17-C aerial camera and an Eclair 35-mm motion-picture camera.

In order to analyze the data from the cloud photography, it was of prime importance to know the spatial orientation of the photographic axis during every exposure and the time of every exposure. This was accomplished by mounting the K-17-C camera and the Eclair motion picture camera on a modified A-28 gyro-stabilized mount. All cameras were modified to record time-clock, tilt, and azimuth readings of the camera heading on the lower third of the negative frame.

The instrumentation of the cameras worked out very well on all events. Minor malfunctions occurred on the time clocks, such as slow starts and time lags, during the operating period. These errors were generally able to be compensated for in the analysis of the negatives. In addition, it was also necessary to know within ± 2 miles in horizontal coordinates the location of all aircraft from H-hour throughout the required mission time. The results on this portion of the mission were not too satisfactory. Owing to constantly changing flight patterns, navigation was extremely difficult, and at times it was impossible to maintain to the required accuracy.

All four aircraft flew on every shot. Of the 24 missions, 6 were spoiled because of interference by natural clouds. Four of these were on Shot 3, which was fired under such bad weather conditions that no useful cloud photographs of any sort were taken from the ground or air.

The data obtained were more complete and accurate than any from previous operations (see Table 9.1; Ivy data is included for comparison). Good measurements of cloud height and diameter over a 10-minute interval were compiled by EG&G for the five shots photographed. It was found possible to apply suitable corrections for the effects of earth curvature and atmospheric refraction, for the slight tilt of the camera platform, and for the altitude of the aircraft. The resulting data agreed quite well from one aircraft to another, and it was possible to assign smaller uncertainty to the results than had been anticipated. Unfortunately, it was not possible to evaluate the few data taken later than 10 minutes after detonation.

TABLE 9.1 CLOUD PARAMETERS

No data were obtained for Castle Shot 3.

Shot	Maximum Height	Top at H + 1 min	Diameter at H + 1 min	Diameter at H + 10 min
	10^3 ft	10^3 ft	10^3 ft	10^3 ft
Castle 1	114	47	38	370
2	110	44	33	316
4	94	35	26	125
5	110	44	34	270
6	72	25	19	147
Ivy Mike	98	39	30	200
Ivy King	76	28	11	90

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Appendix
PROJECT SUMMARIES

Brief summaries of the specific activities of each Castle project are presented herein as a complement to the more-general discussion of the test programs contained in Chapters 2 through 9. The shot participation of the various projects is summarized in Table A.1.

A few of the final project reports were as yet unpublished at the time this final summary report was prepared. In general, the draft manuscripts of such reports were available and were consulted in order to make these project summaries as complete as possible. In any case, the published versions of the final (WT) project reports should be referred to for complete, final information. The report title and short title (WT number) are indicated herein for each project; information on the availability of these reports may be obtained from Headquarters, Armed Forces Special Weapons Project, Washington, D. C.

TABLE A.1 PROJECT SHOT PARTICIPATION

Project	Shot 1	Shot 2	Shot 3	Shot 4	Shot 5	Shot 6	Project	Shot 1	Shot 2	Shot 3	Shot 4	Shot 5	Shot 6
1.1a	X		X	X			3.1			X			
1.1b	X	X	X	X	X	X	3.2	X		X	X		
1.1c	X	X		X	X	X	3.3	X		X			
1.1d	X	X	X	X	X	X	3.4				X		
1.2a	X	X	X	X	X	X	3.5	X					
1.2b	X	X	X	X	X	X	4.1	X					
1.3	X	X	X	X	X	X	6.1	X	X	X	X	X	X
1.4	X	X		X	X	X	6.2a	X	X	X	X	X	X
1.5		X		X	X	X	6.2b	X	X	X	X		X
1.6	X	X	X	X	X	X	6.4						
1.7			X				6.5		X		X		X
1.8			X			X	6.6	X	X	X	X	X	X
2.1	X	X	X	X		X	7.1	X	X	X	X	X	X
2.2	X	X	X	X	X	X	7.2	X	X	X	X	X	X
2.3	X	X					7.4	X	X	X	X	X	X
2.5a	X	X	X	X	X	X	9.1	X	X	X	X	X	X
2.5b	X	X	X	X		X	18.2*	X	X	X	X	X	X
2.6a	X	X	X	X	X	X	18.3*	X	X	X	X	X	X
2.6b	X	X	X	X		X	18.4*	X	X	X	X	X	X
2.7					X	X	18.5*	X	X	X	X	X	X
2.7a					X	X							

* Thermal project sponsored by LASL, but partially supported by and of interest to the DOD. See Text.

PROGRAM 1: BLAST AND SHOCK MEASUREMENTS

Project 1.1a, 1.1b, and 1.1d "Blast Pressures and Shock Phenomena Measurements by Photography" (WT-902), Naval Ordnance Laboratory; C. J. Aronson, Project Officer.

The objectives of these projects were to (1) determine the peak shock overpressures in air as a function of distance from ground zero, (2) to obtain information on the formation, growth, and magnitude of precursors and other visibly observable thermal effects which may occur, and (3) to measure the motion of the shock wave on the waters surface to obtain the pressure-distance relation.

The smoke-rocket photography and direct-shock photography results were in general satisfactory. Some data were lost due to photographic difficulties and the presence of cloud cover at the time of detonation for several shots. The project participated on all shots, but no film was usable from Shot 3 because of the low yield of the device. Pressure-distance data vertically above the shot were obtained only on Shot 2. The uncertainty of the measured data was such that it was not possible to define the effect of a nonhomogeneous atmosphere on blast. Measured surface data of both pressure and arrival time appear self-consistent, as well as comparing favorably with Jangle and Ivy data. It seems justified to conclude that cube-root scaling of blast data from events of this yield range is valid. No precursors as such were noted; however, anomalous wave forms were recorded by the pressure-time gages. A dense water cloud following immediately behind the shot on Shots 4 and 5 may explain the anomaly. The aerial photography was unsuccessful. The extreme range of the aircraft and the obscuration of the field of view by clouds prevented the project from obtaining any readable film.

Project 1.1c "Base Surge Measurements by Photography" (WT-903), Naval Ordnance Laboratory; C. J. Aronson, Project Officer.

The objective was to gather photographic data obtained during the operation which could be of value in the formulation of scaling laws to predict the base-surge effects from surface detonations.

The experiment was almost entirely unsuccessful, since photography was rendered useless when it was decided to schedule detonation of the shots before sunrise. A minimum effort was maintained throughout the series, which indicated a possible base surge formation on Shots 1 and 2; however, a detailed study could not be accomplished.

Project 1.2a "Ground Level Pressures from Surface Bursts" (WT-904), Sandia Corporation; C. D. Broyles, Project Officer.

This project was directed toward obtaining measurements on blast pressure versus time at ground level with Wiancko gages. Measurements were obtained on all six shots. Non-ideal wave forms obtained indicated that water does not constitute a perfectly reflecting surface, as had sometimes been assumed. Shot 3 was detonated in the rain and showed the effects there in low pressures and rounded wave forms. It was concluded that peak pressures generally correspond to about 1.6W instead of 2W free air when the hydrodynamic fireball yields, using 2W theory, are the reference yields.

Project 1.2b "Ground Surface Air Pressure versus Distance from High Yield Detonations (WT-905), Ballistic Research Laboratories; J. J. Meszaros, Project Officer.

The principal mission was to obtain pressure-time data in the region greater than 40 psi. A secondary objective was to field-test a newly developed self-recording pitot gage. Pressure-time measurements were made on all six shots. Two blast lines were activated for Shot 3, and pressure measurements were obtained on both lines. Extensive dynamic-pressure measurements were made on Shot 6.

Air-pressure measurements using the self-contained flast-initiated gages were successful. Overpressure data were obtained up to pressure levels of 250 psi. Dynamic-pressure measurements using newly developed self-recording q-gages were very successful. Measurements were obtained over a dynamic pressure range of 0.43 to 138 psi. Shot 3 produced anomalous results: two blast lines oriented approximately 180 degrees apart obtained two distinct pressure-distance relations. The pressures obtained on the Tare line, over which rain or fog was evident during detonation, were as much as 20-percent lower than the pressures at comparable distances on Uncle Island.

The validity of the cube-root scaling law to scale distances for yields as great as 15.0 Mt appears to have been substantiated. It was concluded that overpressures from a surface burst are the same as would be obtained from a burst of 1.6 times the yield in free air.

Project 1.3 "Dynamic Pressure Measurements" (WT-906), Sandia Corporation; C. D. Broyles, Project Officer.

The objectives were to spot check the theoretical relationship between dynamic pressure and overpressure in the 10-to-40 psi overpressure range, and to evaluate a group of gages measuring various blast parameters.

The single measurement of dynamic pressure obtained on Shot 6 in an overpressure region of 21.5 psi agreed with that normally associated with the overpressure. The instrument was located such that the shock had travelled 800 feet over land immediately before reaching the gage. On Shots 4 and 5, measurements of dynamic pressures by the gage group were higher than values calculated from the measured overpressures; the records showed peculiar wave forms, indicating that the shock had picked up water. For these two shots, the gage group was located near the edge of the water

The force plate and density gage seemed to be suitable for field use, but study was needed on their response to dust.

"Instrumentation for Projects 1.2a, 1.3, and 1.7" (WT-907), Sandia Corporation; R. H. Thompson, Project Officer.

The primary objective of this project was to make support measurements of pressures, shock winds, and ground accelerations from large scale detonations for Projects 1.2a, 1.3, and 1.7. A secondary objective was to field-test several new gages.

The primary measurements were made with Wiancko and Sandia pressure transducers, differential-pressure q-tubes, and accelerometers. Other instrumentation used included drag q-tubes, force-plate stagnation-pressure gages, density gages, temperature gages, and displacement gages.

Of the records taken on 112 data channels, 99 gave complete information; 6 gave information up to arrival of the shock wave; and seven gave no information. Preliminary evaluation of new instrumentation indicated that: (1) the density gage needed better waterproofing, (2) the force plate operated satisfactorily, (3) the temperature gage was still too delicate for field use, (4) the gage q-tube was easy to calibrate but needed waterproofing to protect the cantilever from rusting and to protect the E-coil, and (5) the differential pressure gage was easy to calibrate but needed waterproofing.

Project 1.4 "Underwater Pressure Measurements" (WT-908), Office of Naval Research; W. J. Thaler, Project Officer.

This project was designed to measure the underwater pressure-time field produced by large-yield surface bursts. Pressure-time measurements and ball-crusher-gage measurements were obtained for Shots 2, 4, 5, and 6; ball-crusher-gage measurements were obtained for Shot 1. The gages were located as close as 6,000 feet from ground zero.

Some difficulty with instrumentation was experienced during the operational phase; as a result, a lesser amount of reliable data were obtained than originally anticipated. The major result of the recorded data indicated that the maximum, or peak, underwater pressures are of the same magnitude as the air-blast peak overpressures at the same range. It was concluded, therefore, that a nuclear weapon detonated on the surface of a relatively shallow water layer, under conditions as experienced on the Castle shot, produces underwater pressures which are probably of small military significance.

Project 1.5 "Acoustic Pressure Signals in Water (SOFAR)" (WT-909), Office of Naval Research; J. W. Smith, Project Officer.

The objectives were to make special observations at several Underwater Sound Transmission Experimental Facilities (USTEF) stations in the Pacific and at similar research stations in the Atlantic. The studies were designed to lead to a better understanding of the underwater sound propagation and to determine the accuracy of device yield figures that might be extracted from the measurements.

Shots 2, 4, 5, and 6 were monitored by detecting stations located on the California coast and at Bermuda. No clear-cut signals were recorded which could be attributed to sources at either Bikini or Eniwetok. It was concluded that the positions of the shots, inside the lagoon and on the atoll rim, precluded the coupling of energy into the SOFAR channel in the frequency channel to which the instruments were sensitive.

Project 1.6 "Water Wave Measurements" (WT-910), Scripps Institution of Oceanography; R. R. Revelle and John D. Isaacs, Project Officers.

The objective was to study water surface waves generated within the lagoon by a large-yield surface detonation. The measurements of wave height were obtained from underwater gages designed to record the hydrostatic pressure vibrations produced by the passing wave. In addition, surveys of inundation levels on land areas were made.

In contrast to the Ivy-Mike results, Castle data indicated that the recorded waves did emanate from the central region of the detonation. The time of arrival of the first crest of the direct water wave showed a propagation velocity fitting the relation $V = (gh)^{1/2}$, where h is an average depth of 170 feet assumed for the Bikini lagoon. Refraction and reflection against the reef or shoreline can significantly reduce or amplify the destructive capabilities of water waves at termination. Where focusing effects and the reflection-refraction potential of the adjacent lagoon topography was a minimum, the heaviest inundation and potential damage occurred with the first crest. These results were obtained under particular conditions of geometry, in a region of relatively shallow depth; such damage criteria are applicable to conditions that depart only slightly from those under which the data were obtained.

Project 1.7 "Ground-Motion Studies on Operations Ivy and Castle" (WT-9002), Sandia Corporation; W. R. Perrett, Project Officer.

This project was designed to obtain measurements of three components of ground acceleration on Shots 3 and Echo. These measurements were to be closer in to ground zero than those obtained on Ivy-Mike and hence augment and extend those measurements previously obtained. Unfortunately, the yield of Shot 3 was only about a tenth of that expected and Shot Echo was cancelled.

As a result of the low actual yield of Shot 3, set ranges for the gages were too high, recording a very-low signal amplitude. With such a low signal-to-noise ratio, the identification of phase arrival, frequencies, and amplitudes was uncertain. The air-induced signal propagated with a velocity of the air-blast wave, decreasing with increasing ground range, while the ground-transmitted shock propagated with a velocity of about 8,700 ft/sec. The determination of velocities and displacements by means of integration of the acceleration traces was not attempted—the precision of the data was too poor to support such an analysis.

Project 1.8 "Dynamic Pressure Investigation" (WT-911), Ballistic Research Laboratories; E. J. Bryant, Project Officer.

The objective was to evaluate dynamic pressure as a damage parameter. In addition, some information regarding the damage effect of long positive-phase duration was to be obtained. A total of 27 jeeps were exposed on Shots 3 and 6; the ground ranges were selected to obtain dynamic pressures comparable in magnitude to those acting upon the jeeps experiencing light to severe damage on Shot 10, Upshot-Knothole.

The yield of Shot 3 was too low to give any significant results. The limited results of Shot 6 were not conclusive enough to permit an evaluation of dynamic pressure as a damage parameter to be applied to the jeep as a drag-sensitive target. Further, the results did not allow a separation of the effect of dynamic pressure on damage from the effect of the long positive-phase duration. Based on a comparison of Castle and Upshot-Knothole data, Project 1.3 proposed cube-root scaling for vehicle damage. However, a composite AFSWP report, TAR 514 "Damage to Military Field Equipment from Nuclear Bursts" was subsequently prepared which included the Castle, Upshot-Knothole, and all other nuclear-test data. This report concluded that $W^{0.4}$ scaling was the most appropriate method for predicting damage to military field equipment.

PROGRAM 2: NUCLEAR RADIATION STUDIES

Project 2.1 "Gamma Radiation Dosimetry" (WT-912), Signal Corps Engineering Laboratory; Robert Dempsey, Major, USA, Project Officer.

The objectives were to document the initial and residual gamma radiation exposure from high-yield bursts in order to assist in the evaluation of the resultant gamma radiation hazards, provide data for the correlation of results for other projects, and extend the use of gamma-radiation dosimetry techniques to higher gamma-exposure ranges.

Radiation exposure from a series of nuclear detonations was measured by photographic films and chemical-dosimetry vials of various sensitivity ranges. The film and chemical detectors were placed in protective detector stations at positions from 1 to 15 miles from ground zero for Shots 1, 2, 3, 4, and 6. Calibrated exposure range of dosimeters used extended from 1 to 60,000 r.

In general, it was concluded that (1) initial-gamma-radiation exposure is of little significance at distances beyond 16,000 feet for surface bursts of yields up to 15 Mt, (2) the decay rate is affected by the capture products of the thermonuclear devices fired, and (3) the initial-gamma-radiation spectrum for Shot 3 appears harder than that obtained from fission devices.

Project 2.2 "Gamma Rate versus Time" (WT-913), Signal Corps Engineering Laboratories; Peter Brown, Project Officer.

The objective was to document the gamma-radiation rate from the detonation of high-yield thermonuclear devices. Two types of measurements were made: (1) initial-gamma rate versus time at various fixed distances from ground zero and, in particular, the effect on the initial-gamma rate due to the passage of the shock from ground zero through the detector station, and (2) gamma-radiation time-intensity data, which gives information on fallout rate of arrival and gamma-field radiation-decay rate during the period up to 36 hours after the detonation.

All measurements were made using scintillation detector techniques. The instrument stations were self-contained and required no outside facilities other than timing signals to turn the stations on at a predetermined time prior to the detonation.

The expanding fireball and the passage of the shock front from ground zero through the detector station had a marked effect on the initial-gamma rate and hence on the integrated exposure. In general, the initial-gamma rate decreased relatively slowly after reaching its peak value immediately after the detonation, began to rise slowly, and then rose rapidly to the same value as the peak received at time of detonation. After reaching the second peak value, the rate decreased rapidly toward zero value.

The initial decrease in rate was attributed to the natural decay of the fission products, the slow rise to the expanding of the fireball and approach of the shock front, and the rapid rise to the passage of the shock front through the detector station. These effects were also evidenced in the integrated exposure prior and subsequent to the arrival of the shock front.

The average velocity of the shock front was found to vary with distance from ground zero, decreasing rapidly with distance.

The decay exponent from the residual contamination and fallout was found to vary with distance and direction from ground zero. In general, the decay exponent appeared to increase rather abruptly several hours after the detonation. This can be attributed to the presence of short-lived isotopes in the residual contamination and fallout.

In general, it was indicated that the magnitude of gamma radiation emitted from high-yield thermonuclear devices is considerably lower than the predictions in the Super Effects Handbook (Reference 11). At approximately 2,390-yard range, this handbook indicates the exposure from initial gamma from a

6.5-Mt yield to be approximately 4×10^5 r, whereas measurements for Shot 4 indicated that only 1.55×10^4 r were received. At approximately 4,500-yard range, this handbook shows a prediction of about 800 r; measurements showed that only about 84 r were received.

It would appear that the initial-gamma radiation is of negligible significance, since the blast and thermal effects in the same range of distances are so great that personnel could only survive if they were disposed inside blast- and thermal-proof bunkers.

Project 2.3 "Neutron Flux Measurements" (WT-914), Naval Research Laboratory; T. D. Hanscome, Project Officer.

This project was assigned the problem of measuring the neutron flux encountered in the detonation of the nuclear devices at Castle, using the same techniques as used at Snapper and Upshot-Knothole. Gold, sulfur, and tantalum were used to measure the flux in the thermal region and the region above 3 Mev. The fission detectors were used to measure the 1-Mev region of the neutron spectrum and to give an idea of the shape of the spectrum above that point.

Because of the short half lives of some of the induced activities, it was necessary to provide counting facilities in the field: two trailers were installed on Elmer Island for this purpose, and were equipped to handle the counting of gold, and plutonium. The remaining samples were sent to the Naval Research Laboratory for counting.

The plutonium samples were included to provide data in the region above 200 ev; the Oak Ridge National Laboratory supplied these samples and the personnel to handle them.

Because of the unanticipated delays and shot-schedule revisions after the firing of Shot 1, the participation of Project 2.3 was considerably modified. Samples were exposed on the first two shots only, and because of shifts in shot sites and the modification of the Shot 5 device, further participation was curtailed.

The data acquired from Shots 1 and 2 indicated that the neutron flux is relatively small outside the radius of extreme damage caused by blast and thermal radiation.

Project 2.5a "Distribution and Intensity of Fallout" (WT-915), U. S. Naval Radiological Defense Laboratory; R. L. Steton, Project Officer.

The gathering of fallout data at Castle was a logical extension of previous fallout documentation. The variation in yields as well as the opportunity to document surface water detonations for the first time made this study of fallout extremely important.

The specific objectives were to sample and analyze fallout material to determine: (1) time and rate of arrival of the fallout and its final distribution patterns, (2) particle and drop-size ranges of fallout and airborne materials at ground level, (3) amount and distribution of radioactive materials in fallout and airborne materials, and (4) gross gamma and beta-gamma decay rates of radioactive materials (some gamma field measurements were also made for correlation purposes).

The distribution and intensity of fallout from all shots was investigated. The residual gamma pattern and some data on gamma decay and particle-size distribution was established for Shot 1. The fallout from Shot 1 was a dry white particulate, irregular in shape; many particles were flaky in nature. Gamma levels of military significance were found to exist at downwind distances to at least 280 nautical miles. The fallout from Shot 2 was more nearly characteristic of an aerosol with no evidence of large particulate. The fragmentary data on the residual gamma field show the level of activity 5 hours after detonation to be 145 r/hr at a downwind distance of 45 nautical miles.

Project 2.5b "Fallout Studies" (WT-916), Chemical Warfare Laboratories, Army Chemical Center; E. F. Wilsey, Project Officer.

The objectives of this project were to determine (1) the characteristics of fallout from land-surface and water-surface bursts, (2) the evaluation of the hazards associated with the residual contamination from such bursts, (3) the evaluation of the contaminating characteristics of fallout debris from such bursts, and (4) information for the evaluation of mechanisms of particle formation and distribution. Intermittent fallout collectors located at Bikini and Eniwetok Atolls were used to sample and collect the fallout.

Most of the data, except the survey data, were obtained from Shot 1. Shot 1 activities which were sampled ranged up to 290 millicuries for areas of 0.6 in² at the downwind stations. The greatest amount of radioactive fallout reached the downwind station east and southeast of ground zero at H + 5 to H + 15 minutes. The main downwind stations received a second wave from H + 25 to H + 60 minutes, and one station sampled a third and smaller wave from H + 4 to H + 5 hours. Fallout continued to occur in very small quantities up to H + 12 hours.

The average Shot 1 decay slopes were −1.69 for the period from H + 210 to H + 450 hours, and −1.37 from H + 400 to H + 1,700 hours.

The Shot 1 fallout consisted primarily of particles that appeared to be coral and salt. Most of the activity associated with the larger particles was located near the particle surfaces, while for smaller particles the activity appeared to be distributed regularly or irregularly throughout the particle.

Project 2.6a "Chemical, Physical, and Radiochemical Characteristics of the Contaminant" (WT-917), U. S. Naval Radiological Defense Laboratory; E. R. Tompkins, Project Officer.

The objective was to determine the chemical, physical, and radiochemical nature of fallout from Castle. This information is useful in deducing the mechanism of contaminant formation, evaluating radiological situations, developing radiological countermeasures, and interpreting field tests of countermeasures at Castle.

Shot 1 produced a dry fallout. Samples from Bikini Lagoon and land stations, and from islands in atolls 8 to 120 miles distant were obtained and analyzed. The fallout from Shots 2, 4, 5, and 6 were chiefly liquid in the form of an extremely fine mist of aerosol. Samples from free-floating buoys, lagoon and land stations, and from the Project 6.4 YAG's were analyzed for these events. Because rain was falling during the period of fallout after Shot 3 (detonated on Tare), the material collected was a slurry. Water samples from the open sea were collected out to 200 miles from ground zero for Shots 5 and 6.

The gamma count of fallout samples from Shots 1 and 3 was found to be associated with the solid fraction to the extent of 92 to 98 percent; for Shots 2 and 4 the solid fraction contained 25 to 38 percent of the gamma count. The remainder was found to be contributed mainly by emitters in the ionic state.

Neptunium was found as 65 ±11 percent Np (IV) as averaged for Shots 1, 2, 3, and 4; the remainder was found as Np (V + VI).

Iodine was found in the solid fraction of the fallout from Shots 1 and 3; it was also found in the liquid fraction of the fallout from Shots 2 and 4. In every case, iodine appeared to be essentially in the −1 oxidation state.

Quantitative analyses were made on all samples recovered from Shots 1, 2, 3, and 4. Island coral, lagoon seawater, and lagoon-bottom materials were also analyzed.

The yields of U^{237} and U^{240}, as well as that of U^{239}, were sufficiently high to contribute significantly to the residual contamination radiation and to affect the gross beta- and gamma-decay curves.

Analyses of all absorption curves show the presence of beta energies as high as 2.6 Mev at H + 15 hours (Shot 4), with the maximum beta energy decreasing to about 2 Mev at H + 3 to H + 10 days. Lead absorption curves were analyzed into three apparent energies: 0.15 Mev (70 percent), 0.44 Mev (16 percent), and 1.3 Mev (14 percent)—averaged for the first four shots from H + 0.3 to H + 13 days

Gamma spectra were taken of the fallout samples as a function of time for Shots 2, 3, and 4.

Project 2.6b "Radiochemical Analysis of Fallout" (WT-918), Chemical and Radiological Laboratories, Army Chemical Center; R. C. Tompkins, Project Officer.

The objectives were to determine (1) the variations in chemical and radiochemical composition of solid fallout with particle size, zero-point environment, and time and distance of collection; (2) the chemical and radiochemical nature of liquid fallout; and (3) the manner in which decay rates are affected by variations in radiochemical composition.

The investigation of radiochemical properties of fallout were conducted in Bikini Atoll and Bikini Lagoon. The adverse effect of mixing upon the liquid and solid fallout was minimized by a new collection system which immediately separated the phases.

Approximately 20 percent of the activity in the fallout from Shot 1 was associated with particles smaller than 10 microns. A trend of decreasing specific activity with increasing particle size was found in Shot 1 fallout below 50 microns. Fractionation of fission-product nuclides was found on Shots 1 and 3. Gross decay of Shot 1 fallout generally followed the equation $I = kt^{-2.0}$, and did not vary with particle size. There was evidence of an unusually high Mo^{99} fission yield on Shot 1.

In order to predict the military effects of fallout from operational nuclear weapons, it was necessary first to understand the basic dependence of these phenomena on environmental and weapon characteristics. Different effects are to be expected from land and water detonations than from shots on the surface and below the surface, from various soil types, and from different depths of water. Rainout may exert a considerable influence on the significance of ground contamination. The experimental nuclear devices in Castle were detonated in peculiar zero-point environments which will be absent in the case of most operational weapons detonations.

Project 2.7 "Distribution of Radioactive Fallout by Survey and Analysis of Contaminated Sea Water" (WT-935), Scripps Institution of Oceanography; T. R. Folsom, Project Officer.

The objective was to obtain fallout data in free-ocean areas, as a result of the fallout phenomena observed following Shot 1. Operational and technical details were hastily contrived so that they could be put into effect for the latter phases of Castle. Participation was concentrated on Shots 5 and 6, and both water-sampling and submerged-radiation-meter techniques were used. Isointensity contours were plotted as though the fallout had been received by a fixed plane at mean sea level. Dose rates at H + 1 or H + 12 hours were calculated at 3 feet above the fixed plane. These contours indicated that for Shot 5 total doses of 250 r or more could have been accumulated throughout an area of about 5,000 mi^2; for the smaller yield of Shot 6, the hazardous area was smaller.

The two survey techniques gave similar results. The direct gamma-radiation meter was well suited for rapid surveys and depth-of-penetration measurements, while the water-sampling technique provided specimens for more-complete gamma-spectrum and other physical and radiochemical studies. It was noted that depth-of-penetration measurements were highly dependent upon the reliability of estimates of fallout below the ocean surface: the rate of descent of the fallout into the mixed layer must be slow enough to allow accessibility for measurement at the time of the survey. It appeared that for both Shots 5 and 6 this requirement was met, since (1) other fallout observations indicated a very-small particle size which could be expected to settle slowly and (2) from the depth-cast data of Shot 5, the descent of the radioactive material into the water mass comprising the mixed layer was of such a rate and uniformity as to make depth-of-penetration calculations feasible.

Project 2.7a "Radioactivity of Open-Sea Plankton Samples" (WT-954), Scripps Institution of Oceanography; T. R. Folsom, Project Officer.

This was not a formal Castle project, but represents work done incidental to Project 2.7 but of sufficient interest to warrant publication in the Castle WT series.

The objective of this study was to ascertain the general relationship pertinent to the uptake of fission products by marine organisms, in order to form a background for more-extensive tests that were to be conducted on Operation Wigwam. Samples of zooplankton were collected, and gross beta activities, beta-absorption curves, and gamma spectra were analyzed after identification of the organisms. A radiochemical analysis was performed by the U. S. Naval Radiological Defense Laboratory. It was found that (1) the feeding mechanism of the organism determined the amount of activity assimilated, (2) solid phases in the water were concentrated in preference to the non-particulate phases, and (3) there was evidence of fractionation of isotopes by different groups of organisms.

PROGRAM 3: EFFECTS ON STRUCTURES

Project 3.1 "Air Pressure Measurements" (WT-919), Stanford Research Institute; L. M. Swift, Project Officer.

The objective was to obtain the air-blast loading pattern (as a function of time, in the 10-to-15-psi overpressure region) imposed upon a rigid, rectangular parallelepiped by a megaton-range detonation. This data was desired as an extension of that obtained by Upshot-Knothole Project 3.1 on target structures of the same type and to develop techniques of prediction that could be applied to the calculations of structure loading, response, and consequent damage from air blast from large-yield nuclear devices.

The test structure was a 6-by-6-by-12-foot rigid concrete cubicle, with the 12-foot dimension normal to the path of the shock wave, located 9,500 feet from ground zero.

A total of 46 gages were installed on the target structure; 12 pairs (24, total) were duplicates to ensure usable results. The gages were the type previously used on Operations Tumbler and Jangle: Wianko balanced variable reluctance transducer type, connected to oscillograph recorders. All instrumentation functioned; good records were obtained, although the magnitude of the data was much less than predicted because of the low yield of Shot 3.

The average values of the recorded free field data were: peak pressure at structure, 3.53 psi; dynamic pressure, 0.38 psi; and positive-phase duration, 1.52 seconds.

Although the data obtained proved of considerable value as a check on the loading theory and the conclusions of related Upshot-Knothole Project 3.1, the immediate objective of the project was not met because the yield of Shot 3 was only 130 kt instead of the expected value of approximately 1 Mt. Nevertheless, the blast-loading data obtained was evaluated in the project reports, and loading-prediction methods derived from Upshot-Knothole Project 3.1—both the AFSWP-226 and ARF prediction procedures—can be considered to have been generally checked by this experiment.

Project 3.2 "Crater Survey" (WT-920), Stanford Research Institute (Assisted by Army Map Service); R. B. Vaile, Jr., Project Officer.

The objective was to obtain dimensional data on craters formed by nuclear detonations for use in developing a generalized theoretical-empirical means of predicting crater dimensions.

In the preliminary planning for this project, consideration was given to determining the dimensions of the true crater as well as those of the apparent crater. No feasible method of obtaining dependable data on the true crater—other than employing drilling or coring operations—was developed. The cost and operational problems involved outweighed the probable value of any data so obtained. Therefore, measurements were limited to those of the apparent crater.

The craters formed by Shots 1, 3, and 4 were measured. No measurements were made for other shots because they were detonated at the sites of prior shot events.

The measurement techniques employed were fathometer traverses, lead-line soundings, and photo interpretation:

A Navy NK-6 fathometer operating at 14.25 kc/sec was mounted in an LCU which traversed the craters, with horizontal control for these hydrograph surveys monitored by a combination of Raydist electronic-positioning equipment loaned by Navy Bureau of Aeronautics, Sextants, Alidades combined with gyrocompass, and anchored taut-wire equipment.

Aerial-photography missions were flown to obtain pictures suitable for employment of stereoscopic photogrammetry techniques by the Army Map Service to provide detail of any above-water crater phenomena.

The body of knowledge regarding craters was materially increased, and the reliability of crater-prediction methods formulated therefrom was improved. Based on the crater data from this project, as well as a considerable amount of high-explosive and other nuclear crater data, the handbook "Cratering From Atomic Weapons," AFSWP-514, dated 29 June 1956, was subsequently prepared.

Project 3.3 "Blast Effects on the Tree Stand" (WT-921), U. S. Forest Service; W. L. Fons, Project Officer.

The objectives were to: (1) determine blast damage to trees in terms of stand breakage, branch breakage, and defoliation, where effects are influenced by their location in a natural tree stand; (2) determine the effects of natural forest coverage on attenuation of the shock wave, in terms of peak overpressure and peak dynamic pressure; and (3) obtain individual tree-breakage data in the region of long positive-phase duration, in order to substantiate the basis for breakage and blow-down prediction.

The availability of the natural tree stands in relation to detonation sites and expected yields limited this project to observations of natural tree stands on Uncle, Victor, and William Islands of Bikini Atoll. Participation was originally planned only for Shot 3, but data was also obtained from Shot 1 because of its unexpectedly high yield.

The principal tree types available for observation were: (1) Pisonia, a tree resembling the American beech tree; (2) Coconut Palm; (3) Tournefortia, a broadleaf species of large shrub-type which were chiefly under cover in Pisonia and Palm groves; and (4) Scaevola, a large, low, green bush-type species.

Instrumentation consisted of snubber tree gages (a simple device for measuring maximum tree deflection), a limited number of self-recording, static, overpressure-versus-time and dynamic-pressure-versus-time gages installed by Project 1.2b, and extensive preshot and postshot photography. Static-breakage tests of representative trees were also made prior to the shot.

The distances involved were from 62,000 to 76,000 feet from ground zero for the inadvertent participation on Shot 1 and from 3,000 to 31,800 feet for Shot 3. Ground-level pressure measurements 2,000 feet into a tree stand substantiated the Upshot-Knothole conclusion of no attenuation in peak overpressure. Since for the first time natural tree stands were subjected to a nuclear blast, the breakage prediction on American and European broadleaf tree stands can now be made with a fair degree of confidence. Observed damage from two devices of different yields compare favorably with TM 23-200 (Reference 7) isodamage curves prepared for broadleaf stands. Damage in broadleaf stands is principally limb breakage and defoliation, with occasional breakage of the main stem or uprooting.

Project 3.4 "Sea Minefield Neutralization by Means of a Surface Detonated Nuclear Explosion" (WT-922), Bureau of Ordnance, Department of the Navy; James Murphy, LCDR, USN, Project Officer.

The specific objective was to determine the effects of a surface detonated nuclear device on a planted sea minefield. Operational considerations limited participation of the project to Shot 4.

The sea minefield in this test was laid in seven rows disposed at ranges from 2,000 to 13,800 feet from site zero. Except for Row 6 and two surface-level Mk 6-0 mines in Row 4, the mines of a given row were laid on the bottom and were linked together by 230 feet of doubled $1\frac{1}{2}$-inch cable extending between mines. Each string so formed was anchored by a 2,000-pound cast-iron block attached to the string by 1,000 feet of doubled cable. Heavy wooden buoys were used to mark the locations of the anchor blocks. In Row 6 the mines were moored individually at depths of 30, 50, and 125 feet.

Postshot recovery was done by reeling in the strings of each row. In some instances this procedure resulted in case damage to the mines. The moored mines in Row 6 and the string of Row 1 were lost and never recovered. In addition, mines closest to site zero that were recovered about 24 hours after shot time were radioactive, with an exposure rate of 10 r/hr.

Although only a limited number of mines were exposed, it was concluded that a surface-detonated nuclear weapon was not an efficient method for minefield clearance.

Project 3.5 "Blast Effect on Miscellaneous Structures" (WT-901), Armed Forces Special Weapons Project; Wayne J. Christensen, LCDR, CEC, USN, Project Officer.

The objective was to document damage inflicted by Shot 1 on structures that had been erected for utilitarian purposes in connection with the test operations. This project was not in the original program, but the unexpected structural damage which resulted from Shot 1—with its yield of 15 Mt approximately three times that predicted—warranted documentation of all the data possible about structural blast damage from high-yield detonations.

It became evident from this survey that the effective lethal range to a light wood-frame building was amazingly great for a high-yield nuclear blast. This type of structure was damaged severely beyond a range of 14.5 miles. Even reinforced-concrete shelter-type structures as far as $\frac{1}{2}$-mile range which were exposed directly to the blast were vulnerable.

The islands of Oboe and Tare were the site of a camp for approximately 1,000 persons, the shipping center for all inter- and intra-atoll shipping, the base for all construction operations in the atoll, the site for one of the later detonations of the test series, and the site of an air strip with minimum aircraft servicing facilities. It had been intended to continue to base operations on this island up to the last shot, although apprehension existed regarding the possibility of radiological contamination of the islands. Most of the structures were of light frame construction. Personnel quarters and many administrative and work spaces were tents supported by wood frames. The estimated overpressure from Shot 1 of about 1.4 psi had a positive duration of about 13.4 seconds, and gave the structures and equipment on these islands the appearance expected from a high-wind storm. Some buildings collapsed, others were pushed out of alignment, and many had their roofing stripped or partially stripped. The damage was too extensive to warrant rehabilitation of a camp for messing and housing, although the use of the air strip was continued, and the islands continued as a base for construction operations.

As opposed to the light construction described above, two massive reinforced-concrete structures for protection of scientific instruments were located at about 2,500 yards from the detonation, at about 130 psi overpressure. One of these was not earth-covered. It was also geometrically unconventional; the other structure was geometrically conventional. These two structures were subjected to air pressures, ground accelerations, and thermal radiation far in excess of that for which designed. The structures were still structurally intact after the detonation, although there had been detail failure to such a degree as to attribute functional failure to the buildings. A study of the design details of these structures should be most rewarding to structural engineers who are concerned with the effective design aspects of nuclear warfare.

PROGRAM 4: BIOMEDICAL STUDIES

Project 4.1 "Study of Response of Human Beings Accidentally Exposed to Significant Fallout Radiation" (WT-923), Naval Medical Research Institute, Naval Radiological Defense Laboratory; E. P. Cronkite, CDR, USN, Project Officer.

Addendum Report "Nature and Extent of Internal Radioactive Contamination of Human Beings, Plants, and Animals Exposed to Fallout (WT-936).

Addendum Report "Medical Examination of Rongelap People Six Months After Exposure to Fallout" (WT-937).

Addendum Report "Exposure of Marshall Islanders and American Military Personnel to Fallout" (WT-938)

Addendum Report "Physical Factors and Dosimetry in the Marshall Island Radiation Exposures" (WT-939).

The project report and the addendum reports noted represent the documentation of the study of fallout effects on those humans accidentally exposed during Shot 1. The main project report (WT-923) represents the overall results of the study; the addendum reports listed are detailed studies of dosimetry and internal radioactive contamination, as well as detailed clinical records of the personnel involved. A general summary of these studies may be found in Chapter 5.

PROGRAM 6: TESTS OF SERVICE EQUIPMENT AND TECHNIQUES

Project 6.1 "Test of Interim IBDA Procedures" (WT-924), Strategic Air Command; Rockly Triantafellu, Col, USAF, Project Officer.

The Strategic Air Command objective for Castle was to determine current IBDA capabilities for high-yield detonations and to provide indoctrination for combat crews.

Three B-50's and crews of the 97th Bomb Wing Detachment staged through Fred Island from Guam for each shot. The aircraft control surfaces were painted with thermal-resistant paint, and all windows and blisters were equipped with thermal protective curtains. Standard APQ-24 radar and 0-15 cameras were used to record shot phenomena.

The B-50's were positioned about 15, 23, and 30 miles from ground zero for each shot at altitudes of approximately 30,000 feet.

Excellent radar-scope photographs of the characteristic returns were obtained. By interpretation of the photographs, ground-zero fixes were determined with sufficient accuracy for IBDA purposes. The technique of using photographic data to compute yields proved unreliable. Since participation was limited to surface bursts, no attempt was made to compute height-of-burst information.

Project 6.2a "Blast and Thermal Effects on B-36 Aircraft In Flight" (WT-925), Wright Air Development Center; G. Miller, Project Officer.

Data obtained during Ivy and Upshot-Knothole had related the response of the B-36 to the thermal and blast forces of nuclear detonations. Project 6.2a was established to prove or disprove the predicted responses of the B-36 aircraft to nuclear, thermal, and blast forces. These predictions, which were based upon theoretical and empirical analysis, were to be used to define the delivery capabilities of the aircraft.

The same B-36D aircraft which had participated in Ivy and Upshot-Knothole was selected because it was already partially instrumented for such a test. The aircraft was flown and maintained by the Strategic Air Command. The Wright Air Development Center was responsible for the installation, maintenance, and operation of the instrumentation as well as the selection of the position of the aircraft relative to the detonation. Measurements of peak overpressure, thermal intensity, and total thermal energy were made to determine the thermal and blast inputs on the aircraft. To obtain data on the response of the aircraft to these inputs, it was instrumented further for the measurement of wing, stabilizer, and fuselage bending moments, stabilizer shear forces, fuselage and wing accelerations, skin-temperature rise, and elevator position.

The aircraft participated in every shot of the Castle series. The limiting condition on the aircraft was either 100 percent of the design limit allowable bending moment on the horizontal stabilizer or a 400 F temperature rise on the 0.020-inch magnesium skin on the elevators. For Shots 1 through 5, the aircraft was positioned at time zero in a tail-to aspect for one of the two limiting conditions, whichever was critical for the maximum predicted yield of the device concerned. For Shot 6, the aircraft was positioned in a head-on aspect for conservative values of bending moments. Data obtained from a head-on orientation were the first experimental verification of theoretically predicted responses and, although conservative, were nevertheless extremely valuable and necessary for a complete evaluation of aircraft response to nuclear explosions.

The maximum useful incremental peak temperature measured was 250 F rise on the 0.020-inch magnesium skin on the undersurface of the elevator during Shot 5. The theoretical overpressure criteria level of 0.80 psi was attained safely on Shot 1, although considerable sheet-metal damage resulted. The maximum gust load measured was an incremental bending moment on the horizontal stabilizer of approximately 80 percent of design limit load. The predicted responses of the critical skin areas to the thermal inputs received were conservative, but sufficient data were obtained to enable a more realistic empirical and theoretical determination of the delivery capabilities of the B-36.

Project 6.2b "Thermal Effects on B-47B Aircraft in Flight" (WT-926), Wright Air Development Center; C. L. Luchsinger, Project Officer

Project 6.2b was a continuation of the experimentation begun on Ivy to determine the effects, principally thermal, of nuclear detonations on a B-47 aircraft in flight. The Castle results, when combined with previous data, will modify existing theories relating the B-47 response to thermal inputs.

The Ivy B-47B, with additional instrumentation, participated on all but Shot 5 of the Castle series. Recorded data included total thermal-input energies, intensities, and spectra as well as overpressures, skin temperature response, and flight attitudes. The aircraft was flown and maintained by WADC personnel who were also responsible for instrumentation and aircraft position determination. The average effectiveness of instrumentation for the series was 93 percent.

The aircraft was positioned on each shot to receive sufficient thermal energy to raise the temperature in the 0.020-inch skin on the ailerons to 370 F above ambient. Assigned positions in space were computed on the basis of the maximum probable yield rather than the most probable. In most cases, higher thermal inputs were realized than for the Ivy tests. In the case of Shot 1, where the yield was slightly greater than the maximum probable, good results were obtained. The aircraft sustained only minor physical damage, and the results indicated that sufficient information was recorded to meet the project objectives. These data indicated that predictions of aircraft skin response to thermal inputs from high-yield weapons were over-conservative. They also indicated the need for a better understanding of the parameters involved in skin responses to thermal flux: e.g., convective and conductive cooling, as well as the possible variance of absorption coefficients with change of incident angle of thermal inputs.

Project 6.4 "Proof Testing of AW Ship Countermeasures" (WT-927), Bureau of Ships and Naval Radiological Defense Laboratory; G. G. Molumphy, CAPT, USN, Project Officer.

The principal objectives were: (1) the evaluation of washdown countermeasures on ships and grounded aircraft, (2) the determination of the shielding effectiveness of ships structures, (3) the tactical radiological recovery procedures on ships and grounded aircraft, and (4) the extent of interior contamination and suitability of ventilation protective devices aboard ship.

Two remotely controlled ships, one protected by a washdown countermeasure, were guided through regions of contaminated fallout. Special structural configurations, boiler air ducts, ventilation test compartments, and aircraft were installed on both ships to act as contaminant-collecting surfaces. Recording gamma-radiation detectors, air samplers, particle and differential fallout collectors, surface samples, and postshot radiation surveys were used to supply data on the extent of contamination.

These data showed that it was possible for personnel to receive lethal radiation dosage aboard unprotected ships and shipboard aircraft if used operationally. Washdown effectiveness on ships and aircraft not in flight was estimated to be 90 and 95 percent based on dosage and dose rate, respectively. Distance and shielding by the ships structures resulted in attenuation fractions ranging from 0.2 in compartments close to weather surfaces to 0.001 in interior compartments below armored decks, with respect to levels observed on weather decks. On unprotected ships and grounded aircraft, excessively long periods of repetitious decontamination were required to achieve satisfactory radiation levels; when a washdown countermeasure had been in operation, very little effort was needed to make the ship or aircraft habitable. Very little contaminant entered either the boiler air system or ventilation systems.

For contaminating events of the type encountered in these tests, it appeared that: (1) washdown countermeasures will enable ships and operational planes to carry out their missions in the event of transit through contaminated fallout, (2) significant attenuation is afforded by ships structures, (3) decontamination procedures require further development, and (4) there is negligible hazard contributed by boiler air, or ventilation systems with fans turned off.

Project 6.5 "Decontamination and Protection" (WT-928), Chemical and Radiological Laboratories, Army Chemical Center; J. G. Maloney, Project Officer.

The primary objectives were to: (1) determine the relative contaminability and decontaminability of conventional building construction materials when exposed to the type of wet-contaminant fallout which would be characteristic of nuclear detonations in harbors, (2) ascertain the relative effectiveness of various decontamination techniques, and (3) determine the need for pre-attack protection measures in reducing contaminability and/or facilitating decontamination.

Fourteen 4-foot-square panels with different types of outside construction surfaces were mounted on both a drone, washdown-protected Liberty ship (YAG-39) and an unprotected drone Liberty ship (YAG-40) which were operated through the fallout area following Shot 2. For Shot 4, an identical set of panels was mounted on board the unprotected ship (YAG-40). For Shot 6, another identical set of panels was mounted on board a barge moored in the fallout area. Subsequent to contamination, the panels were removed to shore, monitored for contamination intensity, and then subjected to decontamination efforts utilizing a variety of hosing and scrubbing techniques.

The salt water washdown appeared to be effective in minimizing contamination of construction surfaces under the conditions of Shot 2.

The contamination resulting from Shots 2 and 4 was very tenacious in nature and was much more difficult to remove than the contamination encountered in Jangle.

A great difference existed among the construction surfaces with regard to initial contamination levels and ease of removal; of the methods employed, the hand-scrubbing technique was the most effective.

Under the conditions of those shots contaminating the YAG's, vertical surfaces became generally more highly contaminated than horizontal and sloped surfaces; this was probably caused by the horizontal wind components across the deck.

Project 6.6 "Effects of Nuclear Detonation on the Ionosphere" (WT-929), Evans Signal Laboratory, Signal Corps Engineering Laboratories; Fred B. Daniels, Project Officer.

Ionosphere recorders were operated both in the Marshall Islands and at distant locations to study the effects of the test detonations on the ionosphere, particularly on the F2 layer (the highest portion of the ionosphere, from about 200 km upwards). The principal objective was to attempt to confirm phenomena observed in the F2 layer during Shot Mike of Ivy, both in the general vicinity and at a great distance from the shots, in order to learn more about the ionosphere and to help determine possible military applications such as long-range detection.

Two ionosphere recorders were operated in the Marshall Islands by project personnel: one at Parry Island, approximately 200 miles west of the Bikini shots (23 miles from the shot at Eniwetok), and one at Rongerik Atoll, approximately 150 miles east of the Bikini shots (350 miles east of the shot at Eniwetok).

At Guam and Okinawa (about 1,400 and 2,600 miles from Bikini, respectively), ionosphere stations, regularly operating as part of the world-wide system, furnished special data to this project at times bearing a specified relationship to each shot time.

When oscillograms from the ionosphere recorders are properly analyzed, they give data on the height and critical frequency (a function of the maximum ion density) of each observable ionospheric layer. On Castle, frequent records (up to four per minute) were obtained with these recorders following each detonation, the timing program varying according to the location and operational conditions. Throughout the operation, regular recordings were made five times an hour to establish normal conditions for comparison.

A tremendous amount of absorption (and possibly scattering) followed all shots, particularly those of higher yields, causing obscuration of the F2 layer for several hours at the Rongerik station and longer at the Parry Island station. However, enough data were obtained at Rongerik to indicate that for shots of megaton yield range an effect occurred which was similar to the rising-F2-layer phenomenon observed after Shot Mike of Ivy. Variations were noted between results of one shot and another which may have been due to different yields or different ionospheric conditions.

The Parry Island operation, though hampered, resulted in a new hypothesis to explain the protracted absorption that may prove significant. It suggests that the absorption occurring at Parry Island several hours after the shots at Bikini (200 miles to the east) was a result of copious ionization overhead, caused by beta particles and radioactive particles carried westward by winds at 60,000- to 120,000-foot levels.

Records from distant stations indicated that ionospheric disturbance resulted from megaton detonations at ranges up to 2,600 miles. These disturbances apparently propagated outward from their origin at a velocity of 8 to 16 km/min.

PROGRAM 7: LONG RANGE DETECTION PROGRAM

Project 7.1 "Electromagnetic Radiation Calibration" (WT-930), AF M. H. Oleson, Project Officer.

A total of 16 stations, one close-in (320 km) and the balance at distances, were operated for the AF electromagnetic experiments.

Both broad-band measurements (up to 40 Mc at close-in distances and approximately 100 kc at greater distances) and narrow-band measurements (approximately 200 cycles) were made of the vertical field component. Close-in wave forms and field strengths were recorded for all shots except Shot 1. Signals were received, and wave forms, field strengths, and azimuths were recorded at distances exceeding 12,000 km for both a north-south and an east-west path.

The National Bureau of Standards (NBS) operated the close-in station: a 2-meter vertical antenna with a cathode follower feeding a coaxial line to recording oscilloscopes set at various sweep speeds and gains. At this close distance (320 km), signal strengths were several volts per meter, and interference from natural sources or transmitting stations in proximity was no problem. Band widths were about 13 and 40 Mc, limited by the type of scopes used; the low-frequency limit was about 160 cps.

Distant stations were operated by the NBS and the Defense Research Laboratory (DRL) using 30-foot vertical antennas with standard cathode followers. Both narrow-band (about 200-cps) and broad-band (about 1- to 70-kc) recordings were made.

Agencies participating in this project under the sponsorship of AF were the National Bureau of Standards (NBS), the Navy Electronics Laboratory (NEL), and the Signal Corps Engineering Laboratories (SCEL). The Geophysics Research Directorate of the Air Force Cambridge Research Center (AFCRC) conducted additional measurements under a different program.

Each station operated by the Signal Corps consisted of four microphone outposts, one at each corner of a quadrilateral, approximately square, 4 to 10 miles on a side. Each outpost was connected to a recording central.

The NEL operated arrays of two to five microphone outposts spaced from 3 to 15 miles apart at three locations. In most cases, microphone outposts were connected to a recording central.

The NBS station consisted of six microphone outposts located at the corners of two roughly equilateral triangles, one having $2\frac{1}{2}$-mile sides and the other 14-mile sides. The small triangle was roughly centered inside the larger triangle. Each outpost was connected by wire lines to a recording central.

The AFCRC stations were similar to those of SCEL, except that individual recordings were made in the immediate vicinity of each microphone outpost.

Two main types of equipment were used: (1) standard detection equipment most responsive to atmospheric-pressure changes having periods ranging roughly from 1 to 60 seconds and (2) very-low-frequency equipment responsive to change in pressure or to rate-of-change of pressure for signal periods ranging from approximately 5 to 300 seconds.

Standard detection equipment (Data Recording System M-2 or NBS Infrasonic Microphone System) was operated at all SCEL stations. Both types of equipment utilized condenser microphones as the pressure-sensitive transducers, wire lines for transmission to the recording central, and Esterline-Angus graphic recorders.

The M-2 equipment responded mainly to pressure changes in the range of periods from 1 to 50 seconds and the NBS from 1 to 35 seconds. The maximum sensitivity for the M-2 was of the order of 15-mm deflection for a pressure change of 1 dyne/cm^2, that for the improved M-2 was about 45 mm/(dyne/cm^2), and that for the NBS was approximately 30 mm/(dyne/cm^2). Recording speed was 3 in/min. Very-low-frequency equipment was also operated by SCEL at some stations. This equipment consisted of a special condenser microphone designed for low-frequency response (5- to 300-second periods) through use of a very-large reference volume, a high-resistance acoustic leak, and elaborate thermal insulation. The electronic and control circuits were similar to that employed in the improved M-2 equipment, and the maximum sensitivity was approximately the same. Recording speed was 1.5 in/min.

Each standard microphone was equipped with a linear, multiple-inlet pipe array 1,000 feet in length, designed to reduce the noise background from atmospheric turbulence. No effective array was available for use at very-low frequencies.

The NEL operated two types of very-low-frequency equipment. One type operated at some stations consisted of a Rieber vibrotron microphone modified for response to periods from 8 to 265 seconds. Output was recorded on a Brush graphic recorder at speeds of 0.2 and 0.5 in/min. The second type, operated at all NEL stations, consisted of a Signal Corps T-21-B condenser microphone modified to respond to periods from 6 to 300 seconds. Output was recorded on Esterline-Angus graphic recorders at 0.75 in/min. At maximum sensitivity, the modified Rieber equipment gave a deflection of approximately 0.2 mm for a pressure change of 1 dyne/cm^2 and the modified T-21-B equipment gave approximately 0.7 mm/(dyne/cm^2). No effective noise-reducing arrays were available for use at very-low frequencies.

All NBS stations were equipped with standard NBS equipment. The microphone was modified to increase the sensitivity, but to retain the same frequency response. At maximum sensitivity, the equipment gave a deflection of approximately 50 mm/(dyne/cm^2). A standard, linear, pressure-averaging pipe array of Signal Corps design was used for noise reduction. Recording speed was 3 in/min.

The three microphones making up the large triangle and one of the microphones from the small triangle were also connected to special multivibrator-type discriminators and low-pass filter amplifiers to produce a response to rate of change of pressure down to very-low frequencies. Sensitivity was approximately 50 mm/(dyne/cm^2) an Esterline-Angus recorder operating at 0.7 in/min.

The AFCRC operated modified T-21-B equipment developed by NEL. Tape speeds and sensitivities were approximately the same as those used by NEL.

The Air Weather Service (AWS) operated crossed-loop goniometers at distant stations to record azimuths. These were similar to their standard sferics low-frequency (10-kc) narrow-band (about 0.5-kc) direction-finding stations used for locating thunderstorm areas as an aid to weather forecasting. The AF operational stations had a slightly wider band width (8 to 12 kc).

Distant stations for the most part utilized locations already in use by NBS, DRL, AWS, or AF. Insofar as possible, sites were chosen on east-west and north-south orientations in an attempt to get some idea of differences due to a daylight path, a dark path, and auroral-zone transmission.

Some distant stations were located in proximity to stations transmitting low-frequency carriers. In order to avoid interference from these stations, their cooperation was enlisted and they were shut down at critical times.

Project 7.2 "Detection of Airborne Low-Frequency Sound from Nuclear Explosions" (WT-931), AF G. B. Olmsted, Project Officer.

Measurements of the airborne low-frequency sound from the Castle detonations were made at fifteen remote locations at a variety of distances and directions from the Eniwetok Proving Ground to study the relation between signal characteristics and the energy released over a range of yields up to 15 Mt.

Both standard and very-low-frequency sound-recording equipment responsive to small atmospheric-pressure variations in the frequency range from 0.002 to 1 cps were employed

Project 7.4 "Calibration Analysis of Close-in Atomic Device Debris" (WT-932), AF D. L. Northrop, Project Officer.

The work of this project was a continuation of a program established to monitor all U. S. nuclear detonations, in order to determine calibration reference points for the analysis of airborne nuclear debris. These data were obtained by the application of chemical, radiochemical, physical, and nuclear analyses to the debris collected by specialized sampling devices. The calibration data were further extended by making similar measurements on nuclear debris collected at great distances from the detonation.

Nuclear-debris samples close-in to the detonation were obtained utilizing sampling devices on F-84, WB-29, and B-36 aircraft. Similarly equipped WB-29 aircraft operated out of Hawaii for the long-range calibration samples.

Close-in particulate and gaseous samples were obtained by F-84 and B-36 aircraft penetrating the cloud from each detonation. Air Weather Service WB-29 aircraft equipped with particulate and gas-sampling devices collected samples at remote distances from the nuclear detonation.

Five F-84G aircraft utilized the method of snap gas-sampling. This consisted of an exterior stainless-steel probe in the nose of the aircraft that fed into a deflated polyethelene bag. Samples were taken by activating a valve and filling the polyethelene bag by ram pressure.

Ten F-84G aircraft were equipped with a dual electrical compressor system feeding into two 500-in^3 compression cylinders (3,000 psi). All of the air sampled was bled from an intermediate stage of the axial compressor of the aircraft and fed into the dual compressors — the squeegee method. Operation Castle provided the first full-scale operational test of this system. In addition, several B-36 aircraft were equipped with the squeegee system; for these, the intake air was bled from the upstream side of the large cabin pressurization filter and fed through compressors into 900-in^3 (3,000 psi) cylinders.

Longer-range samples were obtained using WB-29 aircraft with associated C-1 foils for particulate samples and a B-31 gas-sampling device for gaseous debris.

The collection of all close-in particulate samples was under the technical direction of the Los Alamos Scientific Laboratory (LASL); the collection of gas samples was supervised by AFOAT-1. The University of California Radiation Laboratory (UCRL) was responsible for gas separation and analyses of some samples at the test site.

Instrumentation, techniques, and procedures in the processing, separation, and assay of the nuclear particulate and gaseous debris are included in detailed LASL and UCRL reports.

Close-in gas samples were collected at altitudes in the range of 35,000 to 50,000 feet MSL. Gaseous debris sample sizes collected varied from 10^{-15} to 10^{-17} bomb fractions. Representative sections of each test cloud were sampled, but due to extreme cloud heights obtained on high-yield detonations, only the lower portions of these clouds were sampled. Long-range samples were collected from approximately sea level to 20,000 feet.

PROGRAM 9: TECHNICAL PHOTOGRAPHY

Project 9.1 "Cloud Photography" (WT-933), Edgerton, Germeshausen and Grier, Inc.; Jack G. James, Lt Col, USAF, Project Officer.

Project 9.1 was established for the purpose of recording photographically cloud formation phenomena that would satisfactorily supply data for use in studying the aircraft delivery problem and correlation of fallout studies in relation to cloud drift. The technical aerial photography was conducted by Lookout

Mountain Laboratory, and the terrestrial backup ground photography was made by EG&G in conjunction with Project 13.2.

Analysis and reporting of the data were the responsibility of EG&G. One RB-36 and three C-54 aircraft participated in the aerial photography and flew a total of six missions per aircraft. Usable results were obtained from two or more aircraft on all events except for Shot 3, where photo results were negative due to natural cloud cover obscuring ground zero. Preliminary analysis of the Castle cloud data indicated excellent results for the period of H + 10 minutes.

Aerial oblique photography supporting Project 3.2, Crater Survey, was flown by Lookout Mountain Laboratory personnel. This mission consisted of a series of aerial photographs tracking an LCU during the period of time fathometer readings were being made in the Shot 1 crater.

Preshot and postshot crater vertical aerials were flown on Shots 1 and 3 by Strategic Air Command reconnaissance personnel. Analysis of the crater dimensions was made from this photography by the Army Map Service for Project 3.2.

Technical still photography requirements in support of DOD projects were met entirely by Los Alamos Scientific Laboratory photographic personnel. All project requirements were coordinated and programmed through Program 9, including preshot and postshot photography.

PROGRAM 18: THERMAL RADIATION MEASUREMENTS[1]

Project 18.2, Project 18.5 "Thermal Radiation" Naval Research Laboratory; H. Stewart, Project Officer.

Power-versus-time measurements were made by employment of modulated bolometers. These bolometers were located in 8-by-2-by-8-foot coffins mounted on photo towers on How and Tare Islands for Shots 1 and 2. The How tower was 97,975 feet and the Tare tower 77,765 feet from ground zero of these shots. The bolometers were mounted on a barge near How for Shots 4 and 5; this barge was 62,200 feet from the shot barge for each of these shots. For Shot 6, the bolometer was mounted on a power house on Yvonne Island, 77,522 feet from the shot barge.

The modulated bolometer consisted of two blackened platinum wires whose resistance changed with temperature. One wire was in each of two arms of a Wheatstone bridge, which with a mechanically driven chopper alternately exposed first one wire and then the other wire to the thermal radiation. The application of a dc voltage at one end of the bridge resulted in an ac output at the other end that was amplified and recorded on magnetic tape.

Total thermal energy was measured by use of Epply thermopiles faced toward the detonation site. The output of the thermopiles was recorded on Brown recording potentiometers. These thermopiles were located on Tare, How, and George Islands for Shots 1 and 2. They were located on Nan Island and on a barge near How Island for Shots 4 and 5; for Shot 6, they were located on Fred and Yvonne Islands.

Project 18.3 "High-Resolution Spectroscopy" (WT-950), Naval Research Laboratory; H. Stewart, Project Officer.

For Shots 1, 2, 4, and 5, spectrographs of various dispersions and in selected wave-length ranges were located in a concrete bunker at the base of a 200-foot tower on the south end of Nan Island. Mirrors on the tower reflected light from the detonations to the viewing slits of the spectrographs. For Shot 6, spectrograph installations were established on Fred and Janet Islands.

Project 18.4 "Atmospheric Transmission of Light" Naval Research Laboratory; H. Stewart, Project Officer.

Atmospheric transmission was measured over selected paths. To make these measurements, a searchlight of known luminous intensity was mounted near each zero site for each selected path and trained on a photocell receiver at the other end of the path. The searchlight beam was modulated by a mechanical chopper (60 cps) and the receiver system was arranged so that only light at this modulated frequency was received, thus making the system independent of daylight. The paths for each shot were: Shot 1, from zero site to George, Tare, and Delta Islands (Delta is an artificial island near Able); Shot 2, from zero site to George and Tare Islands; Shots 4 and 5, from zero site to How and Nan Islands; and Shot 6, from zero site to Fred and Janet Islands.

[1] Not a formal DOD program. These thermal-radiation projects of DOD interest were sponsored by LASL (see Chapter 8). Publication information for Projects 18.2, 18.5, and 18.4 is as yet uncertain; information on their availability and the availability of the Project 18.3 final (WT) report may be obtained from LASL.