SSS-R--84-6629

DE84 013062

CALCULATIONS TO ASSIST IN A NEW
HIROSHIMA YIELD ESTIMATE

Final Report for the Period August 19 - December 31, 1983

Lynn W. Kennedy
Louis A. Roth
Charles E. Needham

15 June 1984

MASTER

Work Performed under Contract No. DE-AC03-83ER60148

S-CUBED
(A Division of Maxwell Laboratories, Inc.)
P.O. Box 8243
Albuquerque, New Mexico 87198

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ABSTRACT

This report describes calculations and analysis performed in an attempt to provide a new estimate for the yield of the Hiroshima weapon. Newly discovered meteorological data was adapted for use in one- and two-dimensional hydrodynamic codes, and a series of calculations was then run for different values of yield. The objective was to determine what yield produced an overpressure record which could best be correlated with an actual trace measured at a parachute-dropped canister. Altitude of the bomb and canister-carrying aircraft at drop time was also a variable parameter.

The analysis provides an estimate of 16.6 ± 0.3 kt for the yield of the Hiroshima weapon. A drop altitude of near 35,500 feet is shown to be consistent with the signal time-of-arrival. This yield value is within the range of other estimates, but the drop altitude is higher than that previously assumed to be reasonable.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NOTICE

REPRODUCED FROM THIS REPORT ARE ILLEGIBLE.

It has been reproduced from the best available copy to permit the broadest possible availability.

TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
I	INTRODUCTION	7
II	STABILIZATION OF THE HIROSHIMA ATMOSPHERE	13
III	PHASE 1: INCIDENT WAVE CALCULATIONS	17
IV	PHASE 2: REFLECTED WAVE CALCULATIONS	53
V	CONCLUSIONS	81
	REFERENCES	83
APPENDIX	- CALVAL Subroutine Used in Phase II	85

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Original Interpretation of the Hiroshima Canister Record	9
2	Reed "Enhanced" Version of the Hiroshima Canister Record	11
3	Canister Record Compared with 12 kt Calculation at Range 33.8 kft	25
4	Impulse Compared with 12 kt Calculation at Range 33.8 kft	26
5	Canister Record Compared with 12 kt Calculation at Range 45.3 kft	27
6	Impulse Compared with 12 kt Calculation at Range 45.3 kft	28
7	Canister Record Compared with 22 kt Calculation at Range 33.8 kft	29
8	Impulse Compared with 22 kt Calculation at Range 33.8 kft	30
9	Canister Record Compared with 22 kt Calculation at Range 37.4 kft	32
10	Impulse Compared with 22 kt Calculation at Range 37.4 kft	33
11	Canister Record Compared with 22 kt Calculation at Range 43.0 kft	34
12	Impulse Compared with 22 kt Calculation at Range 43.0 kft	35
13	Canister Record Compared with 20 kt Calculation at Range 33.8 kft	36
14	Impulse Compared with 20 kt Calculation at Range 33.8 kft	37
15	Canister Record Compared with 20 kt Calculation at Range 40.0 kft	38
16	Impulse Compared with 20 kt Calculation at Range 40.0 kft	39

LIST OF ILLUSTRATIONS (Continued)

<u>Figure</u>		<u>Page</u>
17	Canister Record Compared with 17 kt Calculation at Range 38.7 kft	40
18	Impulse Compared with 17 kt Calculation at Range 38.7 kft	41
19	Canister Record Compared with 17 kt Calculation at Range 39.0 kft	42
20	Impulse Compared with 17 kt Calculation at Range 39.0 kft	43
21	Arrival Time vs Slant Range : "Physically Reasonable" and Calculated Values	44
22	Canister Record Compared with 16.5 kt Calculation at Range 37.7 kft	46
23	Impulse Compared with 16.5 kt Calculation at Range 37.7 kft	47
24	Canister Record Compared with 16.5 kt Calculation at Range 38.1 kft	48
25	Impulse Compared with 16.5 kt Calculation at Range 38.1 kft	49
26	Canister Record Compared with 16.7 kt Calculation at Range 38.4 kft	50
27	Impulse Compared with 16.7 kt Calculation at Range 38.4 kft	51
28	Range Plot at 0.5 sec for Horizontal One-Dimensional Calculation	54
29	Range Plot at 0.5 sec for Vertical One-Dimensional Calculation	55
30	Pressure and Relative Pressure Contours at Beginning of Two-Dimensional Calculation	57
31	Energy Contours and Vector Velocities at Beginning of Two-Dimensional Calculation	58
32	Pressure and Relative Pressure Contours at End of Two-Dimensional Calculation	59

LIST OF ILLUSTRATIONS (Continued)

<u>Figure</u>		<u>Page</u>
33	Configuration for Combined Incident and Reflected Wave Calculation	61
34	Relative Pressure Composite Profile Used as Input to Final One-Dimensional Calculation	64
35	Velocity Composite Profile Used as Input to Final One-Dimensional Calculation	65
36	Relative Dension Composite Profile Used as Input to Final One-Dimensional Calculation	66
37	Temperature Composite Profile Used as Input to Final One-Dimensional Calculation	67
38	Canister Record Compared with 16.5 kt Combined Incident and Reflected Wave Calculation at Range 39.4 kft	68
39	Impulse Compared with 16.5 kt Combined Calculation at Range 39.4 kft	59
40	Canister Record Compared with 16.5 kt Combined Calculation at Range 39.7 kft	70
41	Impulse Compared with 16.5 kt Combined Calculation at Range 39.7 kft	71
42	Canister Record Compared with 16.5 kt Combined Calculation at Range 40.0 kft	72
43	Impulse Compared with 16.5 kt Combined Calculation at Range 40.0 kft	73
44	Canister Record Compared with 16.5 kt Combined Calculation at Range 42.3 kft	75
45	Impulse Compared with 16.5 kt Combined Calculation at Range 42.3 kft	76
46.	Comparison of Relative Pressure Profiles Used as Input for Phase 1 and Phase 2 Calculations	77
47	Comparison of Velocity Profiles Used as Input for Phase 1 and Phase 2 Calculations	78

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Summary of Yield Estimates	7
2	Yield Estimates from Canister Record	8
3	Altitude Variation of Atmospheric Temperature and Pressure	13
4	Calculation of Allowable Signal Propagation Times	18
5	Calculation of Vertical Distance Between Bomb and Canister	19
6	Calculation of Horizontal Distance Between Bomb and Canister for Two Different Wind Speed Conditions	20
7	Slant Range and Angles of Propagation for the Different Drop Altitude and Wind Speed Conditions	22
8	Matrix of One-Dimensional Calculations.....	23

I. INTRODUCTION

The recent concern with long-term effects of low level radiation exposure has spurred a renewed interest in the data accumulated in the Hiroshima and Nagasaki nuclear detonations. To evaluate this data base properly, an accurate estimate of the yield of the devices is essential. Yield estimates are directly related to the radiation levels to which persons suffering known medical pathology were exposed. A yield estimate which is too high would indicate that low level radiation effects are not as severe as they actually are, whereas a low estimate would cause errors of understanding in the opposite direction.

The Nagasaki detonation is fairly well defined at 22 kt. The data are reasonably consistent and subsequent tests of the FATMAN device have confirmed the figure. The LITTLEBOY device detonated at Hiroshima, however, was never tested, either before or after its use there. Estimates, based on various assumptions and measurements, have ranged from 12 to 17 kt as illustrated in Table 1, which is from Reference 1. In addition, there are discrepancies, after 35 years, in reported parameters such as aircraft altitude and wind speed and direction which affect the yield determination.

TABLE 1
SUMMARY OF YIELD ESTIMATES (kt) - From Reference 1

	Little Boy	Fat Man
Calculation	15 ± 5	22 ± 1
Radiation chemistry		21 ± 1.5
Fireball		22 ± 2
Thermal effects	15 ± 3	
Blast effects	12 ± 4	
Blast (Penney, Samuels, and Scorgie, 1970)	12 ± 1	22 ± 2
Canister P(T)	17 ± 4	
Suggested yield*	15 ± 3	22 ± 2

*Note: Current estimate for Hiroshima is 17 kt.

John Malik of Los Alamos National Laboratories (LANL), with the assistance of Jack Reed of Sandia National Laboratories (SNL) and George Kerr of Oak Ridge National Laboratories (ORNL) has made an extensive and careful study of all of the available information. One item of this information is a single pressure trace (Figure 1) obtained from a canister dropped by an instrumentation aircraft which accompanied the bomb-carrying aircraft. This record has previously been analyzed, using a variety of methods and different parameter values. The values of yield obtained, as shown in Table 2, vary from 12 to 18.5 kt.

TABLE 2

YIELD ESTIMATES FROM CANISTER RECORD - From Reference 1

Reference	Estimated Little Boy Yield (kt)
Penney (1946)	17.4
Hirschfelder and Magee (1945)	12.0
Reines (1952)	18.5 $\pm$ 5
Brode (1964)	14.0 $\pm$ 3
Caudle (1965)	15.2 $\pm$ 2
Auxier (1977)	13.0 $\pm$ 2
Malik (1976)	15.8 $\pm$ 2
Malik (1980)	17.0 $\pm$ 4

Recently, some new meteoroglogical data have come to light which make a new analysis of the canister pressure trace appropriate. These new data consist of atmospheric pressure and temperature profiles recorded at Tokyo on the day in question, 6 August 1945. General meteorological conditions at the time would indicate that these profiles can be applied to other locations in Japan with reasonable accuracy.² The data have been compiled into a "recommended Hiroshima atmosphere" by Reed.³

In addition, the pressure trace has been looked at again and an "enhanced" record has been produced from the data points.

Figure 1. Original Interpretation of the Hiroshima Canister Record

The new interpretation (Figure 2) seeks to compensate for gage response effects. It was also provided by Reed.⁴

With the new atmospheric data to describe conditions through which the shock wave from the Hiroshima detonation must have propagated on its path from the detonation point to the recording device in the canister, with current best estimates about the relative positions of the canister and the detonation,¹ and with a modern state-of-the-art hydrocode (SAP/HULL), a new series of one- and two-dimensional calculations has been completed which tends to substantiate a yield near 16 kt (our best estimate is 16.6 ± 0.3 kt). Our calculations also point to a higher aircraft drop altitude, near 35,500 ft, than the 30-32 thousand feet indicated in mission documents.⁵ Malik and Reed³ have previously indicated that higher drop altitudes may be more consistent with available information.

This report describes the calculations and analysis performed, and presents results which lead to the above conclusions. The first step was to prepare the provided atmosphere in a form which could be utilized by the hydrocode. Next, our one-dimensional hydrocode had to be modified so that an input propagation angle described radial distance from the burst in relation to atmospheric temperature and density gradients. A series of one-dimensional calculations was run and, as the final step in Phase 1, comparisons of the experimental waveform (incident wave only) were made with calculational results to determine the best value of yield and drop height.

Phase 2 was an attempt, using the yield determined in Phase 1, to match the reflected wave portion of the canister record as well as the incident wave portion. This was accomplished by performing a two-dimensional run with the hydrocode HULL covering the time when the shock wave was reflected from the ground. A cut across the two-dimensional mesh at the

Figure 2. Reed "Enhanced" Version of the Hiroshima Canister Record

appropriate propagation angle was then made and the hydrodynamic parameters read were inserted into a one-dimensional mesh for propagation to the canister location. This procedure is described in more detail in Section IV.

II. STABILIZATION OF THE HIROSHIMA ATMOSPHERE

In performing the calculations for this project, we wanted to use the most accurate atmospheric information available. We felt this would be important because the shock wave propagated for quite a distance through the atmosphere before it was measured at the canister, and atmospheric variations might well modify the wave profile during this propagation.

The atmospheric information was taken from Reference 3. It is an average from seven radiosonde measurements made over southern Japan on 6 August 1945. The radiosonde measurements were made at Fukuoka, Tokyo and Toyohashi, but the Hiroshima surface temperature was used. The pressure and temperature values are given as functions of altitude in Table 3.

TABLE 3

ALTITUDE VARIATION OF ATMOSPHERIC TEMPERATURE AND PRESSURE

Altitude		(a) Hiroshima Recommended		(b) Stabilized for Hydrocodes	
ft	m	p (mb)	T°C	p (mb)	T°C
108	33	1013	27.0	1013.00	27.0
3301	1006	907	23.0	906.16	23.0
6834	2083	800	18.9	799.66	18.9
10285	3135	707	14.3	706.47	14.3
13576	4138	627	8.6	626.43	8.6
17228	5251	547	1.6	546.54	1.6
19938	6077	493	-3.7	492.80	-3.7
23629	7202	427	-9.9	426.72	-9.9
26995	8228	373	-16.0	373.07	-16.0
29790	9080	333	-21.3	332.86	-21.3
33848	10317	280	-31.1	280.66	-31.1
42650	13000			185.18	-74.6
54133	16500			100.85	-80.1

In order to provide an atmosphere which is compatible with the hydrocode, it is necessary to "stabilize" the tabular values given. This ensures that undisturbed air in the calculational mesh will not start to move under the influence of gravity alone prior to shock arrival. The stabilization procedure, due to Brackbill, et al,⁶ consists of adjusting the tabular temperature and pressure values to satisfy the hydrostatic stability equation:

$$\frac{d[p(z)]}{dz} = -\rho(z)g(z)$$

where $g(z)$ = the acceleration due to gravity at altitude z

$\rho(z)$ = the density at altitude z

and $p(z)$ = the pressure at altitude z .

It is assumed that the atmosphere behaves like an ideal gas:

$$\rho(z) = \frac{M(z)p(z)}{RT(z)}$$

where R = the universal gas constant

$T(z)$ = absolute temperature at altitude z

and $M(z)$ = molecular weight of air at altitude z .

Additionally, a linear molecular scale temperature variation with altitude is assumed within each of a number of "altitude groups". The variation takes the form:

$$T_m(z) = T_m(z_i) + (L_i)(z - z_i)$$

where z_i = the base altitude of the i -th altitude group

L_i = the molecular scale temperature gradient over the i -th altitude group

$$= \frac{T_m(z_{i+1}) - T_m(z_i)}{z_{i+1} - z_i}$$

$T_m(z)$ is the molecular scale temperature at altitude z defined by:

$$T_m(z) = \frac{M_o}{M(z)} T(z)$$

where M_o = molecular weight of air at sea level.

Simultaneous solution of these equations provided a balanced atmosphere with pressure values which differed from the original ones by not more than one percent. The adjusted values are also given in Table 3. Temperature values were not changed by this process.

The radiosonde data only goes up to 33.8 kft. Because we wanted to be able to run calculations above that altitude, it was necessary to add high altitude values from an existing atmosphere. The standard tropical atmosphere was used, and a fictitious data point was added between the highest radiosonde point and the next higher standard tropical point to assure a smooth transition. Two points above 33.8 kft are also given in Table 3.

III. PHASE I: INCIDENT WAVE CALCULATIONS

A. Initial Analysis

Before the calculations were begun, some initial analysis was required. It was necessary to determine an approximate angle for propagation of the shock wave through the atmosphere. Also, we wanted to know what values of slant range (distance from bomb to canister) and arrival time (time from detonation to beginning of signal) were reasonable in order to set up the calculation correctly.

To obtain this information, we performed a series of hand calculations similar to those done by Caudle⁷. The objective was to define a "slant-range versus arrival time" curve which is consistent with the best available assumptions about the physical configuration. We considered the altitude of the aircraft to be a variable, and also evaluated two different wind conditions (a 17 mph cross wind⁵ and a 35 mph head wind⁷).

For arrival time, because the total time from bomb drop to signal arrival and the height of burst are known, we can calculate a time of fall for the bomb and subtract to obtain propagation time. Obviously, for higher drop altitudes, a longer fall time will be required and less time will be available for propagation of the signal to the canister. The arrival time calculations are outlined in Table 4.

In order to obtain horizontal and vertical displacement information, and hence slant range and propagation angle between bomb burst point and canister position at signal arrival, we used what we considered to be the best available information to calculate bomb and canister relative positions. These calculations are outlined in Tables 5 and 6, with notations indicating sources for the parameters used. Finally, the range and propagation angle values obtained are given in Table 7.

TABLE 4

CALCULATION OF ALLOWABLE SIGNAL PROPAGATION TIMES

Assumptions:	Height of Burst	-	1903 feet (Reference 1)		
	Time of "Bomb Away"	-	0 second (Reference point)		
	Time of Canister Drop	-	1 second (Reference 4)		
	Arrival Time of Signal	-	80.6 seconds (Reference 1)		
	Elevation of Ground Zero	-	10 feet		
Aircraft Drop Altitude (ft)	28,000	30,000	32,000	34,000	36,000
Distance of Fall (ft) (Drop Altitude-HOB-Elevation of GZ)	26,090	28,090	30,090	32,090	34,090
Free-Fall Time (sec)	40.27	41.79	43.25	44.67	46.04
(t = $\sqrt{2S/g}$)					
g = 32.17 ft/sec					
S = Distance of fall)					
<p>Actual fall times will be somewhat longer than these because of air drag. We assume the time added to free-fall time by air drag is proportional to the square of the total time of fall. A point given by Malik¹⁵ from "Site M" test data defines the proportionality constants, and times are determined from solution of a quadratic equation. The Site M fall time for 28,065 feet is 43.11 seconds. The free-fall time for this distance would be 41.77 seconds.</p>					
Actual Fall Time (sec) (AFT)	41.51	43.13	44.69	46.21	47.68
Signal Propagation Time (sec) (80.6 sec-AFT)	39.1	37.5	35.9	34.4	32.9

TABLE 5

CALCULATION OF VERTICAL DISTANCE BETWEEN BOMB AND CANISTER

Drop Altitude	Vertical Fall of		Vertical Distance Between Bomb at Detonation and Canister at Signal (VFB-VFC)
	Bomb (VFB)	Canister (VFC)	
28,000	26,090	1270 ft for all cases. This assumes 1 second free fall plus 78.6 seconds parachute fall at 16 ft/sec (Ref. 1) ↓	24,820
30,000	28,090		26,820
32,000	30,090		28,820
34,000	32,090		30,820
36,000	34,090		32,820

TABLE 6

CALCULATION OF HORIZONTAL DISTANCE BETWEEN BOMB AND CANISTER
FOR TWO DIFFERENT WIND SPEED CONDITIONS

Constant Indicated Air Speed - 196 mph (References 5 and 7)

True Air Speed - 328 mph (Reference 1)

Wind Speed - Two cases are considered: a 17 mph (25 ft/sec) cross wind
a 35 mph (51 ft/sec) head wind

Ground Speed: Cross Wind Case - 328 mph (481 ft/sec) down course
17 mph (25 ft/sec) cross course

Head Wind Case - 293 mph (430 ft/sec) down course
No cross course component

Horizontal Travel of Canister = offset at drop time + (ground speed · free-fall time)
+ (wind speed · time from chute deployment
to shock arrival)

Offset at drop time [assume canister aircraft was 300 feet behind bomb aircraft (Reference 1),
and canister was dropped one second after "bomb away" (Reference 4)]

Cross Wind Case - 481 ft - 300 ft = 181 ft down range
25 ft cross range

Head Wind Case - 430 ft - 300 ft = 130 ft down range

Total Horizontal Distance of Canister from Bomb Drop Point

Cross Wind Case - 181 ft + (481 ft/sec · 1 sec) = 662 ft down range
25 ft + (25 ft/sec · 1 sec) + (25 ft/sec · 78.6 sec)
= -2015 ft cross range

Head Wind Case - 130 ft + (430 ft/sec · 1 sec) - (51 ft/sec · 78.6 sec)
= 3449 ft down range

Horizontal Travel of Bomb = (ground speed · fall time) - ("Trail angle" · vertical travel)

The trail angle is from practice bombing tables. We assume that the 53 mil value from
Reference 5 is sufficiently slowly varying so that it can be used for the other drop
altitudes considered here.

Cross Wind Case - (481 ft/sec · fall time) - (0.053 · vertical fall) for down range travel
(25 ft/sec · fall time) for cross range travel

Head Wind Case - (430 ft/sec · fall time) - (0.053 · vertical fall)

TABLE 6 (Continued)

CALCULATION OF HORIZONTAL DISTANCE BETWEEN BOMB AND CANISTER
FOR TWO DIFFERENT WIND SPEED CONDITIONS

The following table of values is compiled:

Drop Altitude	28,000	30,000	32,000	34,000	36,000
Fall Time (from Table 4)	41.51	43.13	44.69	46.21	47.68
Vertical Fall Distance (from Table 5)	26,090	28,090	30,090	32,090	34,090
Horizontal Travel of Bomb:					
Cross Wind Case:	18,580	19,260	19,900	20,530	21,130
Down Range					
Cross Range	1,040	1,080	1,120	1,160	1,190
Head Wind Case:	16,470	17,060	17,620	18,170	18,700
Horizontal Distance Between Bomb at Detonation and Canister at Signal Arrival:					
Cross Wind Case:					
Down Range	17,920	18,600	19,240	19,870	20,470
Cross Range	980	940	900	860	830
Combined Horiz.	17,950	18,620	19,260	19,890	20,490
Head Wind Case:	19,920	20,510	21,070	21,620	22,150

TABLE 7

SLANT RANGE AND ANGLES OF PROPAGATION FOR THE
DIFFERENT DROP ALTITUDE AND WIND SPEED CONDITIONS

Drop Altitude	Range Calculations		Angle of Propagation=arc tan (vertical/horizontal distance)	
	Cross Wind	Head Wind	Cross Wind	Head Wind
28,000	30,630	31,830	54.1	51.3
30,000	32,650	33,760	55.2	52.6
32,000	34,660	35,700	56.2	53.8
34,000	36,680	37,650	57.2	55.0
36 000	38,690	39,600	58.0	56.0

Note: Malik (Ref. 1) has made a similar calculation using a drop altitude of 32,700 ft. He obtains a separation slant range of 35,700 ft and a propagation angle of 55.7 deg. This information was not obtained until after the first draft of this report had been completed.

As a result of these computations, we chose 55 deg as an appropriate propagation angle for the one-dimensional Phase 1 calculations. Later, when it appeared from initial results that the higher drop altitudes were provided the most credible waveform comparisons, we also ran some one-dimensional calculations at 60 deg propagation angles. A final one-dimensional calculation was run at 57 deg.

B. CALCULATIONS

The Phase 1 calculations were run using SAP (Spherical Air Puff), S-CUBED's version of the one-dimensional Eulerian, spherical-symmetry hydrocode originally developed at the Air Force Weapons Laboratory (AFWL)⁸. A slight modification was made to the code to accommodate the requirement that the atmosphere be adjusted for a particular propagation angle. This was easily done by modifying the parameter governing altitude at which the atmospheric subroutines are called to equal range times the sine of the angle plus height of burst and ground elevation. Six one-dimensional calculations were run. Yields and propagation angles for these are specified in Table 8.

TABLE 8
MATRIX OF ONE-DIMENSIONAL CALCULATIONS

Calculation Number	Yield (kt)	Propagation Angle (deg)
1	12	55
2	17	55
3	22	55
4	20	55
5	16.5	60
6	16.7	57

Zone size for each of these calculations was one meter. Input was provided from a previously completed SPUTTER run at approximately 0.5 sec. SPUTTER^{9,10,11} is a one-dimensional radiation hydrocode, the results of which are commonly used to initiate HULL and SAP runs. SPUTTER results, obtained about 10 years ago and stored on tape, include a very detailed treatment of radiation transport and the breakdown of air and bomb debris. The SPUTTER calculation used was for a 1 kt burst at sea level, and the information was scaled to the appropriate yield and altitude. SPUTTER results at times between 0.18 and 0.23 sec were chosen, depending on yield, which would scale most closely to the arbitrarily selected 0.5 sec start time. Actual start times were between 0.507 and 0.529 sec.

Each point in the SPUTTER mesh was carefully scaled to its appropriate altitude along the oblique propagation path (the altitude corresponding to range r is equal to the 1900-ft height of burst plus the 10-ft ground elevation plus $r \sin \theta$, where θ is the propagation angle) in addition to the normal scaling for the yield difference.

The SAP hydrocode was run from 0.5 sec out to 42 sec in each case. "Stations", or points at which pressure could be monitored as a function of time, were placed in the mesh every 330 ft between ranges of 33.79 kft and 46.92 kft. The overpressure data from these stations were plotted, as were the time integrated overpressure-impulse data.

C. ANALYSIS OF PHASE 1 CALCULATIONS

The station plots prepared from the six one-dimensional calculations discussed in the last section were compared with the digitized version of the "enhanced" experimental waveform given in Figure 2. For these comparisons, arrival times were disregarded and the midpoints of the first major excursions from zero were matched in time. A similar comparison was made between the integrated records. Obviously, only the first pulse, or incident waveform, appears in these one-dimensional calculation results. Consideration to the reflected pulse will be given by the two-dimensional calculations of the next section.

The first comparison plots are given in Figures 3 and 4. These waveforms are from the 12-kt calculation at the lowest range for which comparisons were made, 33.8 kft. Note that, although the overpressure peaks of the first pulse are in fair agreement, the positive phase duration from the calculation is too short and the impulse is too low. We could improve the impulse comparison by checking a point closer to the burst, but at closer ranges the positive phase duration would be even shorter. At larger ranges, as in Figures 5 and 6, the duration is better, but the peak overpressure and impulse are much too low. Therefore, we conclude that the experimental waveform cannot be replicated with a 12-kt burst.

Similar problems are encountered with the 22 kt burst. We can almost match the phase duration at the closest station (Figures 7 and 8), but the peak values are too high. If we

OVERPRESSURE

S-CUBED HIROSHIMA YIELD ESTIMATE, 12KT YIELD, 55 DEG ANGLE

S-CUBED SAP SECTION PLOT

Figure 3. Canister Record Compared with 12 kt Calculation at Range 33.8 kft

OVERPRESSURE PULSE

S-CUBED HIROSHIMA YIELD ESTIMATE, 12KT YIELD, 55 DEG ANGLE

S-CUBED SLP SECTION 10.1

Figure 4. Impulse Compared with 12 kt Calculation at Range 33.8 kft

OVERPRESSURE

S-CUBED HIROSHIMA YIELD ESTIMATE, 12KT YIELD, 55 DEG ANGLE

S-CUBED SAP STATION 1

Figure 5. Canister Record Compared with 12 kt Calculation at Range 45.3 kft

OVERPRESSURE PULSE

S-CUBED HIPOSHIMA YIELD ESTIMATE, 12KT YIELD, 55 DEG ANGLE

S-CUBED S-P 55 DEG ANGLE

Figure 6. Impulse Compared with 12 kt Calculation
at Range 45.3 kft

OVERPRESSURE

S-CUBED HIROSHIMA YIELD ESTIMATE, 22KT YIELD, 55 DEG ANGLE

S-CUBED SAP STATION PLOT

Figure 7. Canister Record Compared with 22 kt Calculation at Range 33.8 kft

OVERPRESSURE II PULSE

S-CUBED HIROSHIMA YIELD ESTIMATE, 22KT YIELD, 55 DEG ANGLE

S-CUBED SAP STATION PLOT

Figure 8. Impulse Compared with 22 kt Calculation
at Range 33.8 kft

match the overpressure (Figures 9 and 10) or the impulse (Figures 11 and 12), the other parameters are off, and we have to conclude that the 22-kt yield is too high. The 20-kt calculation also proved to have too large a yield for the same reasons (Figures 13 through 16).

With a yield of 17 kt, we begin to converge on a waveform that is in good agreement with the measurement in the positive phase for all three of the relevant parameters. Results from this calculation are shown in Figures 17 through 20. Note that the calculated overpressure peak is a little bit lower than the experimental peak, but this is caused by shock smearing in the hydrocode. The integrated records show excellent agreement through the end of the positive phase, which corresponds to the first peak on the impulse record. Note also that the calculated negative phase is deeper than that recorded in the region between the first and second peaks. This phenomenon was characteristic of all our calculations, and we have no explanation except to conjecture that the gage response may not have been linear in the negative overpressure region.

In an effort to pin down the yield a little more closely, and to determine whether the conclusions being reached were consistent with the best available information about the physical configuration, we used the slant range and arrival time data obtained in Section III-A to plot Figure 21. The negative sloping lines in the figure represent reasonable values for various drop altitudes and wind conditions. The range arrival time curves from the calculations, which have positive slopes, should then cross these physical configuration lines, providing a good indication of the region in which all conditions are met.

The stations with the "best" waveforms from the 17 kt calculation are shown in Figure 21. Because these points

OVERPRESSURE

S-CUBED HIROSHIMA YIELD ESTIMATE, 20Kt YIELD, 55 DEG ANGLE

S-CUBED SAP STATION PLOT

Figure 9. Canister Record Compared with 22 kt Calculation at Range 37.4 kft

OVERPRESSURE IMPULSE

S-CUBED HIROSHIMA YIELD ESTIMATE, 22KT YIELD, 5° DEG. ANGLE

S-CUBED SAP STATION PLOT

Figure 10. Impulse Compared with 22KT Calculation
at Range 37.4 Kft

OVERPRESSURE

S-CUBED HIROSHIMA YIELD ESTIMATE, 22KT YIELD, 55 DEG ANGLE

S-CUBED SAP STATION PLOT

Figure 11. Canister Record Compared with 22 kt Calculation
at Range 43.0 kft

C FRAPESCOPE IMPULSE

S-CUBED HIROSHIMA YIELD ESTIMATE, 20KT YIELD, 65 DEG ALTITUDE

S-CUBED SAP STATION PLOT

Figure 12. Impulse Compared with 22 kt Calculation at Range 43.0 kft

OVERPRESSURE

S-CUBED HIROSHIMA YIELD ESTIMATE, 20 KT, 55 DEG, 1M CELLS

S-CUBED SAP STATION PLOT

Figure 13. Canister Record Compared with 20 kt Calculation at Range 33.8 kft

OVERPRESSURE IMPULSE

S-CUBED HIROSHIMA YIELD ESTIMATE, 20 KT, 55 DEG , 1M CELLS

S-CUBED SAP STATION PLOT

Figure 14. Impulse Compared with 20 kt Calculation
at Range 33.8 kft

OVERPRESSURE

S-CUBED HIROSHIMA YIELD ESTIMATE, 20 KT, 55 DEG, 11 CELLS

S-CUBED SAP STATION PLOT

Figure 15. Canister Record Compared with 20 kt
Calculation at Range 40.0 kft

OVERPRESSURE IMPULSE

S-CUBED

HIROSHIMA YIELD ESTIMATE, 20 KT, 55 DEG, 1M CELLS

S-CUBED SAP STATION PLOT

Figure 16. Impulse Compared with 20 kt Calculation
at Range 40.0 kft

OVERPRESSURE

S-CUBED

HIROSHIMA YIELD ESTIMATE, 17 KT, 55 DEG , 1M CELLS

S-CUBED SAP STATION PLOT

Figure 17. Canister Record Compared with 17 kt
Calculation at Range 38.7 kft

OVERPRESSURE IMPULSE

S-CUBED

HIROSHIMA YIELD ESTIMATE, 17 KT, 55 DEG , 1M CELLS

S-CUBED SAP STATION PLOT

Figure 18. Impulse Compared with 17 kt Calculation
at Range 38.7 kft

OVERPRESSURE

S-CUBED

HIROSHIMA YIELD ESTIMATE, 17 KT, 55 DEG , 1M CELLS

S-CUBED

Figure 19. Canister Record Compared with 17 kt Calculation at Range 39.0 kft

OVERPRESSURE IMPULSE

S-CUBED

HIROSHIMA YIELD ESTIMATE, 17 KT, 55 DEG , 1M CELLS

S-CUBED SATURATION PLOT

Figure 20. Impulse Compared with 17 kt Calculation
at Range 39.0 kft

Figure 21. Arrival Time vs. Slant Range: "Physically Reasonable" and Calculated Values

indicated a crossing consistent with higher drop altitudes, we decided to do the fifth calculation in the one-dimensional series at a 60-deg propagation angle, which was appropriate for these higher altitudes. We also decreased the yield to 16.5 kt in order to bring the point where the best waveform was calculated down in range and arrival time. The results of this calculation are shown in Figures 22 through 25 and also plotted in Figure 21. Based on this one-dimensional series, and taking into account the uncertainties in wind speed and aircraft positioning, we estimate the yield to have been 16.6 ± 0.3 kt and the drop altitude to have been 34.4 ± 0.2 kft.

The final one-dimensional calculation was done after it was discovered that 1,800 ft, rather than 1,910 ft, had been used for the altitude of burst in the earlier calculations. This final calculation was for a yield of 16.7 kt propagating at a 57-deg angle. The results are shown in Figures 26 and 27. Range/arrival time data is included in Figure 21. The results from this calculation provide an equally good fit to the data, and do not significantly change the conclusions reached in the previous paragraph.

OVERPRESSURE

S-CUBED HIROSHIMA YIELD ESTIMATE, 16.5 KT, 60 DEG , 1M CELLS

S-CUBED SAP STATION PLOT

Figure 22. Canister Record Compared with 16.5 kt
Calculation at Range 37.7 kft

OVERPRESSURE IMPULSE

S-CUBED HIROSHIMA YIELD ESTIMATE, 16.5 KT, 60 DEG , 1M CELLS

S-CUBED SAP STATION PLOT

Figure 23. Impulse Compared with 16.5 kt Calculation
at Range 37.7 kft

OVERPRESSURE

S-CUBED HIROSHIMA YIELD ESTIMATE, 16.5 KT, 60 DEG , 1M CELLS

S-CUBED SAP STATION PLOT

Figure 24. Canister Record Compared with 16.5 kt Calculation at Range 38.1 kft

OVERPRESSURE IMPULSE

S-CUBED HIROSHIMA YIELD ESTIMATE, 16.5 KT, 60 DEG , 1M CELLS

S-CUBED SAP STATION PLOT

Figure 25. Impulse Compared with 16.5 kt Calculation
at Range 38.1 kft

[illegible]

50

OVERPRESSURE IMPULSE

S-CUBED HIROSHIMA YIELD ESTIMATE, 13.6 KT YIELD, 57 DEG ANGLE

S-CUBED SAP STATION PLOT

Figure 27. Impulse Compared with 16.7 kt Calculation
at Range 38.4 kft

IV. PHASE 2: REFLECTED WAVE CALCULATIONS

A. CALCULATIONS

The program of one-dimensional calculations outlined in the previous section dealt only with the incident wave which traveled directly from the burst point to the canister. The second shock pulse appearing on the record, which is the incident wave after reflection from the ground, is also of interest. This reflected wave cannot be handled with a simple one-dimensional calculation because it moves always into a medium which has previously been disturbed by the passage of the incident wave. Propagation characteristics of the reflected pulse depend on its position with respect to that of the incident pulse.

To obtain a calculated reflected pulse record which is a reasonable simulation of the actual physical situation, a two-dimensional calculation was performed at a yield of 16.5 kt. This calculation involved a three step process. In the first step, SPUTTER data was used as before to provide input to a one-dimensional SAP calculation. In this case the SPUTTER input was picked up much earlier than for the Phase 1 calculations, at a time which scaled to 0.022 sec. SAP was then run out to the previous start time of 0.5 sec.

The reason for this change in starting procedure was that we were concerned that atmospheric density gradients between HOB and ground would affect the downward propagation of the wave prior to reflection. In order to check this, we ran this early-time SAP both horizontally (no atmospheric gradient) and vertically (maximum atmospheric gradient). The results proved to be identical within about 2 percent as shown in Figures 28 and 29, so we ultimately used the horizontal SAP as input to the two dimensional portion of the calculation.

HIROSHIMA SERIES-16.5KT, 60CM CELLS, 0.0 DEG S

OVERPRESSURE VS RADIUS

PROB= 0.000 TIME 0.5 SEC

Figure 28. Range Plot at 0.5 sec for Horizontal One-Dimensional Calculation

HIROSHIMA SERIES-16.5KT, 60CM CELLS, 270 DEG S

OVERPRESSURE VS RADIUS

PROB= 165.270 TIME 0.5 SEC

Figure 29. Range Plot at 0.5 sec. for Vertical One-Dimensional Calculation

The SAP results were also checked against the direct SPUTTER input as used in Phase 1, and again the two were found to be identical within 2 percent. Mesh size for these early-time one dimensional calculations was 60 cm.

The second step was to run our two-dimensional hydro-code, HULL, from 0.5 sec to 5 sec. At the beginning of the two dimensional portion, the HULL grid with SAP input was as shown in Figures 30 and 31. The HULL calculation was cylindrically symmetric with 5.5-m zones in both the horizontal and vertical directions. Note that, at this time, the shock and fireball are perfectly spherical except for slight differences caused by the atmospheric gradient. The shock radius was 472 m (1,550 ft) at the beginning, well short of the distance from burst height to ground.

The HULL calculation ran with a radiative cooling algorithm and with the ground surface and central axis (bottom and left hand boundaries) treated as perfectly reflective. The top and right hand boundaries were moved out as required whenever the shock system approached them. In this process, called a rezone, all of the cells are expanded in size by 5 percent to accommodate the expanding disturbance. Mass, momentum and total energy are conserved in the rezone process, which is triggered when a significant velocity is detected at either the top or right boundaries. The new portion of the grid is filled with air at ambient atmospheric conditions.

At a time of 5 sec, the HULL phase of the calculation was completed. The shock configuration at this time is shown in Figure 32. This configuration shows all the characteristics of a classic low altitude burst: Mach stem, reflected wave, and fireball rise. Note that, near the vertical axis, the reflected wave is "washed out" because of low material densities and high sound speeds in the fireball region.

Figure 30. Pressure and Relative Pressure Contours at Beginning of Two-Dimensional Calculation

Figure 31. Energy Contours and Vector Velocities at Beginning of Two-Dimensional Calculations

PRESSURE

RELATIVE PRESSURE

Figure 32. Pressure and Relative Pressure Contours at End of Two-Dimensional Calculation

For the third step of the calculation, we transferred data from a one-dimensional cut (or line) across the HULL mesh back into SAP and continued with a one dimensional calculation out to the measurement point. The configuration is illustrated in Figure 33. In this figure, the path of the incident wave from burst to canister is shown by the line labeled I; that of the reflected wave is shown by line R. We had originally planned to assume that, for purposes of this calculation, I, G, and R are parallel to each other. We thought that, reading data along line G from the HULL mesh into SAP, we would have a sufficiently accurate set of initial conditions for one dimensional propagation out to the canister.

The planned procedure proved to be too simplistic for two reasons. First, as shown in Figure 32, the reflected wave along line G is not as strong as along its true path, line R, because of passage of line G through the edge of the fireball. (The three lines in the figure are drawn at 60 deg, which is the propagation angle used for the second-phase one dimensional calculation.) This degradation of amplitude will be preserved as the pulse propagates out to the canister.

The second problem with the planned procedure is a little more subtle. Line G cuts across the incident wavefront at an angle; it deviates from a perpendicular to the wavefront by almost 10 deg. This means that a cut along G would be elongated by about 2 percent, and the positive phase also would be elongated. A similar argument can be made concerning the duration of the reflected wave.

Although these differences seem trivial (and indeed may be), durations are very important in this kind of analysis and we wanted to be very sure that our initial conditions were as accurate as we could make them. One solution, of course, would have been to run the two-dimensional calculation to a later time, say 10 or 15 sec, before transferring to one dimension.

Figure 33. Calculational Technique for Combined Incident/Reflected Wave

The G-cut would then have been more nearly perpendicular to the propagating wavefronts. We decided against this procedure, however, because the expanding mesh required that increasingly large zone sizes be used. We did not want to lose resolution because of excessive numerical smearing. The zone size at 5 sec was about 12 m.

Finally, we adopted a "cut-and-paste" procedure for providing input to the SAP propagation calculation. This procedure, accomplished with a routine called CALVAL written especially for the purpose, operated as follows. First, hydrodynamic variables needed were obtained from the HULL output at 5 sec along the lines I and R. A four-point Lagrangian interpolation was performed within the HULL mesh to obtain density, specific internal energy, and velocity (in the 60 deg direction) at points every 5 m along the lines. Values of pressure were also obtained at these points from the air equation-of-state. The pressure, energy and density values were then converted to relative quantities by dividing them by ambient atmospheric values at corresponding points.

Second, CALVAL located the point on I which indicated first arrival of the shock. This point was given a radius and altitude for the one-dimensional SAP input corresponding to the point at which line G crosses the incident shock. Thus, values read at point A in Figure 33 were effectively transferred to point B. Points along I within the incident-wave region were also transferred to corresponding points along G, without change in the length scale (distance between points).

In a similar manner, the point at C was located and transferred to D (actually, the deepest point of the negative phase along R, which is just prior to arrival of the reflected shock, was used). Values along R between C and the ground were moved to corresponding positions along G. For the short

left-over distance, between where values from R ended and the origin, hydrodynamic variables along line G were retained.

The results of the CALVAL cut-and-paste procedure are shown in Figures 34 through 37. As can be seen, the slight discontinuity resulting from joining the incident and reflected waveforms at D is barely noticeable. As the final step, the combined set of inputs is converted back to absolute values through multiplication by appropriate ambient atmospheric values for altitudes along line G. The CALVAL subroutine which performed this transfer procedure is included in the appendix.

To complete the Phase 2 portion of the calculation, SAP was run from 5 sec out to 43 sec with the input generated by CALVAL. Because input was generated at 5-m intervals, the SAP calculation was begun with 5-m zones. Zone-widths were gradually decreased as the radial dimension increased so that the majority of the wave propagation took place in 1-m cells. For this part of the calculation, ambient values from the Hiroshima atmosphere, described in Section II, were used for zones ahead of the incident shock. The atmospheric gradients were encountered at a propagation angle equivalent to 60 deg. As before, stations were placed at radial distances from 33.79 to 44.62 kft, every 330 ft (10.3 to 13.6 km, every 100 m) in order to monitor overpressure time at a fixed point.

B. PHASE 2 ANALYSIS

Comparison of waveforms generated by the Phase 2 calculation with the experimental waveform was made in the same manner as in Section III. A few of the results are shown in Figures 38 through 43. The radius values (shown on these plots in centimeters) are measured from the ground for this set of plots rather than from the center of the burst. To compare with the slant ranges of Section III, a constant equal

REL PRESSURE

HIROSHIMA SERIES-16.5KT, COMBINED CUT AT YGND

S-CUBED SAP HYDRO PLOTS

Figure 34. Relative Pressure Composite Profile Used as Input to Final One-Dimensional Calculation

VELOCITY

HIROSHIMA SERIES-16.5KT, COMBINED CUT AT YGND

S-CUBED SAP HYDRO PLOTS

Figure 35. Velocity Composite Profile Used as Input to Final One-Dimensional Calculation

REL DENSITY

HIROSHIMA SERIES-16.5KT, COMBINED CUT AT YGND

S-CUBED SAP HYDRO PLOTS

Figure 36. Relative Density Composite Profile Used as Input to Final One-Dimensional Calculation

TEMPERATURE

HIROSHIMA SERIES-16.5KT, COMBINED CUT AT YGND

S-CUBED SAP HYDRO PLOTS

Figure 37. Temperature Composite Profile Used as Input to Final One-Dimensional Calculation

OVERPRESSURE

S-CUBED HIROSHIMA SERIES- COMBINED CUT-16.5KT,60DEG, 1M CELLS

S-CUBED SAP STATION PLOT

Figure 38. Canister Record Compared with 16.5 kt Combined Incident and Reflected Wave Calculations at Range 39.4 kft

OVERPRESSURE IMPULSE

S-CUBED HIROSHIMA SERIES— COMBINED CUT—16.5KT,60DEG, 1M CELLS

S-CUBED SAP STATION PLOT

Figure 39. Impulse Compared with 16.5 kt Combined
Calculation at Range 39.4 kft

OVERPRESSURE

S-CUBED HIROSHIMA SERIES- COMBINED CUT-16.5KT,60DEG, 1M CELLS

S-CUBED SAP STATION PLOT

Figure 40. Canister Record Compared with 16.5 kt Combined Calculation at Range 39.7 kft

OVERPRESSURE IMPULSE

S-CUBED HIROSHIMA SERIES- COMBINED CUT-16.5KT,60DEG, 1M CELLS

S-CUBED SAP STATION PLOT

Figure 41. Impulse Compared with 16.5 kt Combined Calculation at Range 39.7 kft

OVERPRESSURE

S-CUBED HIROSHIMA SERIES- COMBINED CUT-16.5KT,60DEG, 1M CELLS

S-CUBED SAP STATION PLOT

Figure 42. Canister Record Compared with 16.5 kt combined Calculation at Range 40.0 kft

OVERPRESSURE IMPULSE

S-CUBED HIROSHIMA SERIES- COMBINED CUT-16.5KT,60DEG, 1M CELLS

S-CUBED SAP STATION PLOT

Figure 43. Impulse Compared with 16.5 kt Combined Calculation at Range 40.0 kft

to $1800^* \times \cos 60 = 1560$ ft must be subtracted from the given radial values.

The stations choosen for comparison in the figures have their arrival times versus slant ranges plotted in Figure 21. These station data fall near the lines plotted from the physical configuration in the same way that the Phase 1 calculations do, but it is not really clear that these stations provide the best match. The incident and reflected wave impulses, discounting the offset introduced by the large negative phase, seem to match better a little further out (Figures 44 and 45). This station corresponds to a slant range of 40.76 kft, which is probably not credible.

We have checked the inputs to the Phase 1 and Phase 2 calculations at 0.5 sec and they are the same. We have also compared the inputs at 5 sec, as shown in Figures 46 and 47, and seen only seemingly inconsequential differences between the incident pulse waveforms. Therefore the difference in range at which the Phase 1 and Phase 2 impulses for the incident wave match with experimental data cannot now be explained. Apparently there is a difference in the two calculations of which we are not aware. Additional investigation would be needed to pin-point the difference.

In a qualitative sense, the comparisons between the experimental data and the Phase 2 calculation are not bad. In Figure 38, the amplitudes and phase durations of both pulses seem to be well matched. The calculated impulse is a little high for the first pulse and a little low for the second. The

*The use of 1800 ft instead of 1900 ft for HOB in Phase 2 was an inadvertant error, not discovered until the calculation was completed. We believe that this error, although possibly significant for reflected wave detail, has little effect on the qualitative analysis made in this section.

OVERPRESSURE

S-CUBED HIROSHIMA SERIES- COMBINED CUT-16.5KT,60DEG, 1M CELLS

S-CUBED SAP STATION PLOT

Figure 44. Canister Record Compared with 16.5 kt Combined Calculation at Range 42.3 kft

OVERPRESSURE IMPULSE

S-CUBED HIROSHIMA SERIES- COMBINED CUT-16.5KT,60DEG, 1M CELLS

S-CUBED SAP STATION PLOT

Figure 45. Impulse Compared with 16.5 kt Combined Calculation at Range 42.3 kft

REL PRESSURE

HIROSHIMA SERIES-16.5KT, COMBINED CUT AT YGND

S-CUBED SAP HYDRO PLOTS

Figure 46. Comparison of Relative Pressure Profiles Used as Input for Phase 1 and Phase 2 Calculations

VELOCITY

HIROSHIMA SERIES-16.5KT, COMBINED CUT AT YGND

S-CUBED SAP HYDRO PLOTS

Figure 47. Comparison of Velocity Profiles Used as Input for Phase 1 and Phase 2 Calculations

reason that the second pulse is low is that it is riding on a negative phase which is bigger than that measured. We discussed this point in Section III, and it pervades all the calculations. Also, the reflected pulse seems to arrive a little later than can be explained by numerical smearing. This may also be a consequence of the large negative phase, which is seen by the oncoming reflected pulse as an opposing flow.

V. CONCLUSIONS

The calculations planned in this program have been completed and appropriate analysis has been performed. The "new" Hiroshima atmosphere was obtained and stabilized. It was used in the performance of a series of one-dimensional calculations designed to lead, through the comparison of calculated waveforms with a single canister record, to an improved estimate of yield for the Hiroshima weapon. The analysis provides an estimate of 16.6 ± 0.3 kt for yield, which is within the range of previous estimates. The additional conclusion is reached that the drop altitude for the bomb was closer to 35,500 ft than to the 30,000 or 32,000 ft usually given. One recent estimate from temperature measurements (by Jack Reed, Reference 3) places the altitude at about 34,000 ft. We have not checked to see if these higher altitudes are within the capabilities of the aircraft.

The second phase of the calculational program, a combination of one- and two-dimensional segments designed to reproduce the reflected as well as the incident portion of the wave, was qualitatively successful but left some unanswered questions. Probably, additional tinkering would provide improvement in the results obtained from this type of calculation.

REFERENCES

1. Malik, John, "Yields of the Hiroshima and Nagasaki Explosions" in Reevaluations of Dosimetric Factors, Hiroshima and Nagasaki, CONF-810928(DE81026279), published by Technical Information Center, U.S. Department of Energy, 1982.
2. Kerr, G. D., Pace III, J. V. and Scott, Jr., W. H., "Tissue Kerma versus Distance Relationships for Initial Nuclear Radiation from the Atomic Devices Detonated over Hiroshima and Nagasaki", ORNL/TM-8727, June 1983.
3. Reed, J. W. (SNL), letter to John Malik (LANL), February 19, 1982.
4. Reed, J. W. (SNL), private communication, 1983.
5. Kerr, G. D. (ORNL), letter to John Malik (LANL), September 21, 1983.
6. Brackbill, J. U., Nawrocki, E. A. and Whitaker, W. A., "Atmospheric Models for Use in Hydrodynamic Computer Codes", AFWL-TR-67-75, Air Force Weapons Laboratory, August 1967.
7. Caudle, K. F., "Yield of the Hiroshima Weapon", NOL-TR-65-143, U.S. Naval Ordnance Laboratory, White Oak, MD, December 1965.
8. Whitaker, W. A., Nawrocki, E. A., Needham, C. E. and Troutman, W. W., "Theoretical Calculations of the Phenomenology of HE Detonations", AFWL-TR-66-141, Volume I, AFWL, Kirtland AFB, N.M., November 1966.
9. "Optical Interactions, The SPUTTER Program", RTD-TDR-63-3128, Air Force Weapons Laboratory, May 1964.
10. Sharp, A. L., "A Thermal Source Model from SPUTTER Calculations", AFWL-TR-72-49, Air Force Weapons Laboratory, Kirtland AFB, N.M., May 1964.
11. Roth, L. and Connell, R. I., "Utilization of SPUTTER Data", NTE-TN-83-03, Air Force Weapons Laboratory, February 1983.

APPENDIX

CALVAL Subroutine Used In Phase II

This subroutine transfers data along specified lines in a two-dimensional calculation to a "combined cut" for use in a one-dimensional calculation.


```

844      1.      subroutine calval (thull, chull, ygnd)
845      C*****
846      C*
847      C*          *****
848      C*          notes
849      C*          *****
850      C
851      C*      This subroutine fills the arrays required by the SAP code.
852      C*      The SAP code requires pressure, velocity, mass, and energy.
853      C*
854      C*****
855      C
856      C          *****
857      C          common blocks
858      C          *****
859      C
860      2.      integer shkcel,detcel,bdry
861      3.      common/far/x0,x(1000),rdw,prdw,detcel,shkcel,bdry(1)
862      4.      common /blank/      p(1000),u(1000),epg(1000),zm(1000),rho(1000),
863      ccs(1000),temp(1000)
864      5.      common /param/
865      1bursum,  c0,      cl,      angle,      bsum,      burnout,
866      2dstop,   dxmul,   eth,      euler,      head(8),  hob,
867      3imax,    jcsmax,  jpmax,    method,    nstat,    nvarpr,
868      4lbref,   nh,      csine,
869      5nzblk,   ptstop,  qmin,     radsum,   rate,     rez,
870      5sine,    thm,     umin,     visc,     yield
871      6.      integer head
872      7.      common/timcom/ t,dt,cycle,delt,dtmin,dtrad,stabf
873      8.      dimension z(100,2), iz(100,2)
874      9.      common /zzz/ zblk(100,2)
875      10.     equivalence (z,iz,zblk)
876      11.     integer shape
877      12.     common /mater1/ matter(2,1),mat(1),shape(1)
878      13.     common /cells/ mater, i,dx,uzone,ezone,rzone,mnow,mprev,ibdry
879      14.     common /ecssim/ xecs(60000)
880      15.     integer shkclc, shkclb
881      C
882      C          *****
883      16.     dimension
884      C          *****
885      C
886      $ pamb(1000),ramb(1000),pamb1(1000),ramb1(1000),pamb2(1000),
887      $ ramb2(1000),uabove(1000),eabove(1000),pabove(1000),
888      $ rabove(1000),ubelow(1000),ebelow(1000),pbelow(1000),
889      $ xabove(1000),xbelow(1000),yabove(1000),ybelow(1000),
890      $ xp(1000), yn(1000), rbelow(1000), eamb(1000), eamb2(1000),
891      $ eamb1(1000)
892      C
893      C          *****
894      C          evecutable
895      C          *****
896      C
897      17.     sine = sin (angle / 57.2957795)
898      18.     csine = cos (angle / 57.2957795)
899      19.     t = thull

```

```

900      20.      cycle = 0.
901      21.      key = 0
902      c*****
903      c
904      c      generate the SAP cell -x- coordinates based on user input
905      c
906      22.      j = 1
907      23.      1  if (j .gt. imax) goto 10
908      24.          call in2(cycle)
909      25.          do 5 jj = j , i
910      26.              x(jj) = x(jj - 1) + dx
911      27.      5  continue
912      28.          j = i + 1
913      29.          go to 1
914      c*****
915      c
916      c      set ambients into top, center and bottom rows, fill arrays
917      c      with x,y coordinates of top and bottom rows.
918      c
919      30.      10  hh = hob - ygnd
920      31.          off = hh*csine/sine
921      32.          do 1000 ii = 1, imax
922      33.              xcentr = 0.5*(x(ii) + x(ii - 1))
923      34.              xp(ii) = xcentr*csine
924      35.              yp(ii) = ygnd + xcentr*sine
925      36.              xabove(ii) = xp(ii)
926      37.              xbelow(ii) = xp(ii) + off
927      38.              yabove(ii) = yp(ii) + hh
928      39.              ybelow(ii) = yp(ii)
929      40.      1000 continue
930      c
931      41.          do 1010 ii = 1, imax
932      42.              call atmos (yp(ii), ramb(ii), eamb(ii), pamb(ii))
933      43.              call atmos (yabove(ii), ramb1(ii), eamb1(ii), pamb1(ii))
934      44.              call atmos (ybelow(ii), ramb2(ii), eamb2(ii), pamb2(ii))
935      45.      1010 continue
936      c
937      c*****
938      c*
939      c*      get the velocities from file hydro, calculate the SAP input
940      c*      velocities for cell centered values. The matrices must be
941      c*      inverted for function bilint1 to work on
942      c*
943      46.      itype = 1
944      47.      call trans (angle, itype)
945      48.      call swap
946      c
947      c*****
948      c*
949      c*      find the edge of the shock by utilizing umin.
950      c*
951      49.      do 15 ii = 1, imax
952      50.          index = imax - ii
953      51.          uu = bilint1 (xabove(index), yabove(index), key)
954      52.          if (abs (uu) .gt. umin) goto 17
955      53.      15  continue

```

```

956      54.      ii = 1
957      c
958      55.      17  shkcel = imax - ii + 1
959      c
960      56.      do 2000 ii = 1, imax
961      57.      index = imax - ii
962      58.      uu = bilintl (xp(index), yp(index), key)
963      59.      if (abs (uu) .gt. umin) goto 2010
964      60.      2000 continue
965      61.      ii = 1
966      c
967      62.      2010 shkclc = imax - ii + 1
968      c
969      63.      do 2020 ii = 1, imax
970      64.      index = imax - ii
971      65.      uu = bilintl (xbelow(index), ybelow(index), key)
972      66.      if (abs (uu) .gt. umin) goto 2030
973      67.      2020 continue
974      68.      ii = 1
975      c
976      69.      2030 shkclb = imax - ii + 1
977      c
978      70.      do 20 ii = 1, shkcel
979      71.      uabove(ii) = bilintl (xabove(ii), yabove(ii), key)
980      72.      20 continue
981      73.      do 21 ii = 1, shkclc
982      74.      u(ii) = bilintl (xp(ii), yp(ii), key)
983      75.      21 continue
984      76.      do 22 ii = 1, shkclb
985      77.      ubelow(ii) = bilintl (xbelow(ii), ybelow(ii), key)
986      78.      22 continue
987      c
988      c*****
989      c*
990      c
991      c*      Get energies from file mhydro, calculate the SAP input with
992      c*      the values in -xp- and -yp-.
993      c*
994      79.      itype = 2
995      80.      call trans (angle, itype)
996      81.      call swap
997      c
998      82.      do 30 ii = 1, shkcel
999      83.      eabove(ii) = bilintl (xabove(ii), yabove(ii), key)
1000     84.      30 continue
1001     85.      do 31 ii = 1, shkclc
1002     86.      epg(ii) = bilintl (xp(ii), yp(ii), key)
1003     87.      31 continue
1004     88.      do 33 ii = 1, shkclb
1005     89.      ebelow(ii) = bilintl (xbelow(ii), ybelow(ii), key)
1006     90.      33 continue
1007     c*****
1008     c*
1009     c*      Get the densities from file mhydro. These must then be
1010     c*      converted to mass values for SAP. The density values are
1011     c*      saved for caluculation of pressure. The cell centered

```

```

1012      c*      values in -xp- and -yp-.
1013      C*
1014      91.      itype = 3
1015      92.      call trans (angle, itype)
1016      93.      call swap
1017      94.      do 40 ii = 1, shkcel
1018      95.          rabove(ii) = bilintl (xabove(ii), yabove(ii), key)
1019      96.      40 continue
1020      97.      do 41 ii = 1, shkclc
1021      98.          rho(ii) = bilintl (xp(ii), yp(ii), key)
1022      99.      41 continue
1023      100.     do 44 ii = 1, shkclb
1024      101.         rbelow(ii) = bilintl (xbelow(ii), ybelow(ii), key)
1025      102.     44 continue
1026      C
1027      C*****
1028      C
1029      C      find last min relative pressure along all three rows using
1030      C      values in pamb, pamb1, pamb2. First calculate realtive
1031      C      pressures and densities.
1032      C
1033      103.     do 442 ii = 1, shkcel
1034      104.         call airt (eabove(ii), rabove(ii), gmone, pabove(ii),
1035      105.         $          cs, temp)
1036      105.     442 continue
1037      C
1038      106.     do 45 ii = 1, shkclb
1039      107.         call airt (ebelow(ii), rbelow(ii), gmone, pbelow(ii),
1040      108.         $          cs, temp)
1041      108.     45 continue
1042      C
1043      109.     do 46 ii = 1, shkclc
1044      110.         call airt (epg(ii), rho(ii), gmone, p(ii), cs(ii), temp(ii))
1045      111.     46 continue
1046      C
1047      112.     do 1040 ii = 1, shkcel
1048      113.         pabove(ii) = pabove(ii)/pamb1(ii)
1049      114.         rabove(ii) = rabove(ii)/ramb1(ii)
1050      115.         eabove(ii) = eabove(ii) - eamb1(ii)
1051      116.     1040 continue
1052      C
1053      117.     do 1050 ii = 1, shkclb
1054      118.         pbelow(ii) = pbelow(ii)/pamb2(ii)
1055      119.         rbelow(ii) = rbelow(ii)/ramb2(ii)
1056      120.         ebelow(ii) = ebelow(ii) - eamb2(ii)
1057      121.     1050 continue
1058      C
1059      122.     do 1055 ii = 1, shkclc
1060      123.         p(ii) = p(ii) / pamb(ii)
1061      124.         rho(ii) = rho(ii) / ramb(ii)
1062      125.         epg(ii) = epg(ii) - eamb(ii)
1063      126.     1055 continue
1064      C
1065      C*****
1066      C
1067      C      now all values for pressure and density are relative

```

```

1068      c
1069      127.      ipmina = ismin (shkcel,pabove,1)
1070      128.      jj = 1
1071      129.      do 1060 ii = 1, shkclb
1072      130.          if (pbelow(shkclb - jj + 1) .gt. 1.000) go to 1061
1073      131.          jj = jj + 1
1074      132.      1060 continue
1075      c
1076      133.      1061 iplace = shkclb - jj
1077      134.      do 1070 ii = 1, iplace
1078      135.          if (pbelow(iplace - ii + 1) .lt. 1.000) goto 1071
1079      136.      1070 continue
1080      c
1081      137.      1071 iplace = iplace - ii + 1
1082      138.      do 1073 jj = 1, iplace
1083      139.          if (pbelow(iplace - jj + 1) .lt. pbelow(iplace - jj)) goto 1077
1084      140.      1073 continue
1085      141.      1077 ipminb = iplace - jj + 1
1086      c
1087      142.      ipminc = shkclc - shkcel + ipmina
1088      c
1089      c
1090      c*****
1091      c
1092      c      clean out all center variables so as not to get erroneous
1093      c      extraneous values.
1094      c
1095      143.      do 1080 jj = ipminc, imax
1096      144.          p(jj) = 0.0
1097      145.          epq(jj) = 0.0
1098      146.          rho(jj) = 0.0
1099      147.          zm(jj) = 0.0
1100      148.          u(jj) = 0.0
1101      149.      1080 continue
1102      c
1103      150.      do 1090 jj = 1, shkcel - ipmina + 1
1104      151.          p(shkclc - jj + 1) = pabove(shkcel - jj + 1)
1105      152.          epq(shkclc - jj + 1) = eabove(shkcel - jj + 1)
1106      153.          rho(shkclc - jj + 1) = rabove(shkcel - jj + 1)
1107      154.          u(shkclc - jj + 1) = uabove(shkcel - jj + 1)
1108      155.      1090 continue
1109      c
1110      156.      num = min0 (ipminc - 1, ipminb - 1)
1111      c
1112      c      shift the bottom row to center row from 1 to ipminb
1113      c
1114      157.      do 1100 ii = 1, num
1115      158.          epq(ipminc - ii) = ebelow(ipminb - ii)
1116      159.          rho(ipminc - ii) = rbelow(ipminb - ii)
1117      160.          p(ipminc - ii) = pbelow(ipminb - ii)
1118      161.          u(ipminc - ii) = ubelow(ipminb - ii)
1119      162.      1100 continue
1120      163.      delte = ebelow(1) - ebelow(2)
1121      164.      deltr = rbelow(1) - rbelow(2)
1122      165.      deltp = pbelow(1) - pbelow(2)
1123      166.      deltu = ubelow(1) - ubelow(2)

```

```

1124      c
1125      167.      itemp = ipminc - num
1126      168.      do 1105 ii = 1, itemp - 1
1127      169.          epq(itemp - ii) = float(ii) * delte + ebelow(1)
1128      170.          rho(itemp - ii) = float(ii) * deltr + rbelow(1)
1129      171.          p (itemp - ii) = float(ii) * deltp + pbelow(1)
1130      172.          u (itemp - ii) = float(ii) * deltu + ubelow(1)
1131      173.      1105 continue
1132      c
1133      c
1134      174.      shkcel = shkclc
1135      c
1136      175.      do 50 ii = 1, shkcel
1137      176.          p(ii) = p(ii)*pamb(ii)
1138      177.          rho(ii) = rho(ii)*ramb(ii)
1139      178.          epq(ii) = epq(ii) + eamb(ii)
1140      179.          zm(ii) = rho(ii)*(x(ii)**3 - x(ii - 1)**3)
1141      180.      50  continue
1142      c
1143      c*****
1144      c*
1145      c*      calculate pressure.
1146      c*
1147      181.      do 60 ii = 1, shkcel
1148      182.          call airt (epq(ii), rho(ii), gmone, pp, cs(ii), temp(ii))
1149      183.      60  continue
1150      184.      cycle = chu11
1151      185.      shkcel = shkcel - 1
1152      c
1153      186.      return
1154      187.      end

```