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CLOUD RISE FROM HIGH-EXPLOSIVES DETONATIONS

H. W. Church, 9511
Sandia Laboratories, Albuquerque

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ABSTRACT

Data from a series of high-explosives trials of debris product cloud top heights versus time are presented. A brief comparison with some other experiments and with theory is made. It is concluded that so-called stabilization height can be predicted best as a function of explosive yield to the 0.25 power for chemical explosives in average atmospheres.

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CLOUD RISE FROM HIGH-EXPLOSIVES DETONATIONS

Introduction

For the problem of predicting atmospheric pollutant dispersal from contaminant sources in the atmosphere, knowledge of the initial conditions is required before a reasonable description of the dilution processes can be attempted. These conditions are: (1) contaminant source strength, (2) source characteristic, (3) characteristic dimensions, and (4) meteorological conditions which determine transport and diffusivity. The characteristics under Item 2 needing definition are type, geometry, location, and time. Type includes phase, whether gaseous or particulate. Geometry defines whether the source issues from a point, along a line, or over an area. Location, besides defining relative horizontal position to possible receptors also specifies the height of release. Time character specifies the rate of release whether continuously or instantaneously resulting in what is frequently referred to as "plume" or "puff," respectively.

The continuing concern over the safety of transport and storage operations of nuclear weapons has led Sandia Laboratories and others to develop prediction capabilities especially designed for the application to puffs released near ground level. While an accident involving nuclear weapons has an essentially zero probability of causing a nuclear detonation, there is a possibility of causing the chemical explosive components to explode and disperse the nuclear fuel. Such explosions may occur because of weapon exposure to fire or impact. This type of weapon accident was simulated in a field experiment called Operation Roller Coaster in Nevada in 1963.

As a result of joint US-UK effort on this operation, a model for the computation of aerosol transport and diffusion in the atmosphere was developed.[1] A principal input to this model is the top height of the explosively produced aerosol cloud. It is this characteristic dimension that is the main subject of this report.

In treating the problem of predicting cloud height, this report contains a brief discussion on background and theory of detonation cloud rise prediction, followed by a description of some cloud height measurements made in conjunction with Project Roller Coaster, together with some results and conclusions.

Background

The study of the rise of continuous plumes, especially from stacks, has received a great deal of attention. In fact, as stated in Reference 2, at least 20 different formulas have been published since 1950, none of which is universally accepted. The rise of puffs seems to be in a similar state of uncertainty since the only basic differences between plumes and puffs are time scales and the number of dimensions, two and three, respectively, available for their expansion.

A puff rises in the atmosphere primarily because of its buoyancy and initial momentum. The rising puff's motion relative to the ambient air causes turbulent mixing which results in a net entrainment of nonbuoyant air. As the puff decelerates because of decreasing buoyancy, the turbulence at the puff boundary decreases to the value found in the ambient air. When the buoyant force decreases to zero, cloud growth will continue at a rate determined by the ambient turbulence. Thus, beyond several minutes apparent rise of the puff top is simply a continued turbulent expansion. The rate at which buoyancy approaches zero is a function both of entrainment rate and ambient temperature lapse rate or static stability.

Various theories have been advanced which attempt to describe the behavior of convective elements in the atmosphere. The one which seems most appropriate to the present problem is that given by Morton, Taylor, and Turner.[3] In that work the point source is described by the total buoyant force imparted to a large volume of entrained air divided by the density of air. It was found theoretically by dimensional arguments that the height of rise was proportional to the quarter power of initial buoyant force divided by the quarter power of ambient stability. Since the proportionality constant could not be determined from dimensional analysis alone, it was necessary to appeal to experimental data.

Based on some experiments carried out in a stably stratified salt solution where known volumes of a light fluid were released, a regression equation $H = 2.66\ F^{1/4}\ G^{-1/4}$ was determined for cloud top height. The quantity F is buoyancy and G is degree of stratification. In the atmosphere, $F = gQ/C_p \rho T$, and

$$G = (g/T)\partial \theta / \partial Z$$

where g is acceleration of gravity, Q is energy released, C_p is specific heat of air at constant pressure, ρ is air density, T is air temperature, θ is potential temperature, and Z is height. For a standard atmosphere where $C_p = 1.004 \times 10^3$ (kjoules/°K ton), $\rho = 1.225 \times 10^{-3}$ (ton/m^3), where 1 ton = 10^3 kg, and $\partial\theta/\partial z = 3.3 \times 10^{-3}$ (°K/m) or temperature lapse rate of -6.5°C/km, the regression equation reduces to $H = 1.87Q^{1/4}$.

Morton, et al, gave an example of this equation's application to the case of exploding TNT using an energy conversion factor of 1.7×10^3 kjoules per pound of TNT. This gives, W in pounds TNT:

$$H = 67.4\ W^{1/4}, \text{ for H in meters}$$

$$H = 221\ W^{1/4}, \text{ for H in feet, or}$$

$$H = 700\left(\frac{W}{100}\right)^{1/4}.$$

For the more widely used energy conversion factor of 2.1×10^3 kjoules per pound TNT[4] the coefficient 67.4 above changes to 71.0; on the other hand the 67.4 could be retained by taking a slightly more stable lapse rate of -5.7°C/km for an "average" atmosphere.

Least square fit to data from nuclear explosion clouds in the troposphere suggest an exponent on equivalent explosive weight of about 0.3. Some UK AWRE data on small charges (6 to 5000 pounds) suggested (D. M. C. Thomas, unpublished note) an exponent of 1/3. A dimensional argument by Briggs[2] suggests an exponent of 1/2. Thus, it is apparent that there is considerable uncertainty as to the proper regression formula to use. Therefore, in this report least squares fit of cloud top height versus explosive yield is done for the 4 Roller Coaster shots, 19 TNT shots, and for 74 nuclear shots which have been announced in the open literature[4, 5] for yields of 21 kt or less.

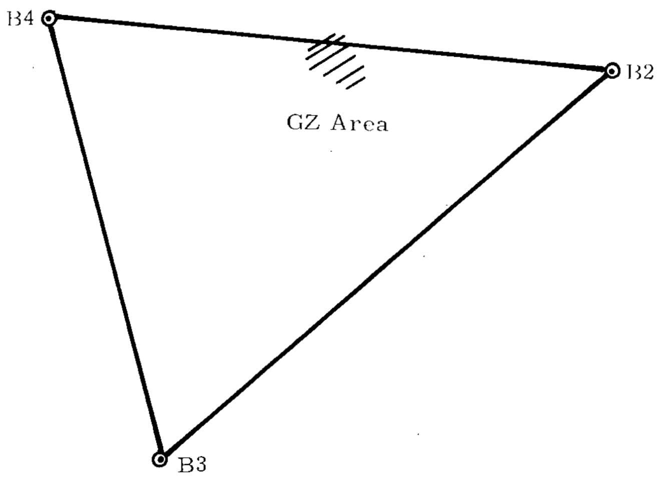
Procedure

During Project Roller Coaster, a photographic technique was developed[6] which allowed observation of cloud top height information to be made at night. It turned out that with reasonable wind conditions (<6 m/sec) clear photographic images could be obtained using the flare illumination technique to about 5 minutes after detonation in most instances. In order to obtain more data on cloud rise from TNT detonations, a series of 13 shots was run one night in June from 5 p.m. to 6 a.m. In addition, an earlier preliminary series was run in April.

Blocks of TNT whose total weight ranged from 140 to 2800 pounds, were stacked in roughly cubical shapes on the dry lake bed of Cactus Flat or Stonewall Flat in south central Nevada. For the June series, three locations previously surveyed to first order were equipped with K-18 cameras and weather balloon tracking theodolites. The observer locations identified as B2, B3, and B4 formed an acute triangle, shown in Figure 1, whose longest side was about 6-1/2 km in length. The detonation area (GZ) was located within the triangle as shown in the figure. The first four of the six April preliminary HE shots were observed with one pair of double theodolites arranged as shown in Figure 2. These shots were done within 2-1/2 hours after sunrise on a clear calm morning in a very stable ground-based layer which was rapidly losing stability as the sun rose. The last two preliminary shots were done in the general area of Figure 1 in somewhat windier weather. The last preliminary shot was placed in a trench covered with a dirt roof about 2-1/2 meters deep but open on one end. The puff shot out the open end of the trench such that the dirt cover had little influence on its total rise and hence probably behaved similarly to the other surface shots.

As done for the Roller Coaster events themselves,[6] observation synchronization was achieved by transmission of radio tones to each observation point and to the flare launcher near GZ. The tones activated the camera film transport mechanism and/or signaled the theodolite crew to read their elevation and azimuth angles. Theodolite operators were instructed to track the cloud top. Observations were taken at 30 seconds and at each whole minute up to 5 after detonation. Table I lists the 13 HE shots, the 4 Roller Coaster shots, and the 6 useful preliminary shots with their time of detonation, explosive weight, and method of observation.

Routine supporting meteorological temperature and wind profile data were taken for the June series and for Roller Coaster.[7] Experimental temperature profiles were obtained for the preliminary series (see Reference 7, p. 24, for measurement systems description; see Appendix for data). Table I summarizes the temperature and wind data from ground to 2-minute cloud top height. The definition of stability S is given in the following section.

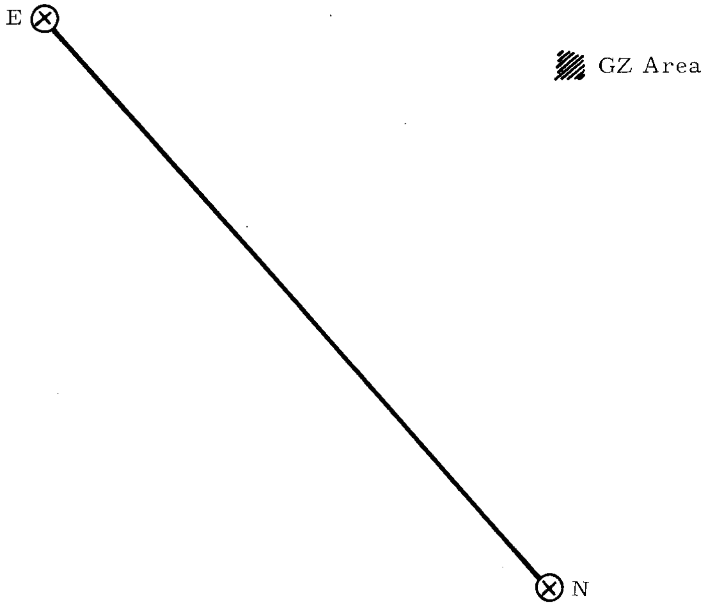


Elevation, Meters Above MSL	
GZ	1636
B2	1642
B3	1695
B4	1665

Baseline, Horizontal Length, Meters	
B2-B3	6521
B3-B4	4975
B4-B2	6136

Azimuth of baseline B4 to B2 = 98 degrees east of North.

Figure 1. Geometry of Ground Zero and Observer Points for the June Series of HE Shots



Elevation, Meters Above MSL	
GZ	1494
E	1502
N	1512

Baseline, Horizontal Length, Meters	
E-N	1302

Figure 2. Geometry of Ground Zero and Observer Points for the April Preliminary Series of HE Shots

Other explosives experiments were sought in the literature in an attempt to obtain data for a wider range of explosive sizes. Reference 8 contained some information on high-explosives tests conducted in Utah and Nevada in 1951. However, these shots were partially buried and no temperature profile data were given with the reported cloud heights. Thus, these data were not used in the present analysis.

Some information was obtained on cloud height data versus time for some 500-ton TNT shots (one in Canada, two in Hawaii) which provided very useful information on large size TNT shots. All of these data will be discussed together in the following section.

TABLE I

Summary of Explosives Experiments, Cloud Measurement Method, and Meteorological Measurements

Shot No.	Date (1963)	Time (PDT)	TNT Yield (lb)	Method*	Stability (S**)	Mean Wind Speed (m/sec)
1	4 June	1720	140	C, T	-0.49	10
2	4 June	1753	140	C, T	-0.40	10
3	4 June	1818	140	C, T	-0.47	11
4	4 June	2150	1600	C	+0.86	5
5	4 June	2248	140	C	+1.55	3
6	4 June	2318	560	C	+1.03	2
7	4 June	2340	140	C	+1.36	1.5
8	5 June	0304	1600	C	+1.36	2
9	5 June	0335	140	C	+2.49	3
10	5 June	0404	420	C	+1.96	2
11	5 June	0428	140	C	+1.73	5
12	5 June	0517	140	T	+0.26	7
13	5 June	0549	560	T	+0.27	6.5
Double Tracks	15 May	0255	118	C	+1.07	8
Clean Slate - 1	25 May	0416	1062	C	+0.97	7
Clean Slate - 2	31 May	0347	2242	C	+1.28	4
Clean Slate - 3	9 June	0330	2242	C	+1.53	2.5
P3	10 April	0535	140	T	+7.07	--
P4	10 April	0613	140	T	+1.59	--
P5	10 April	0648	140	T	+0.49	--
P6	10 April	0730	140	T	-0.29	--
P7	16 April	0602	1400	T	(+1.90)	--
P8	18 April	0514	2800	T	(+1.56)	--

*C - Camera
T - Theodolite

**$S = 1 - \gamma/\Gamma$

Results and Discussion

A tabulation of each shot with observed cloud top height versus time by observation method is shown in Table II. Only three shots provided duplicate measurement between camera and theodolite. Only the first five preliminary shots did not have more than one pair of double theodolites (or cameras).

Because of irregularly shaped puffs, less than optimum lighting conditions, and some high winds, the data are believed to be reliable to within ±15 to 20 percent. Camera data were reduced by conventional photo optical techniques while double theodolite data (June series) were reduced with a computerized version of a vector technique described by Thyer.[9] In general, table entries are averages of the estimates from the three pairs possible.

From the table it can be seen that heights still are increasing at the last observation time (with four exceptions). In general, the buoyant motion of the puffs as a whole had ceased by 2 minutes after detonation. The continuing rise of the top after this time was apparently caused by continuing turbulent growth which caused the whole puff to expand as it was carried downwind.

Stability values and mean wind speeds are shown in Table I as derived from the supporting meteorological data shown in the Appendix. Stability is defined by

$$S = 1 - \gamma/\Gamma ,$$

where γ is the average ambient temperature lapse rate from ground to 2-minute cloud top height, and Γ is the dry adiabatic lapse rate (-9.8°C/km). Wind speeds are averaged over the cloud height.

It was decided to perform a least-squares fit of all cloud heights using the expression of Morton, et al, in order to compare height to yield for average lapse rates. The expression fitted was

$$H = KW^{P} ,$$

where the coefficient K was to be determined either with the exponent P fixed at 1/4 or allowed to vary in order to minimize the squares of the differences between logarithms of observed H (at 2 minutes) and those calculated by the best fit relation. Various combinations of observation data were used in order to determine any systematic differences in the various experiments.

For comparison purposes cloud height data from 74 nuclear explosive tests ranging in yield from 400 pounds to 21 kilotons TNT equivalent were taken from References 4 and 5. Since clouds of yield greater than about 21 kt enter the stratosphere, a region of much greater stability than the troposphere, these yields were excluded in order to study only the region of average lapse rates. These data vary considerably in quality but are included because they provide some information about the higher yield ranges. A bias in the nuclear data may appear for two principal reasons. The first is that reported cloud top heights may be for times greater than 2 minutes after detonation.

TABLE II

Cloud Top Heights (Meters) Versus Time (Minutes)

Time (min)	Shot 1		Shot 2		Shot 3		Shot 4	Shot 5	Shot 6	Shot 7	Shot 8	Shot 9	Shot 10	Shot 11	Shot 12	Shot 13
	Cam	Theod	Cam	Theod	Cam	Theod	Cam	Cam	Cam	Cam	Cam	Cam	Cam	Cam	Theod	Theod
1/2	127	126	111	87	123	111	293	120	147	--	212	122	152	135	155	196
1	225	263	152	143	193	204	385	175	225	197	316	189	219	176	237	291
2	--	397	232	208	345	333	498	257	377	271	450	193	286	283	392	382
3	--	553	--	270	--	343	584	320	458	327	552	189	319	374	478	461
4	--	978	--	266	--	488	--	--	--	--	--	--	--	--	524	557
5	--	--	--	--	--	592	598	419	667	369	680	205	324	--	583	615

Time (min)	Double Tracks*	Clean Slate - 1*	Clean Slate - 2*	Clean Slate - 3*	Shot P3	Shot P4	Shot P5	Shot P6	Shot P7	Shot P8
	Cam	Cam	Cam	Cam	Theod	Theod	Theod	Theod	Theod	Theod
1/2	118	249	242	262	47	84	88	105	251	358
1	164	378	298	377	84	142	142	168	389	432
2	210	558	415	494	76	180	207	280	565	536
3	216 (2-1/2 min)	643 (2-2/3 min)	440	520	--	--	271	--	668	645
4	--	--	428	510	--	--	--	--	759	695
5	--	--	412	--	--	--	--	--	832	740

*Data from Reference 6.

Nuclear clouds are generally thought to "stabilize" some 4 to 6 minutes after detonation in contrast to the 2 to 3 minutes observed for HE. The second reason, which may be the basis for the first, is that it is thought that the much hotter nuclear fireball rises more as a bubble during its early phase because of the extreme density difference between it and the air. Thus, relatively little mixing occurs during about the first minute compared to the case for a turbulent thermal with its attendant turbulent entrainment.

Table III shows the results of the regression analyses, using various combinations of the data. Figure 3 is a plot showing all the data compared to the theoretical results of Morton, et al, along with four of the significant curves of the regression analyses from Table III.

TABLE III

Results of Regression Analyses of Cloud Height (H in Meters)
Versus Yield (W in Pounds TNT)
(Expression fitted is $\ln H = \ln K + P \ln W$.
$\sigma_g(H)$ is the geometric standard deviation of H.)

Data Combinations	P^*	K	$\sigma_g(H)$
Morton, et al, stratified salt solution	1/4	71.0	--
4 RC only	1/4	72.1	1.206
	0.267	60.6	1.205
4 RC, 13 HE	1/4	77.8	1.227
4 RC, 13 HE, 6 PHE	1/4	72.1	1.383
	0.283	59.4	1.380
4 RC, 13 HE, 5 PHE	1/4	76.1	1.232
	0.245	78.2	1.232
74 NE only	1/4	114	1.338
	0.292	61.8	1.302
74 NE, 4 RC, 13 HE	1/4	106	1.370
	0.292	61.6	1.292
74 NE, 4 RC, 13 HE, 5 PHE, 2-500 T	1/4	103	1.382
	0.293	59.4	1.294

RC = Roller Coaster
HE = high explosive
PHE = preliminary high explosive
NE = nuclear explosive
500 T = 10^6 lb of TNT shots.

*Where P is entered as 1/4, this value was fixed and a least-squares fit to K was obtained. Where a decimal format is entered a simultaneous best fit to both P and K was obtained.

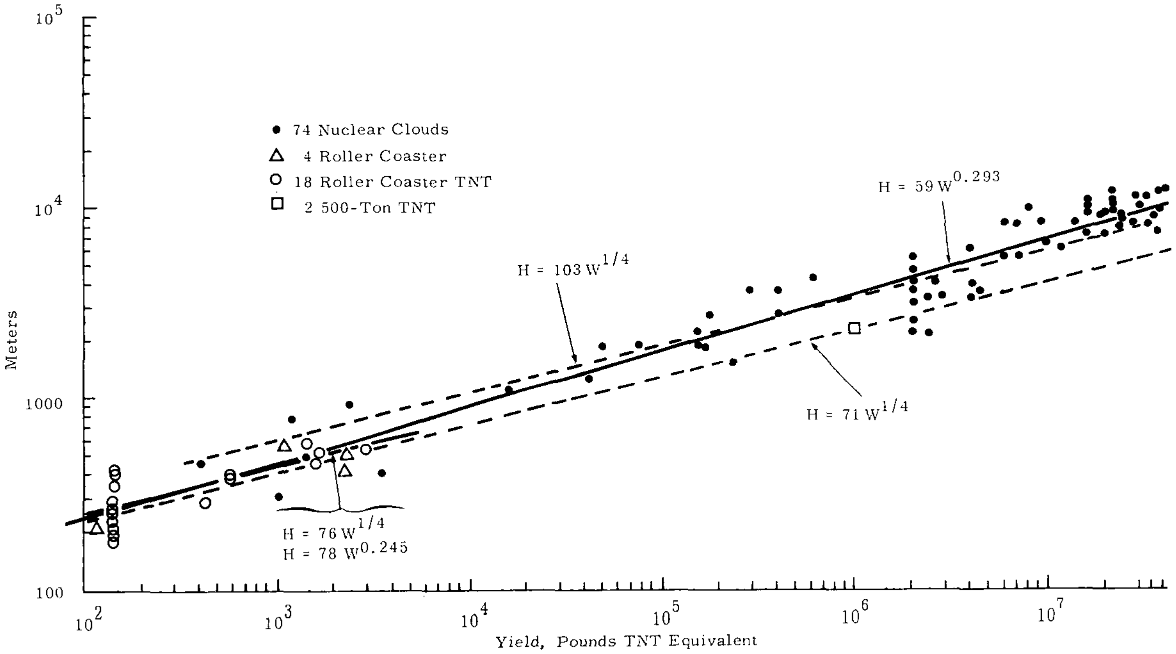


Figure 3. Two-Minute Cloud Top Height Versus Yield

Of all the shots used, only one was fired in a sufficiently nonaverage atmosphere to justify its exclusion. That was the first usable preliminary HE shot, P3. From Figure 3 it can be seen that its height was about a factor of four below the average whereas none of the others was more than a factor of two from the average. A look at the stabilities shown in Table I shows that the stability for shot P3 was almost three times that of the next closest value of 2.5 for Shot 9. All the other stabilities range from -0.5 to 2.5. Figure 4 is a plot of the difference of logarithms of observed height to calculated height versus stability as defined previously. Also shown in Figure 4 is a plot of $\ln (H_i/H_{calc}) = S^{-1/4}$ which represents the character of the stratification dependence in the theory of Morton, et al. It is seen from the data plot on this figure that there is a definite inverse correlation between cloud height and stability, but not necessarily along the $S^{-1/4}$ curve.

There are several problems associated with attempting to correlate cloud height with atmospheric stability. Probably the most important is definition and measurement of stability. The lapse rate γ was defined as the average (uniform) lapse rate from ground to cloud top. It is well known that typical temperature profiles in stable conditions are seldom linear especially in the boundary layer (<1 km). Detailed temperature measurement was difficult both with the usual rugged radiosonde and with the special balloon suspended string of aspirated thermisters supplied by the UK during Roller Coaster. Therefore, the values of stability given can be used only as a general comparative guide among the various shots.

Another problem worthy of mention when comparing cloud heights from various explosives is that of conversion to a standard explosive energy equivalent, usually pounds of TNT. Frequently conversion is based on equivalent blast output from one type of explosive to another. However, for the present problem it is the thermal output which determines the initial buoyancy that lifts the puff. If it is assumed that the energy of explosion or detonation is partitioned similarly between radiation, blast, and residual heat content of explosive products, then it is possible to convert from one explosive to another by the ratio of the given heats of explosion. The equivalent TNT yields shown in Table I for the four Roller Coaster events were converted using the heat of explosion for each explosive and relating it to that for TNT (1080 cal/g).

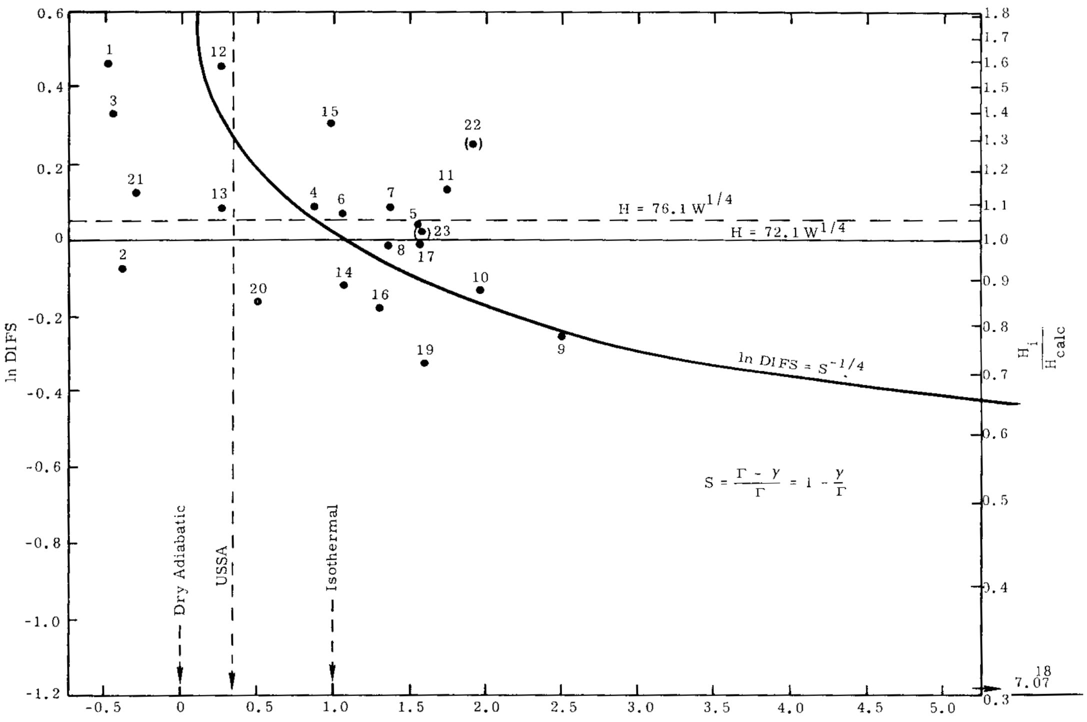


Figure 4. Calculated Versus Observed Heights Versus Stability

Conclusion

As shown in Figure 3 and Table III the agreement between the high-explosive cloud data and the theory proposed by Morton, et al, is quite satisfactory. Only a slight difference exists between the coefficient determined in salt water of 71 and the value of 76 determined from the 22 events measured in the atmosphere. The geometric standard deviation of the heights for these 22 experiments, 1.23, also is quite acceptable considering measurement uncertainties of cloud top height and atmospheric stability. It is interesting to note that the two 500-ton TNT shots each with 2-minute height of 2300 meters is within 10 percent of the best fit curve which was fit to data covering yield range of only 118 to 2800 pounds.

Therefore, it is recommended that for estimating so-called stabilized cloud top heights from explosive sources that K = 76 and P = 1/4 be used. Estimates of cloud height using these values should be within about 20 percent for the stability range $-\frac{1}{2}$ to $+2\frac{1}{2}$ found in average lapse rates.

APPENDIX

METEOROLOGICAL DATA

The following figures show profiles of temperature, wind speed, and wind direction to heights of 600 meters above ground where available. Recording cup and vane anemometers were used at 9 meters above ground with some at 18 and 37 meters in addition. Higher level winds were obtained by radar tracking of slow rising (~2 m/sec) balloons. Temperatures were obtained from modified radiosonde systems with some profile data to 300 meters obtained from tethered balloon-borne, aspirated thermisters. For further details of measurement systems see Reference 7.

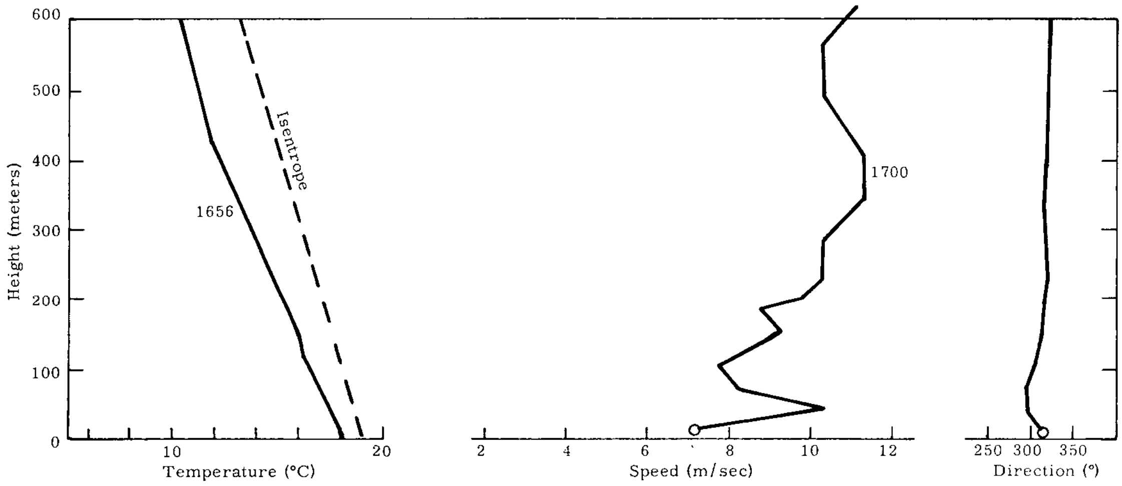


Figure A-1. HE Shot No. 1, 1720 PDT, 140 Pounds

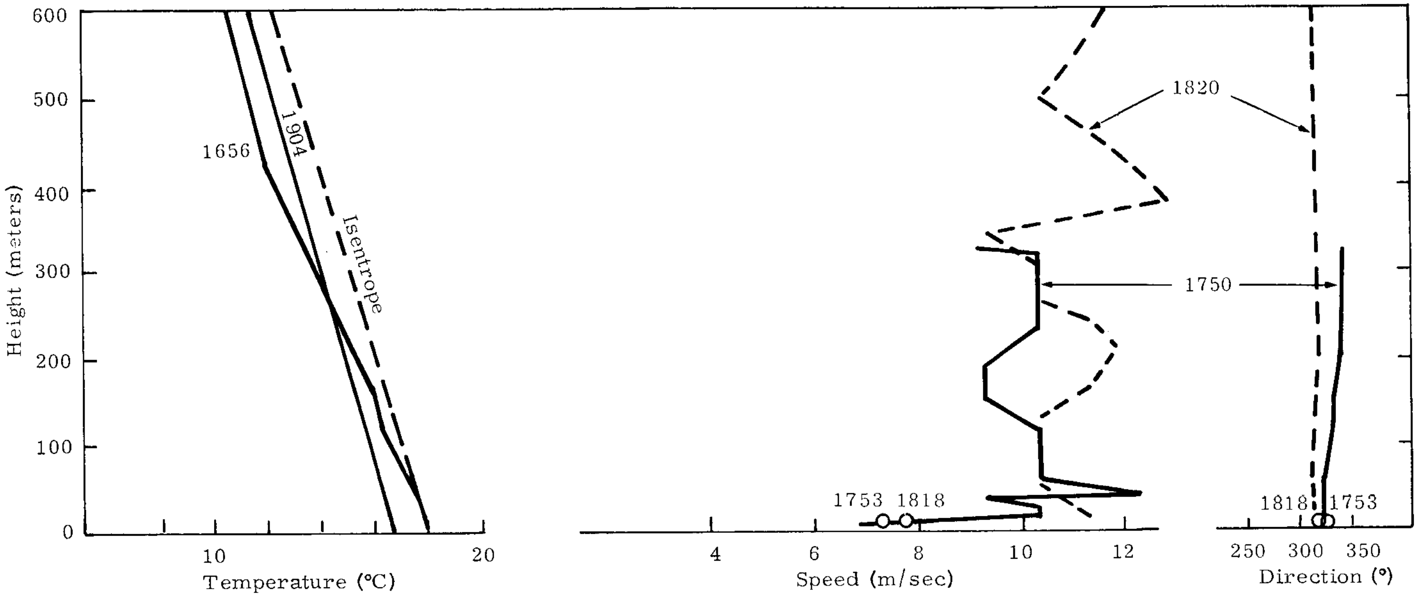


Figure A-2. HE Shot No. 2, 1753 PDT, 140 Pounds;
HE Shot No. 3, 1818 PDT, 140 Pounds

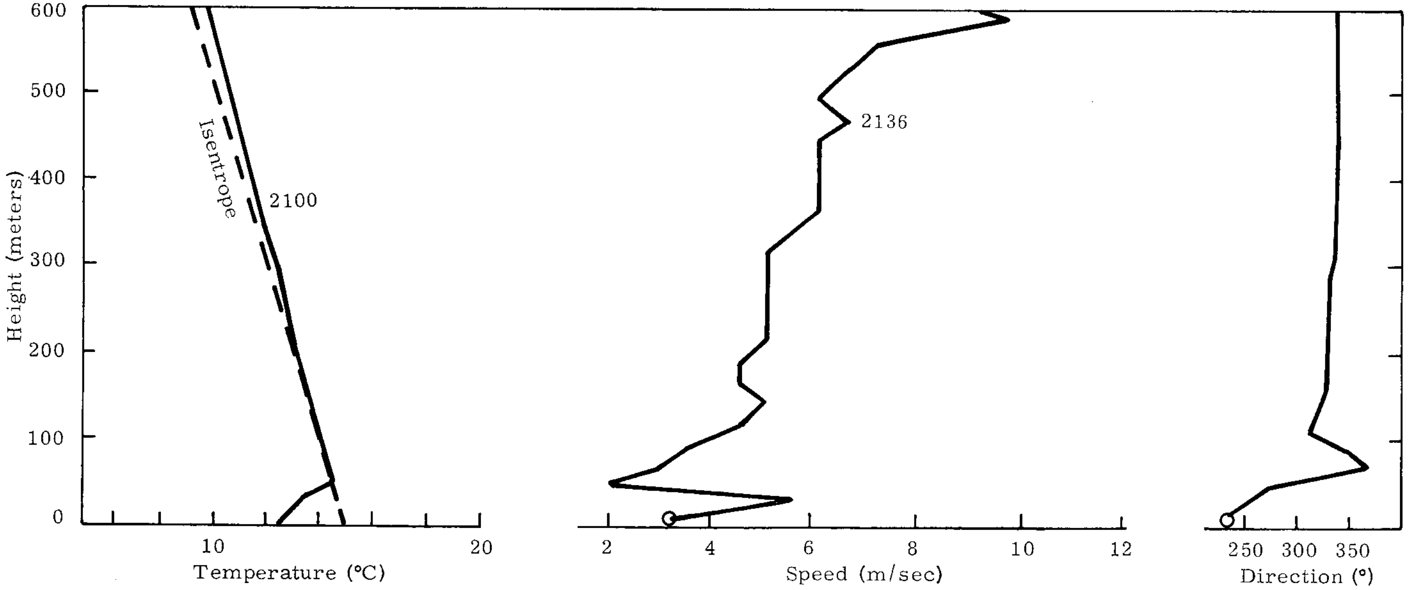


Figure A-3. HE Shot No. 4, 2150 PDT, 1600 Pounds

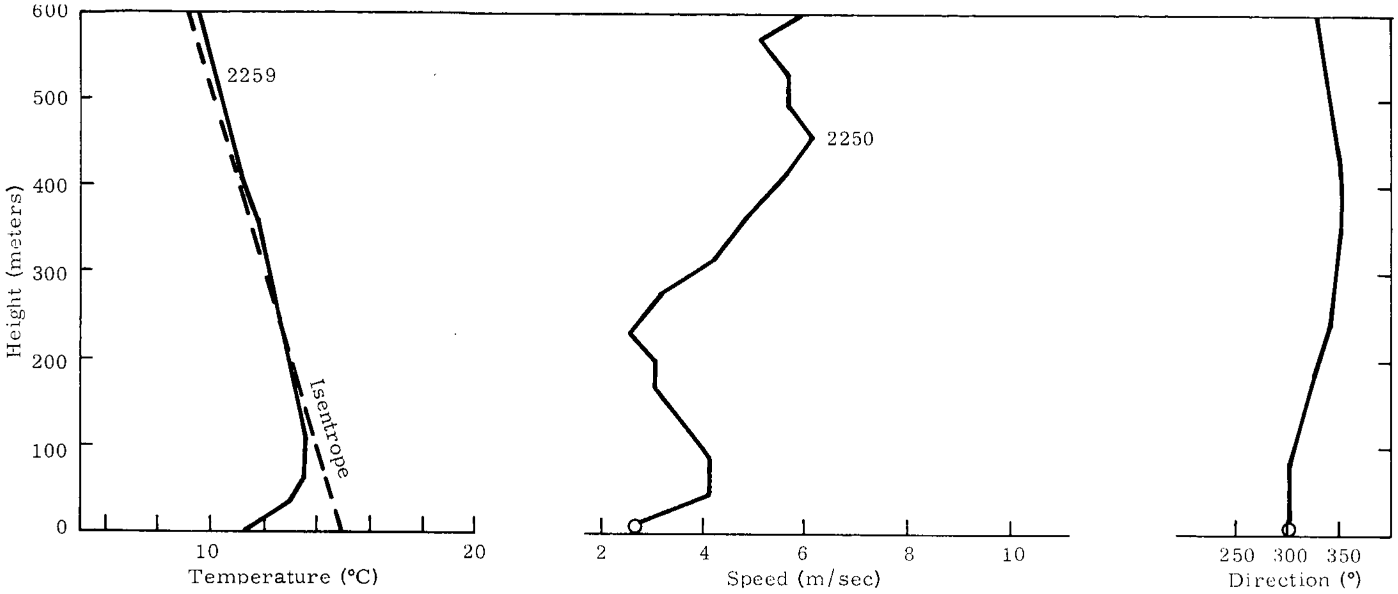


Figure A-4. HE Shot No. 5, 2248 PDT, 140 Pounds

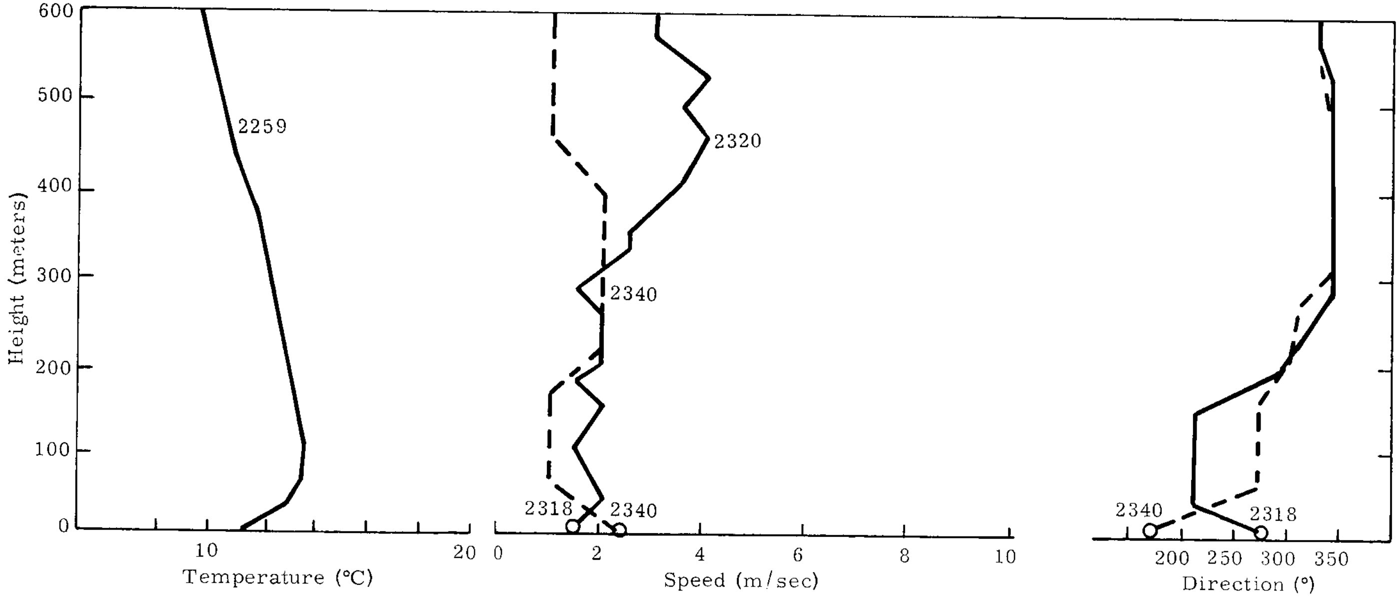


Figure A-5. HE Shot No. 6, 2318 PDT, 560 Pounds;
HE Shot No. 7, 2340 PDT, 140 Pounds

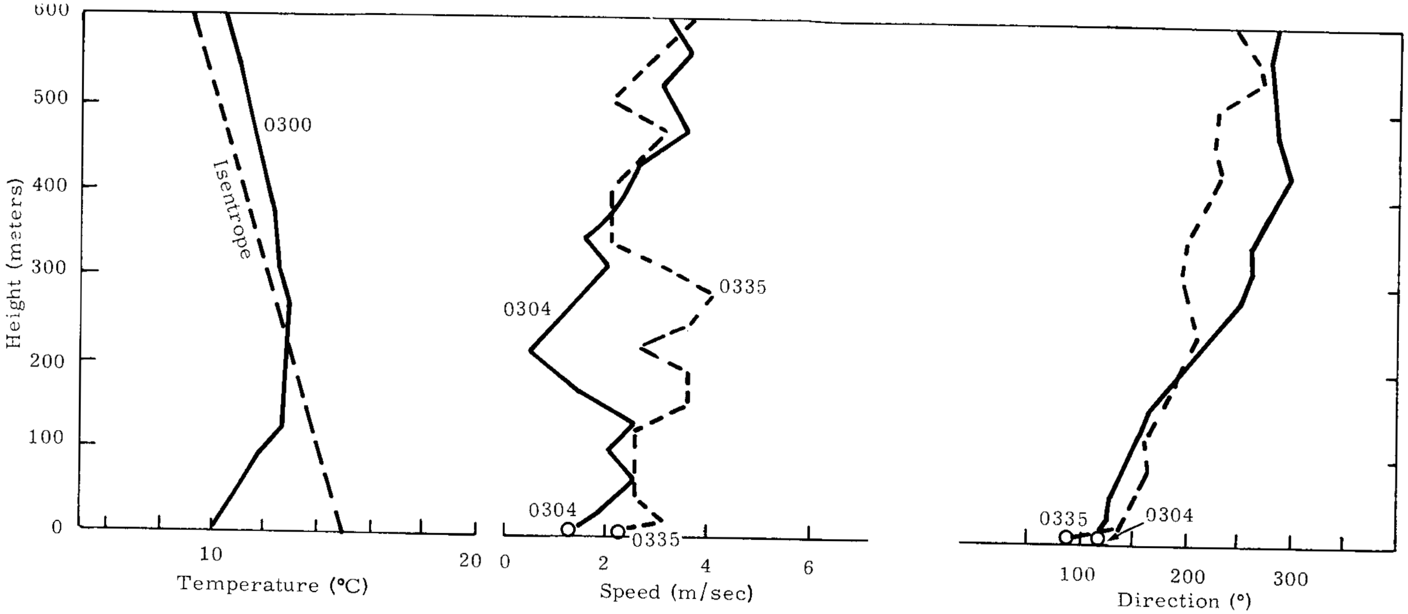


Figure A-6. HE Shot No. 8, 0304 PDT, 1600 Pounds;
HE Shot No. 9, 0335 PDT, 140 Pounds

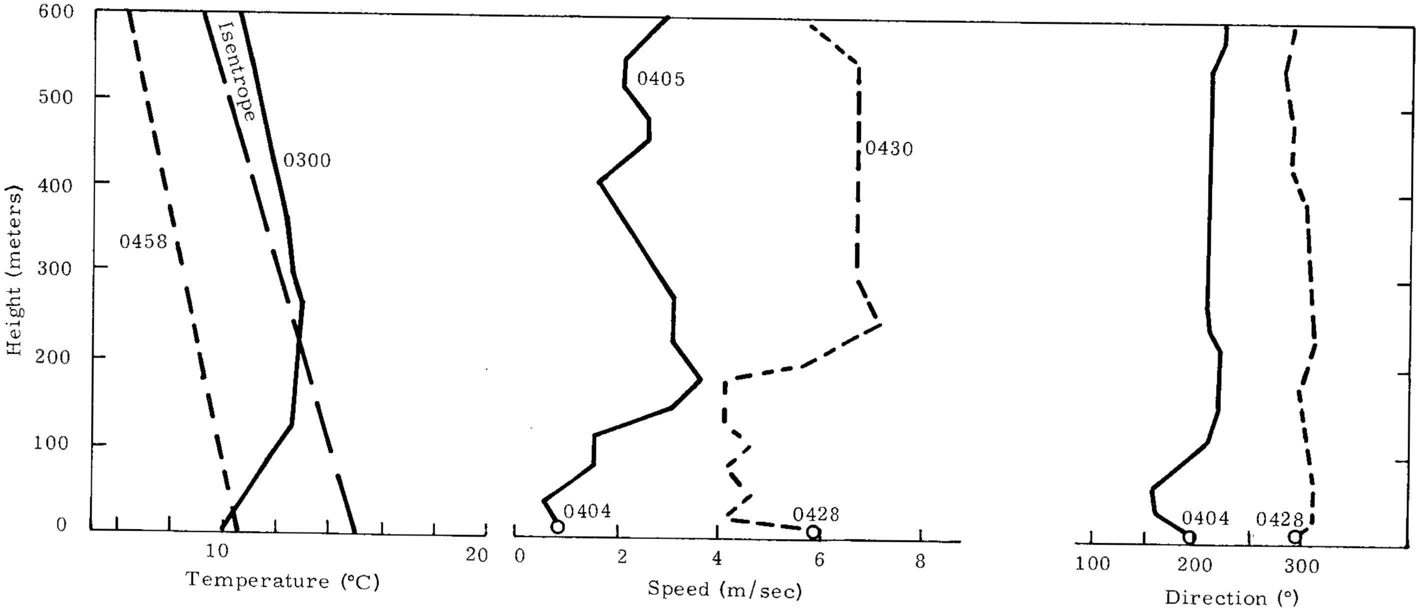


Figure A-7. HE Shot No. 10, 0404 PDT, 420 Pounds;
HE Shot No. 11, 0428 PDT, 140 Pounds

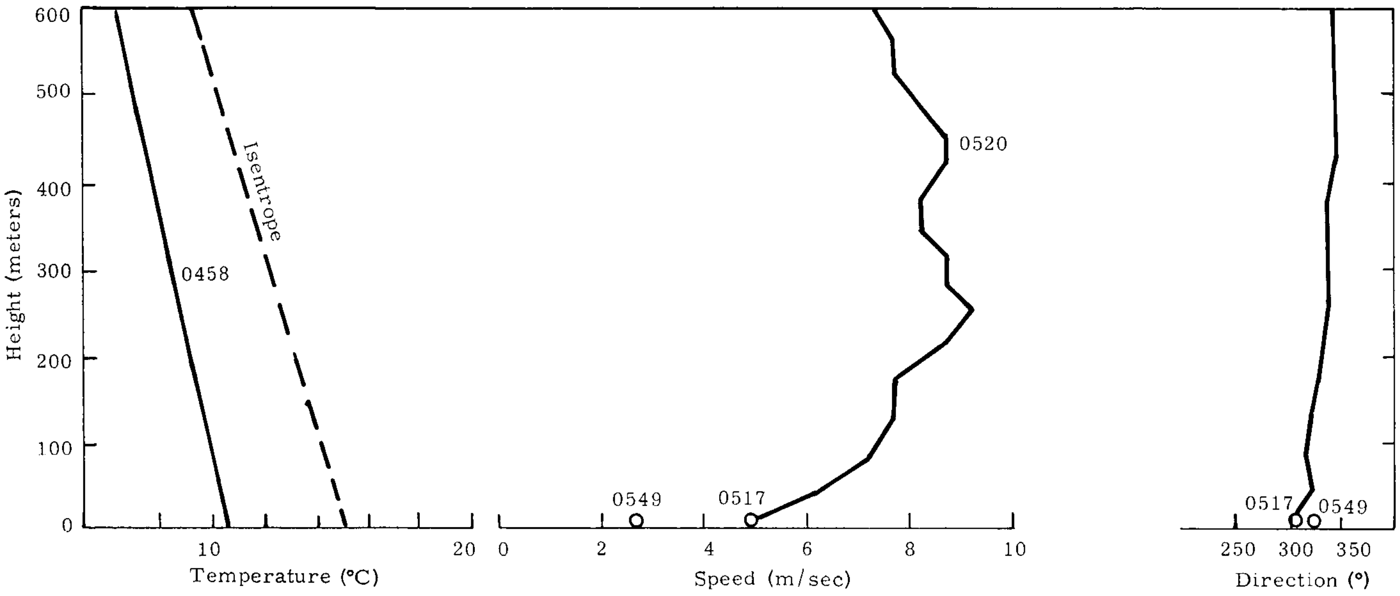


Figure A-8. HE Shot No. 12, 0517 PDT, 140 Pounds;
HE Shot No. 13, 0549 PDT, 560 Pounds

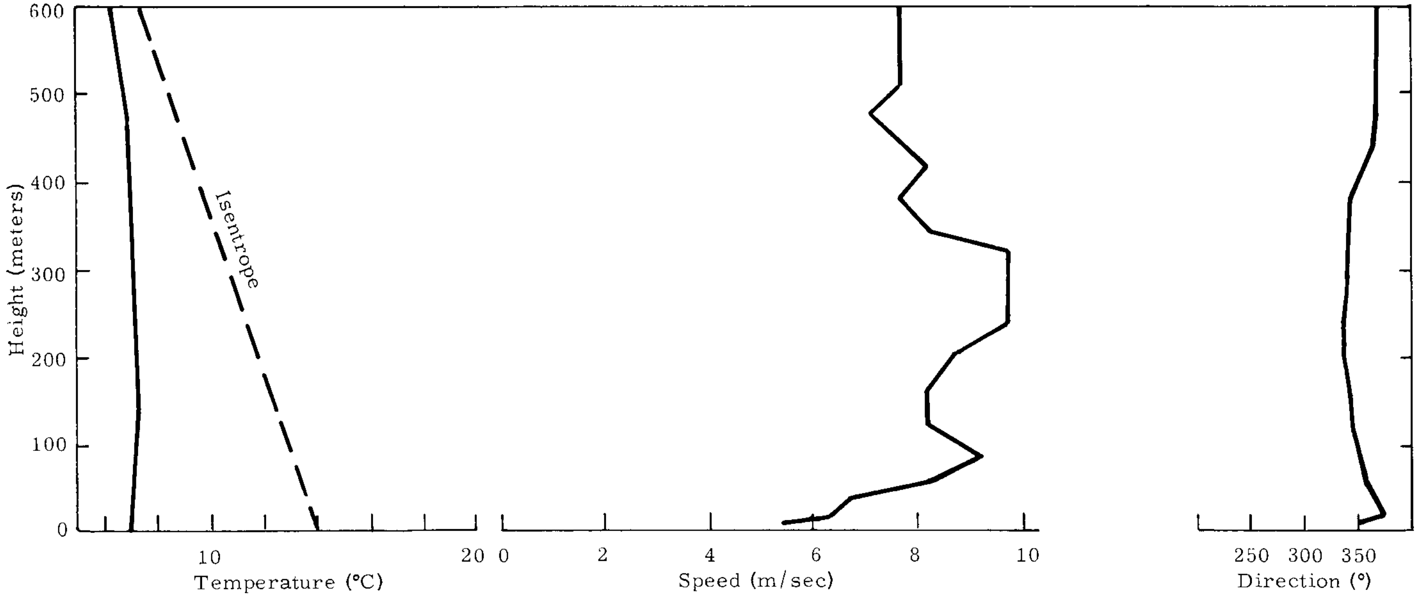


Figure A-9. Double Tracks, 0255 PDT, 118 Pounds

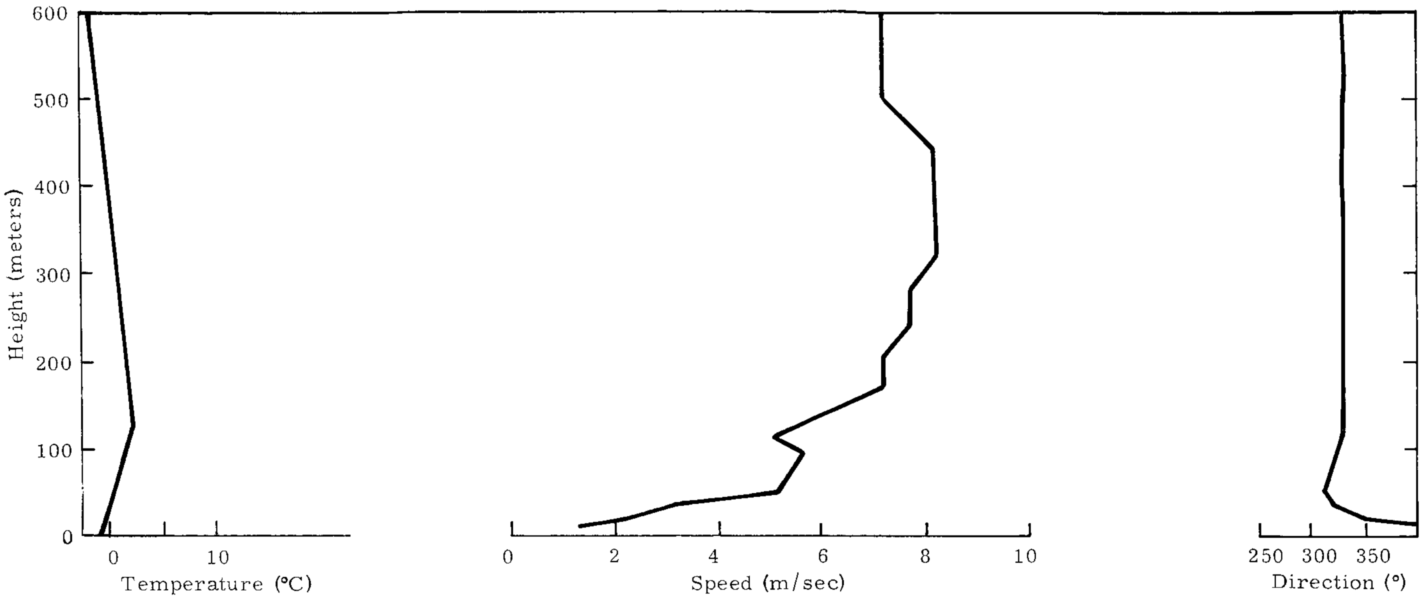


Figure A-10. Clean Slate 1, 0416 PDT, 1062 Pounds

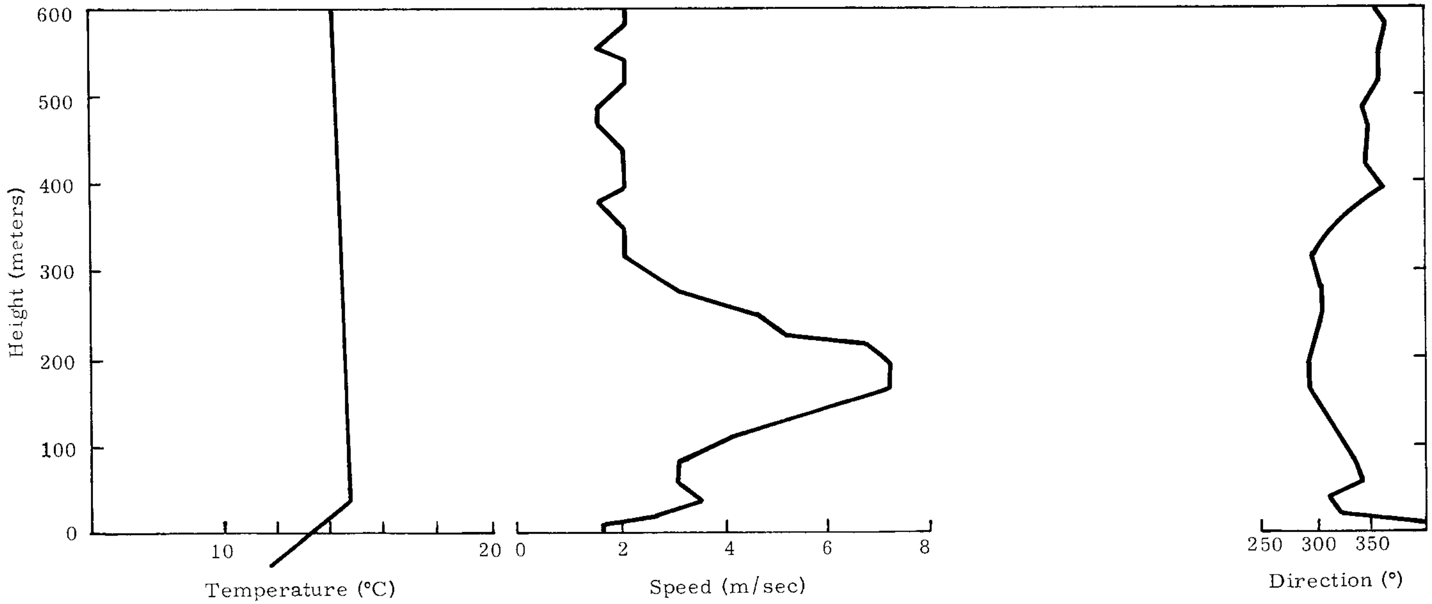


Figure A-11. Clean Slate 2, 0347 PDT, 2242 Pounds

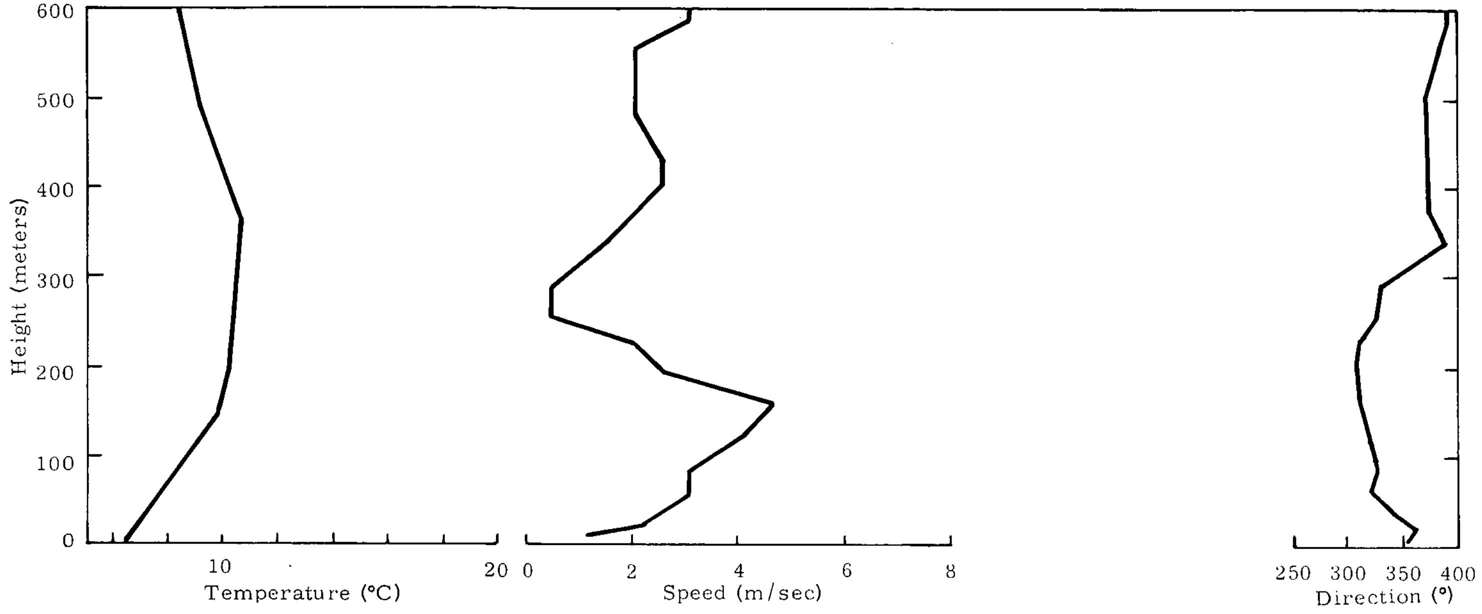


Figure A-12. Clean Slate 3, 0330 PDT, 2242 Pounds

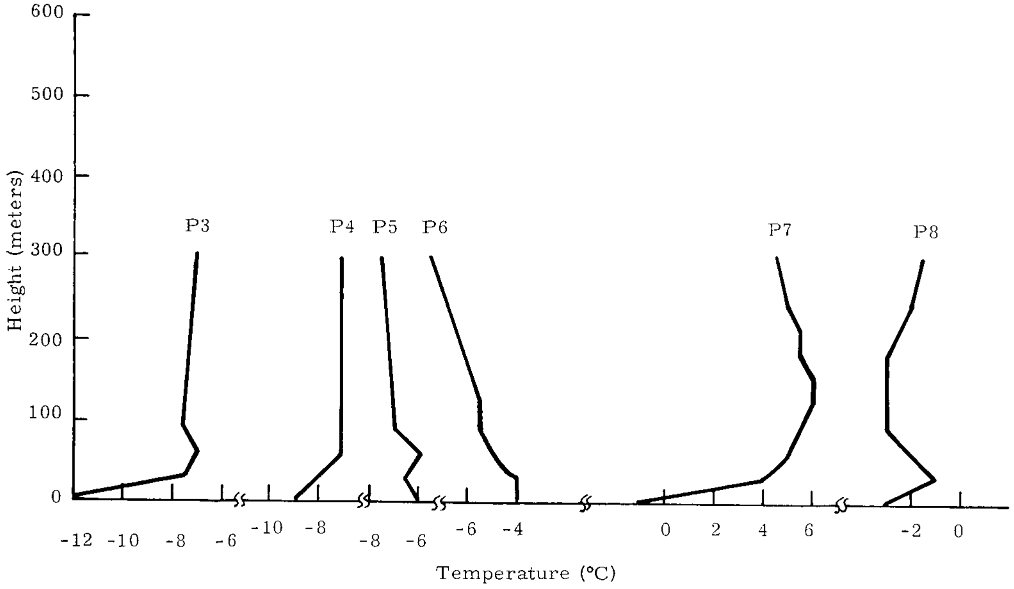


Figure A-13. Temperature Only for Preliminary HE Shots P3-P8

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