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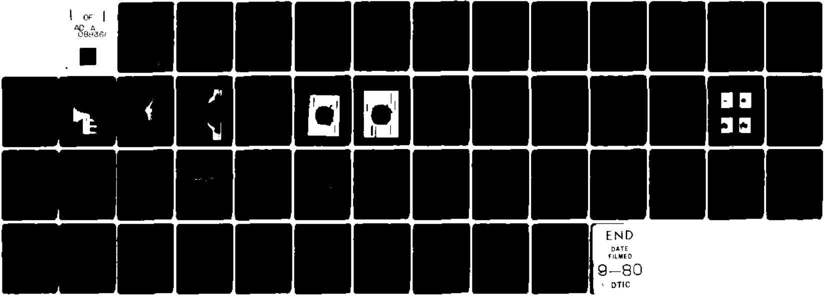

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REVIEW OF LARGE HE CHARGE EARLY-TIME DETONATION ANOMALIES

General Electric Company—TEMPO
DASAIC
816 State Street
Santa Barbara, California 93102

31 December 1979

Final Report for Period 1 November 1978—31 December 1979

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Early-time high-explosive (HE) anomalies from large charges have been a problem to weapon effects experimenters for nearly three decades. It is the unpredictability and near unsuppressibility of these anomalies which are the source of the problem. This Special Report summarizes what is known to date about HE detonation anomalies for charges ranging in yield from 0.25 gm to 500 tons. For source material, extensive use was made of DASIAC Library reports and films, of available papers published in the open literature, and of the National Technical Information Services' (NTIS) computerized library search. This report has been kept purposefully brief and self-contained to provide a useful review and reference to the subject.

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ABSTRACT (continued)

Following an introduction to the subject of detonation anomalies and a brief description of the literature and film searches, the classification and origin of the types of anomalies observed in field experiments and the laboratory are clearly described, and a discussion is provided on the effects of anomalies on field experiments. The last section, while not presenting conclusions and recommendations, discusses a number of methods that have been tried in an attempt to suppress detonation anomalies: it is indicated that anomalies of various types are an inherent part of HE detonations.

Wherever useful to support and clarify the discussion, photographs of typical anomalies are presented. However, in some cases for clarity of exposition and for reasons stated in the text, the author chose to include drawings instead of photographs.

Finally, to help the reader desirous of pursuing the subject further some 40 references have been cited.

PREFACE

The author gratefully acknowledges the helpful suggestions and constructive comments received from Mr. Jack R. Kelso, consultant to GE--TEMPO, and from Messrs. D. Reitz, L. Gonzalez, R. Rowland, and W.W. Chan of DASIAC.

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SECTION 1
INTRODUCTION

This Special Report summarizes what is known to date about anomalies observed at early time during the detonation of high-explosive (HE) charges. The sources of information used in compiling this report are discussed in the next section. The reports consulted are listed as References 1 through 40.

The history of the observations and concerns for detonation anomalies began in the mid-1960s with activities peaking in the early 1970s and declining thereafter. This concern began with observations that various types of detonation anomalies were having an adverse effect on field experiments. In many instances, experimental measurements were either completely invalidated or significantly degraded because of them. The fact that no anomalies were observed prior to about 1964 does not mean that they did not exist; very likely they were not observed because of insufficient camera coverage. Discussions, analyses of data, and field tests specifically aimed at a better understanding of anomalies were stepped up in the late 1960s and early 1970s. These efforts resulted in the realization by experimenters that the presence of anomalies were nearly unavoidable, and in fact Patterson et al. (Reference 19) not only concluded that anomalies are very common, but also that an explosion for which they do not occur might itself be classified as an anomaly (Reference 8).

By this time it was recognized that all observed detonation anomalies could be classed into five distinct categories. As given in Patterson et al. (Reference 15), these are:

- Type 1: Luminous precursor jets from the fireball which move ahead of the main shock front.
- Type 2: Nonluminous precursor jets from the fireball which move ahead of the main shock front.
- Type 3: Nonluminous surface precursor jets containing surface material.
- Type 4: Shock-front perturbations which appear not to contain solid material.
- Type 5: Fireball perturbations which affect the shock front.

These types of anomalies have been observed on charges ranging in yield from 0.25 g to 500 tons.* They have been observed mainly (but not only) on TNT block constructed charges, but also on charges made from ammonium nitrate and fuel oil

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* U.S. short tons = 908 kg.

(ANFO), cast charges (TNT, Pentolite, CE, RDX/TNT, etc.), and confined or encased charges. Anomalies have seldom been observed on detonable gas charges, although a recent report by Sedgwick et al. (Reference 24) shows photographs in which the very early-time fireball is seen to have some jetting of the gas near the top. Whether this is a real phenomenon or a problem of photography is uncertain, and Sedgwick et al. do not mention the anomaly.

The most instructive and complete report dealing with the anomalies described above, their significance, related field tests, and speculation as to their origin is given by Patterson et al. (Reference 15 and 19).

The experimenters' concern over detonation anomalies grew out of the observations that anomalous behavior of the fireball and shock front produced by the 500-ton SNOWBALL event resulted in a number of experimental projects emplaced around the charge not meeting with the test objectives. Unpredicted damage and anomalous pressure gauge records were observed. For example, the SNOWBALL event detonation photography and data analysis showed that an irregular fireball with large proturberances and jet-like fingers could extend to distances as large as 800 to 1000 feet from ground zero. Such irregularities of the fireball have considerable effects on experiments around the charge. In such cases, pressure-recording gauges indicated enhanced pressures in the radial direction arriving before the shock front, as well as azimuthal pressures not expected from radial symmetry.

These concerns resulted in the setting up of various Working Groups reporting directly to Panel N-2 (Shock, Blast and Thermal) of The Technical Cooperation Program (TTCP). For example, Working Group F (Reference 15) was set up to (1) review anomalies from the SNOWBALL event data, (2) deduce explanations for them, and (3) make recommendations for their suppression in future tests. Two years later, Working Group H (Fireball and Shock Wave Anomalies) was set up to (1) review all available evidence of anomalies observed on SNOWBALL and DISTANT PLAIN events, (2) determine the most probable causes of anomalies and recommend methods for their alleviation, (3) recommend laboratory or field experiments for verification of causes and alleviation of anomalies in future large-scale tests, and (4) recommmend most suitable means of monitoring and documenting future tests for the documentation of initial detonation and shock formations.

Subsequently, anomalies were also observed on the DIAL PACK event reported by Patterson (References 16, 17, and 18), the PRAIRIE FLAT event reported by Patterson (References 12 and 24) and Wisotski (Reference 28), and the MIXED COMPANY event III reported by Petes (Reference 20) and Wisotski (References 29 and 30).

As will be discussed in Section 3, by and large the understanding of some of the causes were successful but the suppression of some of the more important anomalies such as those of Types 1 through 3 were largely unsuccessful. Undoubtedly, since References 15 and 16 were published (1970 and 1971, respectively) a lot more work could have been done to understand the phenomenology, but it soon appeared from earlier experience that such efforts were doomed to become academic since evidence had already demonstrated that despite all precautions undertaken to minimize or suppress anomalies they continued to be present in large-scale chemical explosions. However, it was noted that such anomalies tended to be considerably less important in their effects from the detonation of ANFO charges, and practically absent in detonable gases. But in the case of detonable gases it was recognized that not enough experimental experience and photographic analysis had been accumulated with them to rule out the existence of anomalies.

In more recent reports on field tests with chemical explosives (for example, References 2, 3, 8, 10, 18, 20, 21, 23, 24, and 30), anomalies are discussed only briefly or mentioned in passing.

In this Special Report, the author judged best to approach this summary in a systematic manner and with some brevity. Consequently, Section 3 gives a detailed description of the different types of anomalies; in Section 4, their origin; the laboratory and field tests carried out to understand the phenomenology are given in Section 5; Section 6 discusses their effects on field experiments; Section 7 briefly discusses methods of suppressing anomalies.

It may appear to a casual reader that brevity in this report was unduely stressed thereby affecting completeness or obviating the need for a more thorough review. Actually there is very little new material that has appeared since that published in Reference 15 in August 1970. Thus, little work has been done on the subject of detonation anomalies and preventing their appearance. Consequently, experimenters must learn to live with them, particularly for block-built charges (Reference 40). Moreover, the cooperation and coordination of national research programs in blast and shock under TTCP has essentially disappeared with its reorganization and the demise of Panel N-2 and Subgroup N (Nuclear Weapons Effects). However, while there has been some foreign participation in U.S. HE test events, the backup research in charge design and small-scale testing has not continued. Also, the various measures proposed under TTCP to eliminate fireball and shock-wave anomalies have all been tried and generally found inadequate except in some cases where pressed charges or cemented blocks were used. Another explanation for the reduction in concern over detonation anomalies is the increased use of blast simulators. Kelso (Reference 40) is of the opinion that despite the fact that large HE tests have continued and may even increase, there is very little ground to justify a fundamental research program to attempt to suppress or eliminate anomalies.

SECTION 2

LITERATURE AND FILM SEARCH

In looking for information on detonation anomalies from chemical explosions, several searches were made. The first search was the contents of the DASIAC library. This yielded the bulk of the material listed as the reference list, most of which consisted of field test and data analysis reports. From these reports a number of references to the open literature were followed up. However, this turned out to be mostly publication versions of field test and data analysis reports. For example, Reference 19 is a version of Reference 15 published in the journal, *Combustion and Flame.* Incidentally, this paper is an excellent and concise description of detonation anomalies. A report by Holsgrove (Reference 32), which seemed important from the context in discussions in some reports, could not be located in time for the compilation of this Special Report.

A computer search of the National Technical Information Service (NTIS), file COMPENDEX, was performed by Anderson (Reference 31). The files were searched under author names and key words. This only turned up 29 report and paper titles with abstracts. All but three of these were relevant and cross reference disclosed that they had already been located in the DASIAC library.

A limited film search was made, particularly of events DISTANT PLAIN, PRAIRIE FLAT, and MIXED COMPANY. This turned out to be a rather lengthy and tedious process as most films were not relevant to the objectives of this report. However, of those films examined that were of any interest at all, excellent photographs of some of the frames already appear in references cited in this report. More to the point, in many of the references cited, composite drawings were made by the various authors from film sequences that reveal the essential nature of detonation anomalies better than the film sequence could in a report. Consequently, the film search was soon abandoned in favor of using drawings and photographs already shown in the cited references.

Finally, budgetary limitations made it impossible to develop plots correlating jet and contact surface growth as a function of time, range, and charge yield. Since to some extent, as will be discussed below, anomalies are difficult to suppress, performing such a task may be neither important nor relevant.

SECTION 3

DESCRIPTION OF ANOMALIES

In this section we give detailed descriptions of the types of anomalies that were cited in the Introduction. It will be recalled that these anomalies have been observed on charges ranging in yield from 0.25 g to 500 tons.

3.1 TYPE 1 - LUMINOUS PRECURSOR JETS

Luminous precursor jets have been observed after the detonation of block-built TNT charges with yields ranging from 500 pounds to 500 tons. An example is shown in Figure 1. The shapes of these charges were hemispherical with the equatorial plane in contact with the ground; spherical with the charge half-buried, tangent to and above the ground; and supported on a tower above the ground surface.* These jets have also been observed on 1000-pound cast TNT spherical charges, on 60- and 500-pound cast TNT hemispherical charges, and on small (1/4-gram) pressed pentolite spherical charges. Jets similar to the Type 1 or Type 2 anomalies observed on TNT field tests have been observed on 20- and 100-ton ammonium nitrate-fuel oil (ANFO) charges contained in fiberglass hemispherical shells.

Early-time photographs of the detonation show irregularities in the fireball whose sizes are consistent with the irregularities of the original charge surface. At a later time (20 milliseconds in the case of the 500-ton PRAIRIE flat event), the luminous precursor jets can be observed moving ahead of the fireball. At this time, they are also ahead of the main shock wave. Jets from TNT charges have been observed to move out radially from the fireball and to emerge from the top of the fireball, at 30 to 45 degrees to the horizontal and nearly horizontally. Examples of these can be seen in the report by Patterson and Dewey (Reference 13).

Some of these jets are short-lived and quickly overtaken by the main shock wave. Others propagate out to considerable distances in front of the main shock wave and can travel to a distance of about 8λ, where $\lambda = R/W^{1/3}$, before

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* GREENHOUSE was a nuclear device detonated on a tower restrained at the top by guy wires. Films of the early-time fireball show luminous jets along the guy wires. These anomalies are not to be confused with HE Type 1 or Type 2 anomalies. The observed jets on the GREENHOUSE event were produced by the intense x-ray preceding the development of the fireball: these x-rays caused the metal guy wires to vaporize out to some distance from the detonation point and only reached full luminosity as the fireball was developing. Thus, these jets appear to come from the interior of the fireball.

being overtaken by the main shock wave. Here, R is the range in feet and W is the yield (tons). The jets have a higher velocity than the main shock wave when they first appear, but are always observed to be decelerating.

These jets normally have a pointed leading tip and a distinct bow wave (see Figure 1). Some jets separate from the fireball completely or are separated from the fireball by a nonluminous region.

A number of luminous precursor jets have been observed to become nonluminous and to continue as nonluminous jets. Other jets gradually dissipate and become nonluminous. At this point they decelerate rapidly and do not propagate as nonluminous jets. The effects of these jets on the blast parameters can be observed for some distance and time after the jet has dissipated.

The jets appear to be formed of a relatively narrow central core which expands into a series of ring-like sections as shown in Figure 2. Viewed from the side, the ring-like sections appear as striations. On the PRAIRIE FLAT event three cameras observed one of the luminous jets which traveled very close to them. The striation pattern was observed and the tip of this jet appeared to be a burning piece of solid material (Figure 2).

3.2 TYPE 2 - NONLUMINOUS PRECURSOR JETS

Nonluminous jets as shown in Figure 3 have been observed on TNT and possibly on ANFO explosions of 20 or more tons. This is not to say that they do not occur on smaller charges. These jets are similar to the luminous precursor jets described above in that they emerge from the fireball at about the same time as the luminous jets. They have a sharp leading tip, are normally observed with a distinct bow wave, initially have a higher velocity than the main shock wave, and are decelerating as they travel outward. These jets usually are as large as the larger luminous jets observed in field tests.

Some nonluminous jets have been observed to become luminous after they have emerged from the fireball.

Both the luminous and nonluminous jets originate from within the fireball so that the luminosity or nonluminosity of a jet may be a function of its time history, or a change in the rate of reaction of the detonation products.*

3.3 TYPE 3 - NONLUMINOUS SURFACE PRECURSOR JETS

Nonluminous surface precursor jets have been observed only on the 50-, 100-, and 500-ton TNT and 100-ton ANFO field tests. They emerge from the fireball at ground level at about the same time or shortly after the emergence of the luminous jets from the fireball. They move out ahead of the main shock front and decelerate

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* TNT is oxygen deficient so that burning or detonation could begin after the material forming the jet exits the fireball. This would explain the transformation of a nonluminous jet into a luminous one.

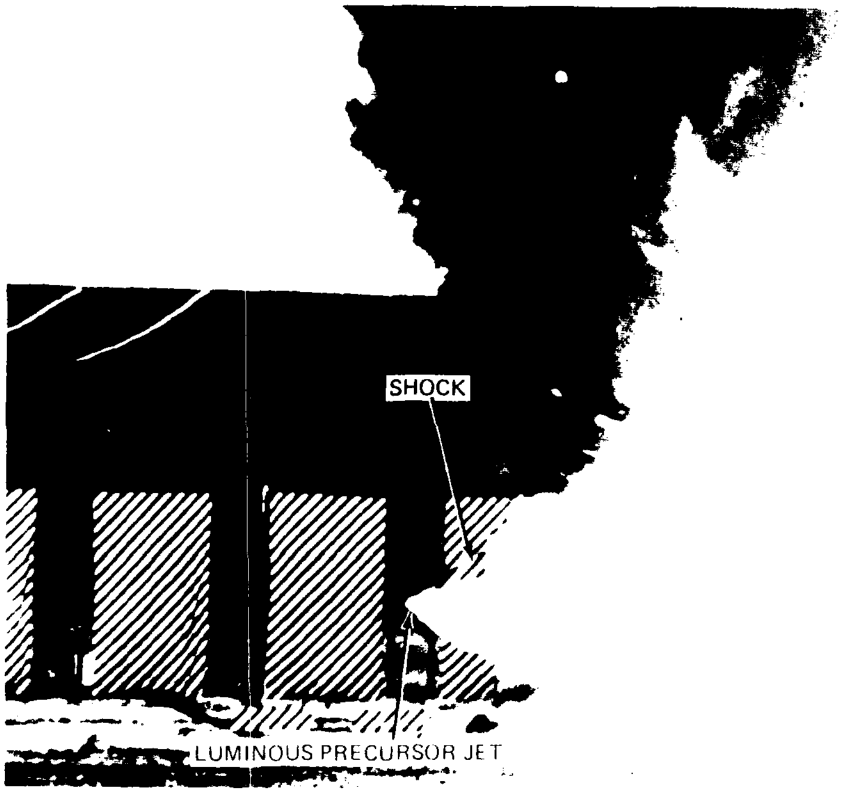

Figure 1. Luminous precursor jet. DISTANT PLAIN Event 3 — 20-ton TNT block-built charge, half-buried sphere.

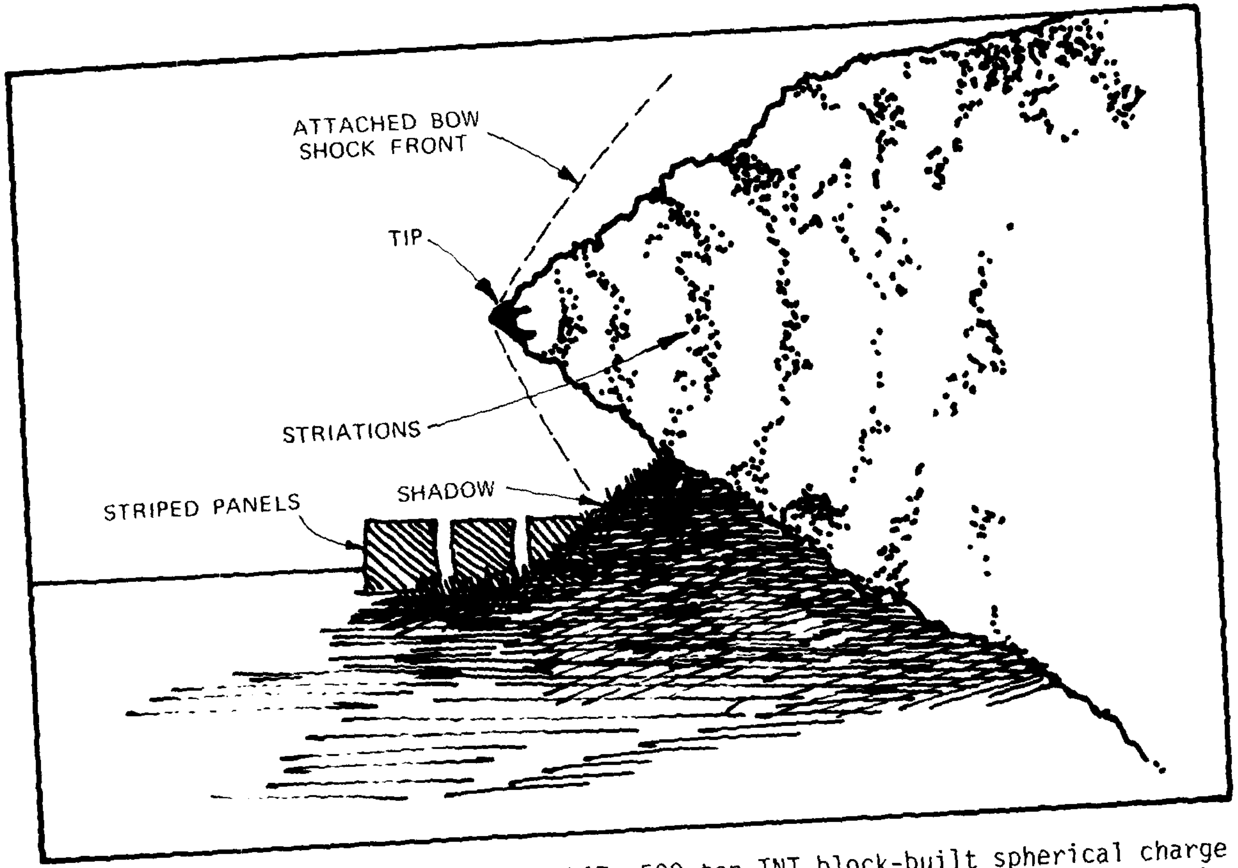

Figure 2. Luminous precursor jet, PRAIRIE FLAT —500-ton TNT block-built spherical charge tangent above ground. (Sketch made by the author from a photograph; original could not be located.)

Figure 3. Nonluminous precursor jet shown at extreme right along the ground surface. DISTANT PLAIN Event 6 — 100-ton TNT block-built spherical charge tangent to and above the ground.

during the time they can be observed. The precursors observed at Suffield* appear to be composed of dust. Two precursors observed in another field test appeared to be composed of water particles. These jets do not lead the main shock front by as much as the luminous or nonluminous precursor jets, and do not appear to broaden appreciably with time as do the luminous or nonluminous precursor jets.

The nonluminous surface precursor jets have round leading edges and the presence of a bow wave is seldom if ever observed on the photographic records, which does not mean they are not present. The effect of the jet on the pressure records can persist for some time after it has been enveloped by the main shock front. On the PRAIRIE FLAT event, the precursor jet along the Canadian gauge line extended out to 805 feet (8λ) from ground zero, but the pressure-time records at 830 feet (8.3λ) still showed a stepped shock wave and it was only at the 1100-ft (11λ) station that the pressure-time record assumed the normal classical wave shape. The majority of these jets can be associated with roads, disturbed areas, or regions over which there has been considerable traffic to and from the charge site. Not all of the jets observed are radial; three on the PRAIRIE FLAT event were nonradial.

Similar nonluminous dust jets have been observed behind or near the main shock front on most ground explosion tests. They have a similar appearance to the precursor type but sometimes appear to start outside the fireball area. Although there are many more nonluminous surface precursor jets than luminous or nonluminous precursor jets, they do not seem to have as marked an effect on the shock front as do these other anomalies. However, the dust they create may have a very significant effect on drag-sensitive targets and on pressure records.

3.4 TYPE 4 - SHOCK PERTURBATIONS

Large shock perturbations have been observed on the SNOWBALL event, a 500-ton TNT block-built hemispherical charge; on DISTANT PLAIN Event 6, a 100-ton TNT block-built spherical charge; and on the block-built 60-pound hemispherical charges detonated at The Atomic Weapons Research Establishment (AWRE) in the United Kingdom (Appendix F of Reference 15).

In the aerial photographs, shown as Figures 4 and 5, these appear as local changes in the curvature of the main shock front. There is no sign of solid material behind the shock front as is observed for the other types of anomalies. Some of these perturbations appear to be related to perturbations on the main fireball or to a dust-free compacted area while others do not appear to be related to either of these.

In the case of the small charge (approximately 60 pounds) work at AWRE (Appendix F, Reference 15), shock perturbations have been observed which appear to be related to the shape of the charge. The shock wave opposite the flat face of the block-built charge lagged behind the shock front opposite the face of the charge containing a large number of re-entrant corners.

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* Defence Research Establishment Suffield (DRES).

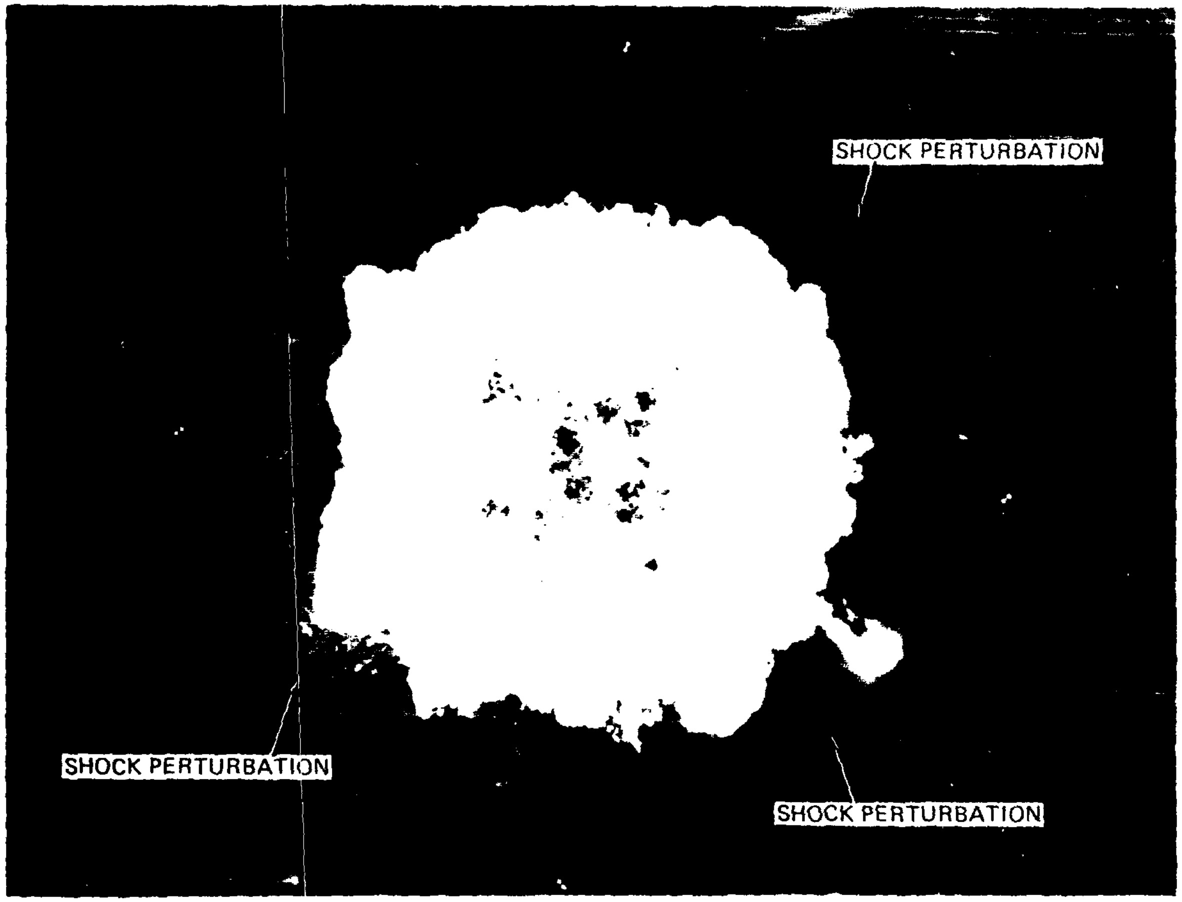

Figure 4. Typical shock perturbations.

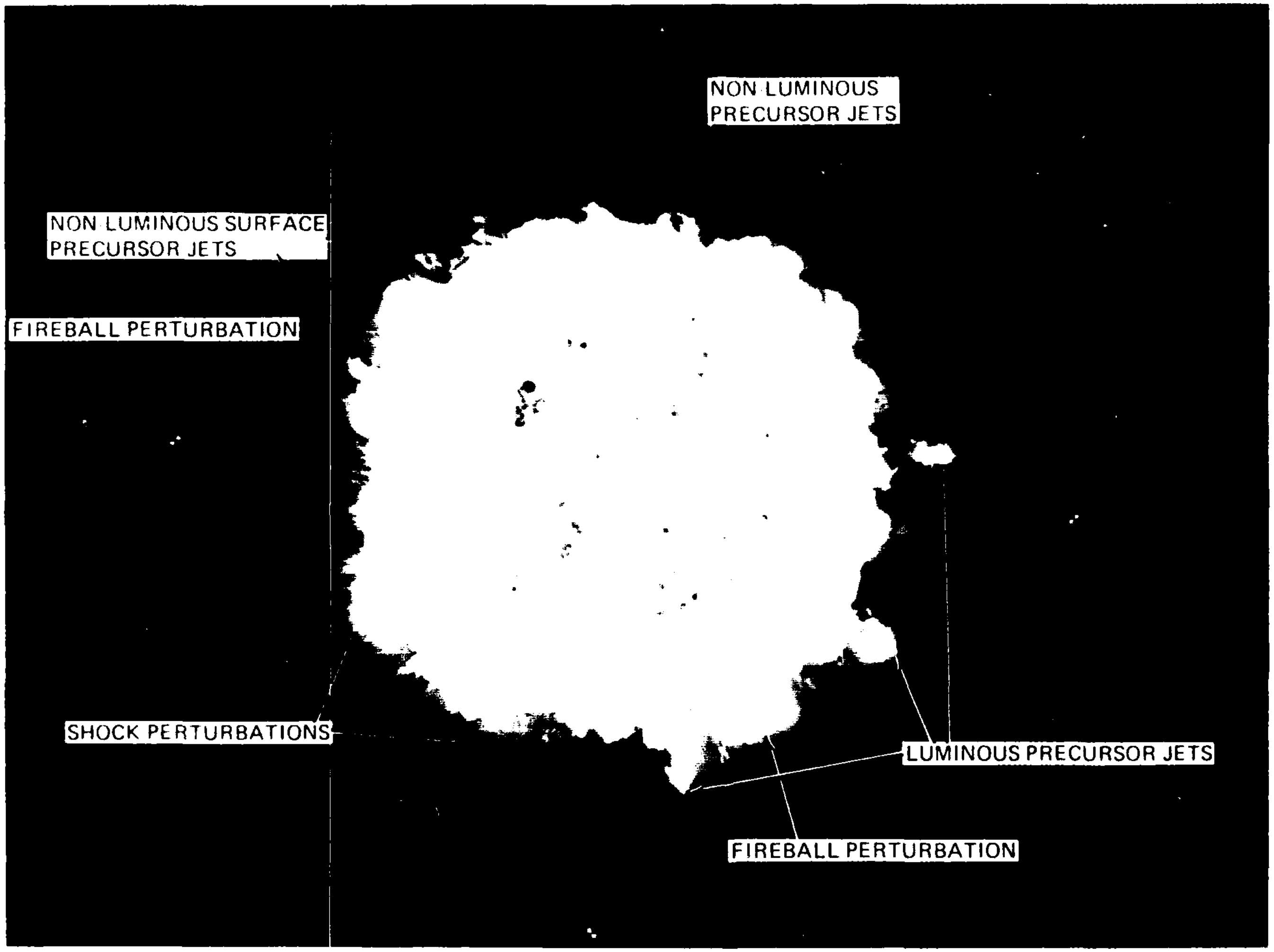

Figure 5. Anomalies on DISTANT PLAIN Event 6 (100-ton TNT block-built spherical charge tangent to and above the ground).

The shock perturbations usually tend to smooth out with time, but in the case of the SNOWBALL event, two perturbations persisted beyond the 10-psi pressure level (1000 feet or 10λ from ground zero). The effect of the cross flow in the vicinity of these perturbations affected some of the targets in this area sufficiently to invalidate the experiments.

3.5 TYPE 5 - FIREBALL PERTURBATIONS

Perturbations of the fireball have been observed on the majority of TNT tests as well as on ANFO tests and on small-scale charges using RDX/TNT and Pentolite. Most of these perturbations are quickly overtaken by the main shock wave emerging from the fireball and do not appear to perturb the shock front to any great extent. The large perturbations can extend a considerable distance from ground zero but have not been observed to travel as far as the large luminous percursor jets.

Fireball perturbations are luminous, have rounded leading surfaces, and are usually broader than the luminous precursor jets (Figure 6). The fireball perturbation is similar to the luminous jet in that it has been observed to separate from the fireball completely or to be separated by a nonluminous region from the fireball. Some of the large perturbations initially have a jet-like appearance which changes to the more rounded tip. The bow shock waves observed on the large perturbation are detached, unlike the luminous precursor jets which have attached bow shocks, and remain so until they are overtaken by the main shock front. Some of the shock perturbations observed can be associated with the large fireball perturbations.

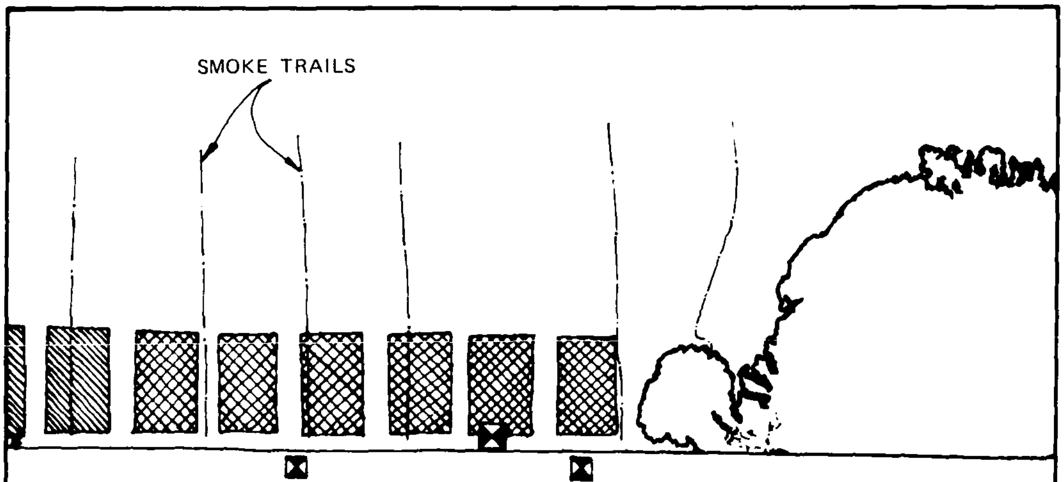

Figure 6. Fireball perturbation observed on 5-ton TNT block-built hemispherical charge. (Sketch made by the author from a photograph in Reference 15; original could not be located.)

SECTION 4
ORIGIN OF ANOMALIES

Before describing the mechanisms postulated for the appearance of anomalies, it is best to summarize the observations of the anomalies described in the previous section. Jetting and perturbations of the shock-front profile have been observed on small as well as large charges, cast and pressed charges as well as block-built charges, rectangular and hemispherical as well as spherical charges, Pentolite and PETN as well as TNT, and free-air as well as surface-burst charges. Indeed, the anomalies observed appear to be due to the nature of explosions emanating from solid explosives.

In contrast to the anomalies observed on solid charge explosions, no anomalies have been observed on detonable gas, liquid charge explosions, or bagged or bulk ANFO contained in cardboard shells. Anomalies have been observed on 20- and 100-ton ANFO charges contained in fiberglass shells. Admittedly, few observations have been made on these types of charges. However, the little evidence in hand on their behavior and the observations of the gross characteristics of the anomalies from the solid charges offer a clue as to the probable causes for these anomalies, namely, the intrinsic mechanical structure of the charges or their containers. Solid charges, prepared by casting, have a definite crystalline structure; solid charges prepared by pressing and prilled ANFO have a granular structure; and liquid and gaseous charges are fluid with no structure. Block-built charges have a structure characteristic of the stacking arrangement.

4.1 TYPES 1 AND 2 - LUMINOUS AND NONLUMINOUS PERCURSOR JETS

In small solid and pressed charges, the detonation process progresses from crystal to crystal or grain to grain. Each successive explosive crystal, as it is engulfed by the high-pressure, high-temperature detonation wave, detonates, thereby further maintaining and propagating the detonation front. However, it is possible that some isolated crystal or grain or series of crystals or grains do not detonate. This denser material, whether within the charge or on the surface, will, due to its greater inertia, decelerate more slowly than the fireball and emerge from the fireball at supersonic velocity. Because of its density, a bow wave will accompany this ejected or spalled explosive material.

It is most probable that this undetonated material will be burning rather than detonate. Therefore, when it is ejected from the charge the combustion products will trail the still solid piece of explosive giving rise to a jet-like appearance such as shown in Figure 7. These jets may be luminous or nonluminous depending on the temperature of the combustion products. In fact, the jet may go from luminous to nonluminous and vice versa. At the very start of its trajectory the deflagrating material would be luminous and its combustion products luminous because of the temperature involved. In the course of its travel, the deflagrating material

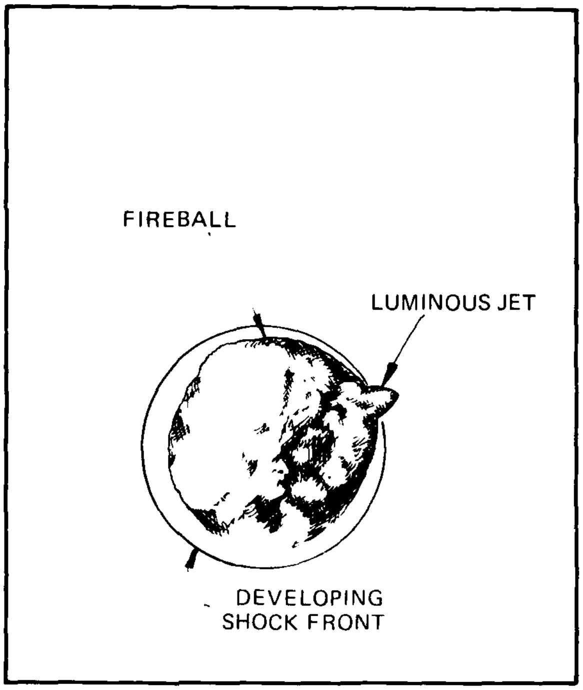

Figure 7. Luminous precursor jet on 13.7-gram spherical Pentolite charge. (Sketch made by the author from an unidentified photograph.)

and the combustion products may cool and become nonluminous. On the other hand, if the ejected piece of explosive has not reached deflagration conditions but is only burning at a relatively slow rate, the jet may be nonluminous. As the jet contents mix with the air, the oxidation rate will be increased and the burning will be enhanced. This could lead to the jet becoming luminous. As the ejected piece of explosive is consumed by burning or deflagration, the jet will dissipate. The size and density of the ejected material will determine the physical length and duration of the jet and its gross physical appearance. In some situations, the jet will detach itself from the main fireball; in others it may remain attached to the fireball throughout its history. It is the supersonic flight of solid or highly dense matter which produces an attached bow wave so often observed in photographs (see Figures 1 and 2.)*

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* It is fitting here to remind the reader that there is a distinct difference between detonation and deflagration: they refer to different points along the Rankine-Hugoniot curve. Without going into a lot of mathematical details, what this means is if we designate p_o and p_f the initial and final pressures, respectively, and ρ_o and ρ_f the initial and final densities of the material, respectively, then for a detonation $p_f > p_o$ and $1/\rho_f < 1/\rho_o$, while for a deflagration $p_f < p_o$ and $1/\rho_f > 1/\rho_o$.

In small charge experiments, it appears that undetonated and unburned pieces of explosive are thrown off from the charge and produce bow waves. On other small charge explosions no particulate matter or gases may be observed behind the protruding bow wave, that is, a nonjet-like anomaly is present.

Another hypothesis, similar to the preceding one, has been advanced for the generation of the jets. Some crystals or grains within the charge may not detonate but only deflagrate or burn. These create pockets of dense combustion products within the fireball. These pockets are ejected in a manner similar to the solid pieces mentioned above. Depending on their temperature, these dense masses are luminous or nonluminous when they first appear and, depending on the mixing pattern of these combustion products with the air in the course of their trajectory, they may become luminous or nonluminous just as described for the solid ejected explosive combustion products.

It is not necessary to establish precisely whether the jetted material is solid or simply a pocket of dense material. It is sufficient to note that because of nonuniform detonation within or at the surface of the charge a high-density mass of material is ejected at high speed. This fast-moving mass generates a bow wave. If the material burns, it also generates a smoke trail behind it, which, depending on the rate of oxidation, appears luminous or nonluminous. This phenomenon is called a precursor jet of Type 1 or 2.

Note that in the above, reasons have been given for jetting from small, solid, pressed, or cast spherical charges carefully prepared for laboratory study. These charges have relatively uniform grain or crystal structures. Experience with large charges, particularly large cast charges, indicates that large-scale inhomogeneities in them may exist. Cross-sectional cuts of large cast TNT charges have shown many voids, irregular crystal patterns, hairline cracks, and gradations in color which would correspond with density variations.

In view of the experiments made with small charges, it is not surprising to see jetting from large charges. The large charges, because of their nonhomogeneity, offer many opportunities for incomplete or nonuniform detonation of isolated portions of the charge, leading to the formation of pockets of dense combustion products or solid pieces of undetonated charge which subsequently are ejected and burn causing the observed jets.

Block-built charges may be even more susceptible to producing jets than solid charges. In addition to the inhomogeneities present in most cast blocks, the block construction introduces discontinuities between blocks. In some preliminary work Holsgrove (Reference 32) has demonstrated the sudden drop in detonation velocity as the detonation wave propagates from one TNT block into the abutting block. He also indicated that it takes about 4 inches of travel through the next block before the full detonation velocity is reached. Wisotski (Reference 33) in his experiments with a single row of stacked pressed TNT blocks showed discontinuities in the envelope of the explosive product as each interface between blocks is reached. In short, experimental evidence indicated that a degradation in the detonation can have an adverse effect on the detonation potential of any small volume of charge.

It should be noted that in the normal stacking of large charges with 12- x 12- x 4-inch blocks only the blocks in the equatorial plane have their 12- x 12-inch planes perpendicular to the direction of propagation of the detonation front. Most other blocks have a shorter radial path for the propagating detonation front. The blocks in the vertical direction have only 4 inches of charge for full detonation velocity to be achieved. In the light of Holsgrove's work (Reference 32) 4 inches of charge length is not quite sufficient to attain full detonation velocity for TNT. Consequently, Holsgrove's work implies that the detonation front would reach the equatorial plane prior to reaching the pole of spherical or hemispherical charges. However, ultra-high-speed films (for example, Reference 39) show the luminosity of the emerging detonation front at the charge surface to be nearly uniform over the sphere or hemisphere implying that the detonation front arrives at most points on the surface at the same time, at least within a few tens of microseconds. Therefore, there are apparent contradictions in our understanding of detonation-front behavior in single block versus stacks of blocks of explosives.

With the type of charge construction usually employed for the large TNT field tests, it would be unlikely if full detonation velocity of about 6500 m/sec were maintained throughout block-built charges. At block interfaces the velocity could drop below 6000 m/sec and at voids within the blocks and gaps between the blocks, the detonation velocity could be reduced still further. If high-resolution detonation velocity measurements could be made throughout the whole charge configuration, significant fluctuations in detonation velocity undoubtedly would be observed. This would imply an irregular detonation front. Such a front has been observed for a 20-ton block-built charge detonated on a tower. Ultra-high-speed photographs from the DISTANT PLAIN event 1 recorded at 264,000 frames/sec shows this very well (Figure 8). With such an uneven front, there is a high probability that isolated portions of the mass of charge might not detonate. This would lead to the jetting phenomenon discussed above for small solid charges and the jetting which has been observed to occur for block-built charges.

In the preceding discussion it was considered that in the block-built charges, the blocks in the vertical or near vertical plane are in the least favorable orientation for high-order detonation. Consequently, jetting could be expected to be more prevalent in the vertical directions than in the horizontal ones. This appears not to have been the case. On the post-1960 Canadian field tests this has not been observed; there were more horizontal and near horizontal jets than vertical or nearly vertical ones. On the SAILOR HAT and FLAT TOP events, no Type 1 or 2 jets were observed.

An explanation for the observed pattern of jetting has been advanced considering the basic structure of the individual blocks. The 12- x 12- x 4-inch blocks used on the post-1960 Canadian field tests and on the SAILOR HAT field tests were simlar; both were made of reclaimed TNT and both were cast in the same way and at the same temperature. However, there was one basic difference in the preparation of the blocks. The Canadian blocks were cooled after pouring in a cold water bath until solid. The SAILOR HAT blocks were cooled in a cold water bath for only 45 minutes and continued solidification of the blocks took place at room temperature in about 5 to 6 hours. These slightly different cooling procedures resulted in

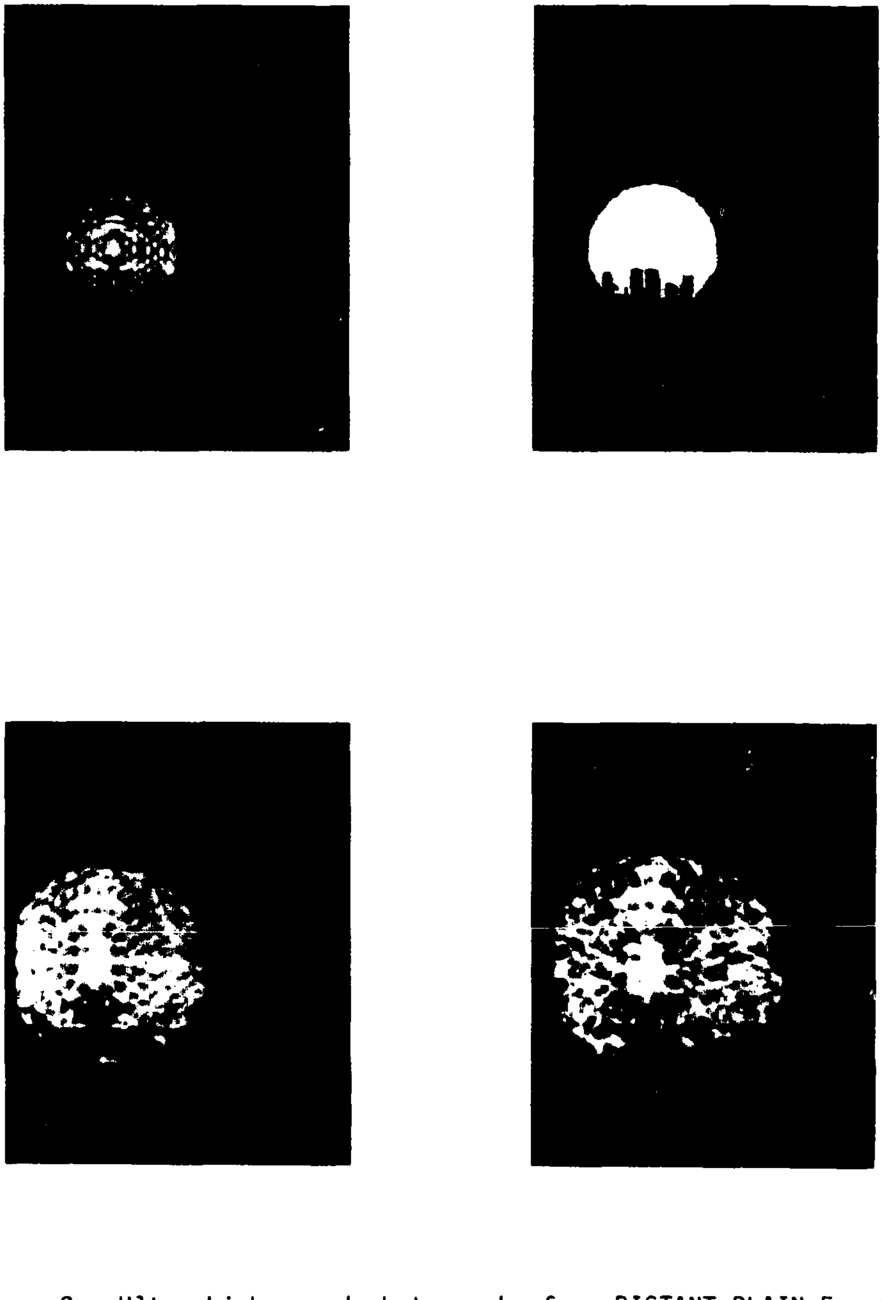

Figure 8. Ultra-high-speed photographs from DISTANT PLAIN Event 1 recorded at 264,000 frames per second (Reference 39).

large shaped crystals across the 4-inch width of the fast-cooled Canadian blocks with plane cleavage faces. The slower cooled SAILOR HAT blocks had somewhat smaller crystals with some interlacing of crystal structure and irregular cleavage faces (Reference 15). It was observed that the Canadian blocks were more fragile than the SAILOR HAT blocks and consequently tended to break easily along the crystal boundaries.*

It can be surmised that in the Canadian field tests, those frangible blocks in the vertical plane that did not detonate broke into small crystal-size pieces. These pieces, as solid explosive or, after deflagration, as small pockets of dense material, were thrown out only to short distances before being completely consumed. Their mean travel distances were so short that they never reached outside the fireball and hence, few vertical jets were observed.

The above explanation also can be offered for the observed lack of vertical jets on the SAILOR HAT field tests. Although the SAILOR HAT blocks were slightly stronger than the Canadian blocks, they nevertheless were frangible and subject to shear along crystal interfaces.

The lack of jetting in the FLAT TOP event (if in fact there was no jetting on that event) may be attributed to the different size of the blocks. Here the block size was 8 x 8 x 8 inches. The 8-inch dimension is adequate to attain full detonation velocity in each block. The crystal structure of these blocks is unknown. Unfortunately, no information could be found which presents discussions relating jetting and other anomalies to the block sizes.

Summarizing the probable origin of Type 1 and 2 jetting, it is assumed that random parts of the charge do not detonate. This assumption is based on observations and some corroborative knowledge of explosive behavior. Nonhomogeneities in the individual blocks and at the interfaces between blocks are conducive to irregular detonation as the detonation wave progreses through the charge. The undetonated piece of charge in its original solid form, or as a pocket of dense combustion products resulting from deflagration or burning, is ejected from the main charge at supersonic velocity. This dense mass produces a bow wave and a trailing luminous or nonluminous cone of swirling matter. The luminosity or nonluminosity of this jet is dependent on the mixing temperature and mixing of the ejected material with the surrounding air. Once outside the fireball, extensive oxidation can be expected because TNT is oxygen deficient.

Early in the study of jetting anomalies on block-built charges it was postulated that there was a preferential direction along layered interfaces for jet production. This explanation could be applied to horizontal jetting, but could not explain vertical jetting since there were no large vertical plane interfaces.

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* In making the initial SAILOR HAT blocks, using the Canadian procedure, difficulty was experienced in removing intact the solid charge from the mold. The cooling procedure was then altered to provide longer cooling time and resulting in a block of apparently greater mechanical strength.

Although this mechanism is not discounted at this time, its significance appears to be secondary.

Lest the influence of the booster on jetting be questioned, it is noted that for most of the Canadian large-scale field tests, cylindrical or spherical boosters were used. In contrast, on the SAILOR HAT series, rectangular boosters were employed. Remembering that almost no jetting occurred on SAILOR HAT and considerably more on the Canadian field tests, it is apparent, at least for large charges, that booster shape has little influence on the detonation pattern farther out so long as detonation is achieved deep within the charge. This observation has been used to argue for minimum, but adequate sized boosters, since detonation-front irregularities at the booster-main charge interface will decrease as the detonation front progresses radially through the charge.

A question can be raised as to the sensitivity of an explosive crystal to detonation when it is initiated along the crystal axis rather than at right angles to it. This may have a bearing on the detonability of a 12- x 12- x 4-inch block. However, this line of reasoning has not been pursued into experiments.

All in all, inhomogeneities in block-built and cast charges appear to account for Type 1 and 2 jetting phenomena.

4.2 TYPE 3 - NONLUMINOUS SURFACE PRECURSOR JETS

Many nonluminous surface precursor jets have appeared on the 50-, 100-, and 500-ton field tests and none were observed on smaller field tests. As described earlier, the jets on the Suffield tests appeared to be along the ground surface and composed of dust. They were seldom, if ever, accompanied by a bow wave, showed leading edges, and were usually, but not necessarily, expanding along radial directions. They usually have been observed to occur over heavily traveled roads or other work surfaces that were produced during the charge and experiments construction.

The observations that these anomalies are not always radial and that they can be associated with roads or disturbed regions led to the hypothesis that they may have been caused by ground waves. In surface bursts of condensed explosives, exceedingly high pressure waves are generated on the earth material directly through the charge-surface interface, and from the coupling of the air shock with the ground. Ground shock can precede or lag the air shock depending on the intensity of the direct ground- and the air-coupled shock wave, on the ground range of the observation point to the charge, and on the seismic properties of the ground medium.

It is known that heavily traveled road surfaces are well compacted and have a higher density than the surrounding areas. The higher density produces higher ground shock and ground wave velocities than in the lower density ground since the compressional and shear wave velocities are proportional to $\sqrt{M}$, where M is the in-situ material modulus. Thus as the density increases so does M and consequently the propagation velocity also increases. If the road areas are dust covered, or easily spalled, dust and small particulate matter may be raised into the air because of the ground-induced shock wave in these areas of high density (Reference 34).* Where these high-velocity regions are not exactly radial, nonradial, nonluminous surface precursor jets can be expected. The fact that the majority of the jets observed were radial was probably because most of the roads, work areas, cable trenches, and other test configurations were radial.

Summarizing the probable reason for nonluminous surface precursor jet formation based on observations of the Suffield field tests, it appears that dust in relatively large quantities can be raised in a jet-like turbulent pattern in the areas of disturbed soil. Depending on the seismic properties in the area and the condition of the surface material, trailing or precursor jets can arise.

This mechanism can also be used to explain the two surface jet-like anomalies observed on SAILOR HAT over the water surface. It has been noted that the underwater ridges ran radially from the charge in the area of the anomalies. Another possible explanation for these jets observed on the SAILOR HAT event is that the ejected material traveled close to the water surface and created a precursor disturbance.

It should be noted that no anomalies of this type were observed on the surface adjacent to gas balloon detonations. This is undoubtedly due to the fact that the low detonation and shock wave pressures† produced by such shots were insufficient to produce a strong enough ground shock, and hence little or no observable dust was raised into the air.

4.3 TYPE 4 - SHOCK PERTURBATIONS

Another anomaly of considerable importance on large-scale field trials is the shock front perturbation which apparently does not contain solid material. In aerial photography, the shock front appears dimpled, sometimes with relatively sharp cusps and other times with gentler curves (Figure 4). No high-velocity particulate matter preceding or trailing can be uniquely associated with those outward thrusts of the shock front. In fact, it has been noted that in some localized areas the shock front perturbation appears to lag behind the main shock.

There are difficulties in identifying this anomaly in elevation view photographs of the shock front with a plain sky background. In some elevation pictures where clouds are part of the background, slight density variations in the shock front can be discerned but it is difficult to identify these as dimples or protuberances. In some cases, because of the height of the cameras above the ground

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* High-speed photography near the crater edge of gram-size charges detonated on the surface of beds of sand showed a heaving or spalling of the upper layers of sand into the air (Reference 34), this spalling being due to the reflected tensile wave behind the ground shock.

† Solid explosives develop detonation pressures on the order of 70 to 100 kbar (1.02×10^6 to 1.45×10^6 psi) compared to a few hundred psi from methane/oxygen gaseous detonations.

zero terrain elevations, this type of anomaly has been observed. A number of possibilities for the origin of these anomalies are now discussed.

One possible hypothesis has to do with the gross peripheral characteristics of the block-built charge. It has been observed visually, but not well documented, that in a completed multiton charge there are some areas of the surface which appear to be more planar than spherical. This is a consequence of the intersection of block surfaces upon a sphere. If this gross planar surface exists (discounting the small rectangular corners of individual blocks), then some directionality of the shock front can be expected. Work by James and Rowe at AWRE (see Appendix F of Reference 15) with 60-pound charges shows definite flat areas and also areas composed of numerous re-entrant corners. The latter could perhaps give rise to effects similar to a hollow-shaped charge. Measurements have shown nonsymmetrical propagation of the shock front around the charge and differences in pressure amplitude at a given radial distance as a function of the azimuth angle around the charge. This explanation for shock-front perturbations must be viewed with some reservation.

In small size charge experiments, perturbations in the shock front without any particulate matter following the shock front have been observed and a sketch is shown in Figure 9.* Whether or not this is the same kind of anomaly observed on the large shots is difficult to determine. The small-charge shock anomalies have rather pointed leading tips. It may be that these shock fronts contain small solid particles not observable in the photograph, or the solid particles have been consumed leaving the bow wave. The smoother curves of protuberances observed with elevated cameras for 20- and 100-ton ANFO events may be bridging waves between several close-by jets.

The experiments with small charges performed at AWRE and reported by Mawbey and Rowe (Reference 11) show a precursor wave when a small charge is fired over a steel plate. The charge was 1/4-g PETN detonated on a steel plate against the corner of a plasticene wall erected perpendicularly to the plate. Schlieren photographs show a precursor shock moving along a steel plate and ahead of the main shock. The detonating charge causes waves to be transmitted through the steel to the air above, and through the plasticene. These waves appear, in the Schlieren photographs, as interferences running parallel to the steel plate and the plasticene wall (Reference 11). More will be said on this in Section 5. They surmised that a wave runs through the steel plate and generates an air shock wave with no particulate matter thrown into the air, although over a sandy bed particulates are thrown up into the air (Reference 34). In field tests, a similar situation could occur. Close to the charge a ground shock propagates ahead of the airblast producing a compression wave in the air which may perturb the main shock. If the ground material is dust free, only the perturbed air shock would be observed without dust or other particulate matter following it.

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* The film strip for this perturbation could not be identified. Therefore, the author made an ink sketch from a photograph taken from Reference 15 which is shown here as Figure 9.

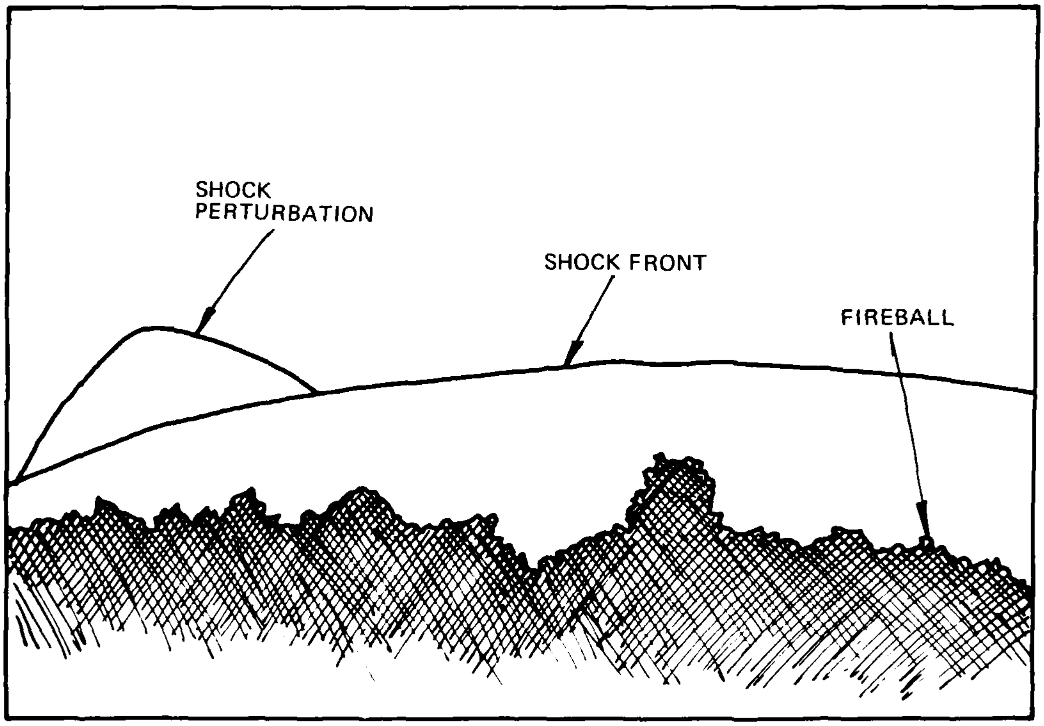

Figure 9. Shock perturbations on 1-pound Pentolite sphere in free air (sketch made by the author from an unidentified photograph).

Shock perturbations of this type have been produced in laboratory experiments by a negative temperature gradient in the air adjacent to the ground surface. This has the effect of increasing the velocity of the part of the shock front in the region of maximum temperature near the ground. Consequently, on encountering such a thermal layer the foot of the main shock commences to lead the remainder. This shock configuration will not support the necessary condition of horizontal flow along the ground. The situation is resolved by the appearance of a lambda-shaped shock near the ground. Following the curve of the main shock front down into the heated air layer a point is reached where it divides into two curved shocks joining this point to the ground. The forward of these two shocks is often termed a thermal precursor.

Experiments at AWRE using 60-pound hemispherical charges, in which a scaled temperature gradient similar to those obtained on the larger Suffield field tests was produced, showed no significant change in recorded pressure-time profiles. Optical observation of the moving shock front showed a small number of weak secondary shocks apparently unaffected by the presence or absence of a thermal layer. Earlier work with 4-lb hemispheres indicated slightly higher shock velocities but these did not correspond to a significant increase in shock overpressure.

Therefore, it is reasonable to conclude that thermal conditions normally obtained near the surface at the site of large HE detonations are not responsible for the production of the Type 4 anomalies. However, in the case of surface nuclear or slightly above-surface nuclear detonations, precursors are expected since the weapon radiation heats the ground prior to shock arrival for a large distance from ground zero. The ground then becomes the source of the thermal gradient necessary for the air shock to develop a precursor.

4.4 TYPE 5 - FIREBALL PERTURBATIONS

Three probable causes of fireball perturbations have been postulated: shape of the charge, instabilities in the fireball, and ejection of detonation or combustion products from within the fireball.

On many field tests, small fireball perturbations have been related to the shape of the charge. For block-built TNT or bagged ANFO hemispherical charges, the perturbations have been associated with regions which are less hemispherical in shape than the rest of the charge. Figure 10 shows the tracings from a Mitchell camera sited south of ground zero. The event is a 20-ton bulk ANFO hemispherical charge. A number of fireball perturbations were observed, and no large anomalies were noted on the photographic records. The fireball was relatively smooth, but it showed a region that appeared to be hotter than the rest of the fireball; it appears as a horizontal white band parallel to the ground at about half the fireball radius and about one-fourth the radius in width. It was plainly visible at approximately 10 msec after detonation, and disappeared approximately 2 msec later. It has been postulated that this band could be associated with an ANFO layer containing a different concentration of fuel oil than the remainder of the charge. Figure 10 shows shock and fireball perturbations to one side and near the top of the fireball. Before about 40 msec the fireball perturbations near the top are ahead of the main shock front, and after that time the shock wave is hemispherical and the effects of the perturbations have essentially disappeared. Note the slight perturbations in the shock on frame 6 tracing in the left quadrant of Figure 10.

For cast TNT spherical charges, fireball perturbations have been associated with the small ridge on some charges where the two halves of the molds meet or with the region of the detonator channel. Small perturbations have also been related to the degree of containment of the charge, for example, the overlapped joints on the fiberglass container used for the ANFO bulk charges or the nets used for supporting charges above the ground. These perturbations are usually quickly overtaken by the shock front and have little apparent effect on the shock front once it has separated from the fireball.

The instabilities in the fireball, which are an inherent part of the detonation process, can give rise to larger perturbations. Some of these perturbations can be associated with gross surface irregularities in the charge or with regions of nonuniformity in the charge or in the charge container; for example, the region of the plug in the DRES cast spherical charges where the grain structure is very nonuniform, or the nonuniform breakup of the fiberglass container used on the ANFO charges.

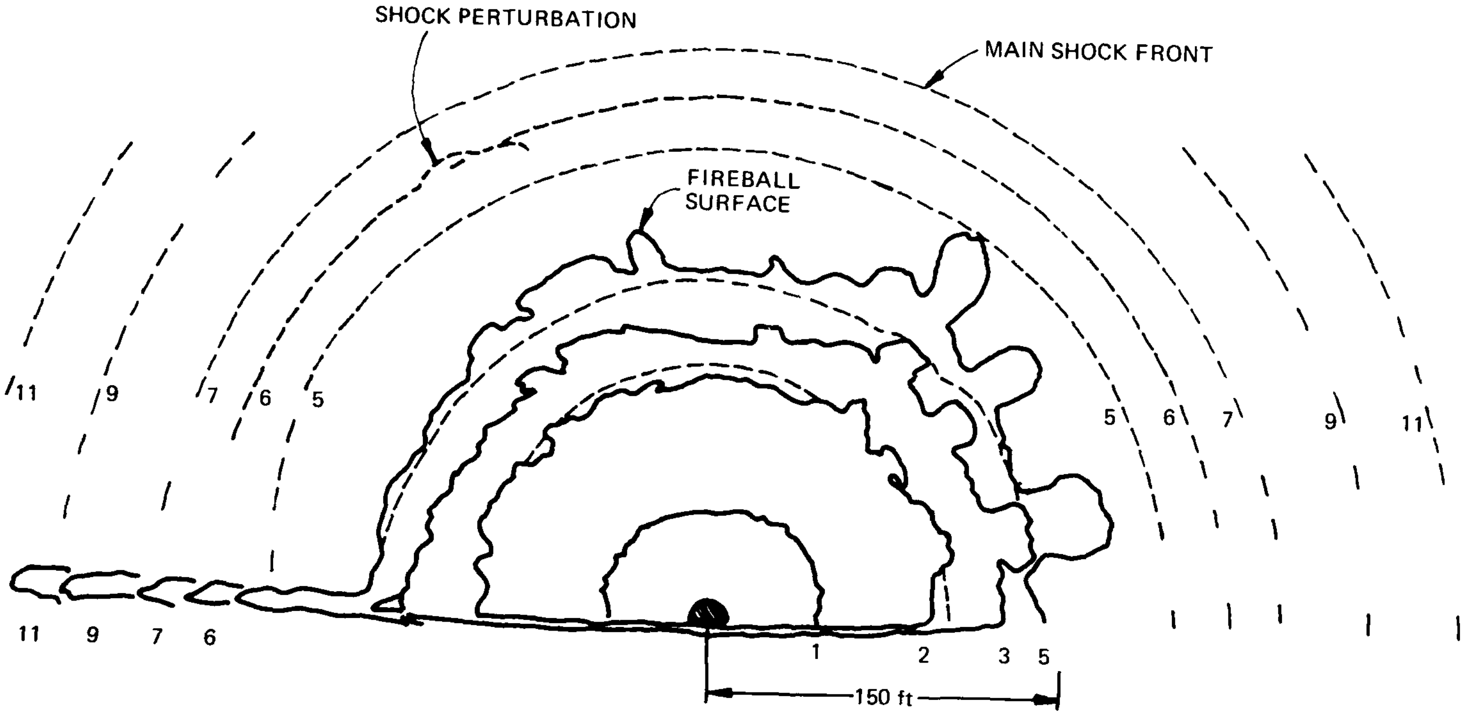

Figure 10. Tracings from Mitchell camera sited south of GZ—ANFO Event II, 20-ton hemispherical bulk charge. (Numbers refer to frame numbers—100 frames per second.)

The third process appears to be similar to that proposed for the luminous precursor jets, namely, ejection of detonation products from within the fireball. In aerial photographs of the early fireball formation it is difficult to determine which protuberances will develop into Type 1 anomalies and which will develop into the round-tipped perturbations. It has been suggested that the controlling parameter is the density of the region causing the anomaly. Large pieces of explosive, regions of smaller pieces of explosive, or high-density regions of detonation or combustion products give rise to the luminous precursor jets, and lower density regions of detonation or combustion products give rise to the fireball perturbations.

SECTION 5
LABORATORY AND FIELD TESTS

In this section we briefly discuss some of the experiments carried out in the laboratory and in field tests with the aim of elucidating the origin of observed anomalies. The results of these experiments then would suggest methods for their suppression, a discussion which will be taken up in Section 7.

5.1 LABORATORY TESTS

The various anomalies occurring on large-scale field tests can be studied only infrequently, when such tests take place, and the occurrence of anomalies cannot be readily predicted. A more convenient approach is to work in the laboratory or on a small field scale where repeated firings can be made under closely controlled conditions in an attempt to produce the various phenomena observed on the large-scale tests. The hope was that the close control possible in small experiments would enable causes to be assigned to each type of anomaly. The small-scale experiments to be discussed here were conducted by the Atomic Weapons Research Establishment (AWRE), Foulness, U.K., under the TTCP (Reference 15).*

The laboratory and small field experiments consisted of the following two programs:

1. Microscale Experiments. These experiments were conducted to produce precursor shocks due to coupling between the faster seismic surface waves and the slower main air shock. Variations in precursor strength with ground material and thickness were investigated.
2. Experiments with 4-lb Hemispheres of PE2. These experiments were small field experiments to examine optically the effect on the shock profile in the vertical plane of various charge deformations such as a hole in the charge, a large fragment loosely attached to its surface, and a small additional spherical charge loosely attached tangentially to the main charge.

The microscale experiments were conducted mainly with 0.26-gram PETN spherical charges detonated tangential to a plane surface and also at low heights of

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* Most of the precursor-type experiments carried out by AWRE in the U.K. with microscale charges have been duplicated by the United States, principally at the Naval Ordnance Laboratory (NOL) (Reference 40).

burst. One hemisphere with its plane surface in contact with the supporting plane was also fired.

In one experiment the precursor shock resembled a skirt at the foot of the hemispherical shock.* In some cases the tangent plane of the precursor turned through an angle of 90 degrees as the point of contact of the tangent moved toward the ground. This is shown in Figure 11 and applies to a charge fired over a steel plate with a change in thickness. Note that the precursor at the right becomes downward-facing, a feature of at least one of the Suffield precursors. This is not so evident on the left where the steel plate is thinner. One would expect a continuation of the main shock in the positions shown by the dotted lines. In fact, this portion is difficult to see because of the turbulence inside the shocked air bubble (Reference 11). To isolate the steel-driven component of the air shock, a wall of plasticene was placed at one side of the charge (Figure 12).

Figure 12 summarizes much of the investigations (References 11 and 15). The detonation produced a precursor at ground level which was joined to the main shock at a height of a few charge diameters. It was suggested that the coupling between the elastic shock in the steel and the air was responsible for the precursor by giving rise to air shocks in advance of the main shock. This precursor resembled closely that photographed against the diagonally striped backdrops by the low-altitude, particle-velocity camera in the 500-ton SNOWBALL event. These steel-driven air shocks can be seen on the right of Figure 12 where the main shock has been blocked by a wall of shock-absorbent plasticene. These shocks appear as a number of parallel lines inclined at about 10 degrees to the horizontal. The replication of such shocks was considered to be due to multiple reflections within the steel plate.

The strength of the precursor appeared to be an increasing function of acoustic impedance of the "ground" material. Some reduction in strength occurred when firing over clay and still further reduction when firing over wood. Precursor strength was also shown to be a decreasing function of height of burst, being zero when the charge was elevated above the ground surface by about 3 charge diameters. For steel, optimum precursor strength was observed when the "ground" surface thickness was between 1 and 3 charge diameters.

Great precursor enhancement relative to that from a 0.26-gram sphere was obtained by firing a 0.15-gram hemisphere in contact with the steel surface. This was possibly due to better energy coupling into the "ground."

From these microscale experiments the following conclusions were drawn:

1. A precursor is well formed at 20 to 30 charge radii. At 40 charge radii it has slowed and appears to coincide with the

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* On the field tests carried out in 1967 and 1968 using spherical TNT charges tangent to the surface (DISTANT PLAIN Events 5a and 6, and PRAIRIE FLAT), a skirt on the main shock, which was due to the shape of the charge, was observed. This skirt on the shock wave was not as pronounced as that observed on the micro-charges.

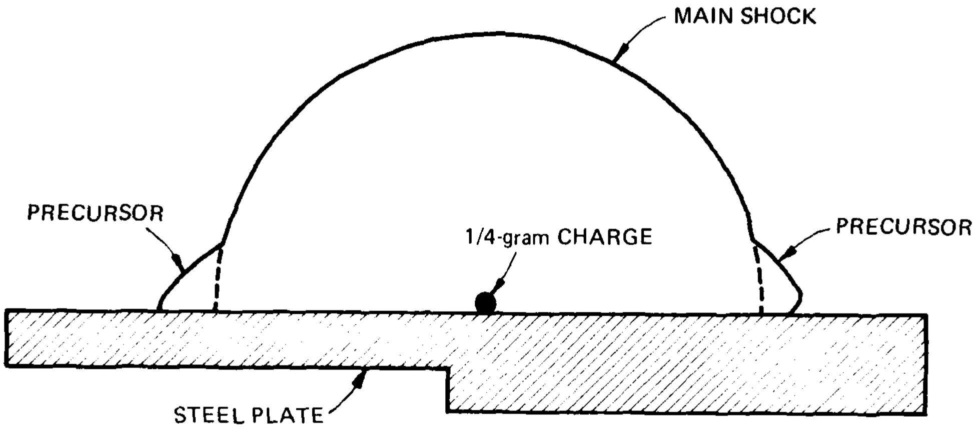


Figure 11. Shock pattern from 1/4-gram charge.

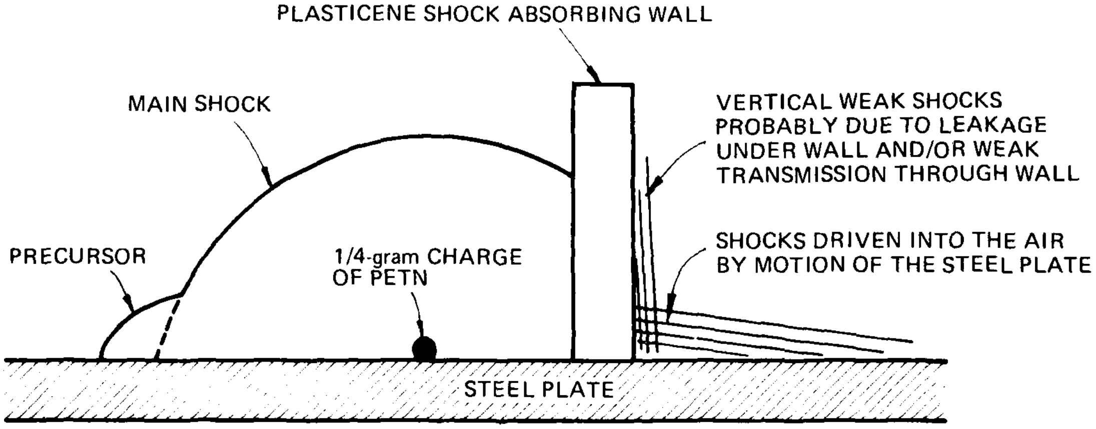


Figure 12. Shock pattern from 1/4-gram charge with wall in position.

incident shock. Such phenomena have been observed on multi-ton field tests.

2. The strength of the precursor varies with the thickness of the compacted layer on which it is fired. In the case of the microscale experiments the precursor shock was strongest when the steel plate thickness lay between 2 and 6 charge radii.

On the assumption that the behavior of well compacted ground will approximate the propagation characteristics of steel, Mawbey and Rowe (Reference 11) estimated minimum compaction layer thicknesses needed to ensure that a precursor will form for multiton charges. These estimates are given in Table 1.

3. The precursor shock strength is a decreasing function of height of burst and is zero when the HOB reaches about 3 to 5 charge radii.
4. For a given plate thickness (say, 1/2 inch), the precursor height varies as the cube root of the charge mass.
5. A hemispherical charge of PETN (0.15 gram) resting on the surface gives a much stronger precursor than the same mass as a tangential sphere. This follows from the mode of energy coupling into the plate.

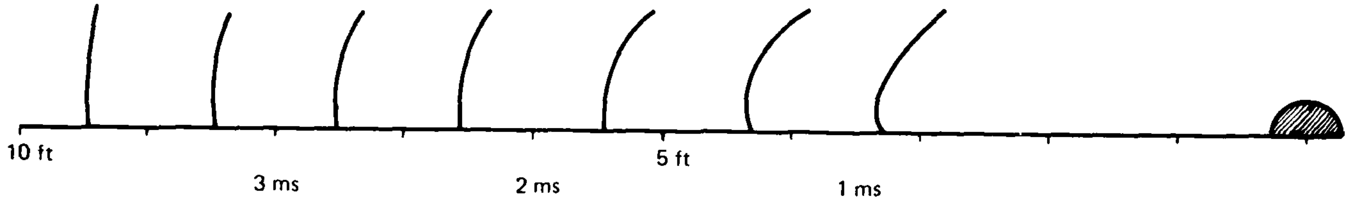
Table 1. Compaction layer thickness to produce precursors.

Charge Mass (tons)	Thickness of Compaction Layer (feet[a])
500	12
100	7
20	4.5

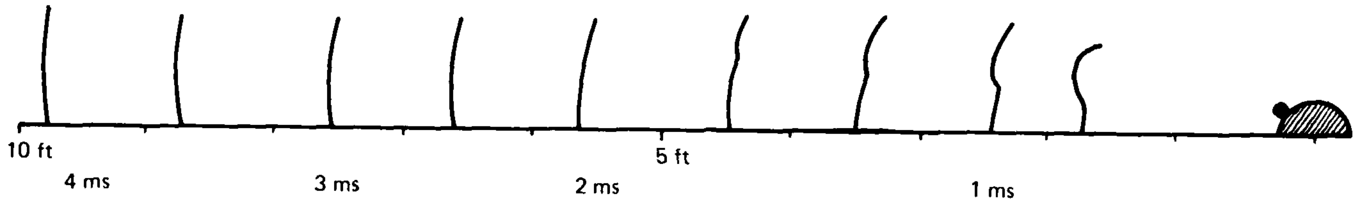
[a] Or depth to an interface such as a water table.

Small-scale field experiments were also carried out at AWRE. The charges used were 4-pound hemispheres fired in contact with the ground covered with short grass, and in contact with a 4-inch layer of concrete. Shock-front profiles were obtained by photographing against a striped backcloth. Only the leading shock could be discerned; no shock behind this could be detected. The following is a summary of the most important results.

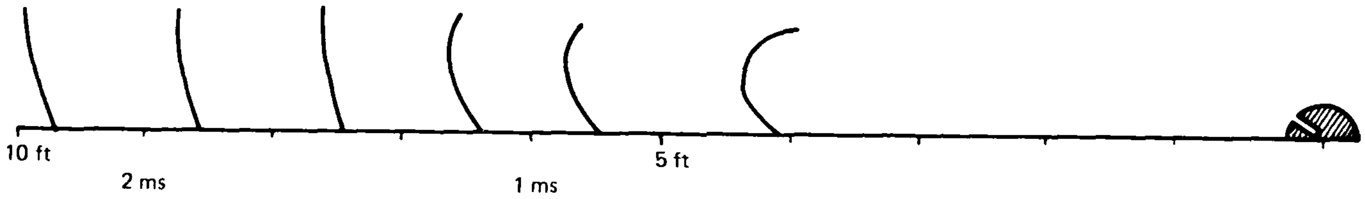
1. An increase of temperature difference of 9°C above the ground gave a measurable increase in shock velocity at ground level.
2. A still greater velocity was attained when firing over concrete under the same temperature conditions. The profile of the shock front at 10 charge radii appeared to resemble that on the microscale. Unfortunately, the half-frame camera used did not show enough of the vertical field to make a good comparison.
3. A 1-inch diameter steel ball placed on the charge, as shown in Figure 13, produced a marked distortion of the shock front due to its bow wave; however, a small bolt did not. Any disturbance present from the bolt may have been too small to resolve optically.



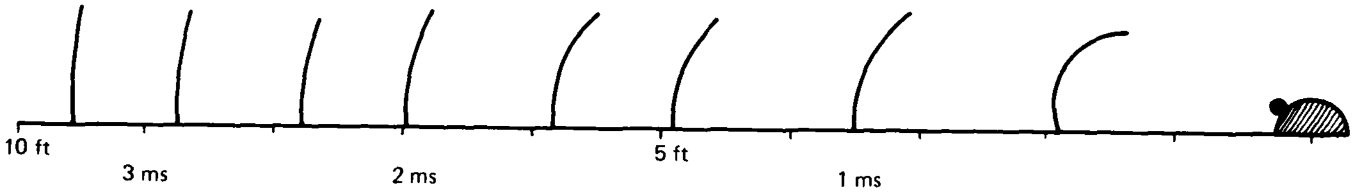
(a) PE2 HEMISPHERE



(b) WITH 1-inch DIA. STEEL SPHERE ON CHARGE SURFACE AT 30°



(c) WITH 1-inch DIA. HOLE TO CENTRE AT 30°



(d) WITH 1-oz. SPHERICAL CHARGE ON SURFACE AT 30°

Figure 13. The shock wave profiles from PE2, 4-pound hemispherical charges detonated on the ground under various conditions.

4. A 1-inch diameter radial hole drilled into the charge produced a jet giving a marked increase in shock velocity along the radius.
5. A 1-ounce spherical charge of PE2 attached to the main charge produced no observable disturbance. The camera did not show whether it detonated or was thrown off.

The results of the laboratory and small-scale field experiments showed that the anomalous shock effects observed in a multiton explosion can be made to occur qualitatively on micro- and small-scale field experiments. This is not to say that it is obtained from the same cause on the multiton scale. It does, however, give a basis for planning multiton shots to investigate precursor effects by assuming the causes are the same on the two scales.

For spherical charges tangent to a surface the pressure enhancement along the ground appears to be confined to distances within about 5 charge radii. According to supporting AFWL calculations,* the effect disappears by 10 charge radii. At this distance, however, the ground shock mechanism feeding the shock is just beginning to get underway and continues out to 50 charge radii. (Shock-front precursor effects near the ground have gained renewed attention recently as evidenced by References 35 and 36.)

5.2 FIELD TESTS

In this subsection we briefly discuss some of the field tests conducted in the past to understand the sources of anomalies.

Experiments with 60-pound hemispheres and block constructed charges were carried out at AWRE. These experiments were conducted in an attempt to reproduce some or all of the anomalies observed on larger yield detonations. The solid hemispheres were expected to radiate an azimuthally symmetrical blast field. Because of this, solid RDX/TNT hemispheres were used in an endeavor to detect the effects on blast propagation of: (1) a scaled negative temperature gradient from the ground surface upward, comparable to those obtained on the multiton events at Suffield, and (2) the change from a hard concrete to a relatively soft earth surface.

Block RDX/TNT charges were used to investigate the difference in shock propagation relative to that from a solid charge. TNT block charges were used to observe the effect of booster size on the blast field. Optical observations of the shock profile against striped backboards and piezoelectric blast gauge measurements were made. Solid and block constructed RDX and TNT charges were also detonated and radial blast pressure measurements were made. Detonations over concrete

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* Reference is made to these calculations in Reference 15 and 40 but no reports discussing these calculations could be located. However, References 37 and 38 discuss theoretical airblast calculations for several events in support of the DISTANT PLAIN and PRAIRIE FLAT events.

and plywood surfaces were also carried out. In the case of solid RDX and TNT hemispheres the transmission over concrete resulted in slightly increased shock overpressures relative to those measured over heated and unheated earth between 10 feet and 20 feet from the charge. Beyond 30 feet these pressures were found to be slightly below the heated earth values. Agreement was found between all overpressures at 50 feet. This behavior was confirmed by high-speed photographic observations of the shock front in the vertical plane, where shock velocity variation could be seen to agree with the blast pressure measurements.

In the case of solid RDX/TNT hemispherical charges, the most important comparison was between the pressure-distance data from the solid charges and the corresponding data from the block charges. In all cases the pressures from the block charges significantly exceeded those from the solid ones at distances shorter than 20 feet. In addition to this a particular radial pressure gauge line was found (over heated earth) along which a marked pressure enhancement was measured at distances closer than 20 feet. Confirmation of this was obtained from shock arrival time data which showed a shock protuberance along this radial direction. Comparison of impulse-distance data between solid and block charges showed a variation similar to that between maximum overpressures. In all cases, the impulses from block charges exceeded those from the solid hemispheres. No particular directional enhancement was noticed as in the maximum pressure case.

A number of tests were also carried out using large-scale ANFO charges. For example, three ANFO events varying in yield from 20- to 100-ton charges were fired. All were hemispherical in shape, either bagged or in bulk. Most of the anomalies observed were perturbations of the fireball, some nonluminous jetting along the ground surface, some jets due to burning pieces of the fiberglass segment joints, and on the 100-ton event, two anomalies appeared along the ground: one was a luminous precursor jet and the other a nonluminous precursor jet. Both of these appeared similar to the ones observed on TNT events of comparable yield. The nonluminous precursor jet for this 100-ton event attained a distance of about 340 feet from ground zero.

The Denver Research Institute showed in experiments with a single row of stacked pressed TNT blocks that discontinuities in the explosion product envelope occurred at each interface between blocks (Reference 33). This indicated detonation velocity fluctuations inherent in block construction.

It has also been suggested that a factor contributing to the enhancement of air blast in a horizontal direction is the horizontal interface between the layers of blocks. It has been observed, from early-time photographs of the end-initiated detonation of several circular cylindrical charges with the flat ends in contact, that marked pressure enhancements and jetting are obtained at the cracks between the interfaces.* The horizontal interfaces of the block charges encourage this effect in a direction parallel to and near the ground. This explanation was suggested to account for the higher pressures near the ground obtained from block charges compared with smooth solid hemispheres.

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* No references discussing these observations could be located.

Tests were also conducted to determine the effects of the booster size upon detonation as a possible source of anomalies. Results indicated that booster size has no detectable effects on observed anomalies. However, the suggestion was made that the booster should preferably overdrive the TNT rather than underdrive it; thus a Comp B booster is preferable to a tetryl booster.

Measurements of the air velocity in a blast wave produced by the detonation of TNT charges ranging in mass from 30 to 200,000 lbs were reported by Dewey (Reference 6). The technique consisted essentially in using high-speed photographic records of the displacement of smoke trails formed close to the charge just before detonation. The initial decay of the velocity behind the shock agrees well with theoretical predictions, such as those of Brode (Reference 4), but at later times there is an extended outward flow, which, it is postulated, is caused by the "afterburning" of the detonation products in the presence of atmospheric oxygen. Dewey showed that this phenomenon does not occur in the case of the detonation of an explosive with a high oxygen balance, or for a nuclear detonation. No analyses of the turbulent afterburning effects on azimuthal and radial variations in the blast parameters have been made.

The following conclusions may be drawn from field tests aimed at understanding the sources of anomalies:

1. Some enhancement of the blast field is obtained from solid charges due to propagation over concrete relative to earth. This is particularly noticeable in the case of positive impulse.
2. For surface temperatures about 15°C above ambient, no effect on blast propagation was observed.
3. Block-built hemispherical charges radiate a stronger blast field than smooth, solid hemispheres of the same mass near the ground.
4. There appear to be radial directions from block charges along which higher shock velocities, and consequently pressures, are measured.
5. A cylindrical void in the charge is capable of forming a luminous jet.
6. A solid fragment attached to the charge surface can be projected with high velocity and modify the main shock front.
7. Because TNT is oxygen deficient, a certain amount of afterburning occurs causing a modification of the blast parameters. This may be a source of shock and fireball perturbations.

SECTION 6
EFFECTS OF ANOMALIES

The five types of anomalies described in Section 3 can have significant effects on the overall results of any type of high-explosive field tests. One Type 1 luminous precursor jet can have an adverse effect on all targets and instrumentation within an area subtended by an angle of about 30 degrees from ground zero. This effect can extend out to distances of 10λ or to an overpressure level of about 10 psi. With as many as 3 luminous jets documented on a single shot this would cause anomalous results in measurements and affect targets over about one-quarter of the available target area out to 10λ.

Some of the effects noted from the luminous precursor jets are: (1) multiple shocks associated with the bow wave and interactions with the main shock, (2) nonradial flow causing nonradial loading and translation of targets, and (3) deterioration or enhancement of the overpressure (or dynamic pressure) causing less than or greater than predicted damage on targets.

The Type 2 or nonluminous precursor jets have been documented on many field tests and can have the same adverse effects as the Type 1 anomalies. The Type 2 jet does not appear as frequently as the Type 1, but both types have been documented on the same event. For example, on DISTANT PLAIN event 6, the combination may have affected over one-third of the available target area out to a range of 10λ corresponding to overpressures down to 10 psi.

The Type 3 or nonluminous surface precursor jets have been observed only on surface bursts ranging in yield from 50, 100, and 500 tons. It is usually associated with great turbulence and large amounts of dust following behind and remaining close to the ground. Adverse effects from this type of jet have been documented, but seldom, if ever, have bow waves been observed to be associated with them. If there were targets in the line of travel of this type of jet they would certainly be affected by the increased dynamic loading due to the increased density within the shock wave because of the dust loading. Density gauges that were in the path of this type of jet on Operation SNOWBALL recorded a density within the shock wave in excess of four times the expected peak values. Since this type of anomaly appears to be a function of surface media rather than a mechanism of the charge, it may be very difficult to eliminate. This means that changing to a different type of explosive or charge geometry may not eliminate this type of anomaly. The nonluminous surface jets lagging behind the shock front have been documented on most surface bursts. They are quite numerous and cover a relatively large percentage of the available target area.

The Type 4 or shock perturbation anomaly is one of the most difficult to observe since it is usually recorded only by the aerial cameras. It has not usually been observed by the cameras installed to record fireball growth and shock wave propagation. Cameras installed for specific target response and translation studies have recorded the shock-front perturbations on a limited number of field tests. The mechanism causing these perturbations is still conjecture. No apparent jetting, solid material, or dense gaseous products have been shown to be associated with them. The effect on target response observed from this type of anomaly is quite significant because the perturbation causes nonradial loading of the targets. Most of the targets in line with the two perturbations recorded on Operation SNOWBALL were translated nonradially and received oblique angle loading. This has affected targets out to the 10-psi overpressure level or to a range of 10λ.

The Type 5 fireball perturbation anomaly has a significant effect on targets only when it moves out horizontally over the surface of the ground or at a small angle of elevation from the surface. The condition which might cause the most adverse effects on exposed targets is also the most difficult to document from ground-surface photography. Although both ground-surface and aerial photography are needed, the Type 5 anomaly is best documented by the aerial cameras. Fireball perturbation anomalies cause shock-front perturbations and therefore can cause nonradial and oblique-angle loading on targets. Although fireball perturbations are rounded and do not travel as far as the Type 1 jet, they can still engulf a heat-sensitive target causing unpredicted damage.

SECTION 7

SUPPRESSION OF ANOMALIES

In this section we briefly summarize recommendations that have been made in the past to attempt to minimize, if not suppress completely, the effects of anomalies on field experiments. Some of these recommendations were made as early as the late 1960s by TTCP (Reference 15) and as recently as 1974 by Petes following the MIXED COMPANY III event (Reference 20). These recommendations were applied, whenever and wherever possible and practicable, to numerous field tests but not always with success. The fact is that anomalies are inherent in HE charge detonations.

Charges should be tailored for specific test requirements instead of the multipurpose objectives generally considered. For example, aboveground targets requiring overpressures below about 600 psi should employ detonable gas or other explosive sources with a low peak overpressure and limiting ground motion energy coupled to the ground. For buried targets requiring overpressures greater than about 600 to 1000 psi, the shape of the charge should give the required ground loading without having to meet airblast requirements at the same time.

For large charges in the 50- to 500-ton yield range, it has been recommended that the charge be as homogeneous as possible. If TNT is to be used for block-built charges it should, if at all possible, come from a single supplier or source. The TNT should be of uniform density in the form of cast or, preferably, pressed cubes having dimensions not less than 8 x 8 x 8 inches. If 12- x 12- x 4-inch cast TNT blocks are to be used, their discrete use in a vertical attitude within the charge should be avoided. Each layer should be rotated 45 degrees from the layer below. However, in some instances this recommendation has been found, when applied to large block-constructed charges, to produce a greater number of Type 1 and 2 anomalies. In the course of charge construction, damaged blocks or those not conforming to standard patterns should be rejected. No noncombustible materials should be embedded anywhere in the charge or its support.

Consideration should be given to the use of explosives other than TNT, such as detonable gas, liquid or slurry explosives, air-fuel mixtures, uncontained ANFO or other solid homogeneous explosives.

Although there is no conclusive evidence that booster shape, mass, and explosive type are related to abserved anomalies, the booster should be of minimum mass, preferably of the same shape as the charge itself, and result in a slight overdriving of the charge. It has been recommended in the past that cast CE/TNT*

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* CE is the term used for tetryl and CE/TNT usually consists of 70 percent CE with 30 percent TNT. CE/TNT is also called Tetrytol.

be used as boosters for TNT charges. For charges larger than 5 tons the size of the booster should be about 100 pounds of CE/TNT or about one perent of the charge mass. As the thermal outputs on different explosives can vary considerably, measurements should be made to determine the effects of temperature on close-in targets.

Disturbance of the ground within approximately 100 charge radii sould be kept to a minimum. If possible, there should be no radial roads or trenches in the vicinity of aboveground projects and targets. This may reduce the effect of Type 3 and 4 anomalies along blast lines and target response projects. It has been recommended that blast lines, project arrays, and roads be installed along spirals leading to the charge. Unavoidable trenches should be filled in and compacted as close to the original soil density as possible. Trenches under the charge which may cause it to sag and open up cracks in its structure should be avoided.

Because of the probabilities of anomalies occurring in field tests, each project should plan on carrying out the required free-field measurements in the vicinity of the project to supplement the measurements made on the main blast lines.

Accurate records of all modifications of the test site should be kept over a range of 50 charge radii from ground zero. Detailed photographic records should also be kept of each stage of charge construction, ionization probe positions, and other pertinent information.

Finally, because so much of the information on anomalies is derived from photographic records, it is essential that good ground-level and aboveground-level cinematography be carried out. Cameras having different frame rates as well as different azimuth locations should be used. Aerial photographic coverage should be carried out also for charges larger than about 10 to 20 tons.

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