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GROUND-BASED VISUAL INSPECTION FOR CTBT
VERIFICATION

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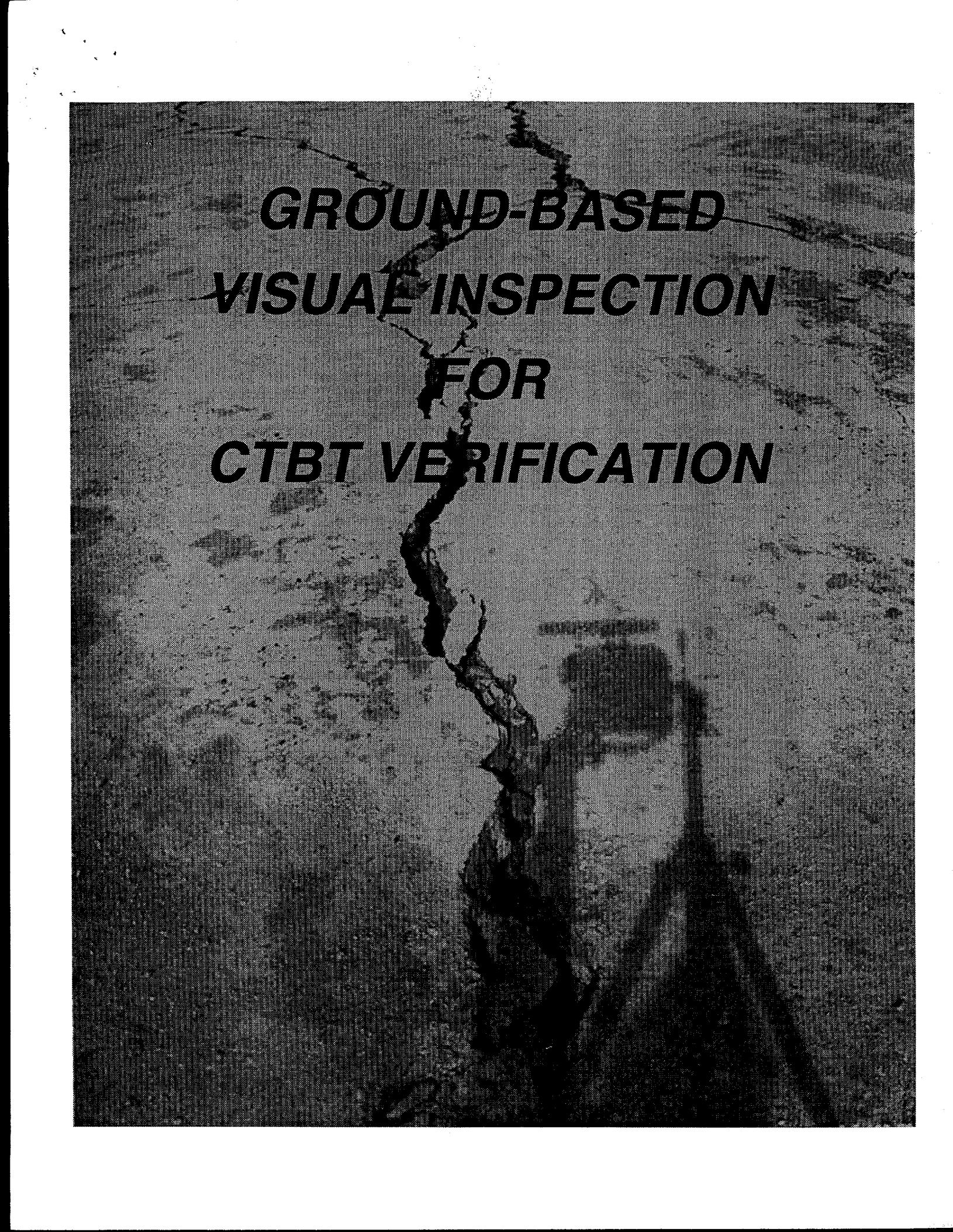
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**GROUND-BASED
VISUAL INSPECTION
FOR
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GROUND-BASED VISUAL INSPECTION FOR CTBT VERIFICATION

by

Ward Hawkins and Ken Wohletz

ABSTRACT

Ground-based visual inspection will play an essential role in On-Site Inspection (OSI) for Comprehensive Test Ban Treaty (CTBT) verification. Although seismic and remote sensing techniques are the best understood and most developed methods for detection of evasive testing of nuclear weapons, visual inspection will greatly augment the certainty and detail of understanding provided by these more traditional methods. Not only can ground-based visual inspection offer effective documentation in cases of suspected nuclear testing, but it also can provide accurate source location and testing media properties necessary for detailed analysis of seismic records. For testing in violation of the CTBT, an offending state may attempt to conceal the test, which most likely will be achieved by underground burial. While such concealment may not prevent seismic detection, evidence of test deployment, location, and yield can be disguised. In this light, if a suspicious event is detected by seismic or other remote methods, visual inspection of the event area is necessary to document any evidence that might support a claim of nuclear testing and provide data needed to further interpret seismic records and guide further investigations. However, the methods for visual inspection are not widely known nor appreciated, and experience is presently limited. Visual inspection can be achieved by simple, non-intrusive means, primarily geological in nature, and it is the purpose of this report to describe the considerations, procedures, and equipment required to field such an inspection. The inspections will be carried out by inspectors from members of the CTBT Organization.

I. INTRODUCTION

This report considers only underground testing of nuclear explosives which is the most likely method for concealing a nuclear test on land. One might conclude that concealment is not a trivial feat, and it might dominate a test program if the program depended on it. We assert the following statements in justification of our work described in this report. Ground-based visual inspection will provide the evidence that considers the following:

- If an on-site inspection is mandated, remote signals may have prompted the investigation.
- Teleseismic interpretation is enhanced by detailed geologic knowledge of the source region.
- Testing will leave evidence of cultural activities.
- Visual inspection constrains or confirms possible source mechanisms.
- Visual inspection documents the geology of the media and the degree of likely seismic coupling.
- Visual inspection guides radionuclide and seismic aftershock detection by indicating surface ground zero (SGZ) and identifying permeable pathways for gas escape.
- If no natural (geologic) or manmade (engineering) features explain the remote observations, a false negative is likely, and must be explained.

Visual inspection can be achieved through simple means, primarily geological in nature. Several key activities involve simple documentation of cultural, geological, and biological disturbances. Many important testing related features have poor documentation and are not publicized, but they can be established by careful assessment of the nuclear testing experience base. A document defining the process, the activities, the equipment, the personnel required, and applications of visual data can provide guidance for inspector training and operational manual development.

II. FEATURES AND EFFECTS OF UNDERGROUND NUCLEAR TESTING

While underground explosions can have both natural and manmade sources and many large manmade underground explosions are nonnuclear, our experience with nuclear testing has taught us that there are a number of surface/subsurface geologic, floral/faunal, and cultural effects that generally accompany underground nuclear testing. There are two main underground testing designs: (1) vertical emplacement and (2) horizontal emplacement. While surface features can always be inspected, subsurface features may or may not be accessible.

The phenomenology associated with underground nuclear testing includes these aspects, illustrated in Figure 1. When an underground nuclear explosion occurs, the shock wave dynamically

vaporizes and melts the rock in the immediate vicinity of the detonation point. The shock-induced outward motion and high internal cavity pressure cause the cavity to expand until the pressure has decreased to the point that the rock can no longer be deformed. The material then rebounds to form a large compressive stress field around the cavity. After cavity growth ceases and internal pressure drops below the amount necessary to support the overburden, the rock above the cavity falls into the void, forming a rubble chimney. Depending on the yield and overburden characteristics, collapse may extend to the surface forming a subsidence crater. As a result of cavity growth, rock fracturing may occur within several cavity radii of the detonation point. At the surface, reflection of the shock produces a rarefaction that propagates downward, causing spallation of surface materials. Surface cracks generally form within this zone of surface spallation and as a response to crater subsidence if it occurs. Geologic structure and pretest in situ stresses influence the nature and extent of fracturing in subsurface and surface materials. All of the above phenomena are strongly controlled by the depth of burst, rock lithology and structure, hydrogeology, and topography.

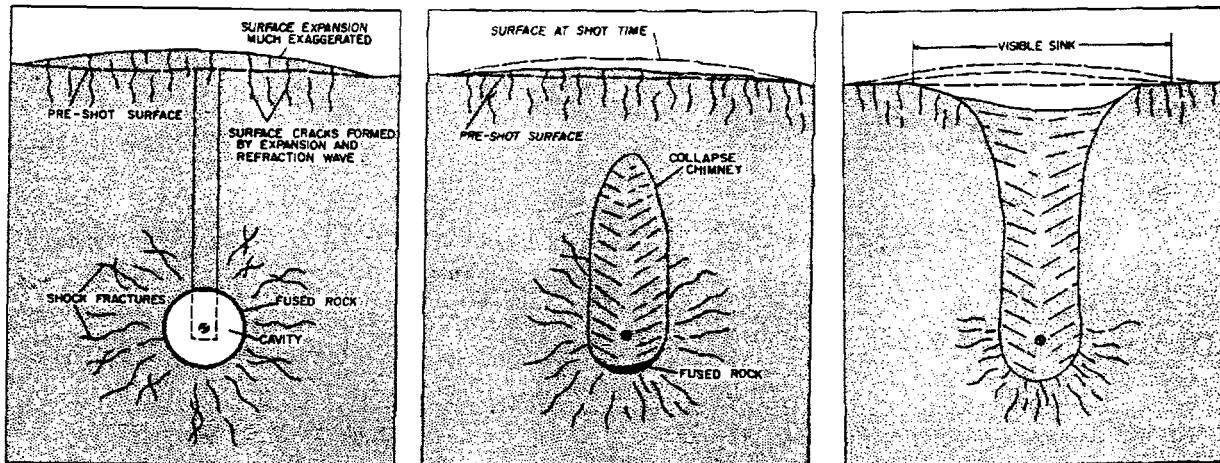


Figure 1. Schematic illustration of underground testing phenomenology.

Adushkin and Spivak (1994) compiled one of the most comprehensive reviews of the geologic characterization of underground nuclear explosions. Their review covers experience gained from the underground testing of high-yield explosions for military use, peaceful use, the stimulation of energy and mass exchange in geologic media, and development of long-distance detection techniques. The geological regimes that form in test media after an underground explosion affect the media to ranges (r) scaled to the explosive yield in kilotons (kt). These regimes, though not always observed, include (1) the melt cavity where rock vaporization and motion have produced a void ($r = 4$ to $12 \text{ m}/\text{kt}^{1/3}$); (2) the crushed zone where the medium has lost all of its prior integrity ($r = 30$ to $40 \text{ m}/\text{kt}^{1/3}$); (3) the cracked zone characterized by radial and concentric fissures ($r = 80$ to $120 \text{ m}/\text{kt}^{1/3}$); and (4) the zone of *irreversible strain*

that causes local media deformation ($r = 800$ to 1100 m/ $kt^{1/3}$). While the scaled ranges of these regimes are highly dependent upon the test media structure and lithology (strength, compressibility, sound speed), rocks within these regimes experience irreversible explosion deformation resulting in changed porosity, permeability/filtration character, and material strength.

Of surface features and effects, geological, cultural, and floral/faunal types can be observed, while subsurface effects are primarily geological in nature. While both surface and subsurface effects are strongly dependent upon the device yield and material properties of the test medium (geology), surface features develop as a function of depth of burial (DOB), scaled to device yield (W in kilotons), giving scaled depth of burst (SDOB): $SDOB = DOB/W^{1/3}$. From the Nevada Test Site experience, an SDOB of ~90 to 125 m/ $kt^{1/3}$ is sufficient to contain an underground test from releasing radioactivity to the atmosphere; this depth is approximately 9 to 10 times the cavity radius. However, surface collapse occurs in most (95%) contained underground tests in tuff with $SDOB < 150$ m/ $kt^{1/3}$, but only about half of the tests with $SDOB < 180$ m/ $kt^{1/3}$ cause surface collapse. It is apparent that with greater SDOB, the chance of producing surface effects decreases so that a clandestine test would be overburied with respect to that depth needed for containment. Considering the results provided by Adushkin and Spivak (1994), for which the zone of irreversible strain reaches up to 1100 m/ $kt^{1/3}$, concealment by overburial may only be practically achieved for small yields or decoupled configurations.

1. Surface Geological Effects from Underground Explosions

- A) Craters.** For underburied tests, surface materials may be accelerated to the point where they are launched as ejecta, leaving a surface crater with a surrounding apron of ejecta.
- B) Collapse Sinks.** The cavity formed around the point of explosion generally collapses, producing a chimney of rubble that migrates upward within several minutes to hours after detonation. If the chimney reaches the surface, the rocks and soil sink, forming a crater.
- C) Depressions.** Generally centered around SGZ and circular in shape, the amount of subsidence is generally greatest at SGZ, decreasing outward to several hundred meters away from SGZ. Where these structures interact with local geological structural features such as faults, the depressed area can take on an oblong shape.
- D) Fractures.** Fractures in rock and soil are caused by underground testing and are often referred to as "cracks". Explosion-produced cracks can be classified as radial, linear, and concentric (Figures 2 and 3).

E) Other Surface Features.

- 1) Pressure ridges - Linear zones of broken ground that are elevated from the surrounding surface.
- 2) Disturbed ground - Elongated zones of ground rubble that have the same elevation as the surrounding surface, or zones of inflated soil ("fluff") caused by rapid accelerations.
- 3) Faults - Linear cracks with one side offset from the other (usually vertical).
- 4) Water table rise - Decrease in the depth to water in wells or new surface seepages.
- 5) Water impoundments - Evidence of water movement in ponds, tanks, etc.
- 6) Rock falls - On high angle slopes loose rocks may be displaced downhill.
- 7) Thermal anomalies - Present only where there has been cavity gas leakage.
- 8) Ground slump - Downslope movement of soil and rock along natural and manmade slopes.

2. Subsurface Geological Effects from Underground Explosions

A) Fractures. Cracks in the rock that are formed in a tunnel complex as a result of an explosion; they can be almost any orientation and dimension.

B) Bedding Plane Movement. Cracks and/or offsets that occur along contacts of different rock types are usually sub-horizontal.

C) Microfracturing. Zone near explosion that shows little distinguishable cracking but has been significantly weakened by the explosion.

D) Faults. Fractures that have offset.

E) Other Subsurface Features.

- 1) Water seeps - Free water entering tunnel can be evidence of formation damage.
- 2) Tunnel deformation - Walls, floor, and ceiling may shift or collapse.
- 3) Thermal anomalies - Present in rock near the detonation point.
- 4) Rock hardness variations - Explosive-driven shock waves degrade rock hardness.

3. Cultural Features (Artifacts)

To conduct an underground nuclear test requires the utilization of facilities and equipment not normally associated with commercial operations. Additional security and safety issues must be addressed. Utility demands will be increased. Explosion diagnostic instrumentation must be fielded.

A) Structures. Facilities required for the housing of sensitive equipment and special nuclear materials as well as scientific personnel.

- 1) Roads - Roadways improved beyond what would be necessary for commercial operations.
- 2) Buildings - Secure and weatherproof facilities for technical activities associated with a test.
- 3) Surface preparation - Excessive surface excavation, treatment, and grading.
- 4) Wellheads and casing - Required for emplacement of explosive device (large diameter), subsurface instrumentation, and post-shot sampling tools.

B) Equipment. The execution of an underground nuclear test may require equipment not associated with regular operations and incorporates unusual levels of safety and precision.

- 1) Emplacement equipment - For a vertical emplacement, this would include lifting and backfilling equipment; for tunnel emplacement, loading and handling equipment not typical of commercial operations.
- 2) Instrumentation - Utilities (power, compressed air, ventilation, etc.) and sophisticated electronic equipment that are in excess of requirements for commercial activities. Cables which would be associated with data acquisition endeavors are typically expensive coaxial or fiber-optic types, only used for the highest quality data transmissions (Figure 4).

C) Other.

- 1) Containment features - Materials, equipment, and activities that would be necessary to contain radioactive gas and debris from escaping to the atmosphere (i.e., permeability - high strength materials, gas blocked cables)
- 2) Security precautions - Limited access areas with protective fencing, guards, and surveillance equipment.

4 . Floral/Faunal Features

Ground acceleration produced by underground nuclear tests can be sufficient to disrupt surface floral and faunal feature. Disruptions include felled trees, disturbed ground at base of trees, vegetation-filled lineations indicating previous cracking, disoriented/agitated wildlife, and renewed or destroyed animal burrows. These features are very sensitive to site environment.

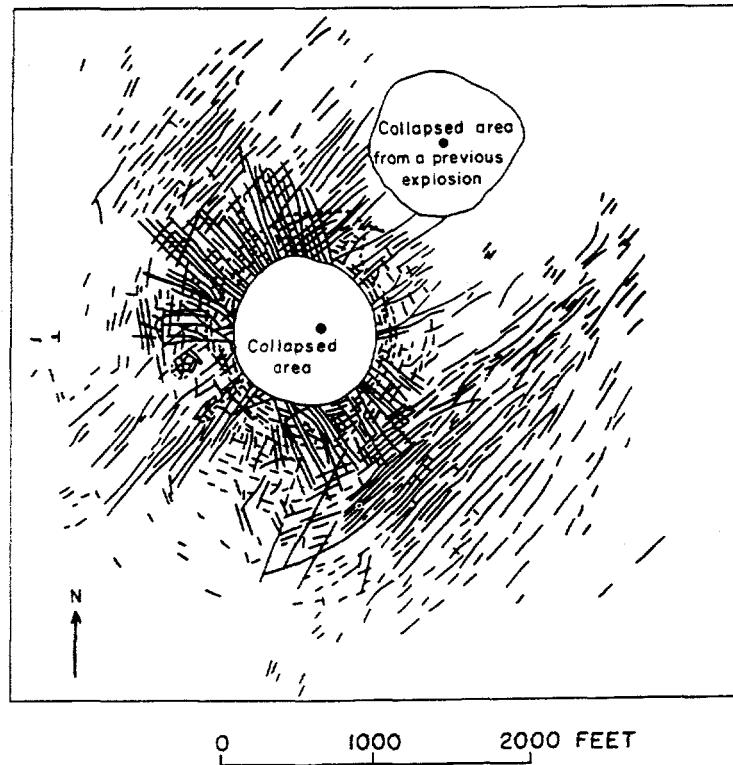


Figure 2. Map illustrating surface cracks around a collapse crater at NTS. Note the radial, concentric, and linear cracks.

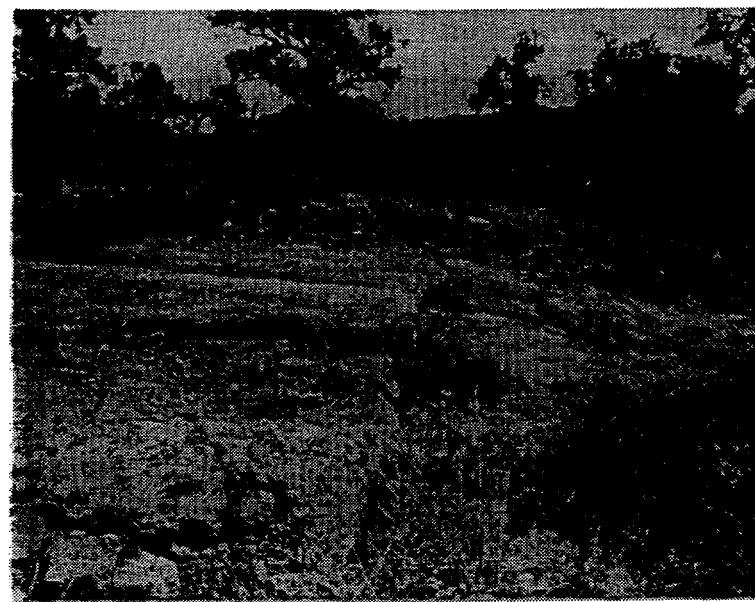


Figure 3. Photograph of surface crack through bedrock.



Figure 4. Cables typical of sophisticated diagnostic measurements and a perimeter security fence post.

III. DIAGNOSTIC TECHNIQUES FOR VISUAL INSPECTION

As described above, underground nuclear testing is generally performed by one of two emplacement techniques: vertical or horizontal. Vertical emplacement requires drilling or mining a large-diameter shaft nominally to the depth necessary to insure containment of explosive effects or conceal the test so that it can not be detected by obvious explosion-induced surface disturbances. On the other hand, horizontal emplacement is achieved by horizontally mining into a mountain or plateau or from a vertical shaft. In the horizontal case surface cultural features near SGZ will be minimal, but in both cases surface geological effects can be evident. Because of the difference in emplacement techniques, we expect that cultural and geological effects may differ and suggested detection techniques will similarly be somewhat different.

1. Vertical Emplacement

Table 1 lists expected cultural artifacts and geological/geophysical effects of underground nuclear testing by vertical emplacement. The table also shows characterization techniques used at the Nevada Test Site and expected to be useful in ground-based visual inspection activities.

Table 1. Vertical Emplacement Artifacts and Diagnostic Techniques

CULTURAL	GEOLOGIC/ ENVIRONMENTAL	TECHNIQUES
cables holes mud pit for drilling stemming material instruments pre- & post-construction <ul style="list-style-type: none"> prepared ground and roads buildings trailers trash disposal security <ul style="list-style-type: none"> perimeter fencing sign posts surveillance equipment lifting equipment <ul style="list-style-type: none"> crane "strongback" utilities	craters (subsidence) fractures and cracks pressure ridges block motion and spall rockfalls floral/faunal disturbance ground rubble and "fluff" groundwater anomalies surface water disturbances	air photo examination sampling (material properties) rocks debris operational assessment geologic mapping <ul style="list-style-type: none"> stratigraphy structure surface effects shallow measurement holes hand trenches displacement measurements geodetic survey photography

2. Horizontal Emplacement

Table 2 lists expected cultural artifacts and geological effects of underground nuclear testing by horizontal emplacement. The table also shows characterization techniques used at the Nevada Test Site and expected to be useful for visual inspection activities. There may be additional, site-specific considerations for other testing environments and further description of its contents.

IV. PROCEDURES

The following section as an outline of the activities, logistics, and personnel necessary for a ground-based visual inspection.

1. Activities

The basic approach to visual inspection activities involves a *remote-to-target* strategy. This approach follows these steps: (1) initial efforts will compile as much geological and cultural information around the inspection site as possible by literature searches, remote sensing techniques, aerial photography, and seismic records; (2) with data from step 1, a rough reconnaissance map will be compiled, showing access routes, target objects such as geologic contacts and structural features, and

Table 2. Horizontal Emplacement Artifacts and Diagnostic Techniques

CULTURAL	GEOLOGIC/ ENVIRONMENTAL	TECHNIQUES
muck pile	<u>Surface</u>	geologic mapping
mining equipment	craters (subsidence)	stratigraphy
muckers, etc.	fractures and cracks	structure
grouting equipment	pressure ridges	effects
instruments	block motion and spall	geodetic survey
utilities	rockfalls	sampling
ore removal & preparation	vegetation disturbance	rocks
security	disturbed ground "fluff"	soils
cables	groundwater mounds	radiation survey
"normal" operations infrastructure	fauna disturbance	
diagnostic tools	surface water	
containment hardware	<u>Subsurface (near field)</u>	
stemming materials	microfracture zone	
epoxies, etc.	block motion	
tunnel hardening	radioactivity	
mine design features	<u>Subsurface (far field)</u>	
device debris	spall	
absence of HE products	floor heave	
	block motion	
	reverse faults	
	bedding plane movement	
	grout injection	
	tunnel collapse	
	tunnel offset	

evidences of human activities; and (3) on-site documentation of features on the reconnaissance map with addition of new features and supporting data. This last step will consist of four components listed below. Each component will add to the observational data base and allow the design of diagnostic geological, geophysical, and sampling tests to be performed.

- Reconnaissance and Initial Visual Survey.
- Photo Documentation: Aerial, Surface, and/or Subsurface.
- Geological, Topographic, Cultural Feature Mapping.
- Sampling, Geological and Geophysical Measurements, and Geodetic Survey.

2. Logistics and Equipment

For the purposes of this paper, logistics includes the overall infrastructure of the visual inspection team, how the team is deployed, chain of authority, how information is exchanged, communication, reporting, and documentation requirements, on-site support, and negotiations with the inspected state. Equipment needs are also part of the overall logistics because such equipment will have to be transported within the inspected state, certified and regulated, and strictly maintained for operations and accountability.

Table 3 shows a list of equipment for visual inspection by activity type. This equipment represents what is typically applied to geological investigations, and it has proven to be useful for characterization and documentation of nuclear test effects and artifacts. Visual and surveying equipment is necessary for effective mapping (location) and documentation. Geological equipment is required to make direct measurements and characterize visually apparent surface and underground features and effects. In contrast, sampling equipment is useful for non-intrusive measurement of features and effects that are not usually visible but nonetheless important for a complete characterization, especially where observable features have been purposely concealed. For example, radiation detectors make positive detection of underground testing even in areas where there are no visual clues.

Table 3. Equipment for Ground-Based Visual Inspection

OPERATIONAL	VISUAL/SURVEYING	GEOLOGICAL
personal computer (palm top) drafting and office supplies communications logistical support	binoculars position location equipment digital/35 mm cameras instant print cameras video cameras tape measure altimeter stereoscope aerial photos topographic maps	Brunton compass transit geologist hammer shovel and pick Jacob's staff geological maps aerial photos sample containers air samplers 2 m soil auger

3. Personnel

A key component to an OSI will be the personnel involved with visual examination of the site and their systematic recording of their observations. In addition to expertise in specific aspects of visual inspection, the OSI team should include personnel familiar with equipment used in testing and diagnostic evaluation of nuclear explosions as well as normal commercial operations. Training will play a major role in selection of team members.

Safety is a major consideration for all personnel activities. Work in the vicinity of SGZ might present specific hazards, but weather and natural hazards are always a factor. Considerations of heat and cold, dehydration, indigenous wildlife, topography, and disorientation must be addressed when sending a field team out. Hazards for radiological and chemical exposure are expected in test areas, as are vehicular operations, drilling/construction equipment, and postshot surface collapse, block fall, and gas release.

V. CONCLUSIONS

In this report we have summarized our investigation of visual inspection as an integral component of OSI for CTBT verification. In giving a brief overview of underground nuclear test phenomena and their effects on cultural, geological, and floral/faunal features, we have illustrated the basic components of visual inspection. Important considerations include knowledge of the geological setting and test emplacement configuration. Although horizontal and vertical emplacement techniques will produce similar cultural and geological effects, there may be significant differences in inspection techniques required for each. In this report, we have only outlined general procedures, logistics, equipment, and personnel expertise required for visual inspection. In conclusion, with this discussion of visual features and documentation techniques, we have shown how ground-based visual inspection is accomplished and why it is an essential component of an on-site inspection.

REFERENCES

Adushkin, V. V., and Spivak, A. A., 1994, Geologic characterization and mechanics of underground nuclear explosions: Defense Nuclear Agency Tech. Rep. (Contract No. DNA 001-93-C-0026), Alexandria, VA.