

Deeply Buried Facilities

Implications for Military Operations

Eric M. Sepp, Lt Colonel, USAF

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**Occasional Paper No. 14
Center for Strategy and Technology
Air War College**

Air University
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The Author

Lt Col Eric M. Sepp earned an undergraduate degree in Business Management and received his commission through the Reserve Officer Training Corps at Miami University of Ohio in 1980. He subsequently served as a Project Manager for both Foreign Weapons Evaluation and the AGM-130 at Eglin Air Force Base, Florida. After earning an undergraduate degree in Electrical Engineering from Auburn University, Alabama, he served as the Small ICBM guidance and control Branch Chief and as Chief of Program Operations Division at Norton Air Force Base, California from 1986 to 1991. While at Norton Air Force Base, he earned a graduate degree in Systems Management from the University of Southern California. In 1991, he was assigned to the Pentagon where he was the ICBM Acquisition Program Element Monitor for the Assistant Secretary of the Air Force for Acquisition. While at the Pentagon, he also served as a weapons inspector with the United Nations Special Commission (UNSCOM) in Iraq, and provided Air Force support to worldwide missile non-proliferation programs. In 1995, he was assigned as Chief, B-2 Requirements Branch, and later served as the Executive Officer to the Aeronautical Systems Center Commander. A graduate of Squadron Officers School, Air Command and Staff College, and the Air War College at Maxwell Air Force Base, Alabama, as well as a graduate of the Defense Systems Management College, Fort Belvoir, Virginia, he completed this research under the auspices of the Center for Strategy and Technology. Lieutenant Colonel Sepp is currently serving as Military Assistant to the Chief of Staff, Headquarters Allied Forces North Europe (NATO), Stavanger, Norway.

Preface

The existence of deeply buried Underground facilities has emerged as one of the more difficult operational challenges to confront U.S. military forces in the twenty-first century. While these types of facilities are not new, they are significant when one considers the proliferation of nuclear, chemical, and biological weapons. The problem is that deeply buried facilities can be used by rogue governments to manufacture and store weapons of mass destruction (WMD), as well as house the critical command and control and governmental functions that are central to the successful prosecution of a war. It is unfortunate that, with the exception of nuclear weapons, the current technologies for locating and neutralizing these types of facilities may not be sufficient for holding these facilities at risk. The purpose of this study is to outline the difficulties that are involved in locating and neutralizing deeply buried facilities, and suggest alternate methods and technologies, other than nuclear weapons or advanced conventional weapons, for holding these targets at risk. This study describes deeply buried facilities and their typical functions, assesses their vulnerability, and presents ideas for neutralizing these facilities with nonconventional means. The broad objective of this study is to ensure that U.S. national and military objectives can be achieved in contingencies that involve deeply buried facilities. I would like to express my appreciation to my Air War College faculty advisors Dr. William Martel and Col (Ret.) Theodore Hailes for their invaluable encouragement and assistance. I would also like to express my thanks to my wife and children for their constant support and encouragement. That being said, I alone am responsible for the ideas outlined in this paper.

1. Introduction

The problem in the early twenty-first century is that deeply buried underground facilities are becoming an increasingly important part of the defense establishments in many states. These facilities allow states to conceal the personnel, equipment, and command and control functions that are essential to the successful prosecution of a war. In general, these facilities can protect a state's most critical governmental and military functions and contribute to victory during war, or at least make it more difficult for the adversary to destroy critical military capabilities.

There are numerous historical examples in which states have used underground facilities in warfare, including the use of underground manufacturing facilities by the Germans in World War II to conceal and protect valuable industry from destruction. During the Vietnam War, North Vietnam developed an extensive system of underground tunnel for concealing transportation routes, storage facilities, and temporary troop containment areas. Since the beginning of the Cold War, the United States and Soviet Union located their intercontinental ballistic missiles and associated command and control centers in underground sites in order to increase their survivability against nuclear attack. The continuing evolution of underground facilities has provided increasing levels of concealment and protection for a state's critical military components.¹

The event that has elevated the general level of concern among modern military planners is the prospect that underground facilities are used for the manufacture and storage of weapons of mass destruction, particularly by such rogue states as Libya, Iraq, Iran, and North Korea.

In the years since the Persian Gulf War, deep underground facilities have become even more desirable to rogue states because it allows them to protect valuable military assets from attack with the increasingly precise and effective conventional bombs and missiles that are at the disposal of U S. military forces. For example, during the Persian Gulf War, precision guided weapons held at risk virtually every above-ground building, including command and control facilities and hardened aircraft shelters. In response, rogue states have devoted considerable effort to constructing hardened, deeply buried facilities by converting existing caves and abandoned mines into bunkers, or constructing new facilities by tunneling deep underground.²

Recently, the *New York Times* reported that Libya is constructing a 2000-mile long network of underground pipes with passageways that are sufficiently large to move military troops and equipment in an undetected and protected fashion.³ According to that report, these pipes intersect with an underground facility that is being constructed in Tarhunah, Libya, which is suspected of manufacturing site for chemical weapons. Furthermore, there are reports suggesting that North Korea has built an elaborate underground network of tunnels with storage facilities and routes that are suitable for use by the vehicles and troops that would be used in a military invasion of South Korea. These tunnels lie as deep as 100 meters beneath the surface and can support the movement of an estimated 8,000 troops per hour, along with the heavy equipment and jeeps that would support an invasion of South Korea.⁴ While at least four of these tunnels have been located and neutralized, it is suspected that many other tunnels are located along the Demilitarized Zone (DMZ) that separates North and South Korea.

Deeply buried facilities have significant implications for national security, principally in terms of giving a state an effective sanctuary for protecting its weapons or command and control functions from attacks with modern precision guided weapons. At the same time, these facilities pose a difficult challenge for U S military forces, which will want to locate and destroy them in the event of a military confrontation. The development that is most worrisome to the defense establishment in the United States is the possibility that deeply buried facilities will contain nuclear, biological, or chemical agents, and that the destruction of these facilities may lead to the release of these agents with devastating environmental and political consequences.

While one military plan for defeating deeply buried targets was to use nuclear weapons delivered by B-2 bombers,⁵ the Clinton administration overturned this policy and banned the use of nuclear weapons to defeat such targets. The reason behind this decision is the concern that the use of nuclear weapons would have grave political consequences, especially in an era when nuclear weapons are less central to defense planning.⁶ While the use of nuclear weapons is a militarily practical way to destroy targets that may be hundreds of meters below the surface, their use involves political and environmental risks that increase when one considers that the location, configuration, and contents of underground targets are often unknown.

The political repercussions of employing nuclear weapon may be greater than the United States would want to contemplate, and the environmental consequences of potentially spreading a warehouse full of potentially deadly biological or chemical agents would be unacceptable. The reality is that the use of nuclear weapons is not a practical option for dealing with underground targets in most circumstances.

The problem with using conventional weapons against such targets is that the depth and hardness of the targets can exceed the physical ability of the weapon to survive passing through tens of meters of rock and rubble. Some experts estimate that new materials will need to be developed to penetrate modern concrete structures.

The result is that the U S military strategy and operational capabilities for holding hardened and deeply buried targets at risk will be deficient until the appropriate technologies and tactics are developed that will allow the United States to put such targets at risk. One element is training military personnel to perform these missions, which is consistent with the guidance provided by the U S Special Operations Command that such specialized skills do not "grow overnight." The second issue is to develop the technologies that permit U.S and allied forces to detect the presence, depth, layout, and contents of underground facilities, and simultaneously possess the weapons that will allow military forces to destroy or neutralize these facilities. These operational strategies should include the ability to achieve various levels of neutralization, including the ability to disrupt life support functions, create internal environments that are unsuitable for human operations, entomb those facilities, and in the extreme case, completely annihilate these facilities.

This study examines the nature of deeply buried facility, explores the problems associated with detecting these sites, and focuses on unconventional approaches for defeating these targets. This study has three central purposes. The first is to establish a framework for the U.S. defense establishment to understand the challenges posed by these facilities for the conduct of modern warfare. The second is to improve the ability of the U S military to successfully destroy deeply buried facilities, and the third is to suggest that the United States must develop new technologies and methods for overcoming the challenges associated with defeating deeply buried facilities.

The sheer complexity of underground facilities, including their location, depth, configuration, and military functions, suggest that this problem will plague U. S. defense planners for years to come.

II. Analysis of Deeply Buried Facilities

One of the lessons of the Persian Gulf War was the effectiveness of using air and space power in military attacks. The corollary, which has been learned by adversaries of the United States, is that it is necessary to go deeper underground if they want to survive U.S. military attacks. Underground facilities represent a serious military challenge because it is very difficult to determine their location, and perhaps more difficult to characterize the activities that are being conducted inside. The future military capabilities of the United States will depend in part on the ability to find critical enemy targets with standoff sensors, characterize their functions, and destroy them with precision guided conventional munitions.⁷ The remainder of this study focuses on locating and destroying these facilities.

In reality, underground facilities frustrate both of these requirements. Underground facilities are difficult to find, are resistant to revealing the physical details that are critical to effective targeting, and in many cases are fundamentally beyond the reach of most conventional weapons. To complicate matters, the most difficult problem may be to characterize the contents of these hidden facilities and their military function. Unless one has high confidence in the nature of these facilities, military attacks may be counterproductive, as exemplified by the potential existence of weapons of mass destruction in these sites. To understand the nature of this problem, it is useful to address the construction of underground facilities and their likely configurations.

There are two basic classes of underground facilities. The "cut-and-cover" facilities are constructed by digging a hole, inserting a facility, and then covering it up with dirt and rocks. These cut-and-cover facilities can be just below the surface of the ground or may reach a depth of perhaps 100 feet, and represent the vast majority of underground facilities today.⁸ In the case of contemporary cut-and-cover facilities, there is no question that conventional munitions can defeat them. There is a self-generating competition between those who design facilities and weapons designers that seek to defeat those facilities. While facilities can be built deeper, this increases the cost of the facility. At the same time, the weapons designer must consider the increasing cost of developing penetrator weapons that can destroy targets.⁹

The second class of underground facilities, which are constructed with tunneling operations, are located deep below the surface or deep within mountains. These deeply buried underground facilities may be hundreds of feet below the surface of the earth and be surrounded by solid rock. This class of underground facilities may be more difficult to locate and destroy, and will be emphasized in this study.

Siting and Design Considerations

The commercial world has long recognized the value of underground facilities for storage or industrial purposes. Abandoned mines, naturally occurring caverns, and rock cavities offer many advantages, including low humidity and little variation in temperature. For example, frozen food companies have used such facilities for decades to store their products. Furthermore, creating such facilities is becoming technically easier for many governments. Modern tunnel boring machines can drill through solid rock vertically, horizontally, or at any angle, and are able to tailor the inside of a rock cavity to support the construction of a facility. For example, the machines used to dig the English Channel project were huge, encased drilling machines whose digging face consisted of a 95-ton, twenty-eight and one-half foot diameter disc that is divided into numerous cutting blades. At its maximum efficiency, the tunnel was dug at a rate of about 50 meters per day.¹⁰ As the machine drilled through the rock, teams of workers would follow behind to line the cavity of the tunnel with concrete and guide the scraps of rock and material from mining down the track for disposal. In a single, continuous operation, the machines drilled a tunnel, removed the earth, and paved the inside of the tunnel with precast concrete segments.¹¹ In the case of smaller facilities, tunnels with a diameter of 6 meters can be dug at a rate of 200 meters per day and larger cavities can be created at any number of locations along the tunnel.

When considering the vulnerability and survivability of deeply buried underground facilities that are designed for military applications, an important factor is having an adequate depth of cover on all sides of the facility. Common sense dictates that the deeper a facility is placed beneath the surface of the earth, the more survivable it will be against attack. Studies by the RAND Corporation and MITRE Corporation suggest that facilities located at depths of 2,000 feet beneath the surface are essentially invulnerable. This does not mean merely 2,000 feet of

overhead cover, but a 2,000 foot minimum distance to any surface point (on all sides), including the sides of a mountain. The material located between the underground facility and the surface of the earth is commonly known as "overburden". Naturally, more overburden between the underground facility and the surface of the earth is preferable, and the depth of overburden should be a prime consideration when selecting the location for a deeply buried facility.¹²

There are several other important design factors in addition to overburden that increase the survivability of deeply buried facilities. One is the use of dry, impermeable rock stratum at the required depth (i.e., no imbedded water). Another is to ensure that the rock stratum is nearly horizontal and at least 100 feet thick to take advantage of the self-supporting mechanical properties of the rock. The use of overburden above (and on the sides of) the rock stratum should be broken in order to help attenuate ground shocks. And the underlayment below the cavity should act as a "mattress" to attenuate shock waves. An aquifer would be ideal since it could also be tapped for water and contribute to the self-sufficiency of the facility. Furthermore, the rock stratum from which the cavity is carved should be self-supporting and not require artificial support or lining, such as reinforced roof and walls, to be structurally sound. Limestone and granite are desirable rocks for these purposes.

Access Tunnels and Internal Cavities

Access to deeply buried facilities can be accomplished through either horizontal or vertical shafts or tunnels, which must be large enough to allow equipment and material to enter and exit the tunnel. At the same time, the size of the tunnel has significant implications for the survivability of the facility, principally because a smaller diameter tunnel is less detectable than a larger diameter tunnel. Tunnel entrances also can be designed to collapse at predetermined lengths in order to attenuate the blast, shock, and overpressure of an explosion and thereby prevent those effects from reaching the critical functions or personnel in the underground facility. This can be accomplished either by the construction of blast doors, which reduces the cost and time associated with building long tunnels, or more simply through the use of long entry tunnels.

If tunnel length is the design feature that is used for attenuating blast, studies have shown that there is an ideal tunnel design ratio of 500

between the length and diameter of the tunnel.¹³ Tunnels that are constructed according to this relationship should fully attenuate the blast waves that travel down the tunnel, but this requires a long tunnel, which thereby increases the cost of construction.¹⁴ For example, if the entry tunnel were 16 feet in diameter, an 8,000-foot tunnel would be necessary to meet the blast attenuation ratio of 500. A 16 foot diameter is reasonable because virtually all construction equipment is designed to fit under 15 foot bridges and is not wider than 8 feet to meet highway standards.¹⁵

Another advantage of using long tunnels is to increase uncertainty about the location of the underground facility. As an example, if the entrance to an underground facilities were known, and an 8,000 foot tunnel was used to gain access to the facility, the radius around this known entry point creates more than 200 million square feet of surface area, or roughly 4,600 acres of possible locations for the facility. Even if one assumes that the tunneling activity does not reverse itself and travel in the opposite direction, an area half this size represents a tremendous area in which to conduct detailed surveys for determining the location of an underground facility. When the exact location of a deeply buried underground facility is unknown, it significantly decreases the ability to locate and neutralize them, and thus increases their survivability.

According to a study conducted by the MITRE Corporation, the internal dimensions of the rock cavity within which an underground facility may be constructed should not exceed 40 feet in width and 45 feet in height. These measurements were made in the case of a 2,000-foot overburden on all sides for maximum survivability.¹⁶ A series of chambers with these dimensions can be connected with a matrix of tunnels, as shown in Figure 1.

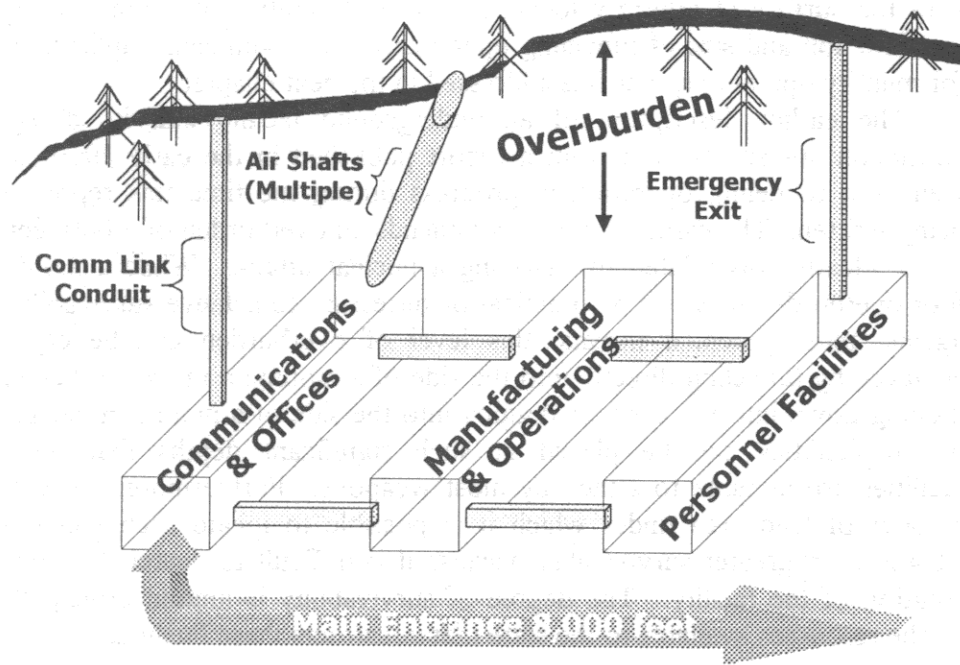


Figure 1. Illustration of Deeply Buried Facility

An example of a tunnel boring operation is the Boston, Massachusetts area water supply improvement project. This project involves boring 16-foot diameter underground tunnels for a distance of roughly 17 miles at depths that range between 200 and 400 feet. Furthermore, two underground chambers will be hollowed out to hold a total of 20 million gallons of water. The estimated amount of material to be removed from the operation is approximately 850,000 cubic yards of rock for the tunnel, and an additional 170,000 cubic yards of material for the two storage tanks. All of these tunnels and storage tanks will be carved out of bedrock. This project is significant because modern tunnel boring operations are capable of digging extensive tunnels without providing any indication on the surface of the direction(s) that the tunnel may take. Short of actually entering the tunnel, the only evidence of the facility is the amount of material removed from the mining operation that must be disposed of as well as the ventilation and elevator shafts that may connect with the surface at arbitrary locations.

The difficulties of characterizing the direction and size of tunneling operations have significant implications for military operations, which is addressed in the next chapter.

The earlier description of an underground facility and its design considerations are derived from a report published in the early 1960s as well as a tunneling operation in progress during the time this report is being written. The earlier report recommends an overburden of 2,000 feet, which clearly was related to surviving a nuclear attack. While a 2,000-foot overburden may not be practical or necessary to achieve survivability against most potential threats, this level of overburden can be easily achieved by tunneling directly into the side of a mountain range. Whether digging down into the earth or digging into the side of a mountain, deeply buried facilities can be placed at such significant depths that these facilities are immune to attack by most weapons. Furthermore, the vast amount of land area under which it is possible to locate such facilities affords even greater survivability because it is difficult to detect the exact location of the facility. The degree of survivability is limited principally by the resources available to the state that constructs these facilities.

Functions

Deeply buried facilities are used by governments and industry to protect their civilian and military leadership, and by industry to protect vital equipment, which are central to prosecuting a war or maintaining vital commercial or industrial capabilities. Today, with improvements in tunneling capability, these facilities can easily be constructed to move troops and equipment as well as manufacture, store, and transport munitions, including weapons of mass destruction. During the Persian Gulf War, ten percent of the more than 18,200 sorties flown by coalition aircraft were aimed at the critical war making capabilities that are typically contained in underground facilities. According to the Defense Department report on the Persian Gulf War, these missions included 429 sorties against national command authorities, 603 sorties against command, control and communications centers, and 902 sorties against suspected nuclear, chemical and biological manufacturing sites.¹⁷ Most of these targets were shallow underground facilities or were located above ground.

However, the success enjoyed by coalition forces in the Persian Gulf War had two important consequences. The first is that the growing capability of precision guided weapons has convinced many states that they need to place their critical functions deep underground. This increases the difficulties associated with locating the facilities, decreases the ability to determine their function, and decreases the ability to destroy them. The second consequence is that destroying facilities whose contents are unknown could have serious effects on friendly forces, as exemplified by the case when US Army forces destroyed a chemical weapons bunker in Khamisiyah, Iraq shortly after the Persian Gulf war. Although the bunker was known to be a chemical weapons storage area, there was the possibility of chemical fallout within two kilometers downwind of the bunker after it was blown up. Researchers are still seeking to determine whether there is a link between veterans who suffer from health problems after the war and their proximity to the bunker when it was destroyed.¹⁸

External Design Considerations

The concept of deeply buried facilities creates an image of a structure underneath the ground that is completely hidden and isolated from view. In reality, however, complete self-containment is neither realistic nor preferred. The reason is that most underground facilities are designed for the conduct of daily operations while remaining connected to the society's infrastructure for electrical power, water, sewage, ventilation systems, and communication systems. While some facilities can "button up" in order to operate on an autonomous basis for limited periods of time, the normal operating mode is a regular connection with the outside world. Accordingly, designers of underground facilities take prudent steps to conceal the existence of such facilities and mask their existence. While it is likely that there will be detection systems near the overburden of deeply buried facilities for discouraging intruders, a reasonable assumption is that the external features of these facilities will be designed to minimize the possibility of detection, particularly by satellites and other reconnaissance sensors.

One study reviews the capabilities of satellites to collect intelligence information about these facilities and provides suggestions for countering such capabilities.¹⁹ It suggests that concealing the facility's intended operating activities, equipment, and location from satellite observation is best accomplished by avoiding attention during the construction phase and after during its daily operations.

Another approach is to adhere to a well-planned deception scheme, which typically seeks to reduce the chance of detection by reconnaissance satellites. These discussions are important because they provide useful insights into the potential design features of deeply buried facilities, and thus ways for avoiding the detection of underground facilities by satellites, as discussed below.

Avoid Manmade Patterns. Exhaust vents, facility entrances, and any accompanying surface infrastructure should avoid the use of square or triangular shapes. Manmade patterns should be broken up with camouflage, and camouflage should be chosen that has a high infrared (IR) signature because this is easily mistaken for natural vegetation, which normally has a high IR signature. The use of natural and confusing patterns, such as hiding equipment under cliffs and locating equipment near streams (which have thicker vegetation), offer ways to integrate the external design features of an underground facility with the natural environment, and thus reduce its detectability by satellites.

Panchromatic Deception. The reflectivity of objects on the ground is an important characteristic in determining the ability of satellites to detect an object. Therefore, the reflectivity of all surface-located support equipment, structures, and antennas can be suppressed through proper paint schemes and masking camouflage. Since black and white satellite images are most commonly used, principally because they highlight the reflectivity and contrast of objects on the ground, the paint schemes selected for surface-located items should use subdued tones, rather than color, to minimize its reflectivity.

Decoys. Since satellites can take stereo images, which are two slightly offset images of the same area, three-dimensional decoys can be effective in concealing the true location of the critical external support equipment for an underground facility. Furthermore, thermal heaters can be placed in mock vents to approximate the temperature of exhaust gases that an underground ventilation system would generate. These mock vents can then be placed at false locations on the surface of the earth to conceal the true location of external support equipment. Mock antenna arrays, entrances, and other features can all be replicated and thermally matched to approximate the signatures of real items, and thereby conceal the true location of a deeply buried facility.

Thermal Imaging Deception. As hot air emerges from air vents for underground facilities, satellites can see this distinctive signature. It also may be detected as hot spots that develop on the surface of the earth over various parts of the underground facility. The ambient temperature of some parts of the underground facility may elevate the temperature of parts of the surrounding earth near air vents, water pipes, emergency exits, or electrical conduits. However, measures can be taken to insulate those parts of the facility that are closest to the earth's surface. Heavy vegetation and thermal blankets can be used to reduce the thermal signatures of external components of underground facilities, and cooler ambient air can be mixed with the warmer exhaust air to minimize its detectable thermal signature.

While there are other deception techniques for defeating the capabilities of reconnaissance satellites, the previously cited study suggested that there are fundamental problems with avoiding detection by satellites. The reason is that one method for evading the detection capabilities of one type of sensor will likely be vulnerable to the capabilities of another sensor. For example, a grid of lights above a target could perfectly match the reflective signature of the surrounding area and therefore be invisible to a multispectral satellite, but this would be quite obvious to a high-resolution panchromatic sensor when viewed from an angle.²⁰

Summary

This discussion focused on defining the two classes of underground facilities, which are known as "cut and cover" and "deeply buried," and describing the possible design features of deeply buried facilities and the deception schemes that will serve to minimize their detection. The robust nature of the deeply buried facilities that are examined in this discussion probably represents a small percentage of the underground facilities that U S military forces might encounter in a military contingency. However, the reason for focusing on the most difficult challenges that are associated with deeply buried facilities is to give military planners the opportunity to understand how to respond properly to this difficult target. The discussion in the next section focuses on the difficulties associated with locating deeply buried facilities.

III. Locating Deeply Buried Facilities

Recent research concludes that searching for and finding underground facilities is the most important step in dealing with these targets, and that the United States must refine its capabilities for locating underground facilities. This line of reasoning leads naturally to the question of what specific approaches and technologies will help to locate deeply buried facilities.

For background, scientists have been wrestling with this problem for decades, and have developed a variety of methods for locating objects that lie beneath the surface of the earth. As shown in Table 1, modern prospectors use instruments that rely on sensing various physical properties of the earth, including geophysical prospecting instruments that measure gravitational fields, electric fields, magnetic fields or sound waves, all of which help to deduce what lies beneath the surface of the earth.²¹ All of these fields (and waveforms) are altered by features in the earth, including contrasts in rock density and porosity, the liquid content of the soil, or changes in naturally emanating magnetic fields due to the density or absence of material from beneath the surface of the earth (i.e., underground facility). Prospecting instruments collect information by using both active and passive methods.

Method	Mode	Applications
Gravity Field Mapping	Passive	Geologic mapping, faults, cavities, fractures
Magnetic Field Mapping	Passive	Geologic mapping, detecting pipeline, burial trenches, utilities
Ground Penetrating Radar	Active	Soil horizons, trenches, utilities
Seismic	Active	Bedrock topography, fractures, rock hardness
Electromagnetic	Active	Ground water depth, soil moisture, acid plumes
Electrical Conductivity	Active or Passive	Ground water depth, soil moisture, fractures, acid plumes
Radioactive	Active or Passive	Geologic mapping, radioactive plumes

Table 1. Common Geophysical Methods of Prospecting source: I J won, "Diagnosing the Earth," *Ground Water Monitoring Review*, Summer 1990, Vol. 10, No 3

Active Subterranean Mapping Methods

Active geoprospecting instruments use the emission of either sound waves or electromagnetic energy to characterize how these waves bounce off unseen objects. This is similar to the approach used by a submarine when it emits a sound (or "ping") and listens for an echo to determine the presence of a solid object. By contrast, passive instruments sense the presence of fields, such as an infrared detector that passively senses the presence of heat.²² There are two other methods, ground penetrating radar and seismic reflection methods, for locating deeply buried facilities.

A Ground Penetrating Radar (GPR) is an active device that transmits a pulse of electromagnetic energy into the ground, which when it strikes objects, is reflected back to the receiving antenna. GPR is an accurate means of detecting objects that are below the surface of the earth. Under the best circumstances, GPR can penetrate about 15 feet of sand, but is completely ineffective in saturated clays and moist soils. The principal use of GPR is by archeological surveys for detecting shallow objects that are embedded in the soil as well as burial pits and trenches, so that they can develop precise digging plans that will avoid destroying artifacts. Although GPR could be used to locate electrical, water, and sewage lines that may supply a deeply buried facility, its current size, weight, limited ability to penetrate the soil, and overt operational characteristics reduce its value for high-risk military operations when discreetness, mobility, and flexibility are critical.

Seismic methods are commonly used by oil and natural gas prospectors to detect the presence of deposits beneath the surface of the earth. Seismic surveys are sufficiently accurate for providing a good characterization at depths greater than 100 meters. Seismic prospecting techniques require the introduction of a shock wave into the ground, normally with an explosion or a hydraulic tamp to generate echoes for detection by precisely placed sensors. Based on the pattern and location of the echoes, which are caused by the shock wave bouncing off underground objects, seismologists can determine the location of faults, rock density, and other underground features, including the presence of underground cavities. This approach may have some merit if it is developed into an operational capability.

For example, during the Vietnam War sensors were mounted on spikes and dropped along trails to detect the presence of enemy forces.

In this way, seismic listening sensors could be mounted on spikes and showered over an area that is suspected of containing a deeply buried facility. The sensor spikes can be fitted with Global Positioning System (GPS) transmitters that communicate their precise three-dimensional position. Sensor spike deployment could be followed within a short time by GPS guided munitions that are programmed to hit the ground at precise impact points. The sensor spikes could listen for the echoes and transmit this data to an orbiting aircraft or satellite for the detection and location of hollow cavities and underground structures. This concept is technologically feasible.

Passive Subterranean Mapping Methods

By contrast, passive geoprospecting instruments operate on the basis of the principle that the continually varying density of the earth's crust alters the earth's magnetic field in measurable and predictable ways. The strength of the earth's gravitational field at any point on the surface of the earth depends on the density of the rock beneath the surface, which changes as one moves across the surface of the earth. This physical law enables the development of gravity sensing instruments, which are commonly used by geologists to measure the force of gravity over many small sections of land.²³ The measurements that are obtained are compiled into a gravity map for an area, which are regularly used by the oil, gas, and mining industries to indicate the presence of hydrocarbon or mineral deposits below the surface of the earth. In the same way, gravity mapping can be used to indicate the existence of cavities or deeply buried facilities. But, defining the exact location of an underground facility is not a simple matter.

Gravity Field Mapping

Given the different instruments that are available for seeing under the surface of the earth, the instruments most widely used for depths greater than 20 meters are those that are based on sensing the force of gravity. Gravity surveys, which are traditionally used for detecting salt domes and cavities in bedrock, are time consuming and overt activities. The gravimeter is moved meter by meter to presurveyed "benchmarks" to precisely measure the gravity vector (i.e., force and direction of gravity) As the force of gravity changes with changes in the density of subterranean features, one looks for the characteristic alterations in the gravity field that result from variations in the density (or absence) of material underneath the surface of the earth.²⁴

Small intervals between measurements are necessary to accurately define the edges of cavities that may exist underground. The microgravity engineering and archaeological surveys that are traditionally used for detecting cavities in bedrock often involve taking measurements at intervals of one meter. But the presence of soft soil under the gravimeter or the effect of wind blowing on the instrument can adversely affect the gravity reading and therefore skew the results. Furthermore, precise measurements of altitude (within 10 cm) and latitude (within 30 meters) are required for accurate results.²⁵ In fact, obtaining accurate altitude and latitude measurements is currently the most difficult and time-consuming aspect of conducting gravity field surveys.

While gravimeters can measure the gravitational force at discrete points, this technology requires highly accurate, three-dimensional prospecting at each point prior to measurement. Fortunately, GPS has vastly simplified this operation. Modern gravimeters can make highly accurate gravity measurements at each station in less than half-an-hour, but are impractical for detecting underground facilities under the pressure of time that would exist in military contingencies.

Another instrument that is used in virtually all commercial and military aircraft, as well as intercontinental ballistic missiles, is the inertial measurement unit, or IMU. In comparison with a gravimeter, inertial measurement units measure changes in acceleration due to movement and reduce the movements to a calculation of its three-dimensional location in space. What would be most useful to prospectors would be to integrate the gravimeter and the IMU into a single instrument that accurately measures changes in gravitational fields while dynamically moving over the surface of the earth. This technology, which is known as a gradiometer, is being improved and miniaturized for mining and prospecting applications, and has operational benefits for military contingencies.

Gradiometers have been used in the US Navy's submarine fleet to stealthily detect underwater obstacles without having to visually sight them, and without having to emit an audible sonar "ping" that reveals the location of a submarine. Gradiometers can dynamically measure extremely small changes in the gravity gradient as the instrument passes over the surface of the earth or near objects.

The concept of gravity gradients is central to understanding gradiometers. As described earlier, while conventional gravimeters measure the overall force of gravity at a given point on the surface of the earth, gradiometers are comprised of up to six pairs of identical sensors (called accelerometers) in an instrument that takes twelve separate measurements of gravity at any given time.²⁶ Each paired set of accelerometers is separated by a small gap between the two sensors.

For an aircraft flying over land whose subsurface consists of both low density and high density rocks, the gravity gradient immediately indicates the presence of less dense rock (or cavities) that lie underneath the surface of the earth, or the increase in force of gravity due to the presence of a large landform, such as a mountain.²⁷ The ability to use gradiometers as a part of airborne surveys has significant military implications for locating deeply buried facilities.²⁸

In the past, airborne surveys lacked detail, principally because of the limitations associated with the sensing equipment on aircraft. Airborne surveys, rather than detailed mapping, were used to determine the gross features of the gravity field over wide areas. The subtle gravity perturbations that are produced by buried facilities would have been missed by a quick overflight of gravity sensing instruments because the instrument is unable to produce sufficiently accurate data, process that information quickly, and sense the micro-perturbations in gravity over the ever-changing subterranean density of the earth. However, with the increasing miniaturization of electronics and sensors, gradiometers can be used for the explicit purpose of detecting deeply buried facilities.

A concept for locating underground facilities involves the integration of a gradiometer, GPS receiver, and the ability to transmit raw gradiometer data to an airborne platform, such as an uninhabited aerial vehicle (UAV). In this case, a UAV could be programmed to survey an area and transmit the results in real-time. The ability to program a UAV to autonomously accomplish such a mission, from take off to landing, is feasible and in fact serves as the fundamental concept for the Air Force's Global Hawk UAV. Depending on the location of a buried facility and the threat posed by it, one could fly small remotely piloted vehicles (RPVs) over the suspected area.

The various RPVs of differing sizes and payload capacities that exist on the commercial market for prospecting and surveying could be modified for military operations. For example, the Sensoar RPV, which is manufactured by Remote Sensing Research, is a slow flying, radio controlled, gas or electric powered aircraft.²⁹ With a wingspan of 12 feet and weight of about 12 pounds, it is capable of taking low-altitude, high resolution photographs, or operating at altitudes greater than 10,000 feet. Its 4-pound payload capacity includes a GPS receiver and camera. However, in place of the camera, a properly sized gradiometer could be integrated with GPS to perform airborne gravity surveys above areas that are suspected of containing deeply buried facilities.

Satellite Intelligence, Surveillance, and Reconnaissance

As the capabilities and flexibility of satellites for gathering accurate and highly detailed intelligence information continue to increase, their role is becoming more central to intelligence operations, including the ability to detect deeply buried facilities. For example, reconnaissance satellites use an array of high resolution imaging and sensors, such as the Landsat's multispectral scanner, to provide clues about the existence of Underground facilities and their activities. This relies on infrared, thermal, and multispectral imaging of the surrounding land and the facility.

Furthermore, reconnaissance satellites can be used to estimate what is being produced at a particular site based on the size of storage tanks, number of rail cars, size of the roads, and other external features. Landsat's thermal imagery can detect, in sections of land that are the size of a front lawn, vent duct arrays or the heat generated by underground facilities if they are close enough to the surface. Its blue-band filter can also detect the smoke and gases that are emitted from underground vents. While underground facilities are difficult to locate, roads or tracks leading into the side of a mountain or disappearing underground often help to reveal their location. Furthermore, commercial firms have developed the software that detects changes between images that are generated over time, which is known as change detection software. Acquiring images of the same terrain over a period of time is a common way for using satellites to monitor activities and changes in areas where deeply buried facilities are suspected to exist.

Human Intelligence, Surveillance, and Reconnaissance

Human sources of information will remain central to the ability to locate deeply buried facilities. The information that is obtained from defectors, covert agents, photographs, documents, and soil samples, among other types of knowledge about a facility, help military planners to deal with these targets.

Summary

Not surprisingly, it is quite difficult to find deeply buried facilities, and to complicate matters this is an area in which experience and technology are not fully developed.³⁰ However, by using an integrated combination of geoprospecting instruments, satellites, and human intelligence reports, it is likely that one can determine where deeply buried facilities are located. There are numerous signs of the existence of underground facilities, including gravity perturbations, the presence of ventilation shafts, electrical power lines (above or below ground), water and sewage hookups, and emergency exits. Satellite imaging with a variety of sensors can indicate the presence and location of underground facilities, and human intelligence can help to locate these facilities. If one uses a broad array of sources, these facilities can be found, but characterizing the shape, depth, and mission of an underground facility may be more difficult than locating it.³¹ While this discussion highlights the value of gravity sensing instruments, it is essential to develop a comprehensive approach for integrating all resources in order to produce reasonable estimates about the location of underground facilities.

IV. Neutralizing Deeply Buried Facilities

For the reasons outlined in this study, it is difficult to locate and neutralize deeply buried facilities, especially when one must consider the fact that these facilities may contain nuclear, chemical, or biological agents whose destruction might inadvertently release dangerous substances into the atmosphere. This condition would endanger friendly forces and non-combatants alike, and create the possibility of regional disasters. An underground facility also may contain important military and governmental assets that have value for subsequent exploitation, non-proliferation purposes, or intelligence analysis. A further complication is that an underground facility may be located in an urban area, perhaps under a school or hospital or surrounded by a neighborhood in which the danger of collateral damage precludes the use of conventional or nuclear weapons. For this reason, specialized personnel who are properly equipped to neutralize a facility may be the best option. In any case, there is no guarantee that neutralizing a deeply buried facility will be an antiseptic operation because it could easily be costly in terms of lives and equipment for both sides.

The concept of neutralization includes the full range of "kill" levels that are necessary to accomplish the objectives of the mission. Those objectives may be to recover weapons of mass destruction or hostages from an underground facility, disable biological weapon manufacturing equipment, or completely destroy a command and control center. There will be cases when the United States will want to destroy or disrupt deep underground facilities that are heavily guarded, largely invulnerable, and possibly located in urban areas.

The U S Department of Defense has weapon systems and development programs that seek to destroy underground targets, including the Congressionally approved Surgical Strike Vehicle, the GBU-28 Laser Guided Bomb that was used during Operational Desert Storm, and other weapons development programs.³² This study explores alternate means of neutralizing underground facilities without the use of air-delivered conventional or nuclear weapons.

It is possible to generate neutralization concepts for targeting the specific exploitable features of an underground facility, as shown in Table 2. From an analysis of deeply buried facilities, the wide array of locations, configurations, and missions suggest that simple solutions for neutralizing these facilities are unlikely to be effective.

Further, it is essential to understand that there is no single technological solution that will accomplish all of the possible neutralization objectives. By contrast, the more reasonable approach is a combination of technologies and ideas, some of which are demonstrated while others are in the conceptual stage, for neutralizing deeply buried facilities.

Critical Nodes	Neutralizing Concepts
Physical Structure/Overburden	Undermine with Suitcase Nukes
	Entombment
Environmental Control System	Air/Water/Food Poisoning
	Elimination of Air/Water/Food
	Elimination of Light
	Overpowering Odors
	Sewer System Failure
	Excessive Cold/Heat
	Sound/Noise
	Humidity
	Allergies (Molds/Mildews)
Electrical Power	High Power Microwaves
	Electromagnetic Pulse
Computer/Comm Systems	Information Network Attacks
	High Power Microwaves
	Electromagnetic Pulse
	Cut Wires
	Destroy Antennas/Satellite Dishes
Other Neutralization Ideas (Related to COGs)	Open Inspection Regimes
	Disease

Table 2. Neutralizing Concepts and Critical Nodes

Source: Derived from: William E. Loose, Air Force Research Lab Proposal for Research on Alternatives to Conventional Destruction of Hard, Deeply Buried Targets, Fall 1 9Y8

The prominent scenario that U.S. forces may encounter is the requirement to neutralize a deeply buried facility that is suspected of containing weapons of mass destruction and other high value assets. Given that the quantity and exact nature of the materiel is unknown, it may be necessary to incapacitate the facility rather than totally destroy it. Thus, it will be necessary to selectively target features of the deeply buried facility in order to achieve varying degrees of incapacitation, which may include entry into the facility. The remainder of this section is devoted to describing various alternate means of neutralization for deeply buried facilities, as outlined in Table 2.

Attack the Overburden

The function of overburden is to increase the invulnerability of deeply buried facilities to attack, and thus to provide a sanctuary from attack. The overburden is critical to the survival of a deeply buried facility. When attacking a deeply buried facility that is covered with hundreds of thousands of tons of rock and earth, the natural approach is to employ means that can either penetrate the overburden, reach the facility's cavity in order to destroy it, or crack and shatter the overburden in order to cause the internal cavity to collapse. A third option is to undermine the facility.

During the American Civil War, Union forces had difficulty breaching the confederate defensive lines around Petersburg, Virginia. Pennsylvania coal miners serving with Union forces tunneled underneath the confederate lines and detonated 8,000 pounds of black powder, which created a massive crater and effectively eliminated that part of the confederate defensive line. In World War I there are similar cases of undermining German positions in order to break open the entrenched lines of defense. Today, the ability to undermine deeply buried facilities represents a potential option for neutralizing them. A study by Lawrence Livermore Laboratories documented the effectiveness of detonating low-yield nuclear weapons underneath ore deposits to produce a low-cost approach to mining. Using a 1.7-kiloton warhead placed 900 feet inside a mountain, an estimated 700,000 tons of the overburden would be cracked and shattered and most of this would cave into the cavity that was produced by the explosion. Furthermore, most of the radioactivity would be trapped in the estimated 700 tons of melted rock that would line the walls of the cavity immediately after the explosion.³³

What is especially impressive is that the relatively low yield of the weapon would create such destruction inside the mountain. There are reports that the former Soviet Union developed small, suitcase-sized nuclear weapons with comparable yields. While this technology has significant implications for these facilities, the problem is to place the weapon underneath or inside the facility. But whether covert mining operations or other methods could place such a weapon inside or near a facility is subject to debate.

In those cases when it might be difficult to get near a deeply buried facility, it may be easier and quicker to entomb it. Explosive charges placed at all of the openings would cause cave-ins of the ventilation, elevator, and emergency escape shafts, along with the main entry tunnel(s). An enhanced version of the commercial product "Great Stuff," which is expanding insulation foam that is available in most home improvement centers, could assist with entombment. If a hyper-expanding version could be developed, it could be used to quickly block the orifices and thereby hermetically seal the facility, which would prevent the release of toxic or radioactive gases or material into the atmosphere. The risk with entombment is the difficulty of ensuring that every orifice is identified, but this may be a realistic option for smaller underground facilities.

In some cases, it will be desirable to enter the deeply buried facility in order to recover high-value assets. There are other overburden features that can be attacked for this purpose, including the entry tunnel and the security or blast doors. A reasonable assumption is that during a conflict or in the case of direct attack, security forces will close the blast doors throughout the main entrance tunnel(s), which will pose a formidable obstacle to entering the main chambers of the facility. Large cutting charges would have to be employed to breach the metal doors. Once main entry is breached, fuel-air explosives could be injected to rapidly remove the oxygen from the tunnel, which would have the effect of suffocating or incapacitating some of the security forces. Depending on the size and compartmentalization of the entry tunnel, overpressure could open some other doors. What cannot be forgotten is that entering a facility through the main tunnels is a risky and time-consuming process that is likely to create casualties.

Another concept for attacking the tunnel system is to employ mobile robotic infantry probes that are outfitted with antipersonnel weapons, TV cameras, and other appropriate sensors for eliminating the defending security forces and clearing the way for the entry of friendly forces. Later, the facility could be destroyed with explosives in order to cause the complete collapse of the facility.

Attack Environmental Control Systems

In order to exist underground, an environmental control system (ECS) is vital for the survival of the personnel and often the equipment in the facility. Light, conditioned air (temperature, humidity, and cleanliness), and water must be provided for the people and equipment that operate Underground. The ability to disable the ECS creates environmental conditions that exceed what people and equipment can withstand, and thereby produce conditions that facilitate entry into the facility. However, the ability to gain access to the ECS for the purpose of creating such adverse environmental conditions can be quite difficult.

In most mining operations, rough-cut emergency escape shafts are drilled to the surface to permit quick exits in the event of an emergency. It is reasonable to expect that deeply buried facilities may follow the same practice. Escape routes may be reamed through the overburden to the surface or just below the surface, with a final cover that can be penetrated from the bottom if it is necessary to evacuate the facility. It may be difficult to locate these emergency exits for potential entry from the outside, even with sensitive geoprospecting instruments, but these routes would provide quick access to the deeply buried facility and its ECS.

Air ducts or elevator shafts used during construction also may provide options for exploiting the environmental control system. Introducing incapacitating agents into the ventilation system, such as atomized narcotics, toxins, vomit gas, or sleeping agents, such as dimethyl sulfoxide, could disable or knock out a large number of people for sufficient time to permit access to the facility.³⁴ Contaminating the air filters with extremely foul odors or allergens also could drive the inhabitants out of the facility. Lastly, inducing a massive failure of the lighting system, principally through failure of the primary and backup electrical power systems (as discussed later) would make it impossible for people to operate inside the facility.

Sound is not only irritating but can have debilitating effects on humans. Acoustic weapons have been used successfully in the past and their performance is continually improving.³⁵ Acoustic weapons fall into the category of non-lethal weapons that could be used effectively to neutralize the security forces that protect an underground facility and the personnel that operate the facility.³⁶

The purposeful introduction of organic allergens to the underground environment through the ECS is another option, but, unfortunately, the temperature and humidity are difficult to alter in deeply buried facilities within a short time, and both of these factors are critical for the propagation of molds, mildews, and fungi. If the environmental control system were disabled, it may get stuffy, but the temperature and humidity would not vary significantly during the first 24 hours given the insulating effects of the overburden. Furthermore, a dry, moderate temperature is not conducive to the purposeful introduction of organic allergens that are targeted at people.³⁷

In summary, because the environmental control system is critical to creating a habitable environment in a deeply buried facility, the ability to disable it will put the inhabitants at such a disadvantage that it might be necessary to evacuate the facility. This condition would have significant operational benefits for the United States. However, US forces will need to be equipped to operate in the adverse underground environments that might result from their actions, including artificial light sources, gas masks, or possibly clothing that prevents the atmosphere from coming in contact with the skin of U. S. personnel.

Neutralize Electrical Power Grid

Virtually all of the equipment in underground facilities, including communications equipment, computers, manufacturing equipment, the ECS, and the security systems, depend on electricity. The ability to locate and destroy the source of electrical power, which means the power plant and power grid nodes as well as the electrical conduits entering the facility, can effectively neutralize the facility. These electrical power conduits are probably located near the entrance tunnel(s), or are buried and inserted through the roof of the entry tunnels. Given the need for electricity in an underground facility, it is reasonable to assume that the facility has an auxiliary electrical generation capability, and therefore, that

severing the primary source of electrical power will not necessarily cut off the power.

An alternative to locating and attacking the sources of electrical power is to destroy the equipment's capability to use electricity. One approach is to use electromagnetic pulse (EMP), which is a wave of energy that is produced by the detonation of a nuclear weapon, and that destroys circuit boards and destroys electronic equipment. But the effects of EMP can be created without detonating a nuclear weapon. The non-nuclear EMP, which is more commonly called high-power microwaves (HPM), can degrade or destroy electronic circuits and associated electrical components, thereby rendering much of the equipment in an underground facility useless. The amount of damage to electronic devices depends on the sensitivity of the components and the amount of microwave energy transmitted through circuit pathways located within the target. Deeply buried facilities include many vulnerable features, including its external antenna array, hard wire communication lines, and electrical power lines, all of which provide conduits for microwave emissions. A microwave attack will not only shutdown the communications link to the outside, but will also destroy or severely damage the electronics that are connected to the link, including communications gear, computers, and the control circuits that are associated with backup electrical generation systems.³⁵

With the development of high-powered microwave weapons, the U.S. military will have a promising instrument for attacking deeply buried facilities. For example, one concept is to integrate HPM into cruise missiles 39 As evidenced from the level of development of HPM weapons, there is great potential for attacking the electronic infrastructure in a deeply buried facility. For the foreseeable future, successfully disrupting the electrical power, or the electrical circuits that depend on it, is an effective means for disabling a deeply buried facility.

Neutralize Computer and Communications Equipment

The effects of HPM weapons described above have the potential to disable or destroy all the electronics that are located in a deeply buried facility, including computer and communications equipment. Attacks with destructive software viruses that are launched through the internet or directly loaded into the computer network that supports a deeply buried.

facility, or manipulating an enemy's databases, also provide an effective means for degrading a facility's capability to perform its mission.

Environmental control, security, databases and certain manufacturing processes are likely to be controlled by computer systems that are located inside an Underground facility. While it is unclear whether computers provide entry points for information operations to manipulate the information, if these computer networks are designed for maximum security and survivability it is likely that these would be designed with a minimum of external connections.

An attack that focuses on destroying the external communication links and computer controls, including antennas, satellite dishes, and hardwire connections, provides another means for neutralizing an underground facility. However, it is not easy to locate the external communication connections because the designers of deeply buried facility will adopt many of the external deception and camouflage schemes, as discussed earlier, including low reflectivity, the integration of manmade structures with natural surroundings, and the use of decoys. Furthermore, since external communication connections are a vulnerable aspect of deeply buried facilities, it is likely that the facility will use redundant communication links in order to avoid the vulnerabilities that are associated with external antennas. Lastly, it may be better to leave external antennas intact and undisturbed, rather than destroy these, because these could be used as conduits for an attack with high power microwaves against the equipment that is attached to the antennas. As discussed earlier, antenna arrays are an ideal entry point for using HPMs to destroy the electrical circuits that supports a deeply buried facility.

Summary

A reasonable assumption is that with a carefully planned campaign, it is possible to destroy or neutralize deeply buried facilities. The concepts that are discussed in this section range from the use of existing technologies to the development of new ideas and technologies that require further analysis. The broader point is that as states realize that the United States is committed to neutralizing deeply buried facilities, those governments are likely to respond by digging deeper, building harder facilities, and developing mobile facilities, as the Libyans are suspected of doing at Tarhunah. As rogue nations are forced to take increasingly

expensive actions to counter U S military capabilities, this represents a success for the United States. The enormous expense that is associated with constructing these facilities will only increase as these states attempt to develop more robust and survivable facilities. Finally, it should be evident that neutralizing deeply buried facilities represents a formidable challenge for the U S military.

V. Conclusions

While deeply buried facilities have existed for decades, these facilities have emerged as an important challenge for the U S military in the early years of the twenty-first century. Their significance reflects the dangers associated with the proliferation of nuclear, chemical, and biological weapons, and the prospect that rogue states could use these facilities for the manufacture and storage of weapons of mass destruction, as well as housing critical command and control function for the government and the military.

The immediate problem is that, short of the use of nuclear weapons, the current generation of technologies for locating and neutralizing these types of facilities are not sufficient for holding deeply buried facilities at risk. This means that the United States should direct its research and development organizations to develop weapons that will allow U.S. forces to locate, characterize, and neutralize underground facilities. One must also consider that a military response to these facilities may involve more than brute force attacks against the facility or its contents. The use of advanced conventional penetrating weapons may not be sufficient to ensure complete success because if a weapon misses an underground facility by a mere 50 feet, the facility may survive. Furthermore, if it is desirable to preserve the contents of the facility or if collateral damage is politically unacceptable, the use of overwhelming force simply may not be a realistic military option. The implication is that alternative means of neutralizing deeply buried facilities must be vigorously pursued so that the United States and its allies will have the widest range of capabilities and options for destroying these facilities.

The ability to locate, characterize, and neutralize deeply buried facilities is critical to the successful conduct of future military operations. Some of the concepts that will contribute to this capability have been presented in this study, as shown in Table 3.

	<i>Locating</i>	<i>Characterizing</i>	<i>Neutralizing</i>
People	Special Forces Special Agents Defectors Geologists/Geophysicists Mining Engineers Utilities Engineers Intelligence, Surveillance and Reconnaissance (ISR) Specialists	Special Forces Special Agents Defectors Geologists/ Geophysicists Industrialists Mining Engineers Utilities Engineers Intelligence, Surveillance and Reconnaissance (ISR) Specialists	Special Forces Special Agents Mining Engineers Utilities Engineers Environmental Control Specialists Environmental Engineers
Equipment	Robotic Faux-Rocks Miniaturized Gradiometers Seismic Sensors UAVs/RPVs Land, Air and Spaceborne intelligence sensors	Robotic Faux-Rocks Miniaturized Gradiometers Seismic Sensors UAVs/RPVs Land, Air and Spaceborne intelligence sensors	Advanced Communications equipment Environmental protective clothing Gas masks Artificial light sources Night/IR vision equipment
Technology	Enhanced Geoprospecting Equipment Remote seismic sensors Enhanced Satellite ISR Enhanced Airborne ISR	Enhanced Satellite ISR Enhanced Airborne ISR Standoff Exhaust Gas Spectrum Analyzers Soil Analyzers Remote seismic sensors	High-Power Microwaves Suitcase Nukes Acoustic Weapons Mobile Robotic Infantry Hyper-expanding Foam Fuel-air explosives Blast door cutting charges Narcotics/sleeping agents
Strategy	All-source intelligence Gravity maps/surveys Acoustic maps/surveys Inspection Regimes	All-source intelligence Inspection Regimes	Attack centers of gravity Inspection Regimes

Table 3. Summary of Responses to Deeply Buried Facilities

In terms of posing a military threat to deeply buried facilities, it will be necessary to coordinate advances in sensor technologies in the geophysical, submariner, and intelligence collection communities. In fact, many of the major U.S intelligence collection systems must be re-evaluated in terms of their ability to solve the problem that is created by the existence of deeply buried facilities.

If the United States is to solve this problem, then its approach must rest on three fundamental realities about deeply buried facilities. The first is that the threat is real and continues to increase. The consequences for U S. national security can be devastating if this problem is not addressed Second, the United States must make a long-term commitment to develop the

necessary technologies and equipment to locate, characterize, and neutralize deeply buried facilities. For example, the U S. Air Force armament laboratory at Eglin AFB has initiated a call for concepts from industry for developing options for neutralizing deeply buried targets. Third, it is essential to develop programs that will integrate all of the relevant technology, equipment, and strategies that are necessary for defeating deeply buried facilities, which includes all of the military services and the intelligence community.

If this strategy is successful, it should influence the decision making process in states that are considering the construction of such facilities, and perhaps may persuade these governments that deeply buried facilities are not as secure and invulnerable as they once thought. Those governments that are committed to constructing deeply buried facilities will eventually realize that the United States will acquire the technological means for finding and destroying these facilities in the event of war. Finally, the U S. defense establishment must contemplate how the development of deeply buried facilities will affect national security in the twenty-first century.⁴⁰

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<http://www.hnd.usace.army.mil/oew/tech/rogppr1.html>, December 17, 1998.

Notes

1. See Gary Curtin, "The Threats Go Deep," *Air Force Magazine*, October 1997, p. 47, for the argument that, "Hardened and deeply buried targets have evolved over the years as one of the lessons of Desert Storm. The old 'cut-and-cover' of targets in Desert Storm (i.e., dig a hole, build a concrete bunker, and cover it with dirt) are no longer perceived as hard enough, so building things into mountains has become the way to perceive the things that are most important to you. We have witnessed this in Korea for many years...and in a lot of other places in the world."
2. William E. Loose, *Air Force Research Lab Proposal for Research on Alternatives to Conventional Destruction of Hard, Deeply Buried Targets*, Fall 1998.
3. Raymond Bonner, "Mysterious Libyan Pipeline Could Be Conduit for Troops," *New York Times*, Tuesday, December 2, 1997.
4. See Joseph S. Bermudez, Jr., *North Korean Special Forces* (Annapolis, MD: Naval Institute Press, 1998, Appendix B, DMZ Tunnels, p. 251.
5. Susanne M. Schafer, "B-2s are Combat Ready," *Air Force Times*, April 14, 1997, Vol 57, Issue 37, p. 16.
6. Patrick J. Sloyan, "A Policy Change Undone; U.S., Says Nuclear Threat Not Needed" *Newsday*, February 26, 1998. See www.newsday.com/mainnews/rnmi021n.htm.
7. There is an important distinction between finding underground facilities and characterizing their functions. The former task of finding facilities is considerably simpler than discerning what is contained in those facilities and what military and governmental functions are performed within an underground facility. The principal focus of this study is on the problems associated with locating and neutralizing these facilities.
8. See Hard Target Smart Fuze Program Office, Eglin Air Force Base, Florida, <http://www.wlmm.eglin.af.mil/public/mnmf/htsf.html>.
9. "The Threats Go Deep," *Air Force Magazine*, October 1997, p. 47.
10. For information on the English Channel digging rates, see Drew Fetherston, *The Channel, The Amazing Story of the Undersea Crossing of the English Channel* (New York: Times Books). It was reported that on the British side, the records in the Marine Running Tunnel North (MRTN) were 71 meters in a day, 409 meters in a week, 1,637 meters in a month. In the Marine Running Tunnel South (MRTS), the records were 76 meters in a day, 426 meters in a week, and 1,718 meters in a month. The British MRTS team averaged 55 meters per week during 1989, 195 meters per week in 1990, and 324 meters per month in the last three months ending February 24, 1991. The numbers for the French MRTN and MRTS teams were similar.
11. William Hamilton III, *Dulce and Other Underground Bases and Tunnels*. See <http://www.wic.net/colonel/cog.txt>, p. 2.

12. See W.S. Attridge, Jr., *The Deep Underground COC, Technical Memorandum TM-3097* (Bedford, MA: The MITRE Corporation, June 19, 1961), p.2. This study noted that the "figure of (2,000 feet) per se, has been derived from theoretical models and is not so conclusive as to stand as fact, but is merely a step in the right direction

13. For reference, this is defined as the length of the tunnel divided by its diameter, which has an ideal value of approximately 500.

14. *Ibid.*, p 4

15. *Ibid.*, p 6

16. *Ibid.*, p 13

17. *Final Report to Congress: Conduct of The Persian Gulf War* (Washington, D.C.:US Department of Defense, April 1992), p.159.

18. Douglas J. Gillert, "Official Describes Scene at Iraqi Weapons Bunker, " *American Forces Information Service News Article*, November 1996. See http://www.defenselink.mil/news/Nov1996/n11181996/n11181996_9611181.html.

19. This discussion draws on Harold Hough, *Satellite Surveillance* (Port Townsend, WA: Loompanics Unlimited, 1991), p. 140.

20. *Ibid.*

21. Dick Gibson, Primer on Gravity and Magnetics, Gibson Consulting Contract, www2.csn.net/~rigibson/gmprmr.html.

22. This discussion draws on I.J. Won, "Diagnosing the Earth," *Ground Water Monitoring Review*, Summer 1990, Volume 10, No 3.

23. Newton's universal law of gravity, which describes the force of gravitational attraction, defined as F , between any two masses, clarifies this relationship in the following equation $F = G (m_1 m_2) / r^2$, where masses m_1 and m_2 are separated by a distance r , and G is the universal constant of gravity. It is evident that if the mass of either of the objects or the distance between them is altered, the force of gravity will be altered. It is this principle upon which gravity sensing instruments operate.

24. See Neil Fraser, "Seeing with Gravity," *New Scientist*, September 14, 1996.

25. Telford, W M., L P Geldart, and R E Sheriff, *Applied Geophysics, Second Edition* (New York, NY: Cambridge University Press, 1990), p. 24.

26. According to Newton's law of gravitation, if the distance between the object being measured and the accelerometers remains constant, there will be a slight difference in the force of gravity (F) detected by each of two accelerometers in any given pair since they are slightly separated. The difference in the force of gravity between the two accelerometers is the gravity gradient. The advantage of mapping gravity gradients, as opposed to simply the gravity vector, is that the gradients provide a more detailed and accurate picture of the subsurface.

27. Robin E Bell, "Gravity Gradiometry," *Scientific American*, June 1998, p 78, who notes that the "erratic motion of the aircraft creates considerable "noise" in any single gravity profile, whereas measuring the difference between two sensors to obtain the gradient automatically eliminates this source of error."

28. *Ibid.*

29. See Remote Sensing Research Home Page at <http://www.rsr.org/platform.html>

30. Bell, p. 34.

31. There are several possibilities, including the taking of soil samples or the use of sophisticated sensors to remotely perform a spectral analysis of the exhaust gases from such facilities, which may provide clues about the activities performed in the underground facility. Another concept is to exploit the use of gravity sensing instruments by encasing gravimeters or gradiometers inside fake rocks (i.e., a large-scale version of the "hide-a-key" rocks one can purchase at home improvement centers) that are outfitted with some means of mobility, such as small caterpillar treads. With these remote controlled, or pre-programmed, mobile surveying tools, it would be possible to slowly define the edges of an underground facility by crawling around an area and transmitting real-time gravity measurements and/or seismic information to data collection nodes. It would therefore be possible to provide some indication of the locations of these facilities and the activities occurring therein.

32. See *Final Report to Congress: Conduct of the Persian Gulf War* (Washington, DC: US Department of Defense, April 1992), p. 166.

33. Fred L. Smith and Thomas Young, *Nuclear Explosives and Mining Costs* (California: University of California Lawrence Radiation Laboratory, UCRL 5928, July 1960), p. 3, which noted that when the molten rock cooled into glass and collected near the bottom of the cavity, there was no detectable radioactivity at the surface.

34. James Adams, *The Next World War: Computers are the Weapons and the Front Line is Everywhere* (New York: Simon and Schuster, 1998), p. 145.

35. *Ibid.*, p. 146. "Sound can be used to attack the human body. Subsonic waves between 1 to 3 Hz cause certain organs in the human body to resonate and vibrate, causing extreme nausea, vomiting and loss of bowel control."

36. See Joseph Siniscalchi, *Non-lethal Technologies: Implications for Military Strategy* (Maxwell AFB, Alabama: Center for Strategy and Technology, Occasional Paper No. 3, March 1998).

37. Author telephone interview with Dr. Michael Vincent, Miami University of Ohio, who said that spores of organic allergens would not likely have the opportunity to propagate to levels that adversely affect people because molds, mildews, and fungi depend on higher levels of humidity to thrive. However, further research into spore-based allergens could be performed to identify potential candidates for fast-growing and fast-acting sources of organic irritants.

38. See Eileen M. Walling, *High Power Microwaves. Strategic and Operational Implications for Warfare* (Maxwell AFB, Alabama: Center for Strategy and Technology, Occasional Paper No. 11, December 1999).

39. See Adams, *The Next World War: Computers are the Weapons and the Front Line is Everywhere*, p. 150, which notes that "the Air Force is developing a cruise missile to deliver electronic knockouts on a scale even greater than what was directed at Baghdad. This technology can disable an enemy without the need to drop conventional explosives in areas where noncombatants are located." For a further discussion of the implications of high-power microwave weapons for military operations, see Walling, *High-Power Microwaves*.

40. Smith, *Nuclear Explosives and Mining Casts*, p. 3.

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Grant T. Hammond, Director
Theodore C. Hailes, Deputy Director
Air War College
325 Chennault Circle
Maxwell AFB
Montgomery, Alabama 36112
(334) 953-6996/2985 (DSN 493-6996/2985)
Email: grant.Hammond@maxwell.af.mil
ted.hailes@maxwell.af.mil

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Naval War College
(401) 841-6428 (DSN 948-6428)
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