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Applications of Underground Structures for the Protection of Critical Infrastructure

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Applications of Underground Structures for the Physical Protection of Critical Infrastructure

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Abstract

The U.S. President's Commission on Critical Infrastructure Protection (PCCIP), convened in the wake of the bombing of the Murrah Federal Building in Oklahoma City, concluded that the nation's physical security and economic security depend on our critical energy, communications, and computer infrastructures.[1] While a primary motivating event for the establishment of the commission was the catastrophic physical attack of the Murrah Building, it is ironic that the commission focused its attention primarily on cyber threats. Their rationale was that cyber vulnerabilities posed a new, unaddressed challenge to infrastructure security. This approach was further questioned by the events of September 11, 2001 and the subsequent bio-threat events in America.

During and shortly after the convention of the President's Commission on Critical Infrastructure Protection in 1997-99, a working group met to look into the physical protection of critical U.S. infrastructure using underground structures. This "Underground Structures Infrastructure Applications" (USIA) group provided a timely balancing discussion of issues surrounding the physical vulnerability aspect of the infrastructure protection problem. The group convened a workshop on the subject under the auspices of the National Research Council's Board on Infrastructure and the Constructed Environment.[2] The present paper draws on the working group deliberations and NRC Workshop proceedings to address infrastructure assurance in the context of maximizing the physical protection of high value infrastructure by the use of underground construction. Although the PCCIP did not directly address a role for underground facilities (UGFs), its final report recommended a program of government and industry cooperation and information sharing to improve the physical security of critical United States infrastructure.

We develop specific recommendations for the use of underground facilities to support implementation of the general PCCIP challenge. It is our contention that underground facilities reduce the risk of infrastructure disruption from both physical and cyber attacks. In the latter case, undergrounds provide secure reserve operations and back-up data storage locations to ensure the reconstitution of critical electronic information systems. In addition, noting that the Norwegians have placed much of their critical infrastructure underground, we provide information on the Norway's experience gathered on a fact-finding trip to that country organized by one of the authors. The events of September 11th, 2001 and the use of underground locations for terrorist security by the Taliban, provide a strong impetus for the use of underground construction to protect vital infrastructure.

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[1] Critical Foundations: Protecting America's Infrastructures, Report of the President's Commission on Critical Infrastructure Protection, October 1997
[2] Use of Underground Facilities to Protect Critical Infrastructures, National Academy Press, Washington, D.C., 1998

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1. Introduction

Civil infrastructures are vital public artifacts that support a nation's economy and quality of life. They present a massive capital investment, and, at the same time, are an economic engine of enormous power. Modern economies rely on the ability move goods, people, and information safely and reliably. Consequently, it is of the utmost importance to government, business, and the public at large that the flow of services provided by a nation's infrastructure continues unimpeded in the face of a broad range of natural and manmade hazards. This linkage between systems and services is critical to any discussion of infrastructure. Although it may be the hardware (i.e., the highways, pipes, transmission lines, communication satellites, and network servers) that initially focuses discussions of infrastructure, it is actually the services that these systems provide that is of real value to the public. Therefore, high among the concerns in protecting these systems from harm is ensuring the continuity (or at least the rapid restoration) of service.

In light of the importance of these systems, there is growing concern over the national dependence on "soft" facilities (aboveground, physically exposed, unhardened) for housing high value civilian infrastructure systems. The terrorist attacks of September 11, 2001 mandate renewed attention and efforts to develop better solutions to this problem. Underground facilities provide the most effective physical protection available and can be designed to provide immunity to aircraft impact, truck bombs and even nuclear weapons. For many reasons, underground construction has not been widely used in the past. However, heightened concern about terrorist capabilities and threats within the United States, the recognized importance of infrastructure to our physical and economic well-being, and significant improvements in underground construction technology and cost-effectiveness argue for a fresh look at underground structures. Most critical above ground functions could be safely housed in underground structures with attendant benefits related to protection, energy savings, and environment preservation. Officials looking to broaden their options for protecting citizens and workers from future terrorist attacks and other emergency situations should seriously consider underground structures as a major resource for high value infrastructure elements.

2. Past UGF Paradigms

During the Cold War, high value defense-related facilities were designed and built underground in a large part to counter the threat of strategic nuclear attacks. Underground facilities were designed to help ensure the continuity of government, assure survivable military command and control of the U.S. strategic forces, and provided the necessary safe havens from which to respond to attacks against the United States.

Within the over-arching national security framework of the Cold War, the general public came to view the federal government's UGFs as necessary tools for military and civil defense purposes, but little else. Under the current national defense paradigm, many of these UGFs have been or are being closed or phased down because no compelling case has been made for other domestic security benefits. Furthermore, stigmas associated with the Cold War in general, and civil defense (e.g., fallout shelter) programs in particular have fostered a negative impression of UGFs in the minds of many Americans.

Over the past several years, growing national concerns have emerged regarding the increased vulnerability of our domestic civil infrastructures to attack or disruption, and the evolution of threats against high value civilian targets. These concerns were tragically validated by the events of September 11th, 2001. The continued reshaping of our national defense strategy and the related transition of many national security functions to civil and commercial enterprises has increased the risks and consequences of infrastructure attack. This growing dependence of national defense on civilian infrastructure was noted with concern in the report of the President's Commission on Critical Infrastructure Protection:

> National defense is no longer the exclusive preserve of government, and economic security is no longer just about business… we are convinced that our vulnerabilities are increasing steadily, that the means to exploit those weaknesses are readily available, and that the costs associated with an effective attack continue to drop.[3]

The current emphasis on Homeland Defense is now further reshaping the national security debate over such topics as infrastructure protection, information assurance, and preparedness for catastrophic terrorist attacks. Physical and cyber attacks on America's critical infrastructures – its telecommunications, electrical power, gas and oil, banking and finance, transportation, water supply, government services, and emergency service systems – are viewed as an increasingly attractive avenue by which terrorists, rogue nation states, and non-state actors can attack the U.S. directly and seek to coerce national public opinion and decision-makers into responding to their political demand. The potential multiplicity of threats to our critical infrastructures (e.g., physical, cyber, biological, chemical, and electromagnetic) provides an opportunity for a fresh look at UGFs – their advantages and new, more widespread applications in the 21st century.

3. Attributes of Underground Facilities

Underground structures possess a number of inherent attributes that make them attractive options for physical protection. They provide increased security from direct physical attack, lower energy costs and maintenance costs, improved environmental control, and better land use efficiency through conservation of the earth's surface environment.

The physical protection provided by UGFs is superlative. They can be built to withstand effects from essentially any explosive device including nuclear weapons. Their physical security benefits make them particularly well suited to ensuring the

[3] President's Commission on Critical Infrastructure Protection, *Critical Foundations: Protecting America's Infrastructures*, Report, October 1997, pp. ix-x (hereafter cited as *Critical Foundations*).

continuity and reconstitution of critical infrastructure functions. Dollar for dollar, underground construction provides higher levels of physical protection than similarly sized hardened above-ground structures since specially designed facade treatments, interior wall reinforcement and blast-resistant window glazing are not needed (more on cost benefits in Section 5). Although UGFs do not provide direct protection against cyber attacks, their physical strength makes them a safe haven for critical backup media crucial for recovery following a cyber attack.

Despite the unprecedented scale of the recent attacks in New York City and Washington, DC, experience over the past several decades has shown that the preferred weapon of choice for attacks against buildings and other infrastructure is the vehicle bomb. Although the magnitude of the threat and the likelihood of an attack against a specific facility will vary considerably, there are four basic concerns of protective design that can be satisfied through the use of underground construction. These protective design principles are: (1) the establishment of a secure perimeter; (2) the prevention of progressive structural collapse; (3) the isolation of internal threats from occupied spaces; and (4) the mitigation of debris resulting from the damaged façade and window glazing. Other considerations, such as the tethering of nonstructural components and the protection of emergency services, are also key design objectives that require special attention.

Secure underground facilities can readily address all of these concerns. For example, with a limited number of access points, the facility can be more easily secured against unauthorized access and interior security maintained with a combination of technology and human assets. By providing full blast protection from conventional weapons, the threat of progressive collapse and debris-related injuries is eliminated. Depending on their geographic location, critical infrastructures and facilities will also be faced with a wide range of natural hazards such as earthquakes, extreme wind events, landslides, and floods. Underground facilities can provide true multi-hazard protection against these events as well.

Underground facilities exhibit some disadvantages when compared to surface facilities. These include limited ingress and egress points and potential safety hazards, particularly from fire, in some underground locations. Additionally, a small fraction of the population is averse to working underground although modern design approaches can make these facilities virtually indistinguishable from above-ground spaces. First costs for small underground structures can be higher than for surface facilities. However, for large facilities, costs per square foot for underground structures are comparable to conventional above ground construction and may be lower for comparably hardened above ground structures.

In the United States, underground facilities have become associated predominantly with defense applications. Their applicability for civilian and commercial purposes is less well known and appreciated. However, most critical infrastructure functions and missions, both military and civilian, are amenable to underground locations. Potential infrastructure applications for underground structures are primarily seen to apply in

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five infrastructure sectors: (1) Information and Communications, (2) Banking and finance, (3) Physical distribution systems (pipelines), (4) Energy, (5) Vital human services.

In many applications, underground facilities can be designed as "dual-use" facilities – serving as locations for normal day-to-day community functions and as well as emergency/ crisis centers.

It is recognized that underground facilities are only one of many potential solutions to the Nation's emerging infrastructure protection problem. Nonetheless, their increased use would provide a major line of defense against physical attack of our most critical domestic systems.

4. Underground Infrastructure Examples and Experience

There are many well known defense applications of underground facilities in the U.S. These include the Cheyenne Mountain Underground Complex, hardened underground switching centers throughout the AUTOVON communications network, ICBM silos, and the former Congressional relocation facility at Greenbrier, West Virginia.

In the United States, applications of underground technology to industrial infrastructure are limited and less well known. Examples include buried telecommunications and cable routes, back-up data media storage, underground warehouse and storage network in Kansas City, petroleum storage, buried electric utilities, and subsurface petroleum and natural gas pipelines. UGFs have been adapted for use as subterranean occupancies for commercial, residential, recreational, and educational use.

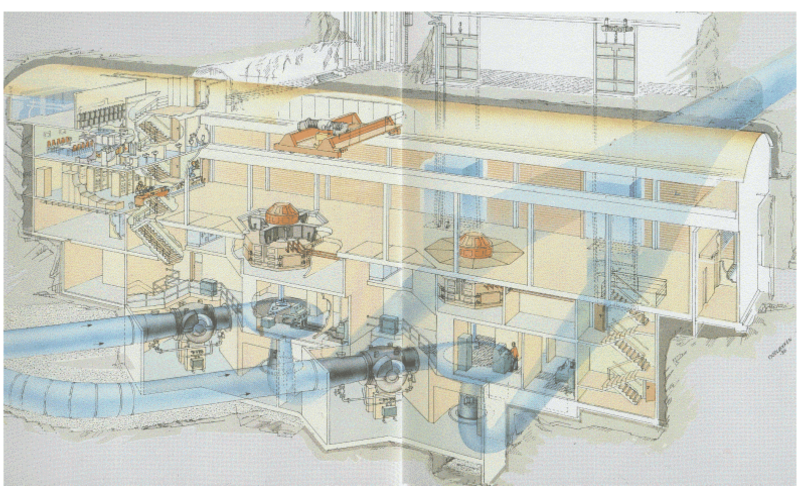

Figure 1. Norwegian Underground Electric Power Generation Station

In contrast, European countries such as Norway, Sweden, and Switzerland have aggressively exploited underground technology to make full use of underground space. These countries have demonstrated the feasibility, affordability and efficiency of using underground facilities, not only for military applications, but critical

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infrastructure protection as well. The experience of Norway is particularly instructive. Norway integrates underground space into all aspects of its national emergency preparedness planning. For example, all electric power generation is housed in underground structures, as are the national archives, water supply and treatment facilities, civil defense, war headquarters, financial centers, and an air traffic control facility. Many of Norway's facilities serve dual-uses for civilian and national security purposes.

The authors participated in a fact-finding tour of Norway's underground infrastructure in October 1998. Norway uses underground technology in every infrastructure sector. Underground facilities visited included a water treatment plant, a munitions factory, a waste water treatment plant, an oil storage complex, a banking center, an air traffic control center, a dairy product processing and storage plant, a dual-use Olympic ice arena – emergency shelter facility, a telecommunications center, and an electric power generation station.

Common site features included multi-layered security (i.e., card-key entryways, CCTV, guards). Many sites had electromagnetic protection against EMP and RF weapon environments. Supporting utilities and personnel were protected by blast doors, air filters, back-up power (including large fuel reserves), alternate cooling services, uninterruptible power supplies and personnel shelters. The Norwegians also provided alternate operating locations for all sites. Plans for relocation were in place and regularly exercised.

In addition to superior physical protection of critical assets, major motivating factors for underground construction in Norway include increased security, lower life cycle costs, conservation of above ground space and environmental protection.

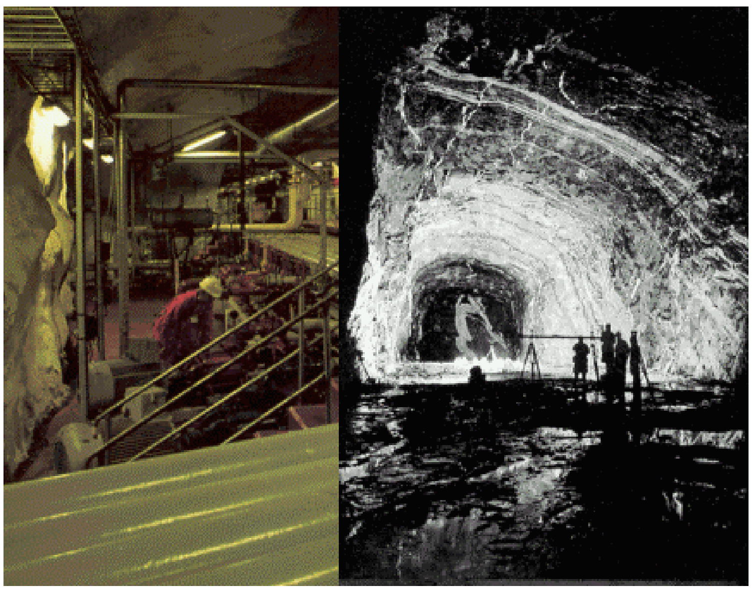

Figure 2. Norwegian Underground Oil Storage Facility

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The geology and topography of Norway are particularly favorable to underground construction and the integration of surface and subsurface facilities. In the Norwegian experience, building underground is equal to or less costly than building comparable surface facilities and provides far greater security.

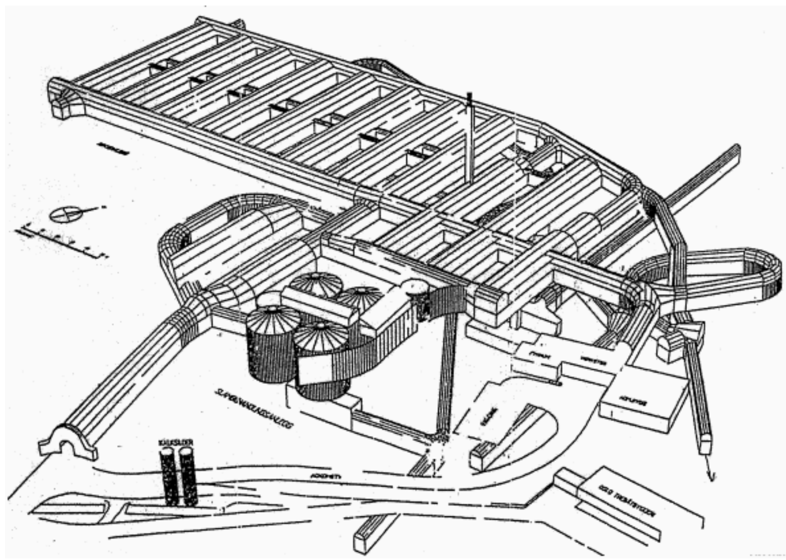

Figure 3. Norwegian Underground Waste Treatment Plant

5. Cost Benefits

Although there is very little published cost data on commercial underground facilities in the U.S., available evidence and life-cycle cost analysis indicates that UGF costs are competitive with standard above ground construction, and over the life of a facility, savings may be realized due to decreased energy and maintenance costs.

Two separate case studies are available. The first is based on data graciously provided by the Norwegian Defence Construction Service on the cost of in-rock versus above-ground facilities[4]. The second is a preliminary analysis of U.S. construction costs comparing the up-front and life cycle costs of hardened above ground versus underground facilities.[5]

The Norwegian Defence Construction Service has compiled comparative data on the investment, operations, and maintenance costs associated with both above-ground and in-rock underground defense facilities. The Norwegian study indicates that capital costs associated with constructing in-rock, inherently hardened, underground facilities are 25% higher than those of standard, unhardened above-ground facilities. The data confirm that up-front costs are higher for underground construction. However, contrary to conventional wisdom, the Norwegian experience shows that <u>life cycle</u>

[4] Norwegian Defence Construction Service, Defence Facilities in Rock, Oslo, Norway, 1998
[5] Frank Gertcher, Benefits and Costs of Protecting Infrastructure Systems Against Terrorist and Related Threats: Cost Analysis, Defense Threat Reduction Agency, Report No: RT-0103-99.

costs for underground facilities larger than 5,000 square meters (~50,000 square feet) are lower than those for above ground facilities. In fact, the Norwegian data shows that large underground facilities are 40% less expensive to operate and maintain on a unit area basis.

Figure 4 is a comparison curve depicting life cycle costs in Norwegian Krone (presently 1 dollar ≈ 9 Kroner) per spare meter. The costs are for facilities with internal areas of up to 30,000 square meters and a life cycle of 20-60 years. Factors included in calculations were investment cost, O&M costs, facility area, operational lifetime, and a 7% discount rate.

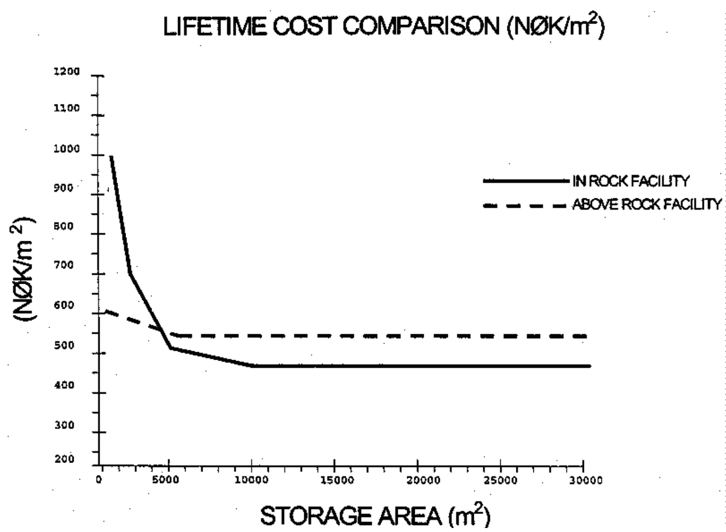

Figure 4. Lifetime cost comparison of facilities in and above rock (Costs in Norwegian Kroner)

It should be noted that the cost of hardening above ground facilities to a level approaching that of underground facilities, significantly reduces any up-front cost differential. This is apparent from the second case study of U.S. facilities.

The U.S. facility cost study indicates that underground, blast-protected, cut and cover buildings can reduce the present value costs compared to semi-buried or above ground buildings, even at lower levels of hardening.

Table 1, from reference 5, presents new construction costs for buildings of 10,000; 20,000; 50,000; and 100,000 square feet of protected interior floor space. Costs per square foot are presented for protection levels 1, 2, 3, 4, and 5. Details on the nature of the cost estimates presented are covered in the notes that follow the table.

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Table 1. Blast-Hardened New Building Construction Costs for Data Processing Center[7]

Interior Floor Area (Ft^2)	Stories		Construction Cost (per square foot[2] FY98 Dollars)[1]				
	Above-ground	Underground[8)]	Level 1[2)]	Level 2[3)]	Level 3[4)]	Level 4[5)]	Level 5[6)]
10,000	1	0	178	202	204	269	---
	1	1	199	204	216	288	394
	0	1	191	191	199	260	352
	0	2	195	196	208	270	356
20,000	1	0	146	153	171	225	---
	1	1	157	165	178	224	267
	0	1	157	163	173	213	250
	0	2	154	160	177	217	256
50,000	1	0	127	134	149	189	---
	1	1	134	142	143	183	227
	0	1	136	144	149	186	219
	0	2	133	139	140	178	212
100,000	2	0	114	119	133	172	---
	3	0	123	128	130	171	---
	2	1	122	127	126	164	---
	1	1	117	129	133	163	205
	0	2	122	127	133	163	197

NOTES

1) Estimates of construction costs per square foot of interior floor area were obtained as an output from the Construction Cost Management Analysis (CCMAS) model. This is a patented, validated, Government-owned model. The model equations are based on actual cost and design data for a large number of Government-owned data processing centers in the continental United States. The model has proven to be a reasonably accurate predictor of actual construction costs. Errors above and below the expected value are stochastic (normally distributed).

2) Level 1 buildings are not hardened.

3) Level 2 buildings blast-hardening features include: steel or reinforced concrete roof, steel or concrete frames, non-load bearing reinforced masonry or concrete walls, a seismic zone 3 foundation and floor, a minimal number of thickened, protected glass windows, and steel doors. Level 2 buildings are designed to withstand the blast pressure of 50 pounds of TNT at a distance of 40 feet. Underground portions of such buildings have substantially greater blast survivability.

4) Level 3 buildings blast-hardening features: steel or reinforced concrete roof, a structural ceiling slab 10 feet below the roof level, steel or concrete frames, non-load bearing concrete or reinforced concrete walls, a seismic zone 3 foundation and floor, a minimal number of thickened, protected glass windows, and steel doors. Level 3 buildings are designed to withstand the blast pressure of 220 pounds of TNT at a distance of 40 feet. Underground portions of such buildings have substantially greater blast survivability.

5) Level 4 buildings features: concrete, heavy steel or heavy steel joists for the roof, a structural ceiling slab 10 feet below the roof level, concrete or heavy steel frames with lateral load resisting elements designed for seismic zone 4, cast-in-place 18-inch thick reinforced concrete walls with 14-foot floor-to-floor heights, concrete, heavy steel, or heavy steel joist floors strengthened to seismic zone 4, a seismic zone 4 foundation, and a minimal number of thickened, protected glass windows. Doors are blast-hardened at a cost of $25K per door (see Fairchild back-up satellite operations center emergency exit door estimates, updated to 1998 dollars). Level 4 buildings are designed to withstand the blast pressure of 500 pounds of TNT at a distance of 40 feet. Underground portions of such buildings have substantially greater blast survivability.

6) Level 5 buildings blast-hardening features: use only semi-buried or underground options, add two feet of earthen cover and a concrete burster slab, a 24-inch thick reinforced concrete slab roof (no ceiling slab), 24-inch thick cast-in-place concrete exterior load-bearing walls, 12-inch thick cast-in-place concrete interior load-bearing walls, and a continuous, mat-type foundation, strengthened to seismic zone 4. Note that a frame is not required, since walls are load-bearing. The building has no windows. Doors are blast-hardened (4 entries) and add $50K per door to the cost of the building (see Fairchild back-up satellite operations center main entry door estimates, updated to 1998 dollars). Level 5 buildings are designed to withstand the blast pressure of 1000 pounds of TNT at a distance of 40 feet. Underground portions of such buildings have substantially greater blast survivability.

7) Costs presented do not include cyber, chemical, or biological threat protection costs. Such costs are assumed to be approximately the same for above-ground, semi-buried, and underground buildings (see discussions in main text). Such costs will increase the per-square-foot costs by the same amount for each entry in the table, but will not change the relative rank order by cost of the alternatives considered (above-ground, semi-buried, and underground).

8) It is assumed that excavation and backfill for semi-buried and underground structures occur in moderate soil conditions (alluvial, clay, soil/gravel mix, etc.). Blasting and other heroic measures are not required. Also, it is assumed that ground water conditions do not require pumping, special barriers, etc., for excavation, backfill, or construction. If extensive rock or groundwater problems exist, they could increase the cost of the building substantially from the amounts presented.

As can be seen in Table 1 – new, smaller semi-buried and underground buildings have higher construction costs when compared with above-ground buildings with lower levels of hardening. Semi-buried and underground buildings are cost-competitive for higher levels of hardening and larger buildings. However, in almost all cases, the cost differences per square foot are not large. Table 1 also shows that economies of scale are clearly present for larger buildings. Finally, initial construction costs are slightly lower for multi-stories underground compared to single stories underground, assuming that excavation and backfill occur in moderate soils (see note 8).

The U.S. cost study supports three important conclusions:

(1) Economies of scale work in favor of larger underground hardened buildings over hardened above ground buildings
(2) Underground or semi-buried buildings can be expected to have significantly reduced annual exterior maintenance and HVAC costs compared to above ground buildings, which lends itself to favorable life cycle cost considerations
(3) For higher levels of hardening (higher threat and risk profiles), the inherent hardness of UGFs often makes them less expensive than above ground facilities.

Although no data are available, the authors believe that these figures suggest that the retrofit of critical infrastructure functions into existing underground space can also provide substantial up front cost savings for infrastructure owners and operators.

In conclusion, the initial construction costs of UGFs can be considerably higher than for above ground facilities, but may be less for higher levels of hardening. Over the entire life cycle, operations and maintenance cost savings greatly improve UGF cost benefits. The life cycle costs of newly constructed UGFs can be very competitive with above ground facilities, i.e., in many cases a life cycle cost advantage can be anticipated.

6. Summary

Domestic infrastructure services and national security functions are increasingly reliant on soft infrastructure and services provided by non-defense organizations. The attacks of September 11, 2001 greatly increased the national perception of the threats against these infrastructures and facilities. Future attacks may be physical, cyber, or electronic in nature. Underground facilities offer physical protection to critical infrastructure elements, can be hardened against electronic attacks, and can provide secure alternate locations for backup data and equipment. The costs of underground facilities costs are competitive with hardened above ground structures and life cycle costs are actually lower for large hardened structures. The Norwegians have shown that critical infrastructure functions (including electric power generation, water purification and treatment, telecommunications centers, banking and finance functions, and air traffic control) are <u>all</u> amenable to underground construction.

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7. Recommendations[6]

Core competencies in underground technology need to be nurtured and revitalized as necessary and redirected to infrastructure assurance applications. In the post 9-11 security environment, the U.S. Department of Defense can play a critical role in providing advice and assistance to private and public sector partners on the construction and operation of secure underground facilities.

Education and consensus building in the infrastructure community regarding the capabilities and utilization of UGFs will be essential. The underground technical community must develop and present a clear message to the larger corporate world and the public. The establishment of an academic center for underground studies would enhance the visibility and encourage the acceptance and use of underground construction. A repository for UGF cost data and capabilities is needed to enable informed decisions on building and using underground space. This center could also serve as a designated clearinghouse organization to hold and distribute information and serve as a "matchmaker" for users in search of suitable underground sites.

Efforts are needed to encourage research and innovation and promote federal government-industry partnerships. Community coordination and partnerships with smaller organizations at the state and local level are also vitally important.
A pilot, or demonstration project would do much to make the case for underground applications for critical infrastructure protection. In this regard, it would be beneficial to select a prime infrastructure application as a point of focus for discussions between government and industry on costs, benefits and implementation issues.

[6] See also Use of Underground Facilities to Protect Critical Infrastructures, National Academy Press, Washington, D.C., 1998