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THE USE OF UNDERGROUND SPACE

By
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I - Introduction

The population of the U.S. increased from approximately four million in 1790 to more than 210 million in 1972 (1). In the period from 1921 to 1960, the proportion of this population living in urban areas increased from 51.2% to 69.9% (2). In 1959 in the Continental U.S., with a total land area of 3,000,000 square miles, land use for urban development totalled 42,400 square miles, with a further 39,300 square miles outside the urban areas used for highways. It is projected that by the year 2000, 140,000 square miles will have been taken out of "natural" use for the provision of services and buildings for man's use (3). For agriculture, 1,734,000 square miles are used (4). Thus, more than 8% of the agricultural land will potentially be swallowed up by urban development by the year 2000. In Europe the problem is, of course, significantly more acute, with an average population density of 162 per square mile in 1972, compared with North America's meager 35 per square mile.

With pressures of this magnitude, allied with pressures induced by the new awareness of the wasteful and environmentally unacceptable uses of much of the land surface already absorbed, it is not necessary to search far for the rationale that leads to the consideration of the potential of underground space for the siting of virtually the entire range of man's industrial, commercial and even residential needs.

Further incentive is provided by the inherent insulant properties of the rock and soil which surrounds underground space. Not only heat, but noise, vibration and cold are attenuated and controlled by the underground environment.

Man has been aware since earliest times of the advantages provided by underground space, and has made use of it to serve his own ends. Before examining the potential for the use of underground space today, it may well be instructive to review briefly man's previous use of it and the development of the various techniques adopted for its creation.

II - Yesterday

The earliest and, to this day, some of the largest underground caverns were created not by man but by nature itself. These caverns, a number of the

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more notable of which are listed in Table 1, were formed by erosion and solution of the softer and more soluble sandstones and limestones. Some of the roof spans in nature are well beyond our present-day capabilities to achieve. There is a message here for the underground space designers of the future which will be discussed later.

TABLE 1

Some Natural Caverns In North America

Name & Location	Principal Dimensions	Rock Types
Rainbow Natural Bridge, Southern Utah	270 ft. wide 305 ft. high	Sandstone
Carlsbad Caverns, Carlsbad, New Mexico	625 ft. wide 300 ft. high	Limestone
Mammoth Dome, Mammoth Cave, Kentucky	150 ft. wide 250 ft. high (max) 400 ft. long	Limestone
Natural Bridge, Virginia	90 ft. span 200 ft. high 50-150 ft. wide	Limestone

There is evidence that the underground, in the form of natural caves or overhangs, has been used as a shelter by mankind since earliest times. Even in Australia, perhaps one of the most recently inhabited land masses, evidence of human habitation dating back to 40,000 BC has been found in the Koonalda Cave (5). In the Americas, mammoth hunters lived in Fells Cave in Patagonia, carbon dated to 8760 BC; the Eskimo Denbigh culture (about 4000 BC) inhabited semi-subterranean houses with walls of sod and stone, occasionally reinforced with whale ribs and jaws.

The majority of these early habitations made use, of course, of natural caves, but there is evidence from the third millennium BC of gradually increasing use of excavation to produce underground space. Because of the limited tools available, much of this work was undertaken in very soft rock which has subsequently collapsed or been eroded so that no evidence is now available. Some of the earliest man-made caves that can still be seen are the catacombs on the island of Malta, which date back to 3000 BC (6). Hewn from solid limestone, these tunnels and niches were used primarily for burials, and also for small chapels and meeting places in rooms up to 12 feet square. Similar catacombs are found in many locations in Europe, including Paris, Rome, Naples and Syracuse. In Rome the catacombs excavated in the 1st to 5th centuries AD cover 600 acres at depths ranging from 22 to 65 feet below ground level.

References are found in the Bible to the Sinai copper mines (7) operated since the Bronze Age (3000 BC), and evidence has been found of Stone Age flint mines (13,000 BC) excavated in the soft chalk of Europe.

The ancient Egyptians obtained their gold from mines excavated by convicted criminals; Hannibal financed many of his ventures with silver from the Baebelo mine, which apparently had such a heavy water inflow that it had to be hand bailed continuously. The Hallstatt salt mine in the Austrian Alps, which dates from 2500 BC, is still being worked (8).

The Mt. Laurian mine in the south end of the Attic peninsula was first worked in the second millennium BC for silver, and subsequently by the Athenians in the 6th century BC also for silver, and much later, in the 1800's by the French for lead and zinc. Some two thousand shafts were sunk at this mine, the deepest reaching about 380 feet below the surface.

In the Middle East we find in the City of Petra a number of huge edifices excavated into the rock face in the 6th century BC, and the magnificent temple of Abu Simbel on the Nile, dating back to 1200 BC, excavated in solid sandstone. Somewhat similar is the Indian rock temple at Bhaja (Figure 1).

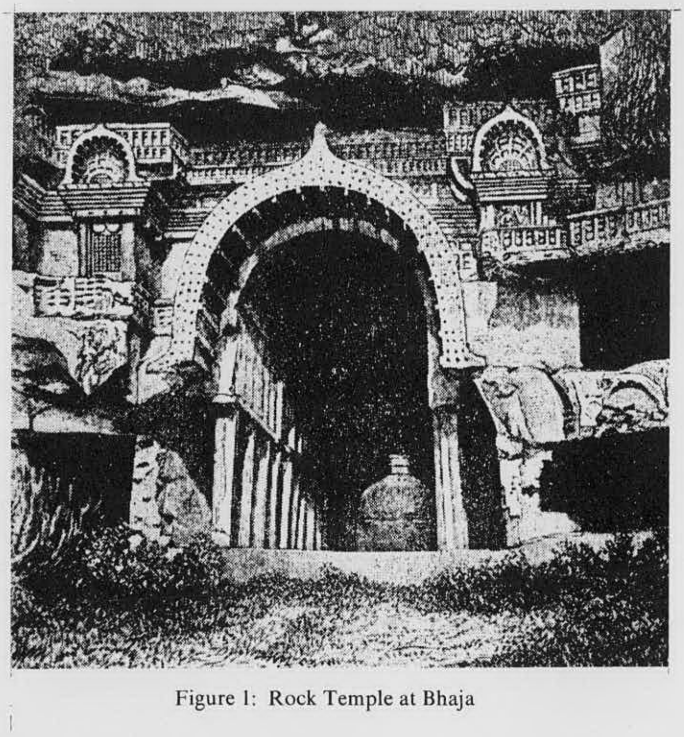


Figure 1: Rock Temple at Bhaja

In Asia Minor is one of the most remarkable underground habitations, at Goreme. Here, a vast assembly of underground tunnels and caverns was excavated in the soft tuff of the region, by hand and by pick, to form complete villages underground, interconnected by long tunnels. Started in the 4th century BC, the underground location provided security against attack by marauding tribes. The towns were excavated to depths of eight or ten floors extending for several miles, with a labyrinth of cramped tunnels (9). The site includes many churches and mosques, beautifully carved and decorated.

In Egypt and elsewhere in the Middle East at this time, qanaats were being excavated to carry water to the cities. These aqueducts, hand excavated, were driven beneath the deserts for distances as long as 7½ miles. They can be traced by their characteristic shafts pierced from the surface at regular intervals (Figure 2).

The methods of excavation used by the early tunnellers developed very slowly over the ages. At first excavation was entirely by hand, with simple hand-held tools. In the flint mines of the Stone Age, rudimentary picks and scrapers have been found (Figure 3) and by the advent of the Bronze Age the technique of wedging, using wooden wedges soaked in water and then driven into cracks and joints in the rock had been developed, and with modifications was still in use up to the 18th century AD. The Egyptian tunnellers and quarriers used the wedge and hammer technique extensively, drilling holes by means of bow drills and tubular copper and bronze bits with abrasives at the cutting end: this technique was supplemented by the use of large dolerite balls mounted on suspended rams and struck against the working face to spall off the rock.

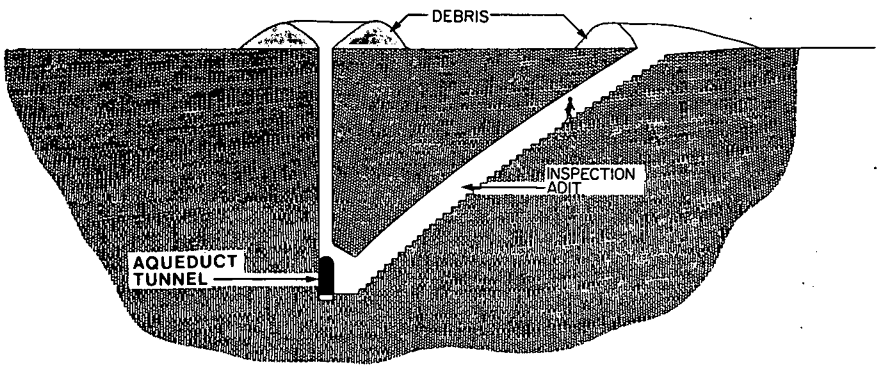


Figure 2: Section of Ancient Qanaat

Another technique developed toward the end of the Bronze Age, used extensively in tunnelling and mining, was the practice of fire-setting; a fire was built against the working face, and once the rock had become red hot, water was thrown against the face, causing the rock to spall off due to the rapid cooling (10). (Figures 4 and 5). Sometimes vinegar was used in place of water under the mistaken impression that it improved the performance of this technique. Regardless of whether water or vinegar was used, the resulting fumes created virtually unbearable conditions underground with appalling effects on the health and safety of the miners. It is no wonder that convicts and captives often provided the underground work forces.

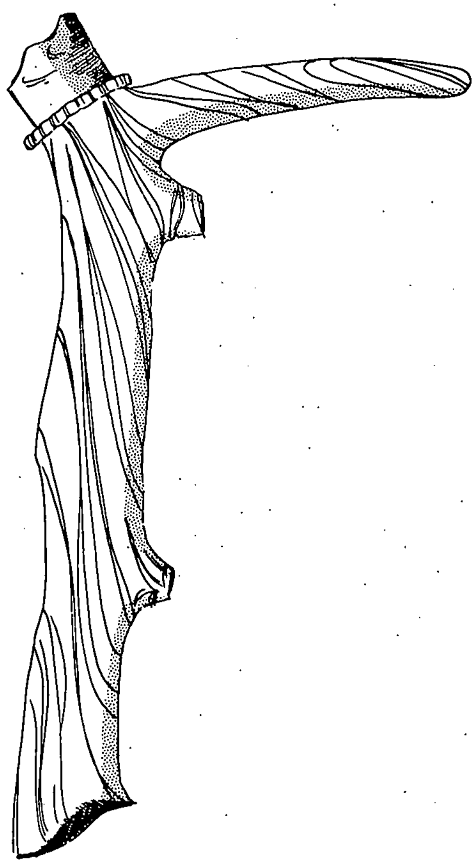


Figure 3: Deer Antler Pick

Throughout the Dark Ages, there were few tunnels and little innovation in mining techniques. Probably the first "modern" civil engineering tunnel was constructed in 1692 on the Languedoc canal in southwestern France near Malpas. It was 515 feet long, 22 feet wide and 27 feet high; it is said to be the first canal tunnel ever built, and probably the first tunnel in which gunpowder was used for excavation. During the following century, many similar tunnels were driven both for canals and water supply. The first such tunnel in the U.S. formed part of the Schuylkill Navigational Canal in Pennsylvania; constructed in 1818, it ushered in the great age of railroad tunnels in the United States and Europe.

In the middle of the 19th century, several of the great Alpine tunnels were driven. The Frejus (Mt. Cenis) tunnel was 7.5 miles long under a maximum rock cover of nearly 4000 feet. Driven from both ends under the direction of M. Germain Sommeiller, the tunnel marks the introduction of the com-

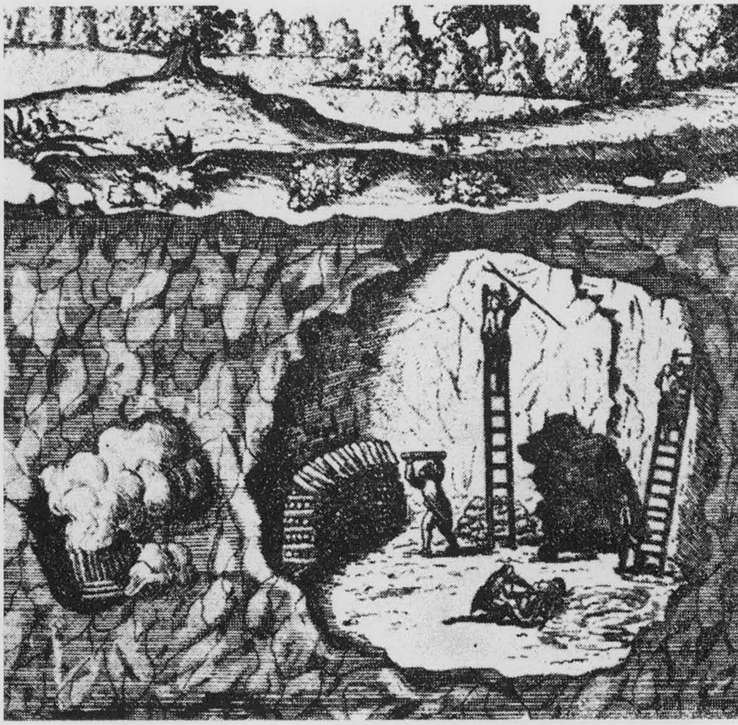


Figure 4: Woodcut Showing the Practice of Fire Setting

pressed air rock drill (originally designed to be steam driven), the use of the drill jumbo on which up to nine drills could be mounted, and the development of hydraulically-operated air compressors. The tunnel took 13 years to construct; it was holed through in 1870 with an error of less than one foot in elevation and 18 inches in alignment.

Almost concurrently with this, the Hoosac tunnel (Figure 6) was being excavated in Western Massachusetts to carry the Troy and Greenfield Railroad under the Hoosac Mountain. Started in 1858, the five-mile long tunnel was eventually completed in 1874, after the expenditure of five contractors, three site engineers, the consulting engineer and several commissioners.* At one stage in the construction, Oliver Wendell Holmes had been moved to note that "when the first locomotive rolls through the Hoosac Tunnel, then order your ascension robes." But if it did nothing else, the Hoosac tunnel did

*Editors Note: See "Construction of the Hoosac Tunnel, 1855 to 1876" by Gary S. Brierley in the Journal of the Boston Society of Civil Engineers Section, ASCE; Vol. 63, No. 3, October 1976.

Figure 5: Tunnel Excavated by Fire Setting

herald the introduction of the mechanical air compressor, giving American industry a clear lead in its subsequent introduction into mining and other underground work. The surveying error in the Hoosac tunnel, incidentally, was less than one inch.

Another interesting aspect of the Hoosac tunnel is that it marked the introduction of electric firing of the powder charges, which before that time had been fired by means of slow fuses, a technique quite frequently fatal to its practioners (hence, the expression the "quick and the dead?"). Nitroglycerin, which had been invented in 1824, was also used for the first time in the U.S. in the Hoosac tunnel: it too was a somewhat hazardous material,

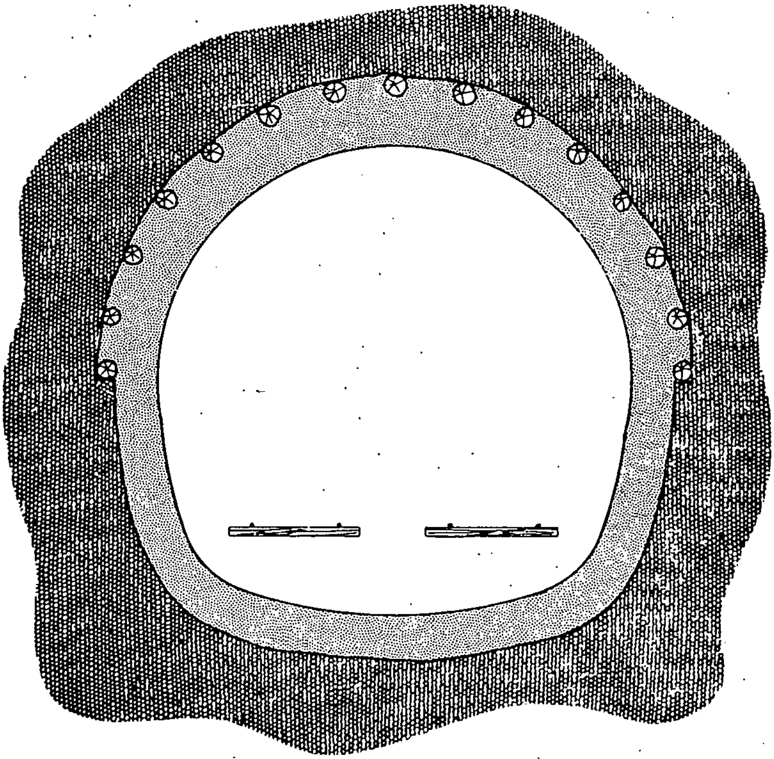


Figure 6: Hoosac Tunnel; Typical Lined Section

being very susceptible to shock. The technique of absorbing the nitroglycerin in kieselguhr was developed in 1867 by Nobel and the resulting dynamite was used for the first time in the St. Gotthard tunnel through the Alps three years later.

Dynamite in various forms has been the basic explosive used in mining and construction work ever since. Because of its high cost and the lethal fumes that it generates, efforts were made to produce a more acceptable material. Since about 1950 ammonium nitrate in granular form has been finding increased acceptance in many applications. Discovered almost literally by accident as the result of the virtual destruction of Texas City in 1947 by the detonation of a large stockpile of ammonium nitrate fertilizer, this material when mixed with fuel oil can be fired by a dynamite detonator and is quite safe to handle and place.

Remarkable advances have been made in the development of the drills used to create the blast holes. Following the Egyptians' use of tubular or copper bits, the Romans introduced iron tools which continued in use until the introduction of the first steels in the 17th century. With drill steels driven

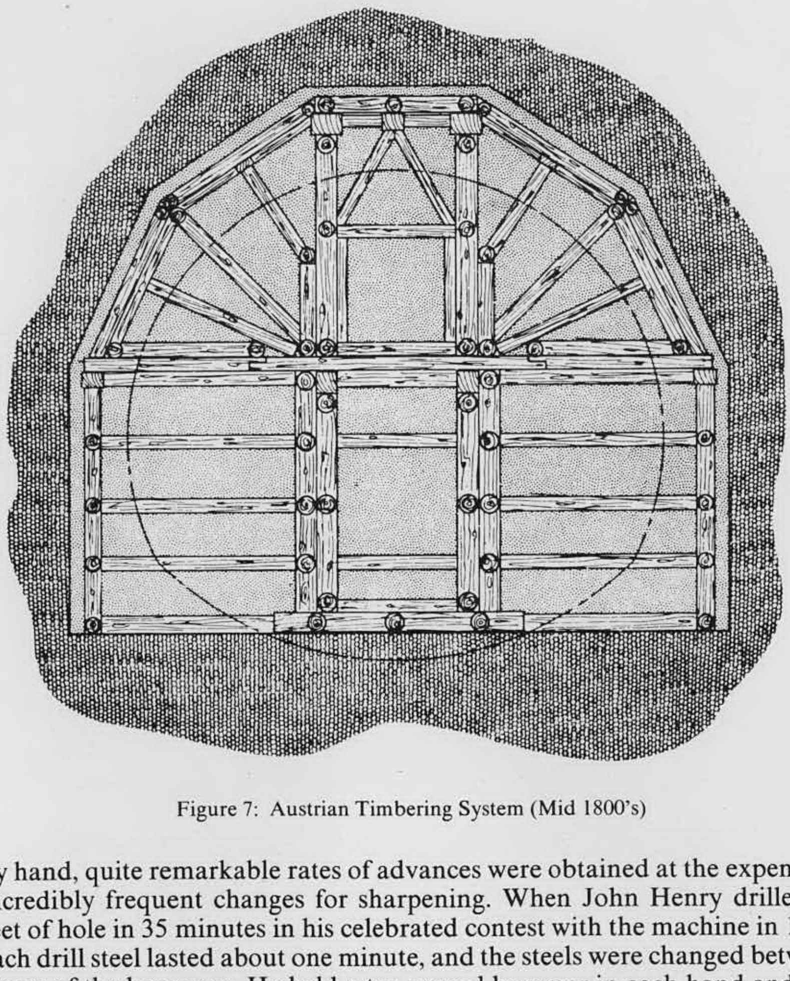


Figure 7: Austrian Timbering System (Mid 1800's)

by hand, quite remarkable rates of advances were obtained at the expense of incredibly frequent changes for sharpening. When John Henry drilled 14 feet of hole in 35 minutes in his celebrated contest with the machine in 1870, each drill steel lasted about one minute, and the steels were changed between blows of the hammers. He held a ten-pound hammer in each hand and was striking the steel at the rate of 90 blows per minute.

When the mechanical compressed air drill was introduced, which struck the steel at more than 2000 blows per minute, the steels lasted only a very short time before requiring sharpening. On the Hoosac Tunnel, for instance, on one 600-foot length of tunnel which took a year to excavate, 153,436 drills were dulled in drilling a total length of hole of only 403,150 inches (or 2.6 inches per use.) Drills spent more time in the blacksmith shop than they did in the hole! The most significant breakthrough was the discovery of tungsten carbide in Germany in the 1920's; kept a closely guarded secret until after the second world war, this material now provides virtually all the percussion drill bits in use. The average life of a drill steel and bit is now more than 2000 feet in hard rock at a drilling rate of more than 30 inches per minute.

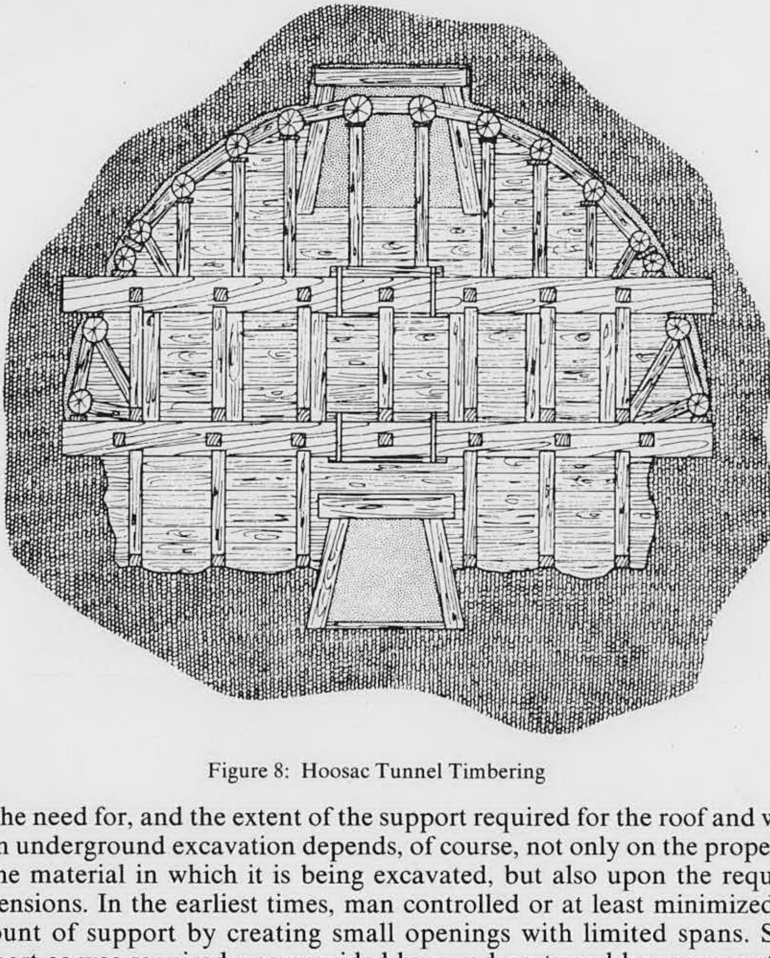
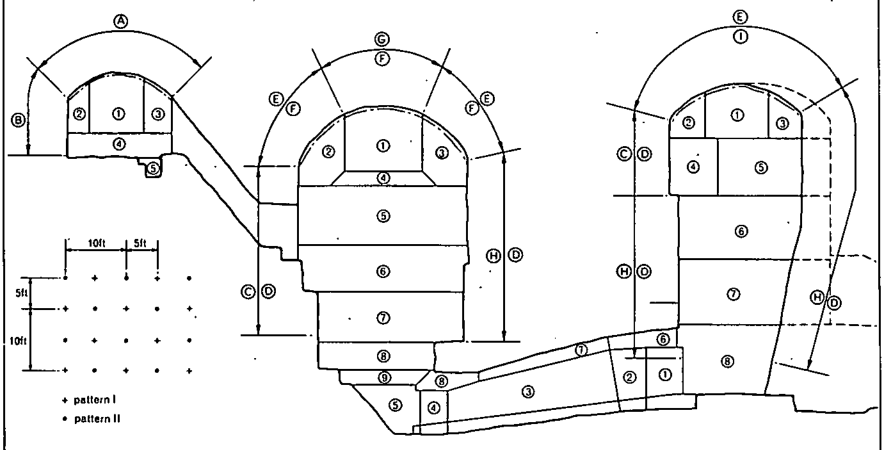


Figure 8: Hoosac Tunnel Timbering

The need for, and the extent of the support required for the roof and walls of an underground excavation depends, of course, not only on the properties of the material in which it is being excavated, but also upon the required dimensions. In the earliest times, man controlled or at least minimized the amount of support by creating small openings with limited spans. Such support as was required was provided by wood posts and beams, a method still in limited use to this day. As man's requirements for larger openings in ground developed, permanent support linings were installed, often of stone in Roman times, and subsequently of brick, block or concrete. However, timber remained the principal means of temporary support (prior to the installation of the permanent lining) because of the flexibility it offered in being cut and shaped to meet the particular situation. Incredibly massive and complex timber support structures were constructed in some of the tunnels excavated in the late 19th and early 20th centuries, with elaborate techniques designed to allow the installation of the permanent lining without affecting the support of the roof or walls. (Figures 7 and 8). The introduction of cast iron (and subsequently steel) provided the tunneller with the means of supporting greater loads, at the expense of reduced flexibility for meeting rapidly changing requirements.



Rock bolt configurations and specifications.

Key letter	Pattern	Bolt type*	Length (ft)	Distance between centres (ft)
A	—	A	15	5
B	—	B	15	7
C	I	B	20	14
D	II	B	15/20	14
E	I	A	20	10
F	II	B	15/20	10
G	I	A	25	10
H	I	B	25	14
I	II	A	15/20	10

*Type A: Max. installed load = 45kips; min. yield strength = 68kips
Type B: Max. installed load = 26kips; min. yield strength = 40kips
Type C: Max. installed load = 15kips; min. yield strength = 23kips

Figure 9: Rock Bolt Arrangement and Sequence of Excavation at Churchill Falls

A major advance in the art of creating underground space was made with the introduction of the rock bolt, first used in the mid-1940's. This device, now the almost universal method of both temporary and permanent support in hard rock tunnels and chambers, provides a means of active support of the rock, mobilizing the rock itself to provide the requisite arching and beam action to span the openings. Used either initially unstressed, or now more frequently prestressed, rock bolts can be designed to meet the specific requirements of a wide range of rock conditions and opening geometry. Available in lengths as short as one or two feet, and up to 100 feet or more, the rock bolt can be rapidly installed after excavation has been completed, to maintain the integrity of the rock mass so that it will not lose its inherent shear and compressive strength by relaxing and opening along joints and fractures. Typical rock bolt patterns adopted for the support of rock faces in a large recent underground opening are shown in Figure 9.

Other measures developed in the 20th century for the support of rock faces, both temporary and permanent, include wire mesh — usually of the chain link variety — pinned to the face with short dowels, and often reinforced by the use of gunite or shotcrete. These materials have the effect of sealing the face to prevent relaxation of the rock, and so allow the rock to mobilize its strength to support itself.

The basic process of underground excavation, particularly from the civil engineering standpoint, has remained essentially the same since such work began. Work at the face follows a continuous cycle: excavation, followed by mucking out, followed by installation of support, followed by the next round of excavation. However, methods of excavation, as we have seen, have advanced from the early primitive hand-held tools through fire-setting to the percussion drill and blast techniques in use today. Since they were first introduced in the 1860's, pneumatically actuated drilling machines have been used in a wide variety of assemblages from the single drill mounted on a pneumatic or hydraulic jackleg to the multi-machine drill jumbo used for the excavation of large tunnel faces. Jumbos have been designed to carry 20 or more drilling machines and have been operated on faces as large as 60-feet high by 40-feet wide. More recently has come the introduction of the multi-arm, wheeled or tracked drilling machine. Designed to handle as many as eight drills, these machines can be operated by one or two men, and offer significant economies in both labor and speed because of their maneuverability. The most recent development in the field of percussion drilling has been the introduction of the hydraulic (as opposed to compressed air) drill. Although significantly larger and more costly then the compressed air-driven drill, the hydraulic drill can provide extremely rapid rates of advance in large size holes, and could well prove to be a most attractive addition to the armory of equipment available to the tunneller.

Depending upon the size of the opening to be excavated and upon the quality of the rock, the excavation may proceed full face, or may start with excavation of a limited size pilot heading followed by subsequent widening and benching of the excavation to the required final dimensions (Figure 9). This latter technique was developed extensively by the 19th century tunnellers to overcome some of the major difficulties encountered in the large tunnels excavated during that period. The technique is still used today, particularly in conjunction with the installation of rock bolts to maintain the integrity of the rock mass in excavating of large-span or high caverns and tunnels.

The tunnel boring machine (sometimes called a "mole" or TBM) is a tool which has existed for many years in various rudimentary (and often not very successful) forms, but has recently passed beyond the experimental stage and into rather general use, thanks in part to modern metallurgy. It is particularly useful for linear excavations such as subways and large conduits, where its rotary cutters can often provide for a full face operation. Further development is necessary in order to make the device work well in certain hard rocks, and also deal with variations in rock types within a single project.

III - Today

Thus we arrive at the fourth quarter of the Twentieth Century with almost 5000 years of experience in the creation of underground space behind us, and with a comprehensive range of techniques and equipment at hand. How are we making use of it, and what are the prospects for the future?

To answer these two questions, we need first to examine just what is, or might be, unique about space created underground. The following unique properties present themselves:

(a) Structural; appropriately designed and constructed, underground space comes with its own enclosure, and does not need the elaborate structural arrangements necessary to support the exterior cladding of interior space created at the surface.

(b) Insulation; underground space is surrounded by an excellent insulant, the rock itself. Insulation properties pertain to heat, cold, fire, vibration, noise, etc.

(c) A third degree of freedom; instead of being tied to the flat surface of the earth, the freedom is available to create structures in three dimensions without recourse to major structural supports.

(d) Reduced environmental impact; "out of sight, out of mind" is still as good a slogan as ever when related to the construction of facilities underground.

In examining the use of underground space, it is instructive to consider the spectrum of potential uses in relation to the required depth and sizes of the caverns as shown in the diagram in Figure 12. Note the scale of increasing personnel involvement from the minimum at dead storage to the maximum for office space, shops, and dwellings. Many of the uses shown on this chart have already been adopted.

It must, of course, be recognized that these unique properties can be utilized only through potentially significant expenditures required for the excavations and accesses. Whether or not the alternative will prove economic in comparison with the equivalent surface-located facility will depend on a number of factors related not only to the particular characteristics of the facility, but also to the characteristics of the location and its geology.

In the following paragraphs, some examples of the economic use of underground space in North America and elsewhere are described:

(1) Hydroelectric Facilities

Other than the use of the underground for the purpose of conveying water, people or goods in tunnels of various shapes and sizes, the first and perhaps major use of underground space in this century has been in the hydroelectric industry for the housing of power plants. The first underground power plant was built in 1908 at Mockfjard in Northern Sweden with an installed capacity of 12 megawatts.

In 1910 a 50 megawatt plant was built at Porjus in Lapland. This was the largest underground structure built up to that time, and incorporated a generator hall 40-feet wide by 65-feet high by 295-feet long, located 164 feet below ground level. Excavated in a granite gneiss, extensive use was made of pilot headings in the construction and subsequent concrete lining of this chamber.

TABLE 2

Some Major Underground Hydroelectric Plants

Name & Location	Principal Dimensions	Rock Type	Date
Poatina Tasmania Hydro-power plant	45 ft. wide 84 ft. high 300 ft. long	Mudstone, Shale	1961
Sarca-Moneno Italy Hydro-power plant	95 ft. wide 92 ft. high 633 ft. long		
Oroville, Calif. Hydro-power plant	70 ft. wide 120 ft. high 550 ft. long		
Churchill Falls Labrador Hydro-power plant	81 ft. wide 145 ft. high 1,000 ft. long (main cavern)	Granite/ Granite Gneiss	1971
Morrow Point, Colorado Hydro-power plant	57 ft. wide 134 ft. high 206 ft. long	Schist, Quartzite, Granite	1968
Portage Dam, British Columbia Hydro-power plant	67 ft. wide 144 ft. high 890 ft. long	Sandstone, Shale	1970
Boundary Dam Washington Hydro-power plant	76 ft. wide 175 ft. high	Dolomite, Limestone	1967

Since the construction of the Porjus plant, more than 300 hydroelectric plants have been constructed underground. Some of the major ones are listed in Table 2. The largest underground plant is currently the Churchill Falls facility in Labrador, with an installed capacity of 5,225 megawatts. The Churchill Falls machine hall is 900 feet underground in a massive granite gneiss and measures 81-feet wide by 150-feet high by 950-feet long (11). (Figure 10). As noted earlier, extensive use was made of rock bolting in the support of the cavern walls and roof. This cavern was one of the first in

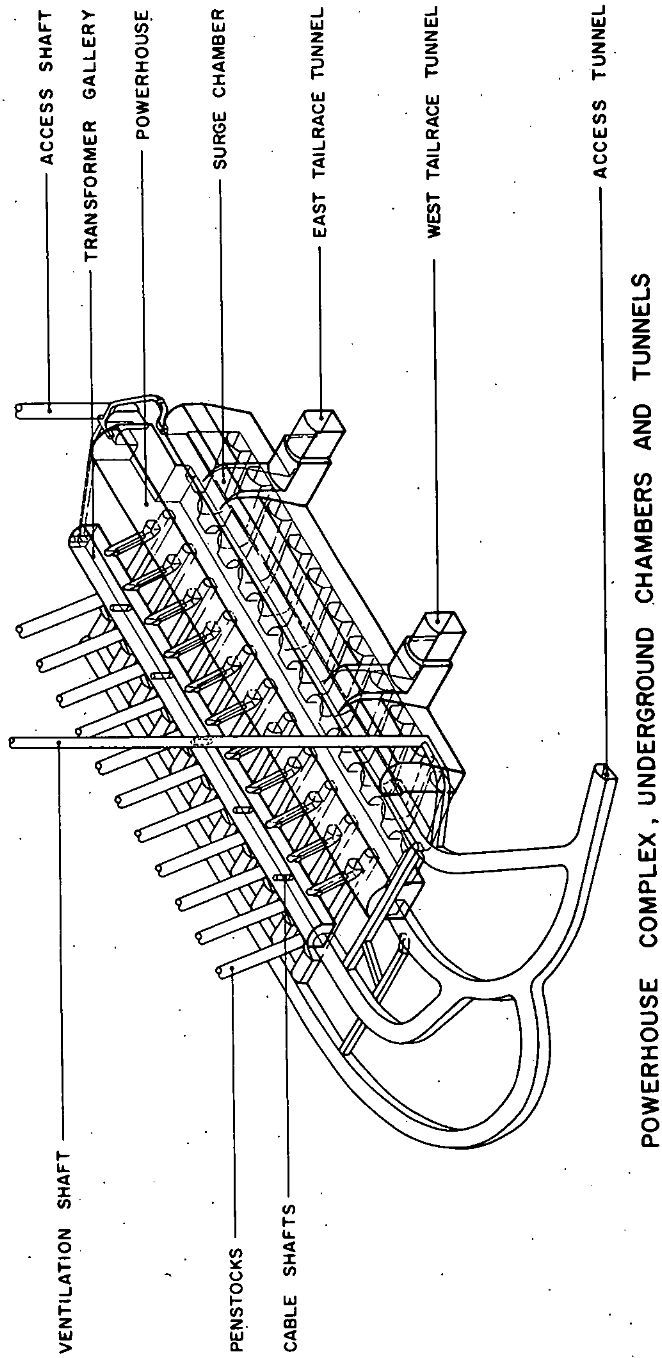


Figure 10: Churchill Falls Caverns

North America in which use was made of the finite element method in the computation of the stresses around the cavern (12) and in the identification of the optimum arrangement of the caverns both with respect to their relative location and with respect to their geometry. The sloping downstream wall of the second chamber was adopted to minimize the tensile stress zone in this area. None of the major caverns at Churchill Falls is structurally lined.

Underground hydroelectric power plants currently under construction in North America include the Raccoon Mountain pumped storage facility of TVA, and Hydro Quebec's LaGrande complex.

(2) Dry Storage and Industrial Use

A current use of underground space of considerable significance for the future is the major underground storage complex at Kansas City, Missouri (13). Initiated about in 1944, a very large complex of underground storage facilities has been developed beneath Kansas City. Based originally on the use of space created by the mining of limestone from the Bethany Falls stratum, the facility has been enlarged and improved to the extent that the mining operation has become secondary to the creation of space, with the production of limestone virtually a by-product.

TABLE 3

Underground Space Users At Kansas City (1975)

Drapery Companies	
Cookie Manufacturer	
Business Supplies	
Time Recorder Supplier	
Candy Supplier	
Chemical Company	
Realty Agency	
Federal Aviation Agency	
Greeting Card Manufacturer	
Printing Company	
Oil Company	
Cold Storage Company	
Instrument Manufacturer	
TOTAL EMPLOYEES:	1,640
TOTAL ANNUAL PAYROLL:	$12,897,750

The mining operation originally created the space through the excavation of a series of rooms and pillars in the flat-lying limestone strata which conveniently outcrop in an escarpment. The space is now being utilized for a wide range of storage and industrial uses (Table 3). Perhaps the most interesting is a massive cold storage facility, the largest of its type in the world. One of the major advantages of the underground location for this operation is the high degree of insulation and thermal "inertia" offered by the rock surrounding the facility. Once the facility has been cooled to the required working temperature, it is estimated that the power requirement will reduce to a third of that required for a surface facility. Furthermore, failure of the cooling equipment for any reason need not be as disastrous as it would be at the surface, because of the considerable reserve of cold in the rock surrounding the facility. The condition of stored materials can be assured for periods up to several days, as opposed to hours for a surface plant. The resultant savings in insurance premiums can be very significant.

At this point, we have more or less covered the current uses of underground space in North America, with the exception of some limited use for the storage of archives and for certain military installations. If, however, we turn to Europe, we can perhaps discern a trend for the increasing use of underground space for a variety of other purposes.

(3) Nuclear Power Plants

Four nuclear power reactors have been installed underground in the Western World to date, all of them in Europe (14). These plants are:

(a) Halden in southeast Norway;
(b) Lucens in Switzerland;
(c) Agesta in Sweden; and
(d) Ardennes in France.

TABLE 4

Existing Underground Nuclear Power Plants

Name and Location	Year of Completion	Reactor Size and Type	Purpose	Reactor Cavern Size	Depth of Rock Cover	Lining
Halden (Southeast Norway)	1960	20 MW (t) BWR	Experimental and Steam Output for Pulp Mill	30m x 10m x 26m high	30m to 60m	Reinforced concrete 15cm to 30cm thick
Agesta (Sweden)	1964	20 MW (e) BHWR	Experimental Heat and Electrical Power	53.5m x 16.5m x 40m high	17m	Concrete and welded steel plate 4mm thick
Chooz (Ardennes, France)	1967	275 MW (e) PWR	Electrical Power	41m x 18.5m x 42.8m high	Not available	3mm steel plate with contact grouting between lining and rock
Lucens (Switzerland)	1968	8.3 MW (e) Heavy water moderated, gas cooled	Experimental and Electrical Power	18m diameter 30m high	40m	Two layers of concrete, sandwiching aluminum foil and bitumen seal

All of the plants were completed in the 1960's and with the exception of the Ardennes plant which is rated at 275 MW (e), they are mainly experimental units of small output. The salient features of these power plants are summarized in Table 4.

A number of studies (15) have been undertaken in the United States and elsewhere during the past 10 years in an attempt to assess the real potential for placing nuclear power plants underground. The general conclusions reached in these reports can be summarized as follows:

(a) Construction of nuclear power plants underground is technically feasible within the current state of the art; the economic penalty imposed by the costs of excavation and longer construction schedule does not appear to be excessive, although cost increases as high as 30% have been postulated.
(b) There would appear to be some safety advantages in siting plants underground, which may permit such plants to be located closer to population (and load) centers.
(c) There is potential for reduction in the design for seismic loads on components of the underground plant.
(d) For rock caverns of the size postulated for current plant designs, conventional drill and blast techniques would appear to be adequate.

An interesting point arises from item (c) in this list; in general, structures located in hard rock tunnels underground are subjected to reduced seismic loading for a given seismic event, as compared to structures located at the surface.

It is, of course, necessary to qualify this statement in relation to specific geotechnical conditions at a given site, as for instance at an active fault or shear zone, but as a general statement it holds true, and has been shown to be the case in a great number of case histories that have been studied (16). The reason for the reduced loading is in part due to the elimination of the inverted pendulum effect on structures located at the surface, in part due to the lack of amplification of the seismic wave which often occurs through uncemented sediments at the surface, and in part due to the elastic properties of rock in seismic wave propagation (17).

Despite the potential benefits to be gained by going underground, it appears likely that without a major change in government policy, no significant move will be made in this direction in the U.S. in the near future. This is due in part to the established momentum of the current aboveground program, and in part because of the horrendous complexity involved in the reassessment and reassembly of the requisite rules and regulations governing plant design when transferred from surface to underground. The development of an optimum design of an underground nuclear plant would require the reexamination of the design of virtually all its components, which are currently designed to meet the requirements of a surface location. Any initiative must undoubtedly come through the appropriate Federal government agencies. However, in closing this section, it is worth noting the recently initiated review of underground siting in California and President Carter's comments that he would like to see all nuclear reactors located below ground level.

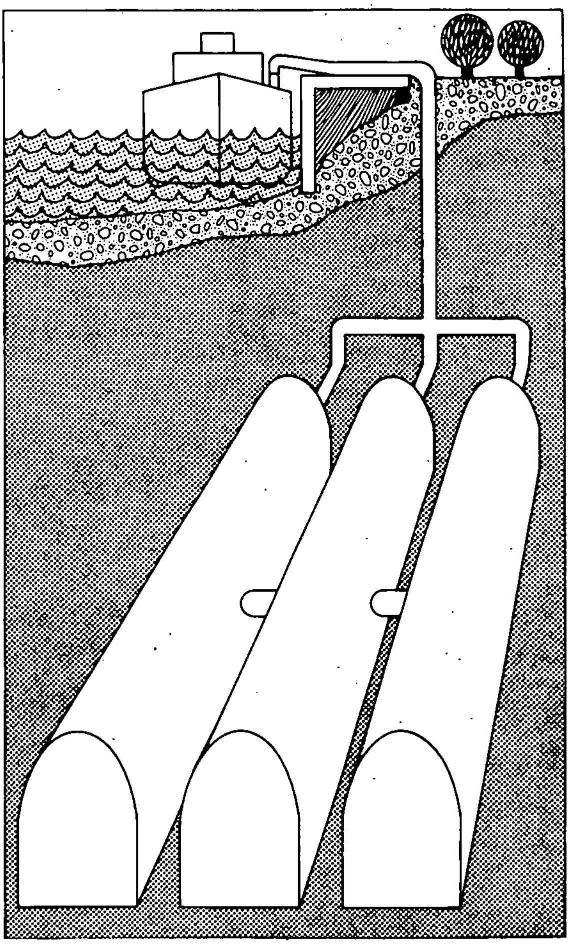


Figure 11: Oil Storage Cavern

(4) Oil Storage

Crude oil has been stored in large caverns excavated in rock since the 1930's in Europe, particularly in Scandinavia where more than 20 million barrels are currently in storage. (Figure 11). Individual storage caverns with capacities of up to one million barrels have been excavated in hard rock at depths up to 400 feet below ground level to provide both strategic and live storage of all types of crude oil and petroleum products.

A key requisite to design of these facilities is a proper understanding of the ground water regime surrounding the cavern, as this is a controlling factor in establishing the containment of the stored fluids; sites are generally selected below the water table, and considerable care is taken during the excavation of the chamber to ensure that the water table is not disturbed.

In the current U.S. Strategic Petroleum Reserve Program, which is aimed at alleviating the potential impact of any future oil embargo such as that which created such havoc in 1973, consideration is being given to the storage of crude oil not only in solution cavities created in salt domes but also in existing abandoned mines, and in new caverns excavated for this purpose. More than 20,000 mines in the U.S. were assessed (18) and the choice was narrowed to five mines — three in salt and two in limestone — judged to have the best potential for the storage of oil. Projected cost of conversion of these mines to oil storage (including interconnection with the crude oil pipeline system) ranges between 20¢ and 75¢ per barrel. At the present time, the excavation of new caverns, estimated to cost between $5.00 and $7.00 per barrel, has been deferred until such time as specific requirements have been assessed in regions (such as New England) in which there are neither salt domes nor abandoned mines. It is interesting to note that the provision of storage in surface-located steel tanks is currently estimated to cost approximately $11.00 per barrel (19).

IV - Tomorrow

(1) The Spectrum of Uses

If we examine the spectrum of potential uses shown in Figure 12 in the light of the key characteristics of the underground and of the current and growing awareness not only of the fragility of our environment but also of the finite limitations in our resources partially of energy and of surface space, we see that underground space has much to offer us in the years ahead.

(2) Dead Storage

Beginning, therefore, at the dead storage end of the spectrum, the primary potential use would appear to be in the disposal of radioactive wastes. Programs are underway in several countries to develop safe waste repositories underground. In the U.S. these programs are being handled through the Energy Development and Research Agency (ERDA) which plans to dispose of low, intermediate and high level wastes in chambers located at depth below the ground surface. A major concern in this program is of course related to the very long half-life of some of the radioactive isotopes to be disposed of. For some materials, half-lives are as long as 24,000 years. Therefore, the storage site must be secure in geological age terms.

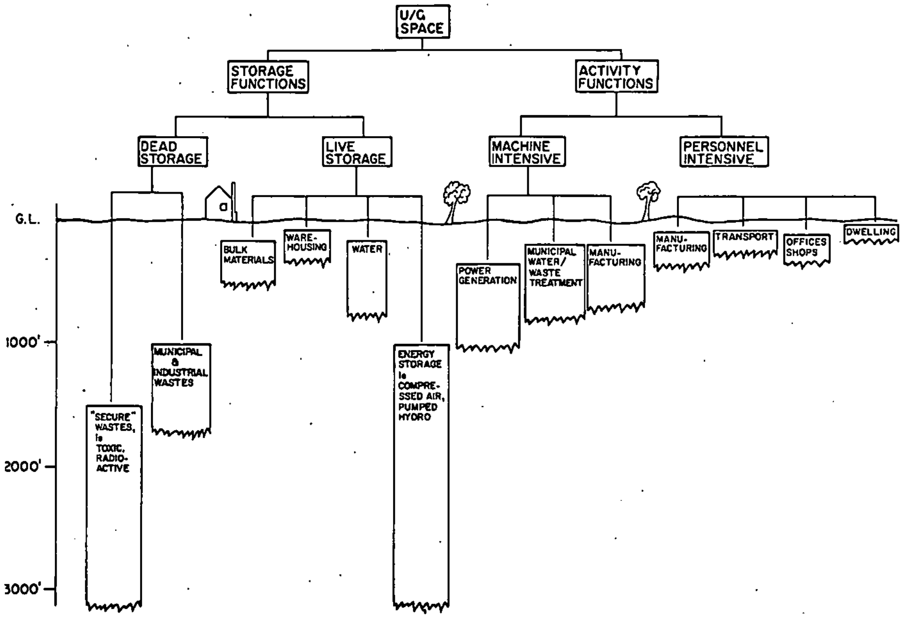


Figure 12: Spectrum of Uses of Underground Space

The U.S. waste disposal program has followed a rather checkered path for the past few years; preliminary plans for a pilot waste disposal facility at Lyons, Kansas (Figure 13) were upset by environmental objections related to the presence of a number of existing boreholes close to the proposed site. The program has recently been redirected (20, 21) toward the consideration of a number of alternative disposal sites around the country. No specific sites have yet been selected. Current plans call for examination of the potential for siting in the Salina salt formation in the north-central region, or the salt domes in the Gulf Coast Region, or the salt and shale formations in the west-central region, as shown in Figure 14. Similar studies to locate waste repositories are also being undertaken in Canada and Scandinavia, primarily concentrating on disposal in hard crystalline rock.

Most of the conceptual designs developed to date for these repositories envisage the waste being enclosed in canisters and sunk into holes drilled in a predetermined pattern in the floor of the underground chamber. In the initial phases of disposal, at least, it will be necessary to be able to retrieve the waste canisters in the event of a malfunction. Ultimately, it is assumed that the chamber will be completely backfilled, although undoubtedly some form of monitoring will have to continue for possibly hundreds of years.

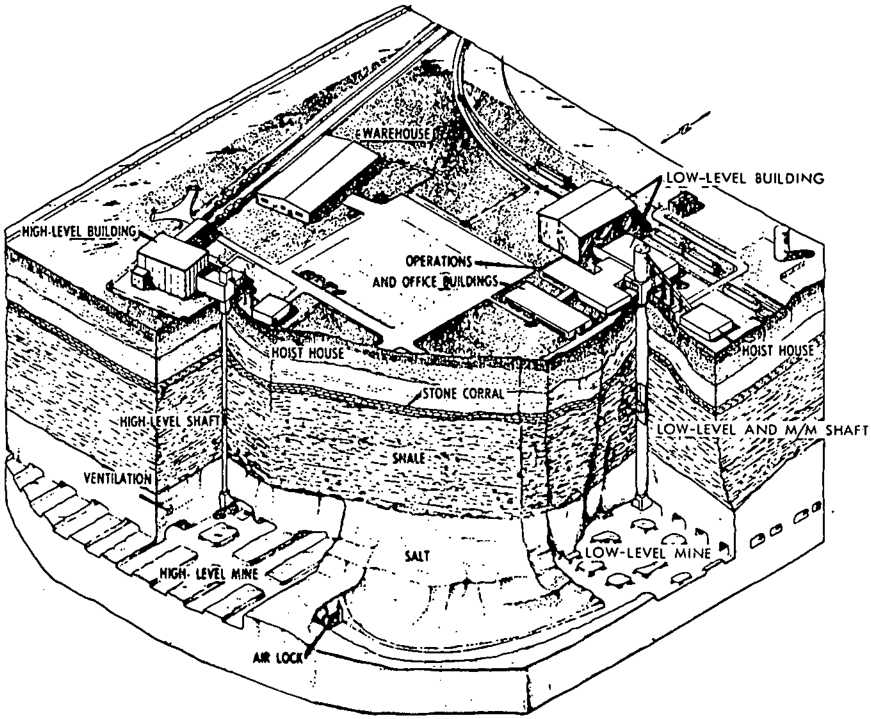


Figure 13: Lyons, Kansas, Proposed Waste Disposal Facility

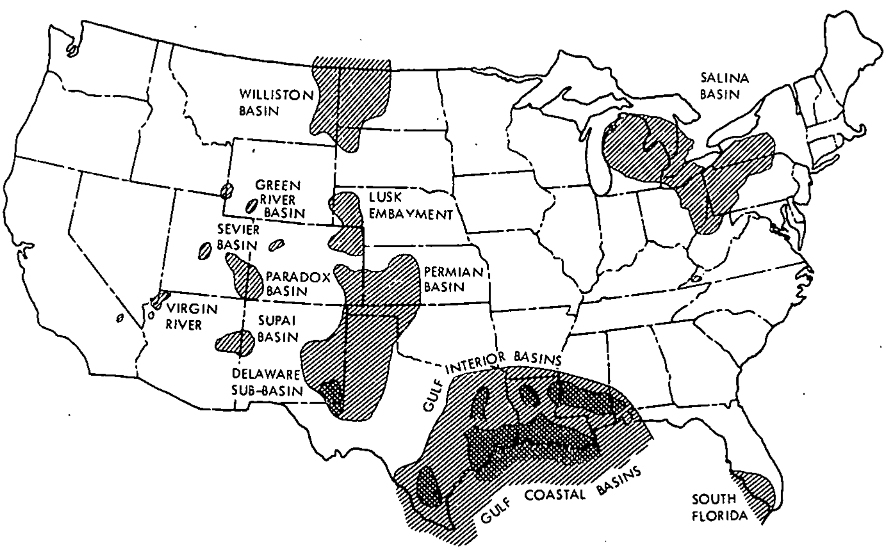


Figure 14: Potential Siting Areas for Waste Disposal Facilities

(3) Energy Storage

The storage of energy in any one of a number of possible forms probably presents the single most likely use of underground space within the next 10 to 25 years. To understand the reason for this, it is necessary to know a little about the function of energy storage in an electric power system.

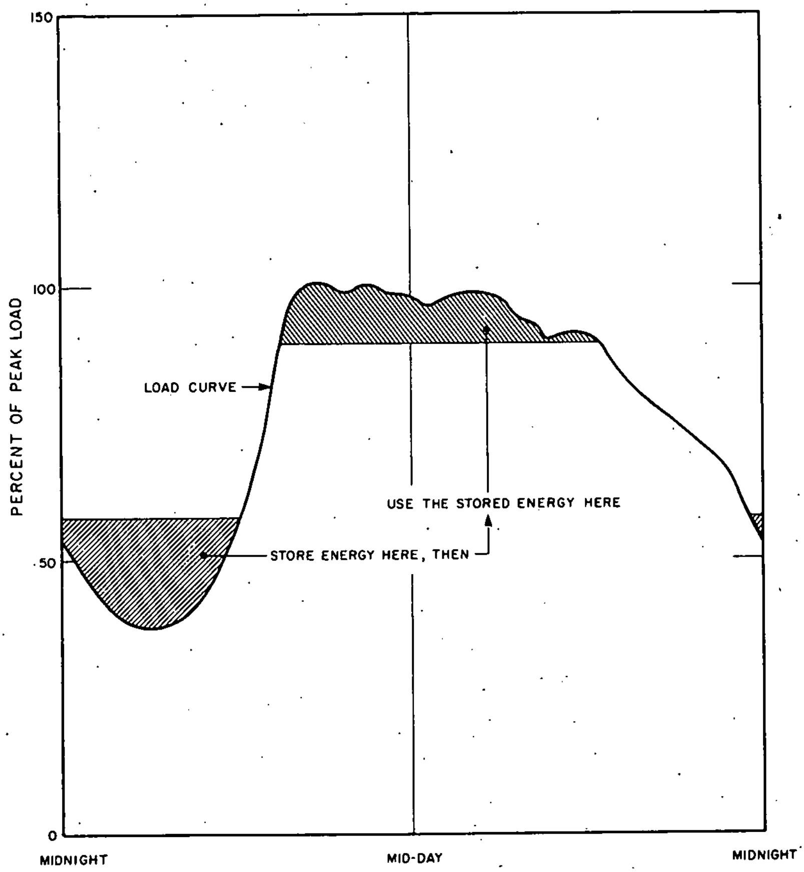


Figure 15: Daily Load Curve

The load demand on an electric utility system varies not only from month to month, but also from day to day, and indeed from hour to hour during each day, generally following the variation shown in Figure 15. The power utility must install sufficient generating capacity to meet the peak demand plus a reserve margin. At times other than peak, the generating plant may be operating at an inefficient part load, or may even be shut down. Operating this way is costly to the utility and to its consumers; improvement can be obtained by providing a means by which unused off-peak generating capacity can be kept in service to charge up an energy storage device, and by using this energy storage later to supplement the peak generating capability, as illustrated in Figure 15.

Hitherto, the only means of storing large quantities of energy has been by the "pumped storage" method, in which spare electrical energy of a hydro plant is used to pump water from a lower reservoir to a higher reservoir, and the energy is reclaimed when required by returning the water to the lower reservoir through turbines to generate peak energy. Pumped storage facilities have been in operation on power systems since the early 1920's, and there is currently a total installed capacity in excess of 10,000 MW in the U.S. Typical plants include Northfield Mountain and Bear Swamp in Massachusetts, and Raccoon Mountain currently under construction by TVA in Kentucky. However, plants of this type suffer from a major problem: they require a fairly large difference in elevation between the upper and lower reservoirs. This is rarely found close to the load center; and more often than not either the site or the transmission line is located in an area of significant environmental sensitivity. As a result, the construction of many of these potentially valuable facilities has been stopped in the planning stage; currently proposed plants at Cornwall (Con Ed), Blue Ridge (AEP), Davis Mountain (Allegheny Power) and Prattsville (PASNY) among others are being delayed or have been abandoned.

To get around these problems, considerable attention is being focused on alternative energy storage concepts, many of which incorporate some use of the underground. The status and potential of concepts is reviewed in a recently published report prepared by the Public Service Electric and Gas Company (22). Of particular interest in the near term are the underground pumped hydro (UPH), and the compressed air energy storage (CAES) systems.

In the UPH concept, as its name implies, the lower reservoir is located in a cavern complex excavated at depth below ground level as shown in Figure 16. The upper reservoir is located at ground level, so that the head that can be developed is no longer dependent on topographic considerations, but primarily on the requirement that the lower reservoir caverns be located in good rock. This means not only can very high heads (up to 5,000 feet) be postulated so that the reservoir sizes for a given energy storage can be kept at a minimum, but also, given appropriate rock conditions, the facility can be located in areas of low topographic relief, often quite close to the load center. The net result is that the environmental impact of the facility is significantly less than that of a conventional surface-located plant. The concept does, of course, present some interesting design and development problems related not only to the construction of the lower reservoir, but also to the requisite mechanical and electrical installation (23).

In place of water, the compressed air energy storage (CAES) concept calls for the storage of compressed air in underground caverns. A number of alternative concepts have been put forward, but the underlying principle is the use of the compressor and turbine components of a conventional gas turbine unit, first to compress air into storage, and later to use the compressed air, generally passing through a combustor in which fuel is burnt, to drive the turbine and hence generate power. The concept requires the conventional gas turbine to be disassembled with clutches interposed between the motor/generator and both the turbine and the compressor. Diagrammatic representations of alternative fueled and nonfueled (the so-called adiabatic) air storage concepts are shown in Figure 17, and a typical section of a "water compensated" facility is shown in Figure 18 (24). The use of a water column to balance the air pressure in the cavern allows the pressure to be kept approximately constant throughout the charging and discharging cycles and minimizes the required size of the cavern for a given quantity of energy storage.

For the storage of 10,000 megawatt hours of energy, the size of the cavern required for underground pumped hydro storage would be approximately 4.5 million cubic yards at a depth of 4,000 feet, while that for a CAES facility it would be approximately 1.25 million cubic yards at a depth of 2,000 feet. The apparent disparity in cost between the two concepts of energy storage is compensated for by the fact that the CAES plant has higher operating costs because of the fuel required.

A compressed air energy storage facility is currently under construction at Huntorf in West Germany using a solution cavern in salt for the storage of the compressed air at an average pressure of 812 psi.

A number of other concepts of energy storage involving the use of rock caverns for the storage of various types of fluids at elevated temperatures have been put forward (25). However, these generally require that the caverns be lined, either to preserve the purity of the fluid being stored or to protect the rock against the effects of temperature. The introduction of a liner is costly and can create problems in relation to the resistance of external pressure caused by groundwater. It is worthy of note that, at a recent National Academy of Science seminar, a key aspect of the underground that was identified, as deserving increased study was the effect of temperatures (both high and low) on the characteristics and performance of rock.

(4) Municipal Facilities

Given the appropriate topographical and geological conditions, there are a number of municipal facilities, quite apart from sewers, utility corridors, roads and subways, which can benefit from being located underground.

These include sewage treatment plants, parking facilities and shopping plazas. There are precedents for placing all these types of facilities underground, particularly in Europe. In Stockholm, there are several underground sewage treatment plants. The plant at Kappala, for instance, has treatment capacity for 460,000 persons and incorporates primary, secondary, and tertiary treatment (26). At Zurich, a fully automated underground parking garage has been installed.

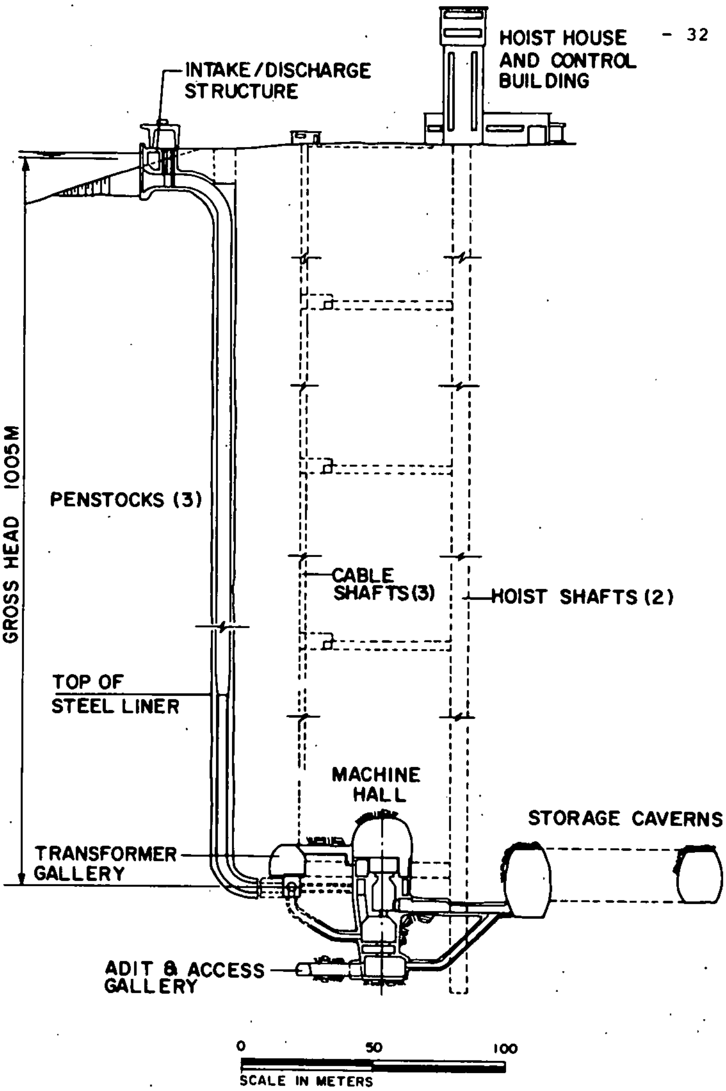


Figure 16: Underground Pumped Hydro Storage

In 1971, the city of Helsinki in Finland initiated the construction of a combined bomb shelter and telecommunications center for the Post Office. The total excavated volume was 137,000 cubic yards. The complex includes nine main halls each approximately 500-feet long by 50-feet wide by 35-feet high. Because the site is close to a hospital and laboratories, and also is beneath one of Helsinki's most beautiful parks, the strictest control of blasting had to be exercised with stringent environmental limitations.

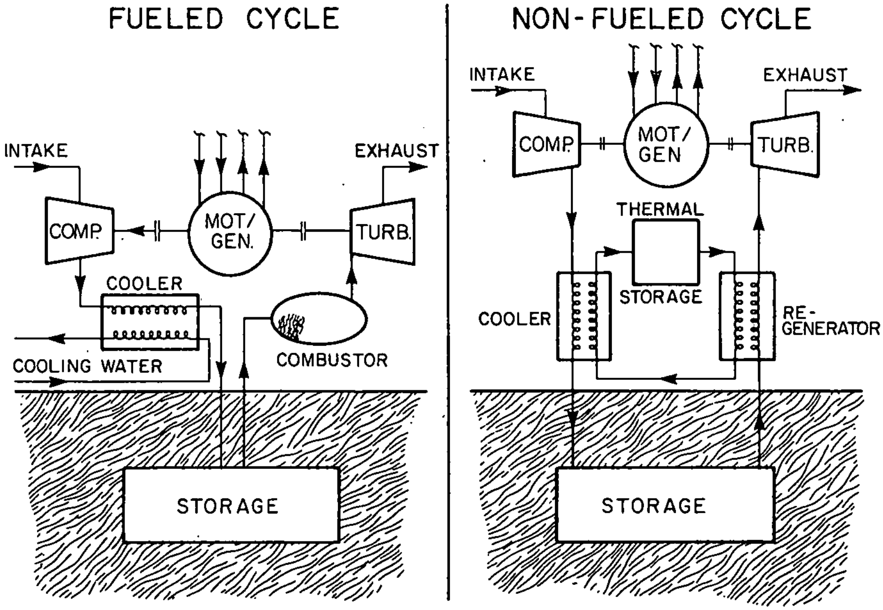


Figure 17: Fueled and Non-fueled CAES Cycles

V - And Beyond?

(1) Economics of Underground Space Use

It is instructive to develop further some figures presented in a recent paper (27) by Thompson Consultants Inc. comparing the net energy consumption of two structures with the same floor area, 42,000 square feet, one located at the surface, the other underground. It was computed that the net saving in energy consumption for the below-ground structure was approximately 20,000 Btu per square foot per year, a 30 percent reduction below that required for the surface structure. At a cost of approximately $5 per million Btu, this means a saving of perhaps $0.60 per square foot per year. The construction cost of the above-ground structure would be approximately $50 per square foot excluding land costs, while that for the below-ground structure would be approximately $64 per square foot if excavation is costed at $50.00 per cubic yard including support. The $50.00 per cubic yard rate for rock excavation is necessarily somewhat high because of the limited size of the structure.

If a value of $5.00 per ton for use as an aggregate is assigned to the material excavated from the cavern, the cost of the underground structure reduces to $61.00 per square foot. It is, however, clear that even if the saving in heating cost is capitalized at 20 percent, the underground cost, overall, is

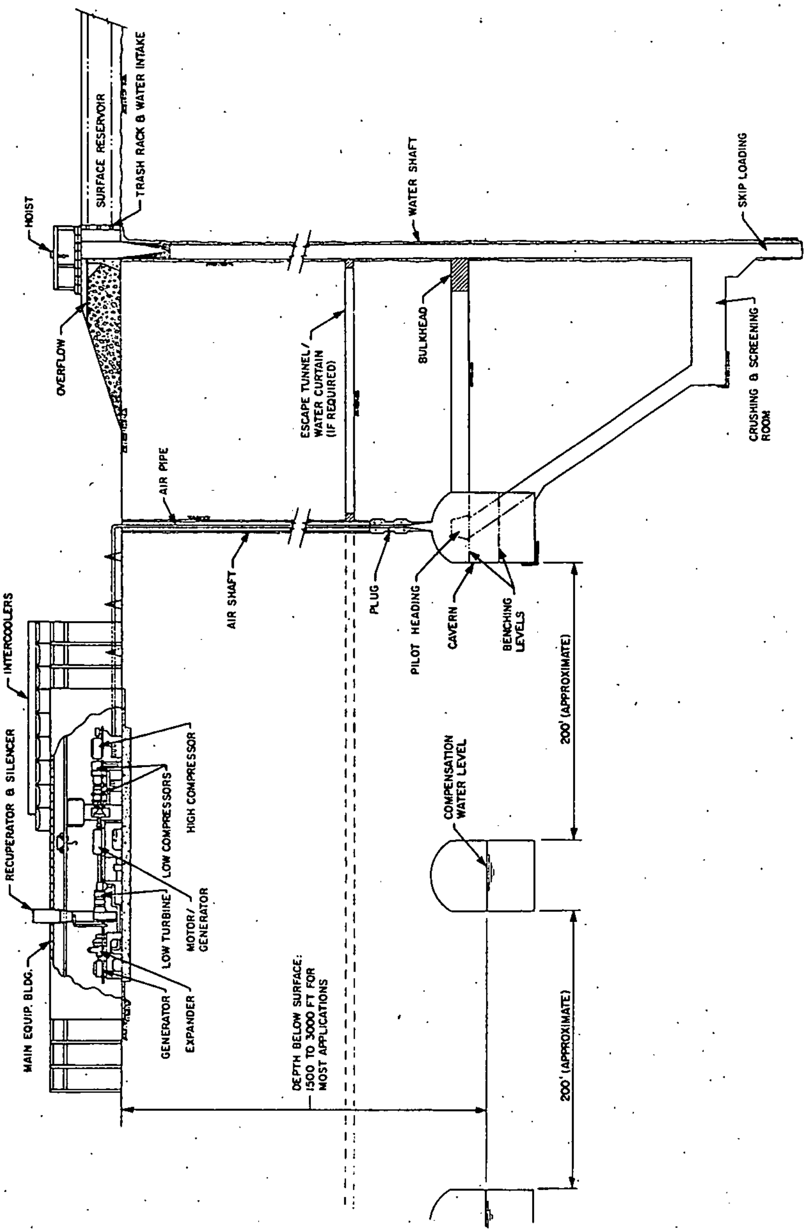


Figure 18: Water Compensated CAES Facility

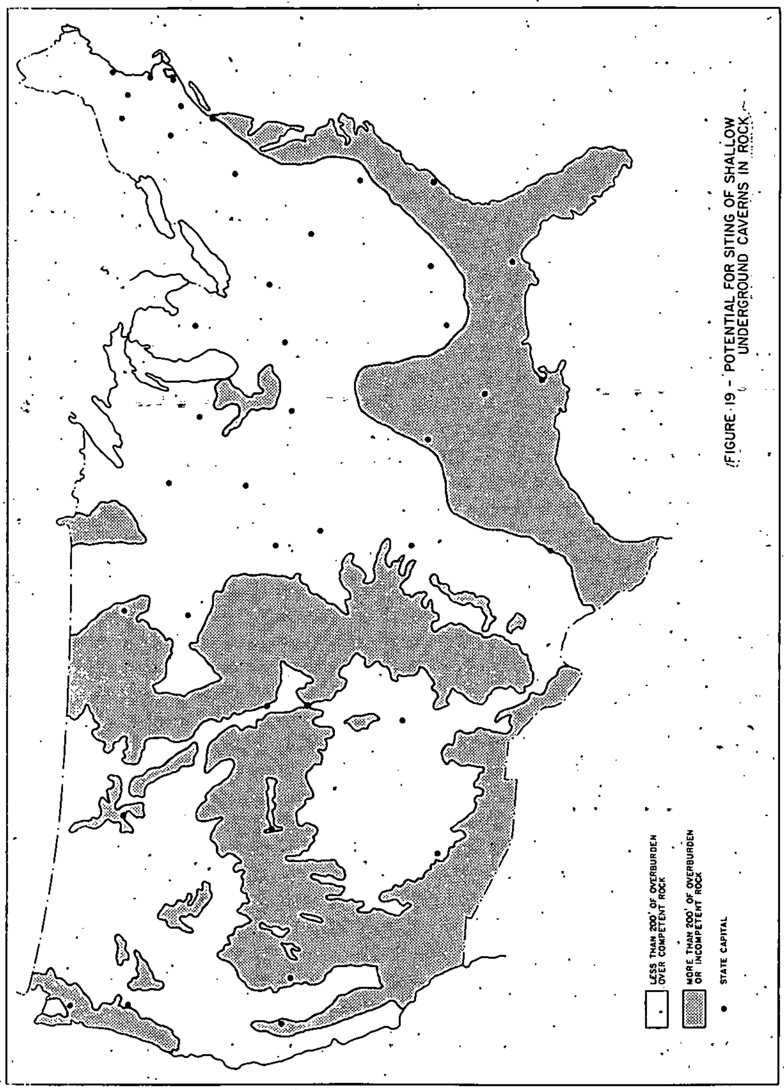


Figure 19: Siting Potential for Shallow Rock Caverns

short of being lower unless the cost of the excavation is reduced to less than $10 per cubic yard. It is interesting to note that the cost of floor space at the Kansas City underground mining operation, in 1975, ranged between $2 and $6 per square foot (28).

(2) Further Advances in Techniques for Creating Underground Space

We have seen in the foregoing review that despite the steady advances in excavation technology over the more than 4,000 years that man has been creating underground space, we are still unable to match the spans that nature itself has created (Table 1). However, research and development are actively underway in all aspects of underground excavation, aimed at improving both the speed and cost of the work. A partial list of rock disintegration techniques currently being examined, with varying degrees of priority, is presented in Table 5.

TABLE 5

Rock Disintegration Techniques Currently In Use And Under Study

1 - Drill and Blast		
2 - Rolling Cutter (TBM)		
3 - Mechanical	- Fluid erosion - Spark - Ultrasonic - Abrasive - Explosive - Implosive - Pellet	
4 - Thermal	- High-velocity flame - Cryogenic - Jet piercing - Electron disintegration - H.F. electric - Induction	
5 - Chemical	- Softener - Dissolvers	
6 - Fusion	- Plasma - Laser - Atomic - Fusion - Electric arc - Electron beam	

(3) Conclusions

Following upon the development and improvement of the techniques for creating underground space, what can we look forward to? I suggest:

1. Techniques of excavation and support now available or in the development phase will enable us to excavate larger caverns in less time and at lower cost.
2. Both environmental and economic pressures will force consideration of the underground to relieve pressures at the surface and to take advantage of the insulating properties (in the broadest terms) of the surrounding rock.

3. New towns will be planned underground and existing towns will be modified to locate many facilities underground, including road and rail transportation. This will particularly apply in northern climates in which the harsh winters make surface-located facilities costly to construct and heat.
4. Power plants will be located underground close to towns. In addition to other advantages, this will allow maximum use of surplus heat for district heating and cooling, and for use in other industrial and municipal processes.

Figure 19 indicates areas of the U.S. in which reasonably competent rock is located within 200 feet of the ground surface. It can be seen that, except in the south and southeast regions, relatively extensive areas with underground siting potential are widely scattered across the country. It remains for the planners to recognize this very real resource for what it is, and to utilize it in the service of mankind. As civil engineers, we are uniquely placed to do just that.

References

(1) World Book 1972, Volume 15, page 599, Field Enterprises.
(2) World Cities, Table 3, World University Library, London, 1976.
(3) Cities and Geology, Page 8, Legett 1974.
(4) World Book 1972, Volume 1, page 142, Field Enterprises.
(5) Archeological Atlas of the World, W. H. Freeman & Company, 1975.
(6) Tunnelling, 6th Edition, Van Nostrand, 1912.
(7) Book of Job, Chapter XXVIII.
(8) The History of Tunnelling by G. E. Sandstrom, Barrie and Rockliffe, 1963.
(9) Arts of Cappadocia, Nagel Publishers, Geneva, 1971.
(10) Pliny - XXXIII:21.
(11) Churchill Falls Power Project, D. C. Willett, Water Power, 1971.
(12) Ph.D. Thesis, R. P. Benson, "Rock Mechanics Aspects of the Design of the Churchill Falls Underground Powerhouse", 1970.
(13) Proceedings of the Symposium on the Development and Utilization of Underground Space, University of Missouri at Kansas City, 1975.
(14) Review of Underground Siting of Nuclear Power Plants, Page 3.2, Report to USAEC by United Engineers with Acres American Inc., January 1974.
(15) Ibid, pp. 3.10 through 3.13.
(16) Ibid Appendix C.
(17) Seismic Considerations in Siting Large Underground Openings in Rock, C. E. Glass, Ph.D. Thesis, University of California, Berkeley.
(18) Underground Storage of Oil in Dry-mined Caverns, Report to FEA by Acres American Inc., 1976.
(19) Strategic Petroleum Reserve Plan, Public Law 94-13, Section 154, December 15, 1976, FEA Strategic Petroleum Reserve Office.
(20) Office of Waste Isolation Program: National Waste Terminal Storage Plan, Contractor Briefing, May 1976.
(21) "A Permanent Home for Nuclear Waste", Nancy Reuth, Mechanical Engineering, January 1977.
(22) An Assessment of Energy Storage Systems Suitable for Use by Electric Power Utilities, EM 264, EPRI Project 225, ERDA E(11-1)-2501, July 1976.
(23) "Underground Pumped Storage Research Priorities", Report No. AF 182 to EPRI by Acres American Inc., April 1976.
(24) Compressed Air Energy Storage Study by United Technologies with Acres American Inc. for NSF, 1977.
(25) "Storage of Off-Peak Thermal Energy and Oil", E. W. Nicholson, ASME Winter Annual Meeting, December 1976.
(26) "To Solve Sewage Treatment Underground", G. A. Rosander, Stockholm, SWEDUC 1976.
(27) "Building Underground: Heating, Ventilating and Air Conditioning Systems", Presented at Harvard University Symposium on Building Underground, June 1976, Thompson Consultants Inc., Marion, Mass.
(28) "Techniques of Mining for Secondary Space", C. R. Christiansen and J. J. Scott, 1975.