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Design Strategies to Alleviate Negative Psychological and Physiological Effects in Underground Space

John C. Carmody and Raymond L. Sterling

Abstract—*This paper summarizes negative psychological and physiological effects associated with underground buildings, identifies design strategies to alleviate them, and evaluates the effectiveness of some of these design techniques. The focus of the paper is on deep underground space with limited connection to the surface environment. A case study of design strategies used in deep underground office space is presented, and two proposed projects that further illustrate design techniques for deep mined space underground environments are described.*

Résumé—*Cet article récapitule les effets psychologiques et physiologiques négatifs associés aux bâtiments sous terre, identifie les stratégies de conception pour les réduire, et évalue l'efficacité de quelques unes de ces techniques de conception. L'article se concentre sur des espaces sous-terrains profonds avec peu de liens avec l'environnement de surface. Une étude de cas des stratégies de conception utilisées pour des bureaux sous-terrains profonds est présentée, et deux projets proposés qui poursuivent des idées de conception en environnement sous-terrain miné profond sont décrits.*

Underground buildings continue to be constructed to take advantage of various benefits, including efficient land use, energy conservation, and isolation from surface noise and vibration. In designing these structures, it is important to recognize the potentially negative psychological and physiological effects associated with windowless, isolated spaces.

The existing literature on psychological and physiological effects has been reviewed and discussed elsewhere in a more complete form (Carmody and Sterling 1984; Collins 1975). This paper summarizes the major issues related to psychological and physiological effects, discusses the impact of building use on these problems, and identifies design techniques to alleviate negative psychological and physiological concerns. A case study of design strategies used in deep underground office space is presented, and two proposed projects that further illustrate design techniques for deep mined underground environments are described.

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This article first appeared in *Advances in Geotectural Design*, Proc. Second Int. Earth Sheltered Buildings Conference. It is reprinted here with permission of the Dept of Architecture, Texas A&M University.

Negative Psychological Effects

Underground buildings display a wide spectrum of physical characteristics and functional uses. In addition, the physiological and psychological responses of individuals to the environment can be radically different. The combination of these factors makes generalizations about underground buildings in relation to psychological effects of limited applicability.

Only a few studies have directly addressed the case of below-grade spaces for working or living environments, and often conflicting data have been gathered. For example, a poor response to the environment of an underground building has been linked to anxiety, tension, depression, and other mental health problems, although other studies have indicated no measurable differences in achievement, health problems, or absenteeism (Collins 1975; Hollister 1968; Lutz 1980).

An extensive survey of underground workers in Kansas City revealed a number of negative and positive perceptions of working underground (Hughey and Tye, 1984). Although lack of sunlight and view, inadequate lighting and ventilation, and fear of structural collapse were seen as drawbacks for some workers, many positive advantages were cited as well. These included constant temperature, protection from weather extremes, a unique work environment, a quiet space with few distractions, and a safe environment protected from disasters. The overall results of the study show that workers have generally favorable attitudes toward the underground. They rate the underground as safe and efficient, view it as comparable to aboveground settings, and evaluate temperature and humidity positively.

Assessments of the distinct physical characteristics of an underground space are extremely difficult to separate from other general physical characteristics of the space and the interpersonal environment. In spite of the lack of definitive data, however, the major issues are fairly clear and repeatedly emerge in all studies of underground and windowless spaces. Below are listed conditions that are associated with producing negative psychological effects in underground buildings. Most of the information also pertains to windowless buildings or interior zones inside conventional buildings.

Lack of Natural Light

The lack of natural light is one of the most often mentioned negative characteristics of underground space. Access to natural light is important to users of a building even if the proportion of daylight to artificial lighting for work tasks is relatively low. The feeling produced by daylight, its variability, and the sense of contact with the outside world are important reasons for its desirability. Another important positive psychological association of natural lighting is that sunlight connotes warmth.

Lack of Exterior View

The lack of exterior view from an underground space is another reason for dissatisfaction with this type of building. In addition to providing natural light and sunlight, windows provide a direct view for observing weather con-

Tunnelling and Underground Space Technology, Vol. 2, No. 1, pp. 59–67, 1987.
Printed in Great Britain.
0886-7798/87 $3.00 + .00

ditions, creating a sense of contact with the environment, and giving visual relief from immediate surroundings (Collins 1975).

Different studies have indicated different relative importances for natural light and view (Longmore and Ne'eman 1974). People in work environments are more likely to favor a view over direct sunlight, especially if no solar shading is provided and if they are not free to relocate themselves out of the sun when desired. Occupants of high-density residential developments are more likely to cite the availability of sunlight in the home as more important than a good view (Bitter and van Ierland 1967).

Underground Location

The location of a building below grade does not preclude providing the above amenities of natural light and view to the interior of the building. There are, however, psychological barriers to the physical location of a space below grade, even if it has identical physical amenities to an interior space in a conventional building.

Some individuals may experience claustrophobia or fears related to safety that result in negative reactions to underground space. It is difficult to explain the negative association some people have with the concept of being underground—even when interior conditions are identical to those in an aboveground space. In addition to fears related to safety concerns, there may be a generally negative association with death and burial related to underground space. It is generally assumed, however, that these attitudes are more closely related to a fear of structural collapse, fear of being trapped in a fire in a windowless building, or fear of flooding in a fully below-grade space. Fears for personal safety need not be related to the actual risk experienced, but merely to the perceived risk.

These negative reactions tend to heighten awareness of and exaggerate objections to other physical characteristics of the space that might go unnoticed in a conventional building. For example, small interior spaces, low ceilings, or entry down a narrow, dark stairway may increase these negative associations with being underground.

Undesirable Internal Conditions

Users of underground or windowless buildings frequently complain of poor temperature and humidity control, and a lack of ventilation and stuffiness (Collins 1975). Generally, none of the problems should be any different for a below-grade or windowless building than they are for a sealed, climate-controlled conventional building. In fact, temperature and humidity should be easier to control than in an aboveground building. Thus, in addition to the actual ventilation air change rate provided, perception of ventilation by occupants is important (Wunderlich 1978). If awareness of the superior internal environmental control of an underground building is clearly apparent to the occupants, some offsetting positive attitudes may develop.

Negative Physiological Effects

The physiological effects discussed in this section are those caused directly by the environment of an underground or windowless structure, rather than indirect ailments or reactions caused by psychological stress. As with studies of psychological effects, the research on physiological effects underground is not conclusive and sometimes contradictory.

• A fairly comprehensive study was made of workers in an underground factory in Sweden in the 1940s and 1950s (Hollister 1968). Although headaches, faintness, and sickness were reported, much of these were initial problems that occurred during a period of acclimatization to the underground environment. The study concluded that no major physiological problems occurred if the proper interior climate was maintained. Blood tests on workers after eight years of working underground showed no alteration in the normal blood condition.

Two studies of children attending an underground school in New Mexico (the Abo Elementary School) also indicated no evidence of greater absenteeism or health problems in children attending the underground school. In fact, respiratory ailments were reduced because of better control and filtration of the air (Lutz et al. 1964 and 1972). Below is a list of conditions that are associated with producing negative physiological effects in underground buildings.

Lack of Natural Light

Lighting is probably the most important physiological criterion to be considered in designing underground or windowless structures. The human body has a direct response to certain spectra of light, including those outside the visible spectrum. For instance, ultraviolet light is known to be important in vitamin D absorption, which is necessary to prevent disease, aid suntanning, and fight bacteria. In animals, the lighting level and its spectral composition have been shown to be important in reproduction, behavior, and physical disposition. Lighting also triggers a neuroendocrine function and affects the metabolic state (Wurtman 1968; Ott 1973).

Although much research has been done on the presence or absence of light, less has been done on lighting levels and spectral composition. Alarming effects of certain light sources have been demonstrated, however, in laboratory animals (Ott 1965). It should be noted that the effects are quite different for different animal species.

Ultraviolet light is not transmitted by normal window glass; hence, a lack of ultraviolet light is common even to buildings with windows. When it is necessary to rely on artificial lighting entirely, it is most desirable to replicate the spectral composition of daylight as closely as possible.

Lack of Fresh Air and Indoor Air Pollution

The underground location of a building with only limited opportunities for window openings often precludes the use of natural ventilation. Adequate ventilation is important to prevent the build-up of indoor air pollutants and to remove excess heat from an occupied underground space.

Low air change rates make ventilation especially important in underground structures. A pollutant of particular concern is radon. Radon is a radioactive gas released in minute quantities by soil and rock materials, including building construction materials such as concrete and building stone. Radon is also absorbed by ground water and then released at a free ground water surface. Normal ventilation rates, i.e. in excess of 0.5 air changes per h, are believed to hold down radon levels to below permissible standards. This is an active area of research, and more specific data and guidelines should be produced over the next few years. In addition, it is desirable to prevent the passage of ground water or water vapor from the surrounding ground to within the building envelope, since this water can be a significant source of radon (May 1981).

High Humidity

Unless controlled, summertime humidity levels will be higher in underground structures than in aboveground structures, because humid outside air is cooled by the earth-covered walls. Humid or damp conditions have not been linked directly with physiological problems, although they may exacerbate certain ailments such as rheumatism. Damp conditions may also encourage the growth of mold and, thus, increase the potential for allergic reactions.

Impact of Building Use on Problems

Before concluding which effects are most critical and suggesting design approaches to ameliorate them, it is useful to review the various factors related to building use that influence either the psychological or physiological effects. These factors, discussed below, can serve to diminish the potentially negative effects and help to alleviate building user concerns.

Activity Within a Building

Internal activity within a building that can offset the lack of external stimuli will normally be beneficial in a work environment, provided it is not too intrusive in terms of noise or distraction. Although internal stimuli may help to alleviate the negative psychological effects produced by no natural light and exterior view, it has no impact on the physiological effects of a windowless environment.

Occupancy Patterns

An individual's reaction to an underground or windowless environment may be substantially affected by the length of time he or she expects to spend in that environment. Underground facilities used primarily for short-term activities, such as indoor sports facilities, restaurants, libraries, and shopping centers, will thus normally raise fewer objections than an underground office. Not only are negative psychological reactions less of a concern when occupants are in underground spaces for shorter time periods, but negative physiological effects are less critical as well.

Need for Underground Location

Employees of underground or windowless facilities appear to be more accepting of their environment if they perceive a rational basis for the location or design of the facility. In other words, since windows are detrimental to the operation of many sports facilities, museums, restaurants, and shops, employees and visitors do not focus on the lack of windows as a drawback. Similarly, windowless laboratory and manufacturing environments provoke less criticism than windowless office buildings. Although this perception of windowless environments as appropriate for some functions can reduce some psychological effects, it has no impact on negative physiological effects.

Job Satisfaction

Employees who are more involved in their work and derive considerable satisfaction from it may be more tolerant of windowless space than employees who work at repetitive tasks. The extent to which this can actually offset the various negative psychological effects is likely to vary considerably from individual to individual.

Design Techniques to Alleviate Concerns

We believe that the potentially negative psychological and physiological reactions discussed above can be diminished or alleviated to a great extent by utilizing proper design techniques. Although designers of deep, windowless underground space have little specific psychological research to guide them, many of the techniques listed below are based on common sense and have been successfully employed in various underground buildings. The most important strategies fall into five general categories.

(1) *Entrance Design*

The entrance to deep underground space may affect its entire image, regardless of the design of the rest of the space. The primary image to avoid is entering through a dark, enclosed area that connotes a basement or a mine. In deeper space, it is impossible to avoid a downward vertical movement; however, the transition from outdoors to the deep space can be made a positive rather than negative experience. Specific techniques include the following:

(a) An entrance that is easily recognizable from the outside (the underground space may be entered through an above-grade building, thereby resolving some transition problems).
(b) An entrance area that is spacious with high ceilings (entering adjacent to a large interior space that is viewed from the entrance can create a spacious feeling).
(c) As far as is possible, natural light provided in the entry area (where this is not possible, high levels of artificial light are desirable).

(2) *Sense of Space, View and Orientation*

Deep underground spaces provide virtually no opportunities for typical exterior views. Small enclosed rooms and narrow corridors underground could contribute to many of the negative effects discussed above, including claustrophobia, lack of orientation, and lack of connection with the outside world. Techniques to alleviate this include the following:

(a) Glass partitions between spaces, as much as possible.
(b) Ceilings higher than typical dimensions in one-story spaces.
(c) Multi-level spaces whenever possible.
(d) Large central atrium spaces extending from the surface to the deep space.
(e) Optical devices to provide some view of the surface environment.

(3) *Natural Light*

The lack of natural light is often cited as a primary drawback of underground space even though natural light is commonly not provided to extensive areas within above-grade buildings.

Three general techniques can be used to provide the benefits of natural light to deep underground space.

(a) Large, deep atrium spaces extending from the surface to the deep space.
(b) Various beamed daylight systems utilizing mirrors and lenses to transmit and distribute light from the surface.
(c) Full-spectrum artificial light.

Unfortunately, opportunities to provide natural light in deep space using atriums and beamed daylighting systems are limited by physical constraints and the available technology to transmit and distribute sunlight through relatively small shafts to the surface.

The use of full-spectrum fluorescent lighting as an alternative can provide some of the physiological benefits associated with sunlight more effectively than other techniques. For example, full-spectrum lights simulate the ultraviolet portion of the spectrum which is normally screened out by window glass. In addition, artificial light—unlike natural light—can be used to provide even light in all spaces at all times. Even where natural light is provided, it can be used in conjunction with full-spectrum artificial light.

(4) *Interior Design Elements*

The sense of space created by high ceilings and glass partitions as well as the provisions of natural light provides the basic framework for the interior design elements. Successful interior design underground can result from a variety of design approaches, just as it can in aboveground buildings. Certain elements, however, generally contribute to creating a positive interior environment underground. These include:

(a) The use of warmer, brighter colors, as opposed to dark colors or completely unfinished surfaces (which connote basement spaces).
(b) Extensive use of green plants.
(c) The use of water in pools or fountains in appropriate locations.
(d) Variations in lighting in special areas, i.e. very bright lights over a plant-filled area, or spotlights illuminating artwork.
(e) Artwork that serves as surrogate windows, e.g. murals of natural landscapes have been successfully used in windowless spaces.

(5) *Mechanical System*

Providing fresh, clean air at comfortable temperature and humidity levels should be no more difficult underground than it is in conventional aboveground buildings. The system must be properly designed to respond to the unique temperature and humidity conditions that may be found below grade, while also preserving the inherent energy-conserving benefits of this isolated environment. In spite of the ability to properly design a mechanical system using conventional techniques, the occupants of underground space may be quite sensitive to ventilation, temperature and humidity problems. To offset negative occupant reactions, strategies include the following:

(a) Provide ventilation in a manner that is perceptible to the occupants.

(b) Provide a flexible mechanical system that can control both humidity and temperature to satisfy the function of each space as well as the comfort of the occupants.

Case Study: CME Mined Space

The Civil and Mineral Engineering (CME) Building at the University of Minnesota, designed by BRW Architects, was completed in 1983. Containing 4500 m² (50,000 ft²) of windowless mined space approximately 33 m (110 ft) below the surface, the building provides an excellent opportunity to examine several of the design techniques described above. A small portion of the mined space is occupied by the Underground Space Center. The authors and other occupants of the building have made the following observations after working in the deep mined space for over two years.

Entrance Design

Because the CME Building is entered by elevator, descending to the deep space is not much different than ascending in an elevator in a conventional building. Both major entrances to the elevator area (one through a sunken courtyard and the other through an above-grade portion of the building) are very spacious, overlook multi-level spaces, and are naturally lighted. On the upper levels of the building, orientation is maintained by entering the elevators while overlooking the structures laboratory, a three-story space that serves as the major atrium space in the building.

Sense of Space, View and Orientation

In the Underground Space Center offices, 11 ft-high ceilings and glass partition walls are essential elements in creating a spacious, attractive environment underground (see Figs 1 and 2). By contrast, underground laboratory and storage rooms converted to offices elsewhere in the mined space lack these characteristics and are less appealing workplaces.

One interesting aspect of using glass partition walls is that, while they have the positive benefit of providing a view out of a small office, they also represent the potentially negative feeling associated with loss of privacy. We have observed that this loss of privacy is acceptable to most occupants when private offices look into a central work area that is controlled and not completely public. This is the case in the Underground Space Center, where private offices are oriented around a reception, secretarial and computer work area in the center.

Glass partitions are less acceptable, however, when the private offices directly adjoin public corridors. We have noticed that where this arrangement occurs, the occupants cover even the smallest areas of glass so that they cannot be observed from close range in the corridor. Generally, it appears that a hierarchy of spaces should be preserved when using glass partition walls. Glass walls are acceptable between public areas and reception or open work areas. They are also acceptable between reception or open plan work areas and private offices, but not directly between individual private offices and public spaces.

Glass walls in private offices are also acceptable when they overlook large public atrium spaces, since they are elevated, distances are increased, and the public cannot observe workers at close range.

A final note related to glass partition walls is that the individual need for view and privacy appears to vary significantly even among a very small group.

Another successful aspect of the CME Building design is the large open staircase to the surface. Contained in a red, cylindrical form, the staircase is easy to locate and provides orientation on each floor of the building. Through the open center of the stair, one can see the sky from 33 m below grade, which provides additional orientation to the surface. The opening also serves as a place to be seen and heard during an emergency.

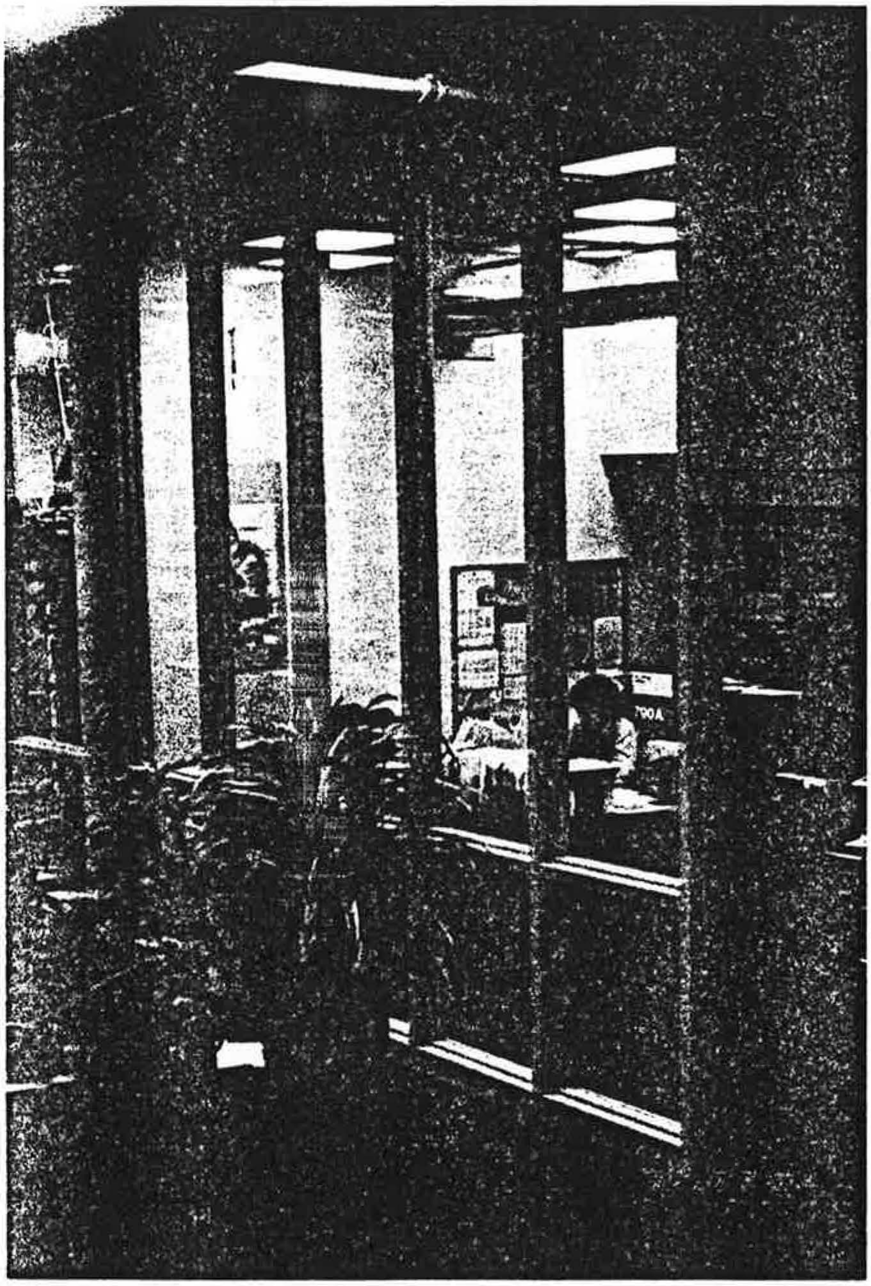

Figure 1. Underground Space Center offices at the University of Minnesota's Civil and Mineral Engineering Building.

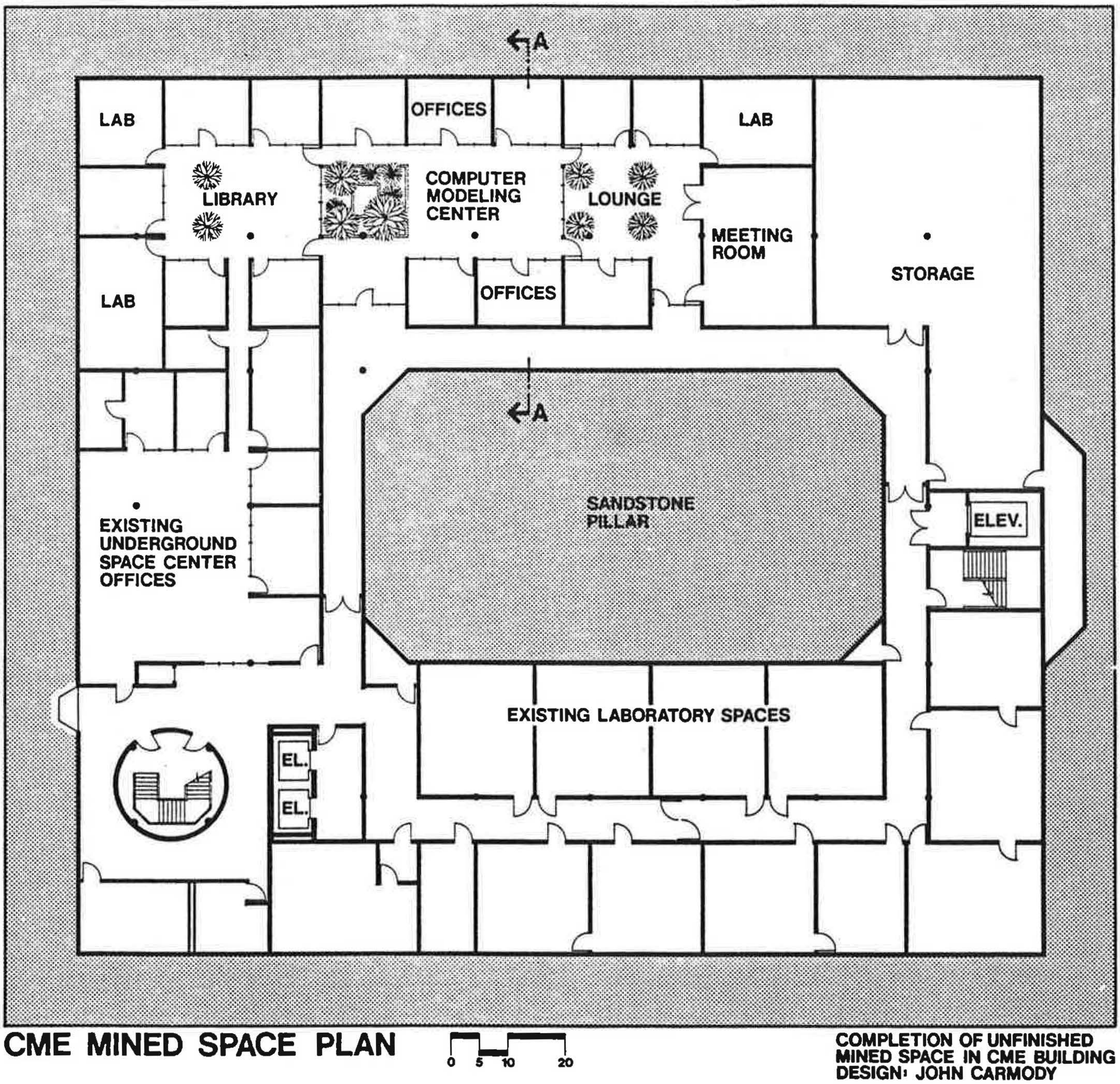

Figure 2. Plan for expansion of mined space in the Civil and Mineral Engineering Building.

Finally, a periscope-like system called an Ectascope is installed in the public area outside the Underground Space Center to provide a view of the surface. Optically, the image is as clear and three-dimensional as it would be through a window. The limitation of the system is that it can only be viewed from one point. Rather than actually serving as a window that is constantly visible for the occupants from various angles, it is a means for checking the weather conditions periodically.

While expansion and modification of such an optical system could be designed to actually provide a constant exterior view to a larger office space, much of the three-dimensional quality of the view would be lost in providing a larger viewing area. The present system was never intended as a complete substitute for windows with exterior views; nonetheless, it does provide a connection to the outdoor environment when information on outdoor conditions is needed. Further exploration of optical viewing devices appears warranted, based on this limited experience.

Natural Light

Except for the open staircase with a skylight overhead, there are no large atriums or other opportunities for natural light to reach mined space in the CME building. The light from the staircase does not extend outside of the stairwell itself. Two other strategies to provide the benefits of natural light to mined space have been explored on an experimental, limited basis in the building.

Natural light is provided to the public area outside the Underground Space Center by a solar optical system. Two heliostats on the roof, operated by a computer program in a caculator, track the sun. The sunlight is reflected off mirrors on the roof, down through a shaft containing lenses at the base, and emerges through the ceiling of the lower level of the building. When operating properly, the heliostat apparatus provides a strong beam of sunlight that has dynamic and pleasant characteristics not associated with most artificial light.

One limitation of the present system is that light is provided to a very limited area. Experiments have been conducted to distribute the natural light to a larger area using mirrors and light pipe materials. Based on this limited application and the fact that the system is not always functioning properly, it is difficult to draw conclusions about its psychological or physiological benefits. Since natural light is generally regarded as such a desirable element in underground space, further research and development of beamed daylighting systems is clearly desirable.

As an experiment, full-spectrum fluorescent lights have been substituted for conventional cool-white fluorescent lights in portions of the Underground Space Center as well as in other windowless areas of the building. No controlled psychological or physiological studies have been undertaken; however, subjective reactions are quite positive toward the full-spectrum lights. Workers report that in addition to the color of the light appearing natural—as though it comes from a skylight—eyestrain is reduced.

Interior Design Elements

The interior design budget of publicly funded structures such as the CME Building is often limited. Within these constraints, the designers chose warm colors wherever possible to offset any cold, negative associations with underground space. Furnishings and all decorations were generally left to the individual occupants to provide. Green plants are the primary elements that most workers in the Underground Space Center find desirable—and even essential—to create a pleasant environment. Wall decorations are often photographs of outdoor landscapes, in order to provide surrogate windows. When asked what is needed to improve the office, some workers suggested larger areas in the center with extensive plant growth and a pool or fountain with the sound of running water. In effect, an interior garden courtyard was desired as a substitute for an outside view.

One drawback of the high concrete ceilings in the Underground Space Center is that a noisier work environment is created in the central open area. This could be alleviated with acoustical treatment of the concrete walls and ceiling.

Mechanical System

During some periods of the year, control of the temperature and humidity in areas of the CME Building is not precise enough to satisfy many occupants. Although the need for heating and cooling in mined space is not great, given the constant year-round temperatures of 10°C (50°F), removing excess moisture from the ventilation air without substantially cooling it is needed in the summer. This higher demand for moisture removal compared to sensible cooling is not typical in conventional buildings but must be considered carefully in the design of underground buildings. More precise control of temperature and humidity conditions by the occupants in individual zones would be a desirable goal in deep underground space.

Generally, every design strategy em-

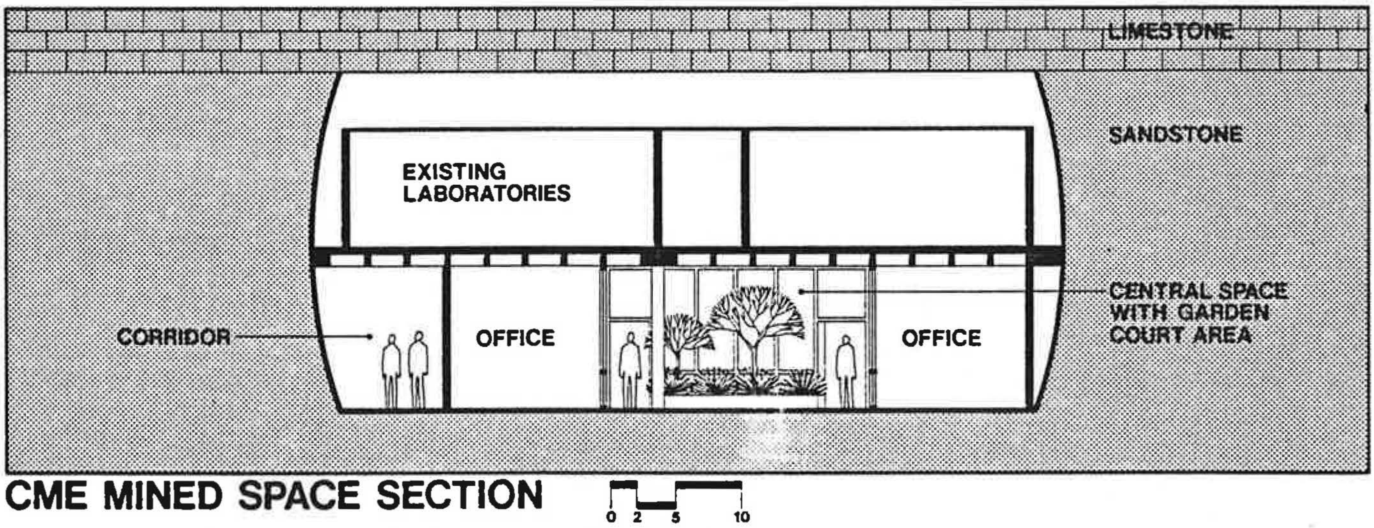

Figure 3. Section of the planned mined space expansion of the Civil and Mineral Engineering Building.

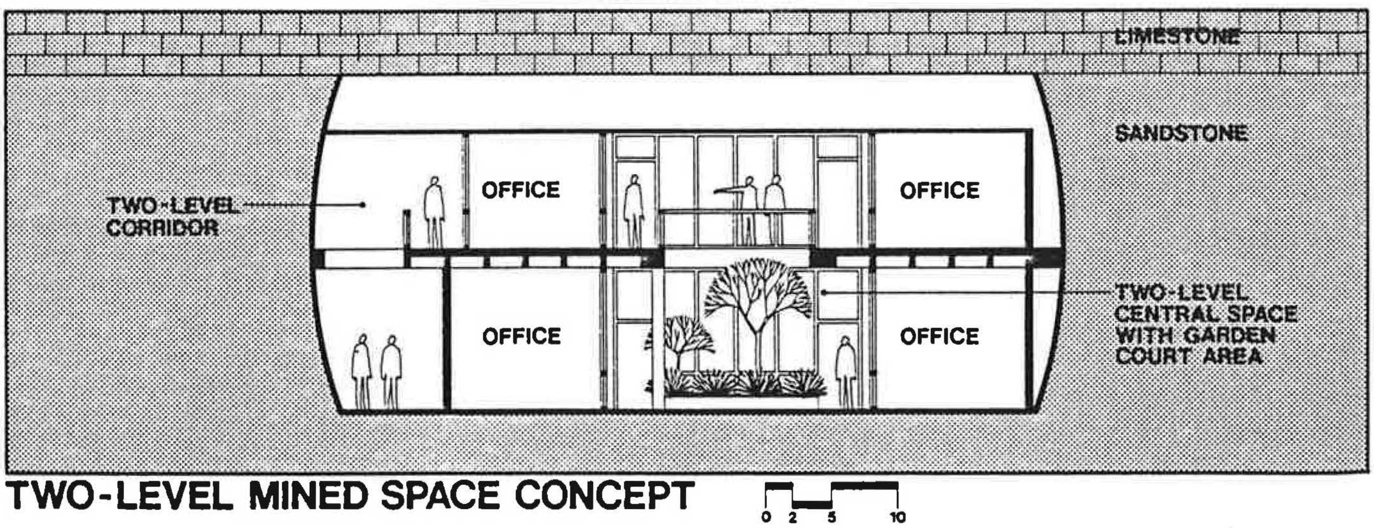

Figure 4. Plan of two-level mined space expansion.

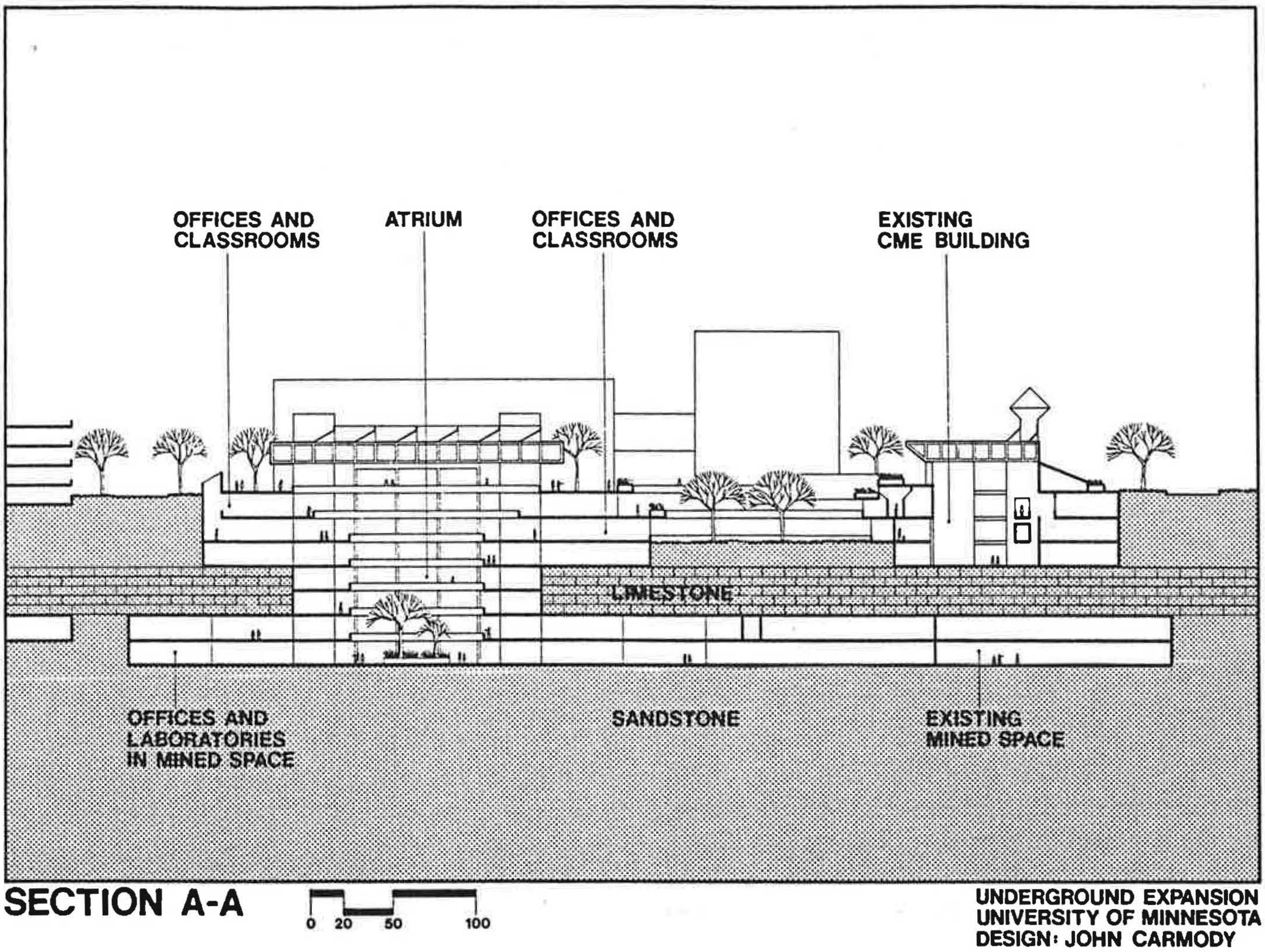

Figure 5. Section of mined space expansion plan for the Civil and Mineral Engineering Building.

ployed in the CME mined space to offset negative psychological reactions appears to work to some degree. Most strategies, such as high ceilings and glass partitions, are clearly successful and should be regarded as essential design elements. Other more experimental strategies, such as the solar optical lighting and the Ectascope, are only applied to limited areas and require further development, with application to a larger area, before their effects can truly be felt. Finally, future design of mined space can benefit from noting the occupants' behavior and reactions with respect to privacy, interior decoration, and suggestions for improvements.

Proposed Mined Space Design Projects

As a means of illustrating additional design strategies for mined space not fully explored in the existing CME Building, two proposed projects are shown here.

Completion of CME Mined Space

The first project is actually the completion of 10 000 ft² (900 m²) of unfinished mined space now existing in the CME Building. The area, located adjacent to the Underground Space Center, is limited to one level in height (see Figs 2 and 3). Several functions are combined in the proposed completion, including a computer modeling center with work spaces for faculty and graduate students; meeting rooms; a lounge; a large storage area; space for a specialized library collection; and additional office and laboratory space for the Underground Space Center.

The design is basically an adaptation of the successful design elements of the existing Underground Space Center offices. Ceilings remain high and glass partitions separate private offices from central lounge, library, and open plan office areas. The public corridor does not pass through the central open spaces. Glass walls at points along the corridor provide views into the reception and semi-public lounge area but not into private offices. Public corridor and office areas must also be separated for security and safety reasons.

An important element of the design is the garden court in the central area, which is to be densely planted and includes a small pool and fountain. A higher than normal level of lighting is suggested over this area to provide variety and simulate the appearance of a sunlit area. Although the central area actually includes several separate functions (library, garden court, open office and lounge), it is designed to be viewed as one large space divided by glass walls for acoustical privacy and security. From one end of the central space, a continuous view of about 30 m (100 ft) is possible, and the garden court area can be seen from most points in the complex.

The remaining unfinished space in the CME mined space is limited to one story in height since laboratories already exist on the floor above. If new mined space is created adjacent to the CME or elsewhere, opportunities exist to provide a greater sense of space and orientation with multi-level designs. As shown in Fig. 4, two-level central office spaces, garden courts or common areas are possible. In addition, opportunities exist to provide two-level spaces along the corridor.

Expanding Underground Facilities at the University of Minnesota

The University of Minnesota requires new facilities periodically on the

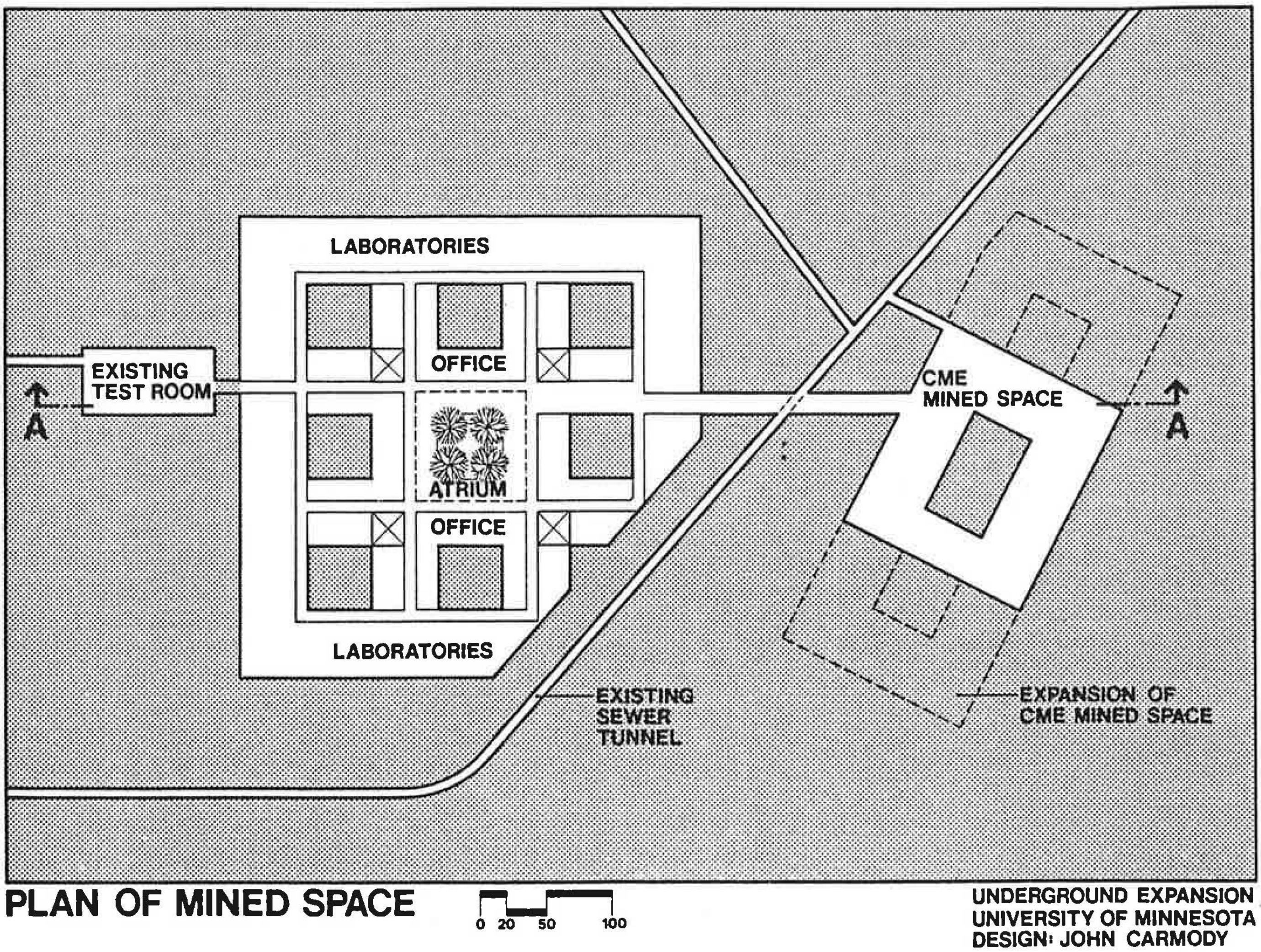

Figure 6. Plan of mined space expansion under the University of Minnesota campus.

Minnesota campus; however, available land area in the center of the campus is diminishing rapidly. In 1975, a planning study investigated the use of underground space beneath the campus to provide a large new source of centrally located space (Fairhurst et al. 1975). This study was one of several factors contributing to the construction of the Civil and Mineral Engineering Building in 1983 to demonstrate the concept of mined space development.

Now that the concept has been demonstrated, mined space continues to be viewed as a possible alternative for a variety of campus needs, including archive space, recreational facilities, isolated special laboratory spaces, parking, and other general uses such as offices, classrooms and conventional laboratories. If mined space is to be developed on a broad scale, comprehensive underground planning integrated with surface planning becomes important. With a large network of mined space, it also is important to consider major connections to the surface and much larger openings to provide entrance, spatial relief and orientation.

One opportunity to provide a major connection to mined space from the surface exists on the site immediately to the south of the CME Building. As shown in Figs 5 and 6, the site is large enough to accommodate a large central atrium extending 33 m (110 ft) down to the floor of the mined space. This space is comparable to many interior courtyards within new and renovated aboveground buildings. With fixed lenses and reflecting surfaces such as those used in the CME Building, sufficient natural light could be provided to the base of the courtyard where a large garden court is shown.

The 150 ft (45.5-m)-square opening required for the atrium is large enough to provide circulation and mechanical services for mined space extending far beyond the perimeter of the atrium itself. Such a large opening could serve as the major entrance to a much larger expansion of mined space that could be extended under a major portion of the existing campus. □

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