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Tempering Air with Tunnels: Full-Scale Tests and Design Dimensions

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The purpose of this project was to determine the effectiveness of subsurface ground tubes or tunnels that passively precondition air for efficient home heating. The designs for ground tubes were based on data collected empirically from a full-scale test and from a theoretical study. The investigation was conducted during a 10-day period of below-freezing temperatures. Air was circulated through an underground tunnel at a constant air flow rate, and rock and air temperatures were observed every four hours at instrumented stations along the tunnel from the portal intake to the exhaust outlet. From this empirical base, suitable designs were developed for ground tubes or tunnels to temper winter air for home heating. It was determined that a heat pump unit could be incorporated as an energy transfer device between the below-ground warmed air and the home heating system.

Even a few meters below the surface, the temperature of the ground exhibits a profile markedly different from the diurnal and seasonal readings that typify surface climatic changes. The earth tends to act as a thermal blanket. The low heat conductivity of either soil or rock slows changes in the temperature, so that at a depth of as little as 10 m an unfluctuating temperature is reached which characterizes the annual mean condition at a geographic location. Further, at shallow depths of two or three meters, conditions are tempered to the extent that variations of only a few degrees throughout the year are recorded. Gillies and Aughenbaugh (1981) observed air and ground temperatures at depth to quantify the damping effect that soil or rock cover has on fluctuating air temperatures. The placement of structures partially or fully underground is a method of making use of this natural insulation to achieve tempered or controlled environmental conditions throughout the year.

In a static environment in which little or no air enters or leaves an underground space, thermodynamic theory can be applied to predict closed-system psychrometric conditions. A number of studies have been done to verify these relationships empirically. Stauffer (1978), Lorentzen (1978), Boileau and Latta (1978), Warnock (1978), and Scott et al. (1984) observed the effects of heating or cooling underground rooms to maintain conditions above or below the ground virgin rock temperature.

In designing underground houses, however, some account must be taken of air movement from the outside. Positive ventilation is necessary to satisfy respiration requirements and, in hot, humid climates, to reduce the condensation of moisture on interior walls. The introduction of outside air changes the static environmental conditions within an underground opening. Significant flow rates of air directly into a dwelling at surface temperatures will cause much of the insulated advantage of the tempered environment to be lost. To overcome this dynamic change in conditions as the air moves, the surface air can be actively conditioned by using conventional, mechanically-operated cooling or heating equipment; or passive systems can be incorporated in an underground opening to assist or replace these units.

The passive system for tempering air involves passing intake air through tunnels or buried pipes before the air enters a subsurface dwelling. Contact with rock or earth pipe surfaces transfers heat and moisture to or from the surrounding surfaces and adjusts the temperature of the air to subsurface conditions. The present study was undertaken to examine the passive heating of air for winter home heating by using such a system. Although some of the concepts examined can be applied to the passive cooling of air for hot climates, this aspect was not comprehensively examined.

Akridge (1981) maintained that pas-

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sive cooling has been proved very difficult compared with passive heating. He affirmed that underground passive cooling techniques in hot, humid regions are not practical; the earth can provide sufficient sensible cooling, but the latent load cannot be adequately handled.

In the ventilation of deep mines, consideration has to be given to the transfer of heat from hot country rock as air is passed through tunnels to ventilate working stopes. Practical engineering criteria used in the design of such mine ventilation systems or, where necessary, underground refrigeration units can be applied to the tempering of intake air for subsurface dwellings.

To study the tempering effect of passing surface air along rock-lined passages, a series of tests were done using the ventilation system in a small, experimental mine in dolomite rock which is operated by the University of Missouri—Rolla. The test results were collated and compared with thermodynamic relationships and heat transfer equations. From this base, suitable designs were developed for ground tubes or tunnels to temper winter air for home heating. These designs led to a plan to incorporate a heat pump as an energy transfer unit between below-ground warmed air and a home heating system. Exercises were then undertaken for homes in three climatic areas of the United States and for various subsurface soil and rock conditions. The use of systems based on both open-flow, below-ground passages and closed-loop airflow paths were examined.

Experimental Procedure

The tempering effect of passing air through a rock tunnel was investigated by using the following in situ test procedure at the University's experimental mine.

A continuous airway was prepared. It was 185 m in length from the surface intake to a flow outlet located inside the mine. This continuous airflow path consisted of a 10-m length of vertical shaft, which was connected to a surface blowing fan and associated ductwork, and a 2-m-dia horizontal tunnel in dolomite. The air was forced to flow around a number of bends in the tunnel. The thickness of the rock and soil above the tunnel was approximately 10 m.

A variable-speed, vane-axial fan powered by a 15-kW motor forced air through the test airway. During the tests an air velocity of approximately 1.0 m/s was measured. This produced a quantity flow rate of a little over 4 m^3/s.

To evaluate the effects of changes in the psychrometric conditions of the air over a period of time, measurements were recorded for a 10-day period. During this time the air temperatures were recorded at regular four-hour intervals at surface and underground stations along the airflow path. Further, the airflow rate was checked regularly and the rock temperatures were recorded at the underground test stations. At these locations the rock temperatures were taken at depths of 25, 100, 300, 1,000, and 2,000 mm from the air/rock interface using previously-installed thermister temperature probes. All the tests were made at an approximately uniform flow rate. Fur-

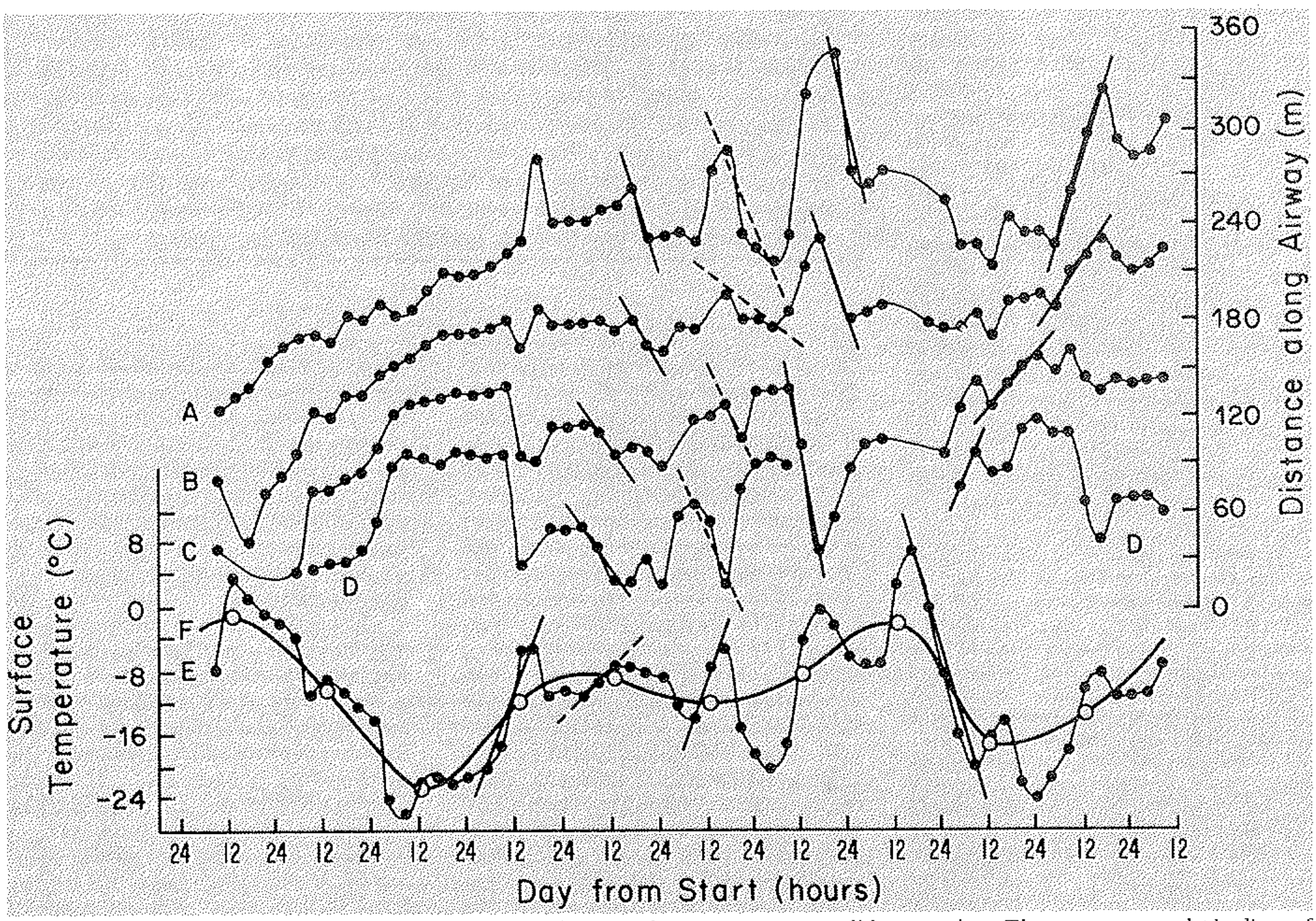

Figure 1. Study of airflow conditions. The lower curves depict surface temperature conditions vs. time. The upper curves depict lines of constant airway wetbulb temperature vs. distance along the airway. A: Distance of 10°C point from airway entrance. B: Distance of 5°C point from airway entrance. C: Distance of 0°C point from airway entrance. D: Distance of −5°C point from airway entrance. E: Outside air temperature at 4-hour intervals. F: Average daily outside air temperature.

ther details of the experimental test procedures are recorded in Smith et al. (1981) and Gillies and Aughenbaugh (1981).

Experimental Results

The University's experimental mine is not a producing mine. Ventilation fans are inoperative for most of the year and the natural flow of air through the workings is slight. Throughout the year the air temperature in the under ground passageways and the temperature of the rock (virgin rock temperature) are almost constant at about 13°C.

Conclusions drawn from test results are based on measurements taken over a 10-day period from 8 a.m. on January 8 to 8 a.m. on January 18, 1982. Interpretations of these tests are supported by data collected during three previous exercises performed in the summer, fall, and winter of the 1981–1982 academic year, when continuous measurements were made for two-and-a-half-day periods in each season. Results from these earlier surveys are reported by Gillies and Aughenbaugh (1981) and Smith et al. (1981).

Climatic Conditions during Testing

Surface air conditions throughout the data collection period were very cold and described by one newspaper as leading to the longest prolonged period of arctic weather of the century. Throughout the 240-hour study period temperatures were consistently below freezing, except for two short afternoon periods. At a number of times the temperatures were below −20°C. Some light snow fell on the fourth day of the tests; otherwise, conditions were dry.

A record of the outside surface temperatures is shown in Figure 1. Two profiles are set out in the lower section of the figure, the four-hourly observation line and the average daily temperature line throughout the period. The temperature profiles demonstrate both the diurnal fluctuations observed and a clear seven-day cycle in climatic pattern as cold air masses moved through Missouri. The study length was extended so that conditions could be recorded over more than one climatic cycle and any influence of cycle repetition noted.

Temperatures along the Airway

A formidable bank of data was collected from airway temperature measurements. In Figure 1 four line profiles are set down in the upper section which, as lines of constant wetbulb temperature for temperatures −5°C, 0°C, 5°C, and 10°C, demonstrate the distance along the tunnel for this temperature to be reached against time. The slanted straight lines on these profiles were used to calculate temperature lag effects; their relevance is discussed later. The constant temperature line profiles were compiled from observed readings and, where necessary, a calculated point extrapolated from the mouth of the intake portal or farther down an imaginary tunnel extending from the exhaust outlet. (As these extrapolated points caused some lines to cross, sections of the −5°C curve were omitted to avoid confusion.)

The 5°C curve shows the effects of cold air being pushed down a previously warm air tunnel. For the first three days of testing, the cold front was pushed down the tunnel a distance of about 175 m. After this adjustment period, the curve becomes level and is almost horizontal, with the fluctuations reflecting warming or cooling trends in the outside air. The average temperature of the surface air throughout the 10-day period was calculated to be −10.8°C. The air in the tunnel and the rock surfaces, after an adjustment period when the temperatures dropped from the virgin rock temperature of 13°C to an intake average level amost 24° lower, reached an equilibrium reflecting almost-constant heat flow from the interior of the rock mass.

In Figure 2 a typical relationship between the wetbulb temperature of the air and the station distance along the tunnel is shown. To minimize any effects of temperature adjustment lag the temperatures were averaged for a 24-hour period. The relationship line of fit is very close to linear, with a statistical least-squares deviation of 0.99. Because changes in wetbulb temperature are known from psychrometric theory to be directly proportional to the total energy levels (or approximately the enthalpy change level) of air, this relationship shows that the heat transfer rate from rock to air was constant along the tunnel length. The air in the tunnel throughout the study was at all times close to being fully saturated, and evaporation and sublimation of water (in floor puddles) and ice took place along the length of the airway.

Rock Temperatures

Temperatures of the rock mass surrounding the tunnel were recorded from previously installed probes sealed in boreholes. In Table 1 the average of the daily rock temperatures at a point 300 mm in from the surface of the rock is shown for each day and station location along the airway. From an initial rock temperature of 13°C the temperature dropped sharply for the first few days of stations near the air intake. After the first three days it can be seen that only minor changes occurred in the temperature and that these reflected the actual or lagged effects of surface warming or cooling periods.

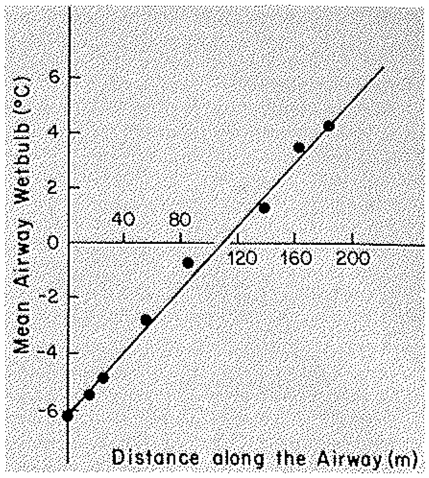

Figure 2. Graph of mean airway wetbulb temperature at various distances along the airway. Temperatures are averaged for the fifth day of study.

From the rock temperature data it was possible to calculate the depth to which the rock from the air-rock interface was not influenced by the cooling air flow. By using linear extrapolation, the depth was calculated from the averaged measurements for each day. In Figure 3 lines of best fit, which show the depth to the virgin rock temperature along the tunnel for each day as a function of distance along the airway, are given.

The rock mass envelope surrounding the tunnel was cooled by the moving air and increased in depth during the first three days of testing to a maximum of 2.0 m from the air-rock interface. In Figure 3 the intercept of each day's line with the horizontal axis of the graph shows the length of tunnel needed to condition air to the virgin rock temperature. The lines for the fourth to the tenth days lie very close together, with the position of each demonstrating an influence of the warming or cooling trends that prevailed in the outside surface temperatures. The crowding of the lines highlights the equilibrium that is reached when the rock mass envelope at the beginning of the tunnel is cooled to an average depth of about 2.5 m (2.9 m if one considers an isolated daily value). Extrapolation shows that a tunnel of about 280 m in length would fully temper the air under these conditions.

The equilibrium situation established reflects the influence on the rock mass of an average temperature

Table 1. Average daily rock temperatures (°C) at a point in the rock 300 mm from the air-rock interface at recording stations along the airway.

Station Location Along Airway	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
16 m	7.4	3.0	1.5	1.7	1.1	0.9	0.8	0.8	−0.5	−0.1
26 m	8.1	4.8	2.9	2.8	2.8	2.1	2.5	2.6	1.3	1.6
56 m	10.3	7.7	7.1	5.9	5.7	5.0	5.4	5.0	4.6	—
85 m	10.2	8.5	7.3	5.7	5.9	4.5	5.0	4.4	3.4	4.2
108 m	11.9	9.9	8.8	7.1	6.7	6.0	6.3	5.6	4.5	5.4
140 m	13.0	12.4	12.2	9.4	9.0	7.8	8.5	8.1	7.3	8.0
185 m	11.7	10.7	10.7	8.4	8.2	7.7	7.6	7.4	6.5	6.7

throughout the period of −10.8°C. As previously mentioned, the study was undertaken during a period of unusually cold winter weather; it is rare for prolonged below-freezing conditions to last more than a few days, even in mid-winter, in central Missouri. Cold periods are normally followed by warm days of above-freezing temperatures, and this warmer air flowing along a ground tunnel or tube reduces the heat energy flow from the rock and the depth of the zone of cold rock surrounding the tunnel. Analysis of the ground passage system throughout the year would demonstrate that, while the enveloping layers of rock are cooled in winter, the reverse energy flow path direction is seen in summer, with hotter airflow warming the surrounding rock. This seasonal variation assures similar operation of the system for all seasons.

Under the severe weather conditions experienced during the tests, a comparatively stable rock temperature profile in the envelope was developed after a short period. The conclusion is that the test measurements defined experimentally the maximum depth of temperature-affected rock that is likely to be measured after either a prolonged period of very cold weather or, at the other extreme, after abnormally hot summer temperatures. The less extreme air temperatures of spring and autumn have a less dramatic impact on the rock. In examining the effects of air temperature change throughout the year, it is considered that the rock temperature depth determined experimentally and discussed in the conclusions drawn from results in Figure 3 defines the maximum zone of influence appropriate to seasonal air temperature fluctuations which could be expected to occur in the area.

Air Temperature Lag

Daily and cyclic surface air temperature fluctuations were reflected in temperature changes at distances along the tunnel. In Figure 1, straight lines of constant slope have been drawn on the surface air curve where pronounced or sudden temperature changes occurred. These changes are related to the temperature increases or decreases which occurred along the tunnel by the slope lines on the −5°C, 0°C, 5°C, and 10°C constant-temperature curves in the upper part of the figure. The constant-slope lines have been plotted in different configuration styles so that one can identify the resulting change from a particular surface influence; resultant slopes of lines are of opposite sign to those recording surface changes. From these it can be seen that the effect of a surface temperature change lags as measurements are taken farther down the tunnel and in warmer air.

In Figure 4 the average time for a surface temperature change to be reflected in changes at points along the tunnel is plotted. The plot is shown as the lag time for a change to cause a movement in the line of a constant temperature. The relationship demonstrates that the lag has an approximately linear proportionality to the temperature increase. (The statistical deviation is 0.87.) It shows that a sudden change in surface temperature is felt much later farther down the tunnel, the lag being about 40 hours at a tunnel length where warmed air is at 10°C. For a system using the warmed air for domestic heating, this lag time has an advantage in that sharp, short cold spells in the climate will have passed before their effect is felt at the end of a tempering air passage.

The temperature lag effect has been further analyzed by comparing the slope of the line of resultant temperature change occurring along the air passage with the slope of the curve of surface temperature increase or decrease.

In Figure 5 the ratio of the slopes of the change lines, as opposed to the airway constant temperature curves, is shown. It can be seen that the rela-

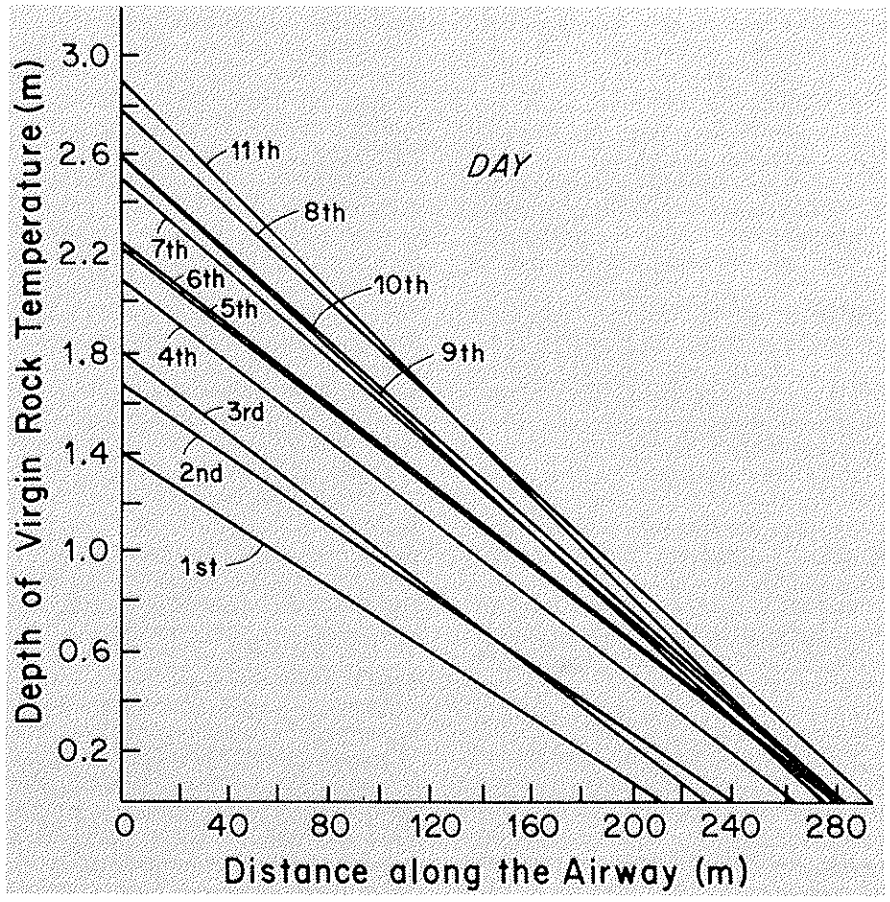

Figure 3. Plot of depth of rock layer surrounding the tunnel which was affected by cold air flow at various distances along airway for each day of study.

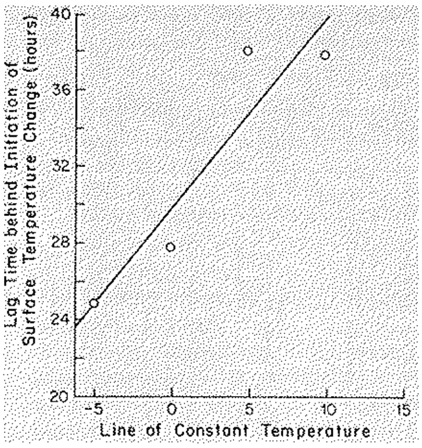

Figure 4. The lag time at points of constant temperature along the tunnel after surface changes have occurred.

tionship is almost linear, with a statistical deviation of 0.96, indicating that temperature changes within the tunnel occur at the same rate (although certainly not with the same magnitude) after a change has been initiated by the warming or cooling trends on the surface.

Analysis of Results

Having examined the data on air and rock temperatures within the tunnel system, it is of interest to assess the energy exchange process that occurred during the study in the ground tunnel system.

The Thermodynamic Balance Along the Airflow Tunnel

An examination of the energy changes demonstrates the existence of a number of heat transfer processes. To assist in understanding the characteristics of these processes, the energy exchange pathways were examined in an endeavor to quantify the magnitude of these changes.

Enthalpy of Air. Enthalpy is a measure of total heat or energy in a system. The enthalpy of air is readily calculated by measuring wetbulb and drybulb temperatures and referring to psychrometric charts or tables. Energy change as air passes through the passageway system is found by calculating the difference in enthalpy between intake surface air and outlet system air.

Energy Changes in the Air Mixture. Energy changes in an air mixture can be described in terms of the heat changes in its following components:

1. Heat change in dry air, or sensible heat change. This is quantified by multiplying an air mass flow rate by an air drybulb temperature change through the system and by the specific heat constant for air.
2. Heat change in water vapor. This is the energy required to superheat water vapor from the wetbulb to the drybulb temperature at a given point. Quantified, this energy level is negligible when air is at or near the saturation level. Because of this, it was not included in the study.
3. Heat to evaporate or condense water. Latent heat changes in an air mixture can be considerable and are quantified by multiplying the moisture mass change in the air passing through a system by the constant for water latent heat of condensation or evaporation. Throughout the study, some sections of the airflow tunnel were at subfreezing temperatures. With this condition, sublimation of moisture directly to a gaseous phase occurs from ice present on rock surfaces.

Calculations of air enthalpy changes along the tunnel were made for each set of station readings and daily average changes were obtained. The average energy changes in air for each study day are listed in Table 2, so that the air energy changes can be compared with the heat flow changes occurring in and from the rock mass. The increase in air enthalpy as flow occurred along the tunnel was calculated as an average value for each day; an average value for the 240-hour study period was found to be 152.1 kW.

Energy Changes in the Rock Mass. The total heat energy change within a rock mass can be ascertained by calculating the heat conducted from the extensive rock mass within which the tunnel is situated and adding this to the heat energy lost from the rock envelope. The rock heat energy flows to the cold air of the tunnel through the process of convection and radiation. For these energy change calculations the airway was divided into 10-m increments and the depth to the virgin rock temperature was calculated. For determining the conduction of heat energy the following formula was used (the symbols are defined in Appendix A):

$$\Delta E_c = \frac{K \times A \times (T_m - VRT)}{r} \quad (1)$$

The calculated values for each 10-m increment were added to find the total heat flow along the length of the tunnel. In Table 2 the average heat flow value for each day is listed. To determine the amount of heat energy lost by the cooled rock envelope, the following formula, which incorporates a rock-specific heat constant, was used:

$$\Delta E_{SH} = C_{PR} \times \frac{(VTR - T_m)}{2} \times RM \quad (2)$$

As before, the calculated values for each increment were added to find the total energy change for the tunnel. This energy value represents the total heat removed from the rock envelope surrounding the tunnel from the beginning of the test; to ascertain the heat change for the day under review, the difference between the average energy levels for two successive days was determined. The calculated value for each day of the test is listed in Table 2. It can be seen that in three instances the heat change was recorded as a negative value. This indicated that a warming trend in surface air temperature produced a lower energy level change in the rock layer than previously.

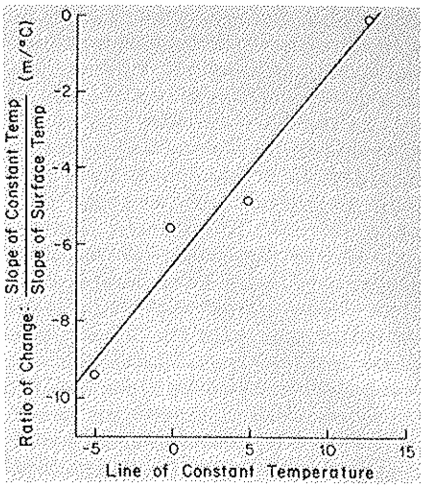

Figure 5. Ratio of the average rate of temperature change within the tunnel and the rate of change of the surface air.

Energy Changes Within the Tunnel Water. Cold air flowing along the tunnel caused water lying on the floor to form sheets of ice, and water seeping from cracks in the rock created icicles and frozen cascades. A significant ice sheet was formed at the forepart of the tunnel; as the tests progressed it increased in thickness to a maximum of 0.3 m. With an estimated 6,000 kg of ice formed by the end of the tests, the average heat energy flow from the system as latent heat of fusion was calculated to be 2.3 kJ/s, or 2.3 kW.

Comparison of Thermodynamic Balance Results

Examination of the system's energy levels demonstrates an extremely good correlation between results. The levels of energy change in the air varied from day to day throughout the test in response to the surface climatic conditions and, as noted in Table 2, produced an average daily change of 152.1 kW. The heat that caused this change came from a number of sources. The rock heat flow varied on a daily basis, depending on the tunnel temperature. Calculations show that the total energy flow from the rock mass averaged 145.9 kW throughout the test. Heat extracted from water lying in the tunnel averaged 2.3 kW. The quantifiable heat flow from all these sources amounted to 148.2 kW, which is 97.5% of the recorded change in the air energy level. The discrepancy in the energy flow balance can be explained by shortcomings in the techniques of measurement, recording, and interpretation, and the validity of the results may have been affected by inaccuracies in the experimental procedures in a number of cases:

1. Reading accuracy was at a level of 0.2°C for temperatures and 0.5 m^3/s for airflow levels.
2. No account was taken of the fact that the airway was not uniformly smooth and straight.
3. Calculated average values were made from data interpolated (and on some occasions extrapolated) from experimental readings. In all cases, linear relationships were assumed in deriving lines of best fit.

Correlation between the results from the tests is excellent considering the experimental conditions under which the tests were made.

Heat Flow in Underground Mine Airways

Although both empirical and theoretical studies have been conducted in many countries to learn more about the heat transfer process and to develop mathematical formulas appropriate to the mining industry, adverse environmental conditions in the South African gold mining industry have led to considerable research concerning heat flow into mine ventilation airways. Two approaches which have received considerable attention, the Goch and Patterson approximation and the Whillier and Ramsden formula, are discussed in Appendix B.

Table 2. Calculated energy change values for each day. Energy flow was from the rock to air along the length of the airway.

Date (1982)	Heat Conducted from Rock (kW)	Heat Energy Change in Rock Envelope (kW)	Total Energy Change in Rock (kW)	Energy Change in Air (kW)
January 8	43.0	125.9	168.9	159.5
January 9	72.1	138.6	210.7	173.7
January 10	97.4	171.8	269.2	200.7
January 11	85.6	98.3	183.9	138.8
January 12	69.2	−13.4	55.8	126.5
January 13	72.1	75.4	147.5	137.4
January 14	59.9	34.2	94.1	123.2
January 15	49.7	17.2	66.9	98.7
January 16	61.2	231.0	292.2	153.2
January 17	66.3	−44.3	22.0	118.2
January 18	55.1	−107.1	−52.1	91.4
Average change per day	73.2	72.8	145.9	152.1

Preconditioning Air for Home Living Space

To harness the advantages of preconditioned air systems for the ventilation of either above-grade or subsurface building space, two approaches are proposed.

1. Air from the outside is either passed through a buried pipe or rock-lined tunnel and blown directly into a building's duct system, or forced through a heat pump unit which transfers the energy to the building ventilation system.
2. A closed-circuit buried pipe or tunnel system is developed for continuous air passage. A heat pump placed in the passageway extracts or dissipates heat from the air and transfers the energy to the building. Air in the continuous passageway will never reach the extremes of temperature induced by surface climate, but will react to the load placed on it by the heat pump and will transfer energy to or from the ground mass.

The system using outside air blown directly into a building has the advantages of simplicity and low operating cost. Power costs to run a small fan are not high; but there are also a number of disadvantages:

- The length of the pipe or tunnel would have to be considerable if the air were to be suitably conditioned in periods of extreme climatic conditions.
- In most climates a large airflow along the pipe would be needed to provide sufficient energy to heat or cool a house. Because the air would have to be exhausted from the house, draughts would be created.
- With a suitable system, air can be tempered to a temperature approaching virgin rock temperature. Further heating or cooling with a mechanical plant would be necessary to bring conditions to suitable interior comfort levels.
- Odors, muskiness, and dampness from the tunnel would be brought into the building.

Heat pump systems overcome many of these problems, as they can separate a building's air system from that in the buried pipe or tunnel. The pipe lengths in a closed circuit system can be made much shorter and the pipe diameters diminished. Power to operate a fan would be needed, but in a closed system, because the pipe length would be shorter, the reduced wall friction on the moving air would lower the power costs as well as the cost of running the heat pump. Heat pump energy efficiency, which is the electrical power needed compared to the energy output, is stated as the coefficient of performance (COP). For systems operating across a low temperature difference, this is typically 2.5–3.0, or an efficiency of 250–300%. Heat pumps operate very inefficiently in extremely cold weather and need auxiliary heating boosters, but they are ideal for tempered air conditions under steady flow. The principal disadvantages of using a heat pump in either an open or closed circuit system are the capital, power, and maintenance costs of operating a mechanical unit, and the lack of fresh air brought into a building.

The costs of using a heat pump can be more than outweighed by designing a closed-circuit system in which the excavation costs for the pipe are markedly reduced. Fresh air intake into an above-ground dwelling would generally not be a problem, although a special intake for underground dwellings would have to be considered.

Design Requirements for a Dwelling

The results from the present study were gathered for the purpose of developing a design for preconditioning pipe or tunnel systems that would be attached to domestic dwellings, and calculations were made to establish the heating load conditions. In performing the calculations, the following assumptions were adopted.

1. The building to be heated would be a domestic dwelling with 140 m^2 of enclosed floor space.
2. The house construction would incorporate modern insulation, with a heat loss of 85 W/°C (530 BTU/hr – °F).
3. The velocity of the air along the pipe would be 1.0 m/s.
4. A heat pump unit would be placed at the end of the air passage to regulate the heat entering the dwelling and to allow the occupant to vary the heat to desired interior temperature levels.

The specification of the design parameters for this exemplary dwelling have been influenced by the dimensions of a model used by Bartlett (1979) in his study of the application of heat pump systems to the heating of a central Missouri home.

The Heat Pump

The heat pump is a year-round air conditioning system which can be used for both winter heating and summer cooling. The operational efficiency of a unit (COP) depends on the temperature difference between exterior and required interior conditions. The COP is defined as follows:

$$COP = \frac{\text{Unit Thermal Power Output}}{\text{Electrical Power Input}} \quad (3)$$

There is a linear relationship between the COP and the outside temperature, T_o. This relationship was described by an anonymous author in 1981 as follows:

$$COP = 0.0306T_o - 2.279 \quad (4)$$

In a domestic heating cycle, the refrigerant of a unit absorbs energy from the air flow source in the evaporator and passes it to the condensor stage located within the dwelling, where it dissipates. In locations where winter source temperatures are low, refrigerants with low boiling points (such as refrigerant 764 sulphur dioxide) are used.

The Heating of Domestic Dwellings

From the study of airflow heating under severe winter conditions in the experimental mine at Rolla, it was found that approximately 150 kW of heat energy were picked up by an airflow of 4 m^3/s along a 185-m tunnel length. The average outside surface temperature during the ten days of study was –10.8°C, while at the end of the tunnel the equilibrium temperature averaged 3°C and had a range of plus or minus 2.5°C, reflecting the fluctuations in the outside temperatures. For comparison with round section tunnels and pipes, the mean hydraulic diameter of the experimental tunnel was calculated to be 2.25 m.

Domestic heating power design requirements are factors that vary from place to place for the so-called standard home. It has been ascertained by Mazria (1979) that a plant with a capacity of 10 kW is adequate for the winter heating of a standard Missouri home. Although the efficiency of a conventional surface heat pump used alone to heat in winter is very low, a unit placed at the end of a tunnel long enough to adjust the air temperature to 10°C would provide for efficient operation. The unit placed at the end of the tunnel used in the study warmed the air to 10°C. This unit had a COP of about 2.5. The average temperature of the air passing across the evaporator unit was 6°C, and the inlet air was cooled from 10°C to 2°C as it passed across the exchange fins. A cooler outlet temperature would, of course, be possible, but the problem of frost formation on fin surfaces would be increased.

To supply the designed heating load of 10 kW for a Missouri home, a heat pump operating with a COP of 2.5 over the above-mentioned temperature range would draw 4 kW of electrical power while transferring 6 kW of heat from air in the tunnel. The water-saturated air in the experimental tunnel, in cooling from 10° to 2°C, released some 85 kW of energy, or enough heat for a maximum of 14 home heat pumps.

The above calculations were made by using data from an open tunnel system. If a closed system were to be used in which the air, on leaving the pump evaporator fins, were to be recirculated, then a shorter length of tunnel could be used to heat air to 10°C and increase the air enthalpy by 85 kW. Such a tunnel would be about 105 m long.

In most circumstances, it would be more practical to incorporate smaller pipe systems in the design of individual houses than for groups of houses to be tied to one large system. With individual pipes, the diameters and sizes could be tailored to the particular needs of a given house. The maintenance of an air flow velocity of 1.0 m/s through an individual tunnel produces an air quantity of 0.30 m^3/s, which is sufficient for heat absorption. Proportionality equations indicate that the pipe diameter necessary to pass this quantity of air through would be 0.62 m.

These calculations were made from assumptions based on empirical data collected in a system where the air picked up moisture as it moved down a tunnel and thus remained in a saturated or near-saturated condition. Within a closed-air system in which water ingress from surrounding rock could be eliminated by sealing, saturated air would not be present throughout the system. Air passing across the heat pump evaporator fins would be condensed with resultant cooling, and the humidity of the air on leaving the unit would be that of saturated air at a cooler temperature. The air would be recirculated through the system, and in successive passes through the heat pump there would be less condensation from the drier air.

Less energy is needed to heat or cool unsaturated air than saturated air within the same temperature range. With regard to the design calculations of a Missouri home, unsaturated tunnel air with a dew point of 2°C would absorb 3.15 kW of energy while increasing the temperature from 2°C to 10°C, or about half the energy level of air exposed continuously to free water. In this situation, an earth-tempering air system would have to pass about twice the flow rate of air through to achieve the same change in energy level; if air velocity were to be held constant, the pipe diameter would have to be increased.

General Energy Transfer Equation for Ground Tunnels

Because the energy flow characteristics of an underground air tunnel and the results from the present study were used to quantify the design parameters specifically for a home in Missouri, it was found necessary to develop a general equation from these results to ex-

Table 3. Design conditions for the study locations.

Location	Rolla, Mo.	Birmingham, Ala.	Freeport, Ill.
Ground VRT	13°C	17°C	10°C
Winter average minimum design temperature	–18°C	–7°C	–28°C
Design domestic heating power	10kW	7kW	12kW

plain the energy exchange phenomenon in other geographic locations. This general equation is a function of a number of factors, including (1) the psychrometric properties of the air and the level of its saturation; (2) the geographic location, climate, and virgin rock temperature of the area; (3) the thermal properties of the rock and soil, and the levels of ground water; and (4) the ground pipe system and the characteristics of the heat pump unit to be used. Because the general equation itself is very complex, its derivation is not given here. The equation is the heat demand ΔH_A divided by the product of $\pi(T_R - T_M)$ and the following term:

$$\frac{2K}{(r_o^2 - r_i^2)}[r_o(r_o + d) - r_i(r_i + d)] +$$

$$\frac{\rho C_{PR}}{6\pi}[r_i(r_i + r_o + 2/3d) + r_o(r_o + 3/2d)]$$

The design of an underground air system for average dwellings in locations other than Missouri was developed on the following basis, and the results were calculated by using the general equation. The accuracy of the design was compared with the results obtained with the formula developed by Goch and Patterson (see Appendix B). Specifications are given for the pipe diameter and length of a system that would be buried deep enough so that the temperature variation from the geographic annual mean would be at a minimum. To ascertain the operation of the system under different conditions, the following situations were examined.

1. Calculations were made for two situations: one in which the air entering the heat pump evaporator would be fully saturated, such as in an open-pipe system or wet conditions; and the other for a sealed, closed system in which the air would have a relative humidity of 50%.
2. Three U. S. continental locations were selected as sites for study: Freeport, Illinois, where winters are very cold and summers are mild; Rolla, Missouri, where moderate winters and summers are prevalent; and Birmingham, Alabama, where winters are mild and summers are hot. The information of the ground virgin rock temperatures, winter climate (given as the average temperature on the coldest winter day), and the design requirements for the heating requirements of a dwelling in these three locations are given in Table 3.
3. Analyses were made of the different subsurface materials. Commonly occurring rock and soil types were examined, and average thermal characteristics as determined by Clark (1967), Toulonkian and Ho (1981), Nichols (1976), and Winterkorn (unpublished notes) are listed in Table 4.
4. Determinations were made for systems in which (a) air would be passed through an open-circuit passage and blown through a heat pump unit to facilitate energy change before being exhausted to the atmosphere; and (b) air would be recirculated through a closed system with a heat pump unit placed within the airflow path.

Design Dimensions for a Domestic Ground Air Tube System

Design dimensions for an air system suitable for an average-sized, well-insulated home were calculated and tabulated as follows.

1. Table 5 gives calculated values for an open-circuit system in which air enters the heat pump unit at 10°C. Ground conditions are wet and the system air is saturated.
2. Table 6 give calculated values for an open-circuit system in which air enters the heat pump unit at 10°C. The system is sealed from the ground and is dry. Air enters the unit at a relative humidity of 50%.
3. Table 7 gives calculated values for a closed-circuit system in which air enters the heat pump unit at 10°C and exhausts at 2°C. Ground conditions are wet and the system air is saturated.
4. Table 8 gives calculated values for a closed-circuit system in which air enters the heat pump at 10°C and exhausts at 2°C. The system is sealed from the ground and is dry. Air enters the unit at a relative humidity of 50%.

Interpretation of Design Dimension Calculations

Examination of the calculated results emphasizes the following points.

The diameter of a system is a function of the extent of the air path cross section that is necessary to allow the required heat energy to be absorbed by the air mass flow while a constant velocity (1.0 m/s) is maintained. In cold climates or in open-circuit systems for which energy requirements are increased, large-diameter systems are required to increase the air mass flow and its energy-carrying capacity. Dry air of low relative humidity exhibits a lower enthalpy level than saturated air; therefore, large-diameter air paths are needed to maintain the energy-carrying capacity of the system. The design diameter sizes that have been calculated are for minimum conditions; increasing sizes should allow for some discrepancies in domestic heating load or air saturation levels.

The length of the ground pipe or tunnel is a function of both the required air temperature change and the thermal properties of the surrounding rock or soil. Again, the length dimensions are for minimum conditions, and any additional length incorporated in a system should allow some margin. However, once the air temperature increases to the virgin rock temperature, no further increase would occur; and any additional length would not increase the benefits.

From the above discussion, it is clear that the diameter and length of a system are largely independent functions; increasing one dimension to compensate for a reduction in the other would not, in general, allow sufficient energy absorption for any particular situation. When the dimensions that are obtained for pipe lengths by using the derived general equation are compared with the Goch and Patterson approach, it is found that the results correlate very closely. The average discrepancy is 2.75%, but the maximum discrepancy for any one location can be as much as 14.07%.

The results emphasize the size dif-

Table 4. Average thermal characteristics of various subsurface materials.

Material	Conductivity (W/m – °C)	Specific Heat (kJ/kg – °C)	Density (kg/m³)
Dolomite	2.23	0.882	2,607
Granite	3.34	0.863	2,666
Sandstone	2.40	0.996	2,310
Sandy Soil (dry)	1.79	1.194	1,926
(moist)	1.79	1.141	2,015
(wet)	1.79	1.078	2,133
Clay (compact, dry)	1.85	1.320	1,742
Loam (dry)	2.00	1.850	1,244
(moist)	2.00	1.438	1,600
(wet)	2.00	1.152	1,997

ferences in pipe diameters and lengths of closed-circuit and open-circuit systems. The open systems require dimensions that are of sufficient size to handle extremes in climatic conditions, although the lag times in temperature changes along the air paths reduce the impact of short periods of adverse weather. The air energy changes which are needed are accommodated by increased volumetric flow through the tube lengths. Pipe lengths for the coldest weather of Freeport would need to exceed 400 m for the various soil types. These lengths are, however, impractical for normal residential use. On the other hand, those calculated for closed-circuit systems require lower volumetric air flows, and most of the systems have dimensions that are compatible with the sizes of normal building lots. Some lend themselves to burial beneath the outer walls of excavated basements.

Care would be needed in the layout of a system to ensure that the effects of interference from other sections of the ground-tempering air path or parallel branches would not adversely affect results. No system branch should be placed closer together than twice the maximum radial length of the rock envelope, to avoid overtaxing the stored energy of the surrounding rock.

Results from this empirically-based study demonstrate that the design calculations for a pipe system are complex, and the cost of investment in a suitable subsurface system is not low. However, the potential for obtaining long-term savings from the installation of a carefully planned system are apparent, and the installation of test units to determine long-term operating characteristics is warranted.

Summary

When air moves through a rock-lined passageway, temperature changes take place as heat energy is exchanged between the air and the rock mass. To obtain a better understanding of this process, an in situ study was conducted to monitor and record the changing conditions of regulated airflow at various locations along a 185-m passageway in dolomite rock. The investigation was conducted during a 10-day period in January of 1982.

From the recorded data, a determination was made of the rate of change in air temperature and in moisture as outside air was circulated through the passageway. The temperature changes which occurred in the surrounding rock as the result of the energy exchange between the rock and the air were also identified. The thermodynamic balance of the system was calculated, and the results of the study were compared with results obtained with empirical and theoretical methods used in deep-mine air-cooling investigations conducted in South Africa.

Once the conclusion had been reached that the model accurately represented the heat energy flow phenomenon in an underground airflow tunnel, calculations were made to develop design dimensions that could be used in planning air-tempering systems for homes in different locations with various subsurface geologic conditions. Ground pipe dimensions for the different situations were calculated using an empirically derived general formula. These were compared with results from a theoretically-based formula developed by Goch and Patterson for use in the underground mining industry. Correlation of the results from both techniques proved to be excellent.

Table 5. Design dimensions for an open-circuit ground pipe or tunnel system carrying saturated air that is passed through a heat pump unit for three U.S. locations and varying subsurface materials.

Ground Material	Freeport, Ill.			Rolla, Mo.			Birmingham, Ala.		
	Diameter (m)	Length (m) I	II	Diameter (m)	Length (m) I	II	Diameter (m)	Length (m) I	II
Dolomite	1.38	392	405	1.33	309	337	1.33	247	242
Granite	1.38	292	328	1.33	225	251	1.33	172	177
Sandstone	1.38	372	420	1.33	292	315	1.33	232	226
Sandy soil (moist)	1.38	453	518	1.33	363	395	1.33	300	284
Clay (compact)	1.38	444	501	1.33	354	382	1.33	292	270
Loam (moist)	1.38	422	479	1.33	335	364	1.33	273	252

I As calculated with the derived general equation
II As calculated with Goch and Patterson's general equation (Appendix B)

Table 6. Design dimensions for an open-circuit ground pipe or tunnel system carrying 50% relative humidity air passed through a heat pump unit, for three U.S. locations and varying subsurface materials.

Ground Material	Freeport, Ill.			Rolla, Mo.			Birmingham, Ala.		
	Diameter (m)	Length (m) I	II	Diameter (m)	Length (m) I	II	Diameter (m)	Length (m) I	II
Dolomite	1.55	380	377	1.51	297	314	1.61	229	—
Granite	1.55	283	311	1.51	217	233	1.61	159	178
Sandstone	1.55	361	394	1.51	281	297	1.61	214	225
Sandy soil (moist)	1.55	439	483	1.51	349	366	1.61	278	274
Clay (compact)	1.55	430	472	1.51	341	354	1.61	270	269
Loam (moist)	1.55	409	446	1.51	322	338	1.61	252	259

I As calculated with the derived general equation
II As calculated with Goch and Patterson's general equation (Appendix B)

Table 7. Design dimensions for a closed-circuit ground pipe or tunnel system carrying saturated air passed through a heat pump unit, for three U.S. locations and varying subsurface materials.

Ground Material	Freeport, Ill.			Rolla, Mo.			Birmingham, Ala.		
	Diameter (m)	Length (m) I	Length (m) II	Diameter (m)	Length (m) I	Length (m) II	Diameter (m)	Length (m) I	Length (m) II
Dolomite	0.73	185	167	0.66	68	63	0.56	33	31
Granite	0.73	133	130	0.66	48	47	0.56	24	24
Sandstone	0.73	175	159	0.66	64	59	0.56	31	30
Sandy soil (moist)	0.73	220	193	0.66	78	72	0.56	39	37
Clay (compact)	0.73	215	186	0.66	78	70	0.56	38	36
Loam (moist)	0.73	202	180	0.66	74	67	0.56	36	34

I As calculated with the derived general equation
II As calculated with Goch and Patterson's general equation (Appendix B)

Table 8. Design dimensions for a closed-circuit ground pipe or tunnel system carrying 50% relative humidity air passed through a heat pump unit, for three U.S. locations and varying subsurface materials.

Ground Material	Freeport, Ill.			Rolla, Mo.			Birmingham, Ala.		
	Diameter (m)	Length (m) I	Length (m) II	Diameter (m)	Length (m) I	Length (m) II	Diameter (m)	Length (m) I	Length (m) II
Dolomite	0.83	175	153	0.75	64	57	0.64	31	29
Granite	0.83	125	117	0.75	46	43	0.64	22	22
Sandstone	0.83	165	147	0.75	60	54	0.64	30	28
Sandy Soil (moist)	0.83	207	177	0.75	76	66	0.64	37	30
Clay (compact)	0.83	202	173	0.75	74	64	0.64	36	33
Loam (moist)	0.83	190	164	0.75	70	61	0.64	34	31

I As calculated with the derived general equation
II As calculated with Goch and Patterson's general equation (Appendix B)

It was found that the ground pipe dimensions which are needed to temper air before it is passed through a heat pump unit are compatible with the size of normally-sized building lots in sites where mild winter conditions are experienced. It was also found that a closed-circuit system offers the greatest economy in excavation cost. Dimensions calculated for an individual residence located in a severe winter area were found to be somewhat impractical for the system constraints studied. Further investigation into the economics of using a heat pump unit, which operates at low air inlet temperatures, is warranted. Communities in the northern latitudes may find it advantageous to utilize a common large-diameter tunnel system for tempering air for a number of residences. □

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References

Akridge, J. M. 1981. Indirect earth cooling techniques. *Proceedings, Earth Integration for Cooling Seminar.* Oklahoma State University.

Anonymous. 1981. *Heat pumps—work book.* EDP Company.

Barenbrug, A. W. T. 1967. The battle of the B.T.U.'s *Journal of the Mine Ventilation Society of South Africa.* February.

Bartlett, A. A. 1979. Temperature setbacks and energy savings in buildings heated by heat pumps. *Transactions, American Society of Heating, Refrigerating and Air Conditioning Engineers.* Part II.

Boileau, G. G., and Latta, J. K. 1978. Calculation of basement heat losses. *Underground utilization.* University of Missouri—Kansas City.

Clark, S. P., ed. 1967. *National Research Council physical constants of rocks.*

Gillies, A. D. S., and Aughenbaugh, N. B. 1981. Passive air-conditioning: flow through rock-lined tunnels tempers air. *Underground Space* 6:2, 114–118.

Goch, D. C., and Patterson, H. S. 1940. The heat flow in tunnels. *Journal of the Chemical, Metallurgical and Mining Society of South Africa.* September.

Hemp, R., and Deglon, P. 1980. A heat balance in a section of mine. *Proceedings, Second International Mine Ventilation Congress. University of Nevada, Reno.*

Lambrechts, J. de V. 1967. Prediction of wet-bulb temperature gradients in mine airways. *Journal, South African Institute of Mining and Metallurgy.* November.

Lorentzen, G. 1978. The design and performance of an uninsulated freezer room in the rock. *Underground utilization.* University of Missouri—Kansas City.

Mazria, E. 1979. *The passive solar energy book.* Professional edition. Rodatic Press.

Muksonov, N. Kh., and Kurenchanin, V. K. 1973. *Analytical calculation of heating of the air in a mine by heat from the solid rock.* Academy of Sciences of the USSR. June.

Nichols, H. L. 1976. *Moving the earth.* North Castle Books.

Scott, N. R., Cooke, J. R., Round, R. H., Koehler, T. A., Parsons, R. A., and Mahan, K. D. 1984. Analysis of earth-air heat exchange. *Proceedings of the American Solar Energy Society, 1983.*

Shcherban, A. N., and Chernyak, V. P. 1969. *Procedures for thermal calculations of mine air.* Academy of Sciences of the Ukrainian USSR. July.

Shcherban, A. N., Dobryanskii, Yu, P., Travkin, V. S., and Pugach, N. P. 1976. *Nonstationary heat exchange with the rocks around a working.* Academy of Sciences of the Ukrainian USSR. October.

Smith, D. J., Orlandi, W. T., and Gilles, A. D. S. 1981. Airflow cooling in rock lined tunnels. *Transactions, Missouri Academy of Science.*

Starfield, A. M. 1966. Tables for flow of heat into a rock tunnel with different surface heat transfer coefficients. *Journal, South African Institute of Mining and Metallurgy.* December.

Starfield, A. M., and Dickson, A. J. 1967. A study of heat transfer and moisture pickup in mine airways. *Journal of the South African Institute of Mining and Metallurgy.* December.

Stauffer, T. 1978. Efficiency in the use of energy has been effected through industrial use of subsurface space. *Underground utilization.* University of Missouri—Kansas City.

Steyn, J. H. 1980. The use of mid-shaft cooling in the Strathmore Shaft System, Buffelsfontein Gold Mining Company Limited. *Journal of the Mine Ventilation Society of South Africa.* March.

Touloukian, Y. S., and Ho, C. Y. 1981. *Physical properties of rocks and minerals.* New York: McGraw-Hill.

Warnock, J. G. 1978. New industrial space—underground: thoughts on cost/benefit factors. *Underground utilization.* University of Missouri—Kansas City.

Whillier, A., and Ramsden, R. 1976. Sources of heat in deep mines and the use of mine service water for cooling. *Proceedings, International Mine Ventilation Congress, The Mine Ventilation Society of South Africa, Johannesburg.*

Winterkorn, H. F. No date. *Notes on soil-heat relationships.* Unpublished.

Zilberbord, A. F., Kornienko, N. D., Vasilev, A. A., and Ladyzhenskii, I. L. 1977. *Measuring the moisture content of the rock around an underground structure.* All-Union Scientific-Research Institute of Hydrogeology and Engineering Geology, Moscow. January.

Appendix A: Symbols

A	Area of rock surface surrounding incremental length of tunnel envelope cone at time of VRT (m^2)
A_T	Area of incremental length of tunnel walls (m^2)
AGE	Age factor for airway used in Ramsden equation (years)
CF	Correction factor used in Ramsden equation (dimensionless)
C_{PDA}	Constant pressure specific heat of dry air (kJ/Kg-°C)
C_{PR}	Constant pressure specific heat of rock (kJ/kg-°C)
d	Diameter of airway tunnel around pipe or tube (m)
d.b.	Drybulb temperature (°C)
ΔE_A	Heat energy change in air (W)
ΔE_c	Heat energy conducted from rock (W)
ΔE_R	Heat energy change in total rock mass ($\Delta E_c + \Delta E_{SH}$ (W)
ΔE_{SH}	Heat energy change in rock envelope surrounding tunnel (W)
K	Rock conductivity factor (W/m-°C)
M	Mass flow rate of dry air (kg/s)
m	Moisture content in air (kg/kg)
P	Perimeter of tunnel (m)
r	Rock depth to line of VRT (m)
r_r	Radius vector from center of tunnel (m)
T	Temperature (°C)
T_M	Mean airway air temperature at a point (°C)
T_R	Airway rock surface temperature (°C)
VTR	Virgin rock temperature (°C)
w.b.	Wetbulb temperature (°C)
WF	Wetness factor of rock surfaces for use in Ramsden equation (dimensionless)
x_l	Length of airway tunnel, ground pipe, or tube (m)
α	Thermal diffusivity constant for rock (m^2/s)
ε	Factor used in Goch and Patterson analysis (dimensionless)
λ_e	Latent energy of water evaporation (kJ/kg)
ρ	Rock density factor (kg/m^3)
τ	Time (s)
ω	Factor used in Goch and Patterson analysis (dimensionless)

Appendix B: Heat Flow in Underground Mine Airways

The Goch and Patterson Approximation

Goch and Patterson (1940) applied developed mathematical theory to the general problem of determining the flow of energy into a tunnel that penetrates a hot rock mass. Their method involves the use of tabled values that simplify the solution of the complex functions encountered in any rigorous solution of the heat conduction process.

To calculate the flow of heat across an air-rock interface, the tunnel is denoted as a circular opening of diameter d, in a rock mass of infinite extent at virgin rock temperature, VRT. At a certain time τ, the temperature T_R of the tunnel wall is suddenly changed to T_{Ro} and is afterwards maintained at this value. The form of the Fourier equation for conductive heat transfer, expressed in cylindrical coordinates, that is appropriate to the problem is:

$$\frac{\partial T_R}{\partial \tau} = \alpha \left(\frac{\partial^2 T_R}{\partial r_r^2} + \frac{1}{r_r} \frac{\partial T_R}{\partial r_r} \right) \quad , \qquad \text{(B-1)}$$

in which r_r is the radius vector (the radius from the center of the tunnel to the point in the rock where the temperature is being determined) and α is the thermal diffusivity of the rock. Diffusivity (in m^2/s units) is a function of other thermal and physical properties of the rock and is found by using:

$$a = \frac{K}{\rho^C PR} \qquad \text{(B-2)}$$

The solution of the conductive heat transfer Fourier equation must satisfy both the initial and boundary conditions as follows: (1) when $\tau = 0$, then $t = T_{ro}$ for $r_r > d$; and (2) when $r_r = d$, then $\tau = \tau_o$ for $\tau = 0$. The integral functions giving the temperature inside the rock at any time and at any distance from the cylindrical boundary and the rate of heat flow across a unit area of the boundary surface were developed by Goch and Patterson. The mathematics involved is complex, and they presented approximate numerical solutions in tabular form. When applying values from their table, the dimensionless term ε is calculated when

$$\varepsilon = \frac{\alpha\tau}{(d/2)^2} \qquad \text{(B-3)}$$

Application of the Goch and Patterson approach to data collected during a study of heat flow while air flows along a dolomite tunnel leads to the following calculations:

$$\alpha = \frac{K}{\rho^C PR}$$

$$\frac{2.268 \text{ (w/m} - {}^\circ\text{C)}}{2770 \text{ (kg/m}^3) \times 0.825 \text{ (kj/kg} - {}^\circ\text{C)}} \qquad \text{(B-4)}$$

$$= 1 \times 10^{-3} \text{ m}^3\text{/s}$$

and

$$\alpha = \frac{\alpha\tau}{(d/x)}$$

$$= \frac{1 \times 10^{-3} \text{ (m}^2\text{/s)} \times 240 \text{ (hours)}}{(1.125)^2} \qquad \text{(B-5)}$$

$$= 0.190$$

The total rock heat flow per unit area into the tunnel (W/m^2) is given by:

$$\frac{\Delta E_R}{A_T} = \frac{2K (T_R - T_{Ro}) \omega}{d} \qquad \text{(B-6)}$$

Therefore,

$$\Delta E_R = \frac{2P \times 1K (T_R - T_{Ro}) \omega}{d} \qquad \text{(B-7)}$$

in which χ_l is the tunnel length. The factor ω is found from the Goch and Patterson tables as a dimensionless unit.

For the study data, $\omega = 1.749$; therefore:

$$\Delta E_R = 8 \text{ (m)} \times (185\text{m}) \times 2.268 \times$$

$$(\text{W/m} - {}^\circ\text{C} \times 23.8^\circ\text{C} \times 1.749) \qquad \text{(B-8)}$$

$$= 124 \text{ kW}$$

The temperature factor ($T_R - T_{Ro}$) is taken as the difference between the virgin rock temperature, 13°C, and the average air intake temperature, −10.8°C.

Comparison of the Goch and Patterson results for energy flow with those calculated from the mine data demonstrates reasonably good correlation in the prediction of heat flow changes. Comparing the average heat flux level of 124 kW with the 145.9 kW calculated from the study reveals only a 15% discrepancy.

The Whillier and Ramsden Formula

Whillier and Ramsden (1976) proposed a formula for calculating heat pick-up along mine airways. This formula was used successfully by Hemp and Deglon (1980), Steyn (1980), and others to determine the heat load on mine refrigeration units.

The relationship adopted for the present study was developed from practical observation and has been found to agree with earlier approximations advanced by Lambrechts (1967) and Starfield (1966). The Ramsden equation takes the form:

$$\Delta E_A = 5.57\,(WF + 0.255) \times (VRT - d.b.)\,CF \quad \text{(B-9)}$$

In this equation, air heat change is calculated in kW per 100 m of airway length, d.b. is the air drybulb temperature, WF is a special airway surface wetness factor (0.0 for completely dry and 1.0 for very wet surfaces), and CF is the correction factor for airway size, airway age since excavation, and type of rock.

In application, the formula requires certain assumptions. First, the wetness factor is estimated subjectively. In designing mines where ground water is prevalent it is possible to estimate very wet conditions rather closely. During the present study, it was apparent that some ground water entered the airway through fissures in the surrounding rock, and the floor area was invariably wet. For much of the time, exposed water along the tunnel was frozen, and ingress of ground water was slight. Although some moisture was being evaporated by the airflow, prediction of an appropriate wetness factor was difficult. Secondly, a correction factor can be applied to account for (a) airway sizes that vary from the normal South African dimensions of about 3.0 m by 3.0 m; (b) airway age of the surrounding rock, which has cooled as a result of heat liberation over time; and (c) rock type for which the thermal characteristics vary from those of quartzite, which is the country rock surrounding the gold reefs mined in South Africa.

Although the application of size and thermal property corrections is fairly straightforward, the decision as to an appropriate age factor is more difficult. In spite of the fact that the airway used for the present tests was excavated many years ago, the relevant question is: Has there been any change in the rock mass temperature since the beginning of the tests and the time of excavation? The rock mass temperature as recorded was initially at or close to the annual mean temperature; consequently, an average age factor for the study period was taken as half the study duration time, which was five days. By incorporating the appropriate values in the correction factor formula, the following was developed:

$$CF = (P/12)^{0.437} \times (AGE/3)^{-0.147} \times (K/5.5)^{0.853} \quad \text{(B-10)}$$

In which P is the perimeter of the airway in meters, AGE the age of the airway in years, and K the thermal conductivity of the rock, W/m°C. The solution gives a factor for the tests of CF = 0.86.

The Ramsden equation can be applied to the test results once an objective estimate has been made of the airway wetness factor. With average test results for the period, the formula yields an air heat energy level change for an estimated WF = 1.0 of 135 kW and for WF = 0.25 of 52.3 kW. Any results of the formula is highly sensitive to the wetness factor. Although the heat flow values calculated on the basis of very wet airway surfaces yield results that compare favorably with measurements taken during the study, the complicating influences of surfaces covered by ice (a condition not accounted for in the equation) affects the results in such a manner that they must be treated with suspicion.

The Ramsden equation does not appear to be an appropriate tool for predicting heat flow changes for those situations where the wetness of airways is not characteristic of the hot and humid conditions of the South African gold mines. Effective use of the equation depends on an accurate estimation of the degree of rock surface wetness. Although it is difficult to make this estimate, the equation does emphasize the pronounced effect that abundant available water in an airway has on the energy exchange rate. Other authors, in particular Barenbrug (1967), Lambrechts (1967), Starfield (1966), and Starfield and Dickson (1967), have developed techniques or models describing heat flow into mine airways. These studies were undertaken primarily to quantify the mine ventilation problem facing the South African gold mining industry; however, each approach depended on the investigator's assessment of the wetness factor appropriate to his particular situation.

From a review of some of the South African studies, the Goch and Patterson approach appeared to provide a general model which could be used to describe the thermodynamic relationships in the air tunnel being studied. Other investigations which have been oriented to specific mining industries do provide predictive techniques that are simpler to apply than the general model, but they have limitations occasioned by the requirements of their individual input factors. For this reason, the Goch and Patterson model was selected to assist in interpreting the results obtained from the study and in formulating designs for home air tempering systems.

Other authors, including Muksonov and Kurenchanin (1973), Zilberbord et al. (1977), Shcherban et al. (1976), and Shcherban and Chernyak (1969) have proposed models, but their approaches are mathematically complex and are directed toward specific European mining problems and thus have limited application to the present study.