COVERED NORTHERN TOWNSHIP

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ABSTRACT

Most of the Canadian population live within 200 miles of the USA border. When work is available further north in the country, this often means that members of families are separated from each other for long periods of time because the adverse climate does not tempt people to resettle either temporarily or permanently. The idea of creating a 35-acre township under a pneumatically supported transparent membrane was studied, and this paper describes the environmental conception and design of a township for 2000 residents with commercial and social support activities. Besides identifying the criteria, basic systems of heating,ventilating, and lighting were planned. The importance of residents seeing as well as thermally sensing the sun is discussed, including a review of current flexible membranes that are suitable for the snow and the wind conditions of northern Canada.

INTRODUCTION

Covered townships and cities were considered by Frei Otto for Arctic regions in the 1950s and for New York by Buckminster Fuller in the 1960s. In order to modify and temper the harsh climate of an area in northern Canada, it was proposed to enclose a landscaped township under a 35-acre 60 metre high pneumatic structure. The township was planned for 2000 dwellings with associated commercial, leisure, and educational facilities. The tempered environment has been designed to provide a pleasant enjoyable area of contrast for people to work and live in without the disadvantages of the climatic extremes yet in a space which has no sense of enclosure. An alternative solution was also investigated using a series of individual tent structures large enough to house 300 to 500 people.

HUMAN RESPONSE TO A LARGE-SCALE ENVELOPE

It is proposed to enclose not just a shopping mall or an office complex but an entire community including 2000 residents within a single envelope. The experience of living within such an environment is unique, and the effects of that experience, as yet, are unknown. There is a considerable difference between visiting an enclosed environment for a specific purpose and actually living and working there with relatively short visits to the outside world. Although it is technically possible to maintain the environment within such a structure at a comfortable temperature, to design the lighting with great care, and to ensure a plentiful supply of fresh, clean air, the question still remains: how will people feel about spending most of their time living inside a totally enclosed structure? Will there be psychological effects, which, in the longer term, will make such a situation untenable?

As well as being totally enclosed, this township will be different from most ordinary centers in a number of other respects. It will be physically isolated from a climate that can be extremely hostile. It may be a partial "new town" and the work opportunities would be dominated by a

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single, large employer. Although these factors are not unique, experience has shown that each can be the cause of serious social dislocation if not anticipated and tackled immediately after the town is occupied and begins to grow. In the past one of the main objections to company towns, or boom towns built rapidly to exploit a mineral resource, has been that they are unimaginatively designed and often occupied by a very limited cross section of the population. The proposal to enclose the center of this township in a dome may be seen as a response to these problems at two levels. First,it provides a comfortable, well-designed environment that protects the residents throughout a harsh winter and thus is of immense practical value. Second, it performs a symbolic function and is telling the world at large that this township is not just another "boom or bust" resource community - it is somewhere where the needs of a wide population are catered for in a humanistic and imaginative way.

Peoples' reactions to any environment are not just a response to the prevailing physical conditions. They are to a large extent determined by the expectations of that place and the kinds of activities available for work and leisure while there. It is also worth remembering that there is never a common perception of a particular environment. In the environmental sense, one man's meat can very well be another's poison. Thus the planned enclosed environment, while functioning perfectly in the engineering sense, could be seen in two quite different ways. If looked at positively, it is something that modifies a harsh climate in order to allow civilized life to proceed at an alien northern latitude, a function it carries out in an extremely elegant way. If looked at negatively, it might itself be seen as an alien object placed in a wilderness area of great beauty, an example of man's domination of the natural environment. From the inside it could be felt to be cutting the inhabitants off from the outside and to be denying them the opportunity to keep in touch with the natural world through the cycles of the seasons and vagaries of the daily climate.

Clearly there is no way to predict all the differing views the population has or will have of the enclosing structure. However, there are some ways in which the design of the dome, the social organization of the project, and the presentation of the whole can positively help in the acceptance of this innovative idea. In design terms the dome can be constructed so that those who live inside see it as a kind of filter, something that keeps out the negative aspects of the natural environment while letting through the positive. Thus the environment within the dome becomes a modified version of that outside rather than a totally sealed and conditioned enclosure. Visual contact is maintained with the climatic conditions outside the dome, and it is possible to see the sun and the clouds and to sense changes in the daily skyscape. The social organization of the community is also of crucial importance with respect to the way in which the dome is used and perceived. Those most at risk in terms of the psychological effects of living within the dome are clearly those who occupy the housing units within it. Perhaps the most important issue here is that of choice. If those who live within the dome do so from choice and provided they know that should they wish they could find suitable accommodation elsewhere, then their perceptions of the dome are likely to be much more positive than would otherwise be the case. This question of choice relates to a more fundamental question of how much freedom the residents are to be allowed in the organization of the community once it is formed. If this Northern township is really going to differ from earlier resource communities, then a high level of authority must be reflected in there being real choices available about how they plan the future of their town.

The environment affects individuals in several ways. Physiologically, heat, light, and sound, besides smell and taste, are sensed by receptors and the signals are relayed from them along the nervous system to the brain. From here psychological factors participate in the response because, leaving aside genetic make up, the experience of the individual has imprinted patterns of behavior in different situations. There are associations between present and past situations that condition the mind. The reactions to some environmental factors are summarized in Table 1.

Most of the information from the environment is acquired by visual means, but the auditory sense also plays an important part in dimensioning the world about us. Light, sound, and smell have associations for an individual that may recall pleasant or unpleasant memories. Some factors impinge on the human system in a more direct way. Air quality is important because it takes the most direct path from outside to inside the body via the lungs and the bloodstream. Ions in the air, for instance,are breathed in and have their effect amplified by electrostatic induction at the lung interface.

The other major senses are concerned with an awareness of space and of people and from these arise an admixture of basic needs within the contexts of place and people. The idea of inside and outside, with the expectancy of the constraints they offer, is probably inborn. Nature seems to have a basic call to everyone to some extent; even city dwellers like to dash off to the country. Wide bands of temperature change and air movement, the sounds of the sea or rustling leaves are all part of an innate need to experience the full range of nature, which is only blunted ultimately by fear of the unexpected that can be so easily induced by darkness or by extreme climatic conditions.

The social needs of man are variable but fundamental. The idea of a community enclosed by a structure in a cold northern climate offers major advantages that relate closely to the quality of life of the people living and working there. An "intermediate" or meso environment is created between the buildings and the outside world within a natural landscape. This can be enjoyed by people throughout all the seasons without the need for heavy clothing because the climate will be mild. The energy requirement of the buildings within the covered township will be decreased because the heat losses from the buildings will form part of a closed-loop thermal feedback system (see Figure 1). The structure will also act as a large-scale solar collector.

The construction of the internal buildings will be less stringent in terms of thermal insulation because any heat emission from the buildings contributes toward the intermediate climate. On the other hand, the need to retain a natural sound field will have some effect on the layout and formulation of the facades of the individual internal buildings themselves.

These factors will only be advantageous if altogether other conditions prevailing on the occupants are balanced and satisfactory.

* The envelope must not give a sense of enclosure due to restriction of view, buildup of heat, smell, or noise. Several factors including claustrophobia and safety need consideration to ensure a feeling of security at all times.

* Natural lighting is essential for plants as well as people. The quality as well as the quantity of light is a prime requisite.

* There must be sufficient contrast between the intermediate environment and the internal environment of the buildings. The sense of "going out" must remain.

* It is essential that there is a wide range of social activities catering to the day and night routines of people. Their scope will be enlarged since the problems of very low temperatures in the center do not occur.

* The visual and auditory perceptual systems in particular should be able to respond to a natural environment in a natural setting, which permits a balanced plant-animal ecological cycle.

If these conditions can be met, then the space will be a successful achievement enhancing the quality of life for people who have come to work in this region.

Light

In the dome light is the principal way in which the space is perceived as "open" to the outside world. For this reason consideration must be given to the effect the envelope will have upon the lighting within the structure. In general, the greater the amount of light incident upon a scene, the brighter it will appear. Because of the unequal response of the eye, the spectral distribution of the light will partly determine the brightness of a scene, but this effect is minor compared to changes in brightness occurring during the winter/summer and day/night cycles. Changes in the color of daylight resulting from changes in spectral distributions are certainly apparent, but the visual system can adapt to a wide range of spectral distributions.

In recent years more attention has been paid to the nonvisual effects of radiation, and, although there is evidence that the total deprivation of this type of radiation may be detrimental to people already suffering some ill health, there is no firm evidence that where people are deprived of daylight for long periods, the use of full spectrum lamps to supplement UV radiation improves health or well-being. Considering the spectral response curves for these nonvisual physiological effects, it is clear that they are primarily in the UV region; and in northern latitudes, where there is little natural UV in the winter, any deficiency in the exposure to UV would be best provided by the use of solariums.

There is tentative evidence that spring fever in northern latitudes may be linked to the color of daylight in conjunction with the low illuminances and short days in winter. Visual fatigue in such circumstances may be reduced by ensuring adequate views out and side lighting within buildings. Although the length of day is known to adversely affect people, whether or not the effect is physiological or purely psychological is unclear.

In any interior the view out is of prime importance for a number of reasons: it provides contact with the external world, and it provides information about the passage of time and allows visual escape from the interior. Coupled to this experience is the perception of space, and within small interiors windows are an essential element in creating an adequate impression of space.

Where there is a physical barrier, such as a structural frame or mesh material, to hinder a view out, certain points must be considered. Loss of visual detail will be increased by a higher mesh luminance, increased solid/void ratio, and increased size of mesh. Also, where the frequency of the grid is near to that of the detail seen through the grid, there may well be confusion and loss of information. Further, there may be disturbing patterns similar to optical illusion effects under certain frequencies and proportions of grid patterns.

The minimum discernable detail depends upon the form of detail, and the eye is particularly sensitive to long continuous lines in the visual field. It is therefore unlikely that any grid will be fine enough to remain totally unobserved, although at a height of 60 metres it will be almost undiscernable.

In defining the quality of the visual environment it is important to distinguish between translucent materials, which allow light to pass through but scatter it and prevent focussing; opaque materials, which do not transmit light; and transparent materials, which allow the eye to focus through the surface on objects outside because the light retains its directional quality.

Translucent surfaces emit light equally in all directions and display high scatter; consequently, the vector/scalar ratio is very low at all times, whereas transparent ones exhibit low scatter and have a high vector/scalar ratio.

The membranes comprising the dome structure should be transparent so that the spectral quality of daylight is retained, the vector/scalar illumination is high (i.e., low scatter), and the light transmission is high. Materials can be affected by dirt, but some new membrane materials are self-cleaning.

Thermal Conditions

The acceptable range of temperaturedepends on the activity and hence the metabolic rate, the air velocity, and the insulation value for the body, taking into account the clothing, and may be calculated from: $\theta = 37 - M\,(0.12 + 0.6R_C)$ where R_C is the clothing resistance, 1 clo being equivalent to $0.155\ m^2.^{o}C/W$; M is the metabolic rate in W/m^2. Using this equation, Table 2 shows that for a dome globe temperature above $0^{o}C$, there is a substantial reduction in the clothing needed to carry out outdoor leisure or sporting activities . The range of sporting activities can be extended beyond the usual cold climate ones, which may be important if people are coming from the southern parts of this region.

An important advantage of using a tempered intermediate space is that people are protected from the wind, because in very cold weather the dominant factors affecting heat loss from a person are temperature and wind speed. The rate of the cooling of the skin surface at $33^{o}C$ is expressed by the windchill index (WCI) thus:

$$WCI = (10\sqrt{\nu} + 10.45 - \nu)\ (33 - \theta)$$

for a wind speed ν(m/s) and air temperature $\theta^{o}C$ giving WCI in $kgcal/m^2h$. The subjective ratings shown in Table 3 are for Arctic explorers in suitable clothing.

More recent work has derived the windchill equivalent temperatures shown in Table 4; this gives the temperature at which a windspeed of 2.23 m/s would give equivalent cooling.

This work on windchill equivalent temperature suggests that the maximum velocity within the dome should be in the order of 2m/s so that there is no windchill effect at any temperature. Inside buildings the air velocity needs to be only 0.1 m/s to avoid stagnation, but within the dome there should be more contrast in the air motion because small-scale random turbulence patterns are a part of "fresh' atmospheres. Another reason for advocating higher air velocities is because the metabolic rate for many outdoor activities is more than that for indoor occupations and the perspiration rate increases. Light breezes make these conditions more acceptable because the velocity over the body promotes convective cooling.

Ventilation covers a wider range of needs than air movement because it is required to provide fresh air in addition to recirculated air to dilute odors, smells, and other pollutants; provide free cooling in summer; redistribute heat between the upper stagnation and lower occupancy zones; provide some control of moisture, decreasing it in winter but increasing it in summer; introduce an outside level of atmospheric ions into the dome, which is another desirable constituent of "fresh" atmosphere; and provide smoke removal in the case of fire. Ventilation provides the most effective way of controlling air quality, and limiting pollution, but it costs money to install and operate fan systems and space requirements also tend to be large. In the case of pneumatic structure there is a need to pressurise the space, and this air can be used directly for supplying the fresh air requirement. Other economies can be effected by recovering heat from the fan motors and by recirculation of air within the space and to the ventilation supply systems.

In the night when there are 2,000 residents there is 70 m^2 of space per person; during the day when there are 10,000 people in the dome, the space availability is 14 m^2 per person. This means that, using the normal ventilating system standards, the intermediate space should have 0.5 fresh air changes per hour but inside the buildings this ventilation rate should be increased to 1.0. The summer ventilation rate is higher to assist in limiting heat gains.

Since the occupancy of local areas of space is different as well as variable, the ventilation requirements should be designed to be adjusted accordingly to maintain both fan efficiency and the quality of the local environment. Management of the envelope space must ensure that local rates of ventilation are controlled to appropriate levels. Variable air volume systems permit the airflow rate to be adjusted as the simultaneous peak zone load patterns vary. The relative humidity should be allowed to be as high as possible in summer (up to a maximum of 60%) and as low as possible in the winter limited by comfort (40%) and condensation criteria; in this way there will be a small saving in the energy needed to cool and dehumidify the air. A summary of the principal design criteria is given in Table 5.

CHOICE OF MEMBRANE MATERIALS

The options considered were: fluorocarbon coated glass cloth; glass fiber grid weave laminate; transparent reinforced fiber; mineral glass; rigid thermoplastic.

Comparison of the spectral transmission curves demonstrates that certain lightweight foils transmit appreciably more UV than glass or thermoplastic. They also transmit in the low infra-red range and so prevent build up of heat in summer.

Because of the low altitude of the sun in winter and the paucity of sunshine, it is necessary to make the most of what daylight is available and provide an envelope that transmits as much light as possible. The fluorocarbon coated glass cloth construction transmits only 5.5% of the light as a totally diffuse source. Glass and thermoplastics have a similar transmission curve to the foils but have the advantage of being optically clear. The foils, though nearly transparent, display a slight haziness.

The modeling of objects by light and the exploitation of the variability in daylight are both seen as essential in providing an environment that is sufficiently interesting to people who may stay within the dome for some length of time. Modeling can be measured by the ratio of direct light to diffuse light. A diffuse sky produces even lighting flattening three-dimensional form, whereas directional light casts shadows. Natural daylight is diffuse on overcast days but when the sun is out is strongly directional. To get this degree of variety in the dome, the roof should be as transparent as possible. The foil option best satisfies these criteria. The additon of a glazed wall ensures a view out and a feeling of contact with the outside.

PREDICTION OF TEMPERATURE IN THE INTERMEDIATE SPACE

The equation of thermal equilibrium of the enclosed space has on one side heat gains from solar radiation and from heat inputs into buildings from lighting, cooking, machines, and people. On the other side heat is lost through the membrane by conduction, convection, and radiation and by mass transfer from cold air being introduced into the space and warm air leaking out. The mass of building structures and paving materials within the space plays an important role in storing the solar heat gains, thus delaying the temperature rise and reemitting the heat when the temperature falls.

It is not intended that the temperature within the space should remain constant. In winter it will fall, but if necessary heat will be added to maintain the temperature slightly above zero. In summer heat will be rejected by high rates of ventilation to limit the maximum temperature (see Figure 2).

Ideally the excess heat gain would be stored and re-used in the colder periods. This can be done on a daily basis using reversible heat pumps to heat or cool the buildings and storing the heat in water, but it is probably impractical on a monthly or annual basis.

The thermal equilibrium is a dynamic situation in which temperatures and heat flows vary continuously and in addition many of the variables are interdependent, so an exact calculation of temperature requires a dynamic computer model that is run iteratively. Here a quasi-static procedure has been used in which the daily mean is first calculated followed by swings from this during the day. The temperature calculated is the dry resultant temperature at the center of the space.

Thermal Gains

The total solar energy entering the dome was calculated from the 21st day of each month using values of direct and diffuse radiation for clear skies. The transmission through the membrane took into account the angle of incidence of the sun's rays on each surface. The results are plotted in Figure 2. Radiation factors for cloud were found by comparison with measured values of radiation on a horizontal surface.

The heat exchange from internal buildings was calculated by consideration of the heat transfer through walls and windows and by ventilation exchange. The temperature of internal buildings was taken as 21°C in winter and 24°C in summer. The U value of walls was taken as 0.3 $W/m^2 \cdot {}^oC$; double glazing was taken as 25% of the external walls with a U value of 3.2 $W/m^2 \cdot {}^oC$. Gains from people within the space were also taken into account with a maximum number of 2000 people.

Heat Loss

The equivalent thermal transmittance (U value) was calculated by taking into account the radiation component and the surface resistances modified by air movement. The effect of passing outside air between two membranes was also calculated. In this model the outside air passing between the skins is warmed up by the heat from the enclosed space. Because the air temperature between the skins is reduced, the heat loss to the outside is reduced by about 20% in winter.

Mass Storage Effects

The effect of the mass of building walls, roofs, and paving surfaces is to store thermal energy and subsequently release it. This effect smooths out the daily swings of temperature, reducing the peaks. In the temperature calculations, 75% of the buildings were taken as heavyweight construction; the roofs and 50% of the ground were taken as paved.

Temperatures

The temperatures, which are plotted on the Graphs in Figure 3, were calculated using the above data and the ventilation rates shown on Figure 2. Those for the winter months show that on average days the nighttime temperature will remain at zero or a little above and the day temperatures will rise to comfortable maxima of 10 or 12°C. The curve for an extremely cold day in January calculated with the same ventilation and heating rate falls down to -20°C at night when the outside temperature is -41°C. This indicates that considerable amounts of additional heat will have to be put into the recirculated air at street level during very cold spells.

The curves for a typical March day indicate how the temperature will rise to uncomfortably high levels if winter rates of fresh air supply are maintained. The lower curve demonstrates how increasing the ventilation rate reduces the temperature; if the higher rate is only used during the day, then temperatures on the dotted line could be obtained.

The curves for a typical June day show a dramatic rise in temperature at midday even with full summer ventilation. Conditions at street level will be considerably different since large volumes of outside air are being supplied at outside temperature with plenty of movement. The cool air will tend to remain in the streets while the warm air rises. Shades and leaf canopies over the streets will reduce the radiant heat from the sun and hence mean temperature in the streets.

ENVIRONMENT OF ADDITIVE TENT

In many respects the environmental physics of the tent are similar to those of the air support structure. The major differences are the ability to support a large area of translucent insulated roof and the ease of natural ventilation at the perimeter.

A typical tent unit has a volume of 110,000 m^3 and a maximum height of five metres. Each unit is planned for a specific use together with accompanying landscape and recreational space and would be occupied by 500 permanent residents (22.00 to 07.00) and 2,000 people maximum during the peak daytime use (07.00 to 22.00). Because of the scale of the unit, exits are no further than 50 metres away.

Groups of tents are planned to break up the external airflow into local patterns and give a measure of shelter to internal courtyards.

Tents are very responsive to the external climate. In spring they accept sufficient light to enable satisfactory planting but reject high level solar radiation. In summer the insulated opaque part of the roof surface cuts off high altitude direct radiation, enabling the internal temperature to be held to around 26°C on hot days with the use of three air changes per hour. Since the opaque northern roof with high insulation ($U = 0.3\ W/m^2 \cdot {}^\circ C$) makes up two-thirds of the total surface, heat losses in winter to the outside will be considerably decreased so that average temperatures in the intermediate environment can remain above freezing without the input of any additional heat from natural heat losses from the internal building. Losses can be further decreased by the use of night blinds on the south-facing surfaces. In this way, the tent can be made approximately 30% more efficient than the conventional buildings in terms of energy usage, whereas the air structure is only 16% more effective (see Table 6).

The natural form of this structure (see Figure 4) enables any smoke generated by an internal fire to be convected upwards to the extract system at mast tops. Smoke can also be exhaled through additional smoke louvres incorporated in the north lighting roof surfaces above the buildings. In all other respects the envelope structure is safe within the intermediate space, provided internal spaces are sprinklered and all structural services have good flame spread resistance.

The shape and height are conducive to natural ventilation for parts of the year. The edges of the tent and louvres of the tree canopy in hot external conditions can be controlled via fly-screened open windows to increase the supply of fresh air to 100 m^3/s (three changes per hour) without creating draughts at the perimeter. Since there is no need for continuous supply of air for structural support purposes, in cold times it is also possible to minimize the supply of fresh air to the intermediate environment to only that required to eliminate build-up of smell (10 m^3/s).

The internal buildings will require their own ventilation intake, but this can generally be directly from the intermediate space. However, because of the large volume to perimeter of this tent form, the ventilation to the intermediate space will need to be augmented by small fans and air ducts to the interior capable of supplying up to 50 m^3/s via discreetly located sheet snorkels.

The load chart is shown in Figure 5.

Lighting

Although the tent membrane is translucent and hence the lighting has a diffuse character, the envelope contains a significant proportion of double glazing so that daylight and sunshine are plentiful. Solar heat gain is reduced considerably by using a 20% translucent membrane.

Lighting levels during the winter will be in the order of 3,000 lux at the south side diminishing to 2,000 lux minimum at the rear due to the opaque northern roofing surfaces. Glare in the summer will be prevented by this opaque cladding and by eliminating direct high angle solar radiation. At nighttime attractive diffuse low levels of street lighting can be created by back lighting of fair-faced ceilings from spots located on the roofs of the internal buildings.

COMPARISON OF ENERGY REQUIREMENTS

The total energy consumption of the center inside the air-supported structure is made up of:

1. the heat input to internal buildings in a moderated climate
2. the heat input to fresh air to maintain a minimum supply temperature at 0°C
3. the power consumed by all ventilation plants

The center under the tent also requires fans for supplying air to the buildings and for ventilating the streets in summer. Solar gain reduces the heat requirements of the membrane structures (see Figures 2 and 5).

The heat input to buildings during winter consists of fabric losses plus heating of fresh air. For the buildings in the enclosed environment, the incoming air has already been heated to 0°C, thus the heat requirement is taken as that necessary to raise the incoming air from 0°C to room temperature plus the fabric losses from room temperature to the intermediate environment.

The net heat supplied to the enclosed space is taken as the heat supplied to the incoming fresh air raising its temperature from outside temperature to 0°C, plus the heat supplied to recirculated air to maintain the temperature above 0°C.

Proportions of different ventilation rates were estimated from the temperature curves. The energy consumptions are given in Table 6.

The load charts shown in Figures 2 and 5 give the background to the figures derived in Table 6. The tent solution makes better use of solar gains in winter because of the large areas of glazing favorably orientated to the low-angle winter sun. The opaque parts of the tent form also limit the solar gain in summer. The air structure traps more solar gain in summer but less in winter. The double membrane is transmissive to longwave infrared radiation, hence the greenhouse effect is reduced.

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ACKNOWLEDGMENTS

This project was designed by a large team of people and the author acknowledges Frei Otto and his team; Community Pathfinders Limited; all his colleagues in Buro Happold and Bath University besides the many other consultants who offered advice, including W. Bird, J. Yates, J. Newby, D. Holt, E Van Dyke and P. T. Stone.

TABLE 1

Effects of Partial Climate

Partial Climate	Climatic Effect: Induces Organic Reactions	Stimulates Sensory Organs	Creates Assoc-iations	Describes the Environment
Light	*	*	*	*
Sound	*	*	*	*
Smell	*	*	*	
Heat	*	*		
Air Quality	*			
Electrical Climate	*			

TABLE 2

Clo Values for Different Globe Temperatures in the Dome Compared with Those Required Outside

	Metabolic Rate (W/m^2) (M): 100 (Walking/Shopping at about 3 km/h)	200 (Light walking at about 5.8 km/h)
	Clothing Insulation Values	
Winter temperatures in Dome		
$5^{o}C$	2.1 clo	0.85 clo
0	2.7	1.4
External Temperatures		
-20	4.8	3.5
-35	6.5	5.2

Note: Arctic uniform has a clo value of 4.0
Sporting activities have metabolic rates in the range of 270 W/m^2 (tennis) to 420 W/m^2 (squash)

TABLE 3

Subjective Response to Windchill Index

WCI (kgcal/m^2h)	Sensation
200	Pleasant
400	Cool
1000	Very Cold
1400	Exposed Flesh Freezes
2500	Intolerable

TABLE 4

Windchill Equivalent Temperatures

Actual Temperature (^{o}C)		Windchill Equivalent Temperature (^{o}C) Actual Windspeed (m/s) calm	5	10	15
Intermediate	0	1	-2	-7	-11
Space	-5	-4	-9	-13	-16
Average Exterior	-10	-9	-13	-19	-25
Space	-15	-13	-19	-26	-33
	-20	-18	-26	-34	-42
Extreme Exterior	-30	-28	-37	-50	-
Space	-40	-37	-50	-	-

TABLE 5

Principal Environmental Design Criteria

	MAN Winter	MAN Summer	PLANTS Winter	PLANTS Summer
External Design Temperature (exceeded 2½% of the time)	- 41°C	28°C		
Internal Mesospace	0 - 5°C	28°C	0 - 5°C (air)	15 - 20°C (air)
Internal Buildings	21°C	23°C	2 - 5°C (soil)	8 - 12°C (soil)
Absolute maximum temperatures	8°C (January)	35°C (July)		
Absolute minimum temperatures	- 46°C (January)	2°C (July)		
Mean daily temperature range	9.3 deg C (November)	14.6 deg C (June)		
Daylight hours	6 (December 21, solar altitude 11°)	19 (June 21, solar altitude 64°)		
Mean monthly sunshine hours	70 (January	200 (June and July)		
Annual sunshine hours	2100 with 70% cloud cover			
Solar radiation	6 $MJ/m^2 \cdot$ day	40 $MJ/m^2 \cdot$ day		
Solar collection tilt angle	58°	73°		
Degree-days	6778°C degree-days per year (base 18°C)			
Winds	W/SW April - May and September - October Mean speed 10-14 km/h: maximum speed 62-72 km/h			
Mesospace Relative Humidity	> 50% gives condensation		50 - 80% (> 60% saves water)	
Latent gain	Mainly from people		6 L/m^2 soil per week (Drip emitters reduce this to 1 L/m^2 per week)	20 L/m^2 soil per week
Light	Daylight spectrum with high vector-scalar ratio		Daylight spectrum 1000 - 3000 lux	
Sound	Free field: sound level depends on zone			

TABLE 6

Energy Consumption Comparison for Lightweight Membrane and Traditional Structures Assuming 24-hour Operation (Excludes Efficiencies of Generation and Transmission)

	Energy Consumption (GWh)		
	Airhouse	Tent	Normal Building
Power consumed by fresh air fans for enclosed space and buildings	9	5	1
Heat to fresh air in enclosed space and buildings to ensure $0^{o}C$	23	17	-
Thermal requirements of internal buildings	11	10	50
TOTAL	43	32	51

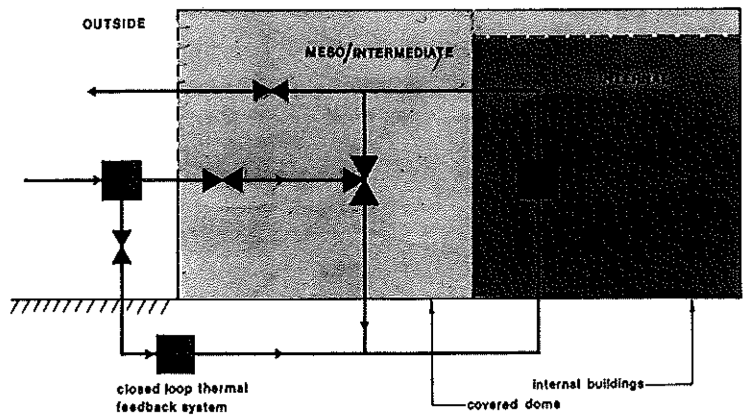

Figure 1. Closed loop thermal feedback system

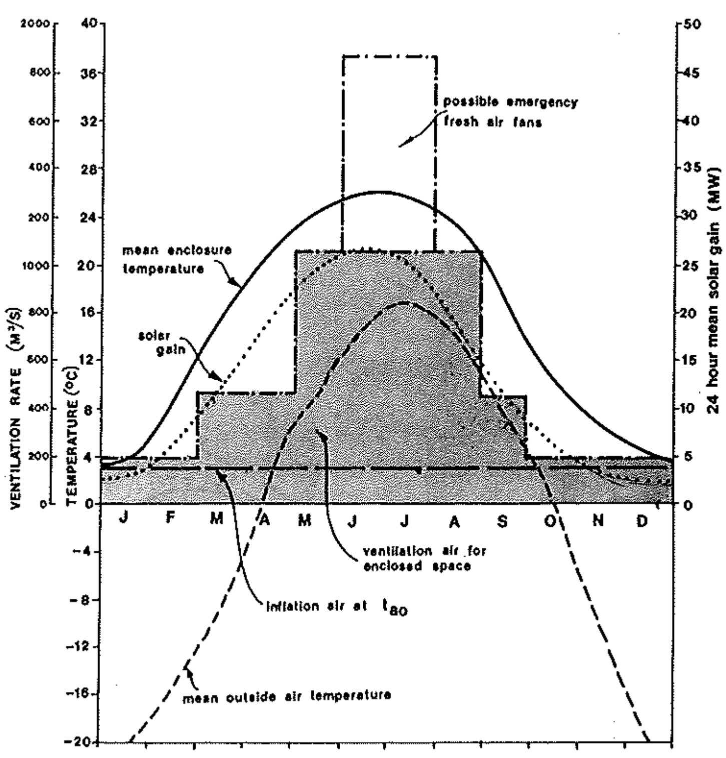

Figure 2. Thirty-five-acre air-supported structure; load chart

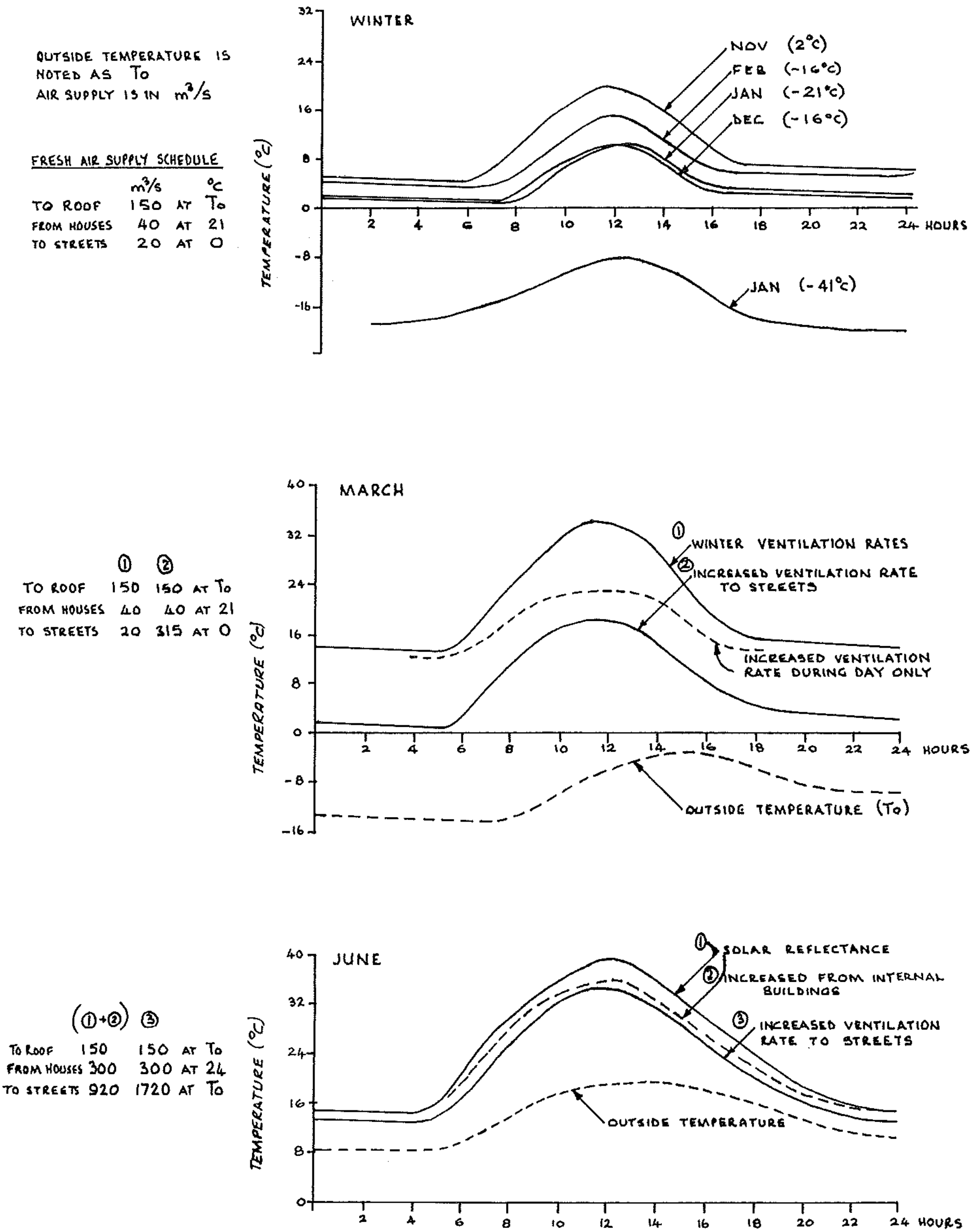

Figure 3. Temperatures inside at center of dome (30 m from floor) for various outside temperatures

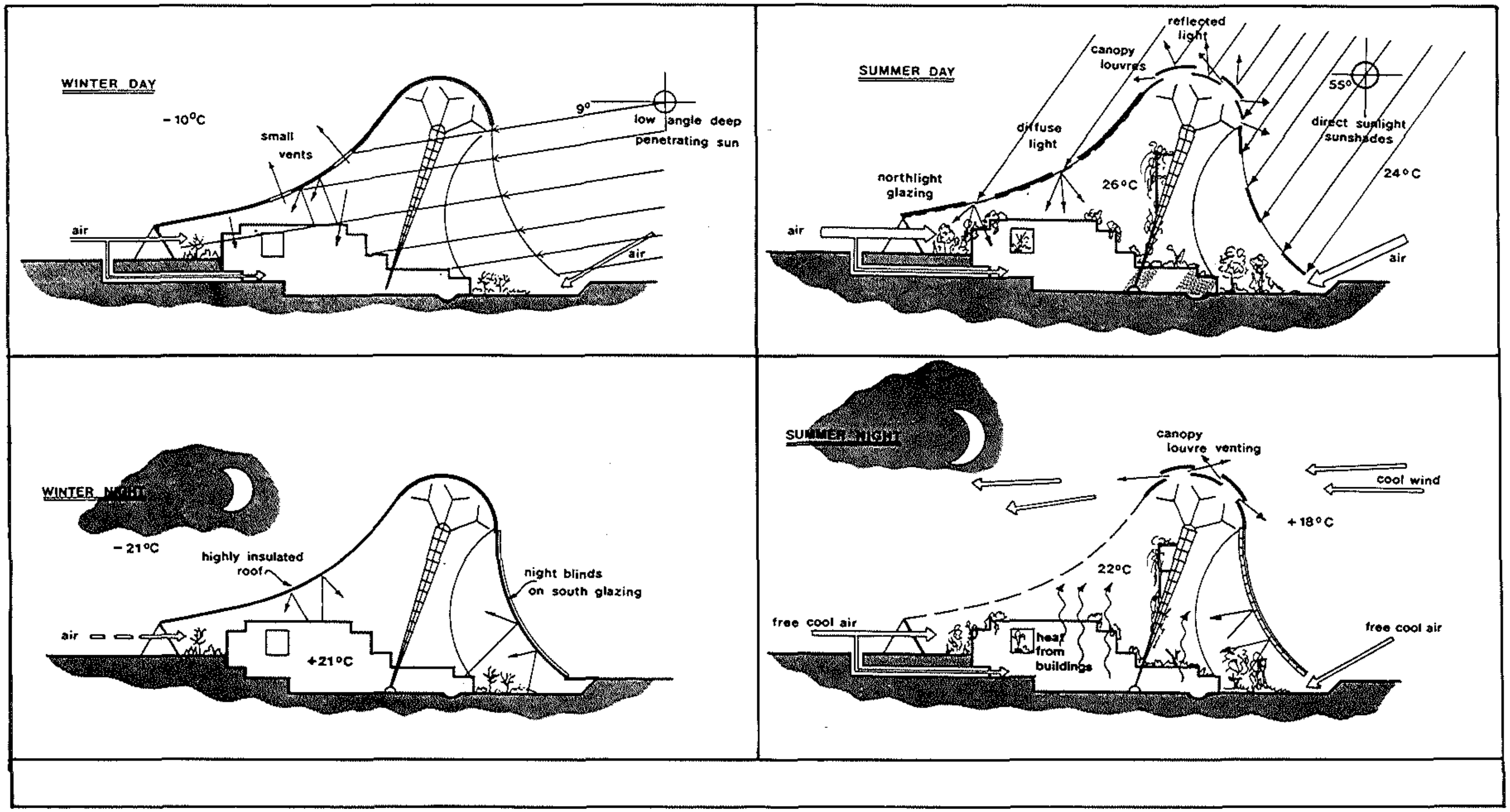

Figure 4. Environmental response of tent structures

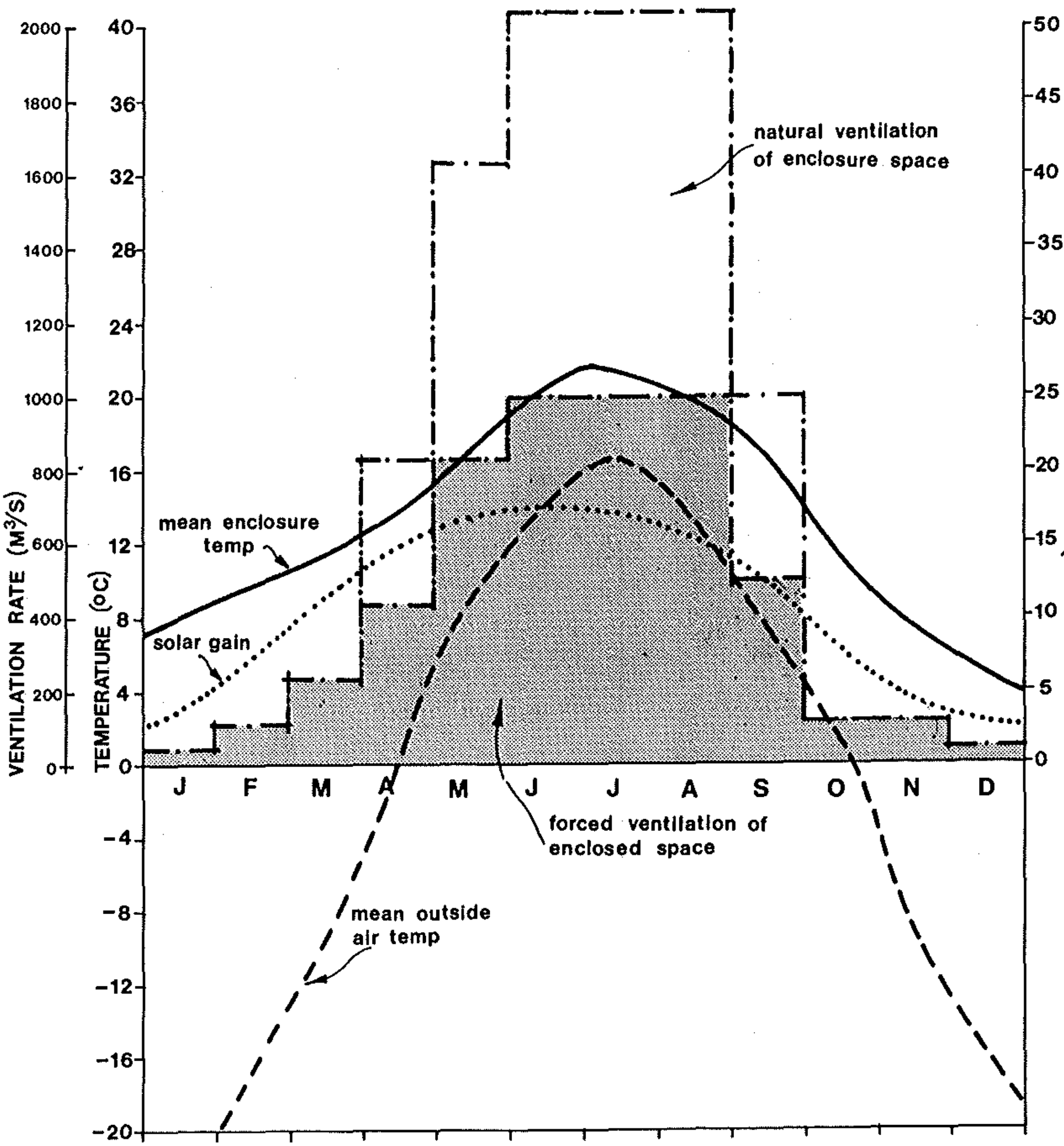

Figure 5. Thirty-five acres covered by tent; load chart