PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
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# Air-Curtain Walls and Roofs-`Dynamic' Structures

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# V. FUTURE POSSIBILITIES AND CHALLENGES

## Air-curtain walls and roofs—'dynamic' structures

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### Preface

In preparing this paper, we have been mindful of Professor Lighthill's injunctions '...these introductory statements should avoid very detailed technical considerations...', '...present a broad survey of the selected subject...', '...stimulate discussion about future activities...'.

Its inclusion in a session entitled 'Future possibilities and challenges' was also taken as a suggestion that a somewhat speculative, possibly controversial, approach would be quite in order.

Consequently, this is not a typical scientific paper, i.e. not a detailed report on our own research, but rather a broad-ranging discussion, at times a little visionary, of a potential development in environmental control.

We wish to point out that we are really the spokesmen for a group of people who have all contributed to the investigations reported—Mr Jekabs Zvilna, Dr G. K. Korbacher, Dr P. C. Hughes, Messrs W. B. Graham, Y. K. Lee, T. J. Ravishankar and H. W. Teunissen. We gratefully acknowledge their cooperation and assistance.

### Notation

| | |
|---|---|
| $b_0$ | see figure 7 |
| $C_p$ | specific heat of air |
| $D$ | diameter of annular jet |
| $e$ | jet energy per unit length |
| $h$ | heat transfer rate |
| $H$ | see figure 7 |
| $j$ | jet momentum per unit length |
| $t$ | jet thickness |
| $V$ | jet speed at exit |
| $w$ | dry width |
| $\rho$ | air density |

### Introduction

In the historical development of building structures, significant advances in building technology have typically been accompanied by a reduction in the bulk of structural elements. The extrapolation of this trend to its ultimate conclusion would result in enclosures with no structure at all.

In our study here of air-curtain walls and roofs, we explore what we consider to be possible next steps in this process, steps towards the use of jet sheets of air as a total structural envelope. We call these new containers 'dynamic' structures since they are characterized by the expenditure of energy rather than by the utilization of mass as in conventional static structures, and because they can have variable form and 'strength'.

Looking briefly at the history of architectural form, we see that in addition to the particular social expression required of the built form, the ability and daring of designers to make use of the inherent qualities and capabilities of the materials used gave a particular style to the total architectural result. We observe as well that the material used dictates the form to a considerable extent. In stone, for instance, the most obvious example of this is in the religious expression of the church epitomized by the Gothic cathedrals of the thirteenth and fourteenth centuries, whose masons and master builders used the compressive quality of masonry to its practical limit. In wood, we have for example the Todaiji temple built in Japan in 751, which was (and apparently the reconstruction still is) the world's largest timber structure, and which exhibited a remarkable use of wooden cantilevers of up to 9 m (30 ft) (Drexler 1955). Recognizing the inherent tensile quality and particular capabilities of wood became part of the temple's total expression. The design of steel and reinforced-concrete contemporary structures generally tend toward improved strength/weight ratio, thereby reducing the bulk of material and reducing cost. This can be seen in the applications of high-strength steels and in the pre-tensioning and post-tensioning techniques used in reinforced-concrete structures.

Recently we have witnessed the emergence of air-supported or pneumatic structures as a new container principle, which has all but eliminated the material components and has relegated the provision of stiffness to continually-running air pumps. Although the mass and bulk of material used has been reduced markedly in this new container form, nevertheless the thin plastic envelope—a membrane under tension—remains and behaves as a *static* structure.

This is the common feature of conventional structural forms—i.e. their use of matter in an essentially static manner. The external loads and the weight of the structure itself are resisted by the development of internal strains and stresses. The pneumatic structure has added a new element—expenditure of energy—and the question naturally arises as to whether or not it would be feasible to eliminate the static use of material entirely and expend only energy to provide a barrier against the environment. Air curtains are of course just such structural elements.† The energy needed for air curtains is small in some applications, large in others. It may be that at present the cost of energy and the associated capital costs for equipment—motors, blowers, etc.—will not put this structure in a good competitive economic position in relation to conventional structures. We think, however, that it would be unwise to assume that future developments in energy production and in technology generally will not change this balance. We think dynamic structures are worth studying.

Part of the dynamic aspect of an air curtain is its ability to produce an 'instant' enclosure, and conversely its ability to be 'turned off' or used intermittently. The ease of varying the air supply allows sophisticated sensing and computing devices to call for different 'strengths' of the container as required by light or heavy precipitation, wind, or thermal imbalance. This structure, unlike conventional ones can *respond* to the environmental need.

Transparency is one of its obvious qualities, and being invisible gives it a rather special aspect. The basic sight sense which provides the greater part of architectural appreciation is non-existent for these forms. We may say that it represents the ultimate architectural form—that of no form. The last quality peculiar to this structure is sound. The noise level generated by the establishment

† The static/dynamic dichotomy may also be identified with the basic physical laws that apply to the two cases—Hooke's law in the former, Newton's laws in the latter.

of the structure, as well as being a design constraint, is more significant than the visual aspect since we are now able to 'hear' the structure while not being able to see it. 'Acoustic structure' might therefore become part of the architectural vocabulary.

## Prior applications of air curtains

The 'air curtain' is probably best known for its application to air-curtain doors, illustrated in figure 1.† The first attempt to replace a solid door with moving air has been attributed to Theophilus Van Kennel in 1904 (Norton 1959). His scheme is illustrated in figure 2. There is

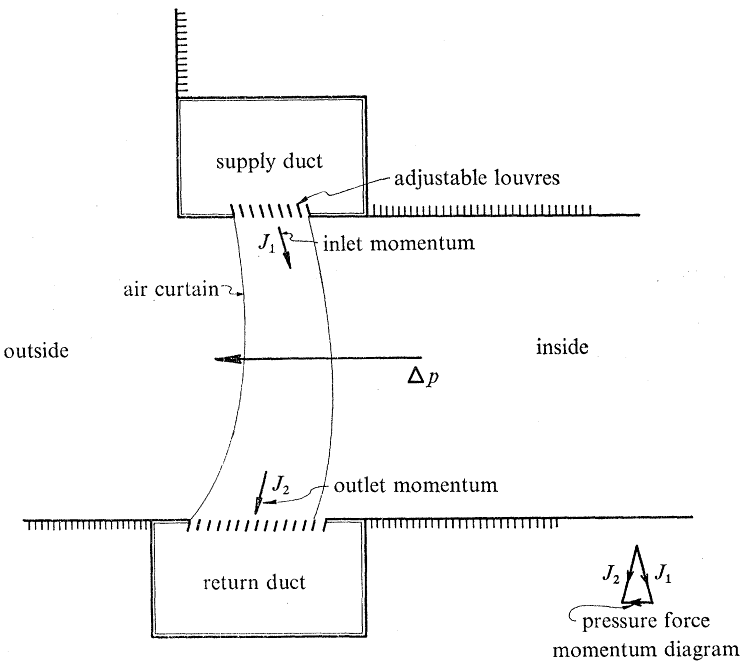


FIGURE 1. Principle of the air-curtain door.

no record of its ever having been used, and one doubts that it would have succeeded in quite that form. A number of attempts were subsequently made to install air-curtain doors during the period 1916 to 1952, but these appear by and large to have been unsuccessful. The first application that worked well seems to have been to a department store entrance in Berne, Switzerland, in 1952 (Norton 1959). This marked the beginning of the present era, in which new installations, supplied commercially by several companies, are appearing rapidly in Europe and America. Presumably they now number in excess of 1000.

The principle of the air door is relatively simple. The moving sheet of air, if its thickness and speed are high enough, prevents mixing of the interior and exterior air, providing an effective barrier to insects, dust, heat and cold, fumes, etc., while permitting easy passage of pedestrians and vehicles. When the pressure on the inside of the door is not the same as on the outside—a situation that can result from wind, operation of heating and ventilating equipment, or the 'chimney effect' in tall buildings—then the curtain has to resist a force tending to push it one way or the other. Owing to its momentum, the curtain has a certain 'stiffness' with which it can

† Other variations of course exist, in particular ones with no return duct. The curtain air in these designs flows away along the floor.

resist this force. The situation is illustrated in the schematic of figure 1 in which the inside pressure is the higher one. For this case the jet nozzles at the top are so angled that the jet-momentum vector is initially directed inward. Owing to the outward force the air velocity has changed its direction by the time it reaches the exit, and the vector diagram shows the relation between momentum and force. The limit to the 'load' the door can withstand clearly depends on the

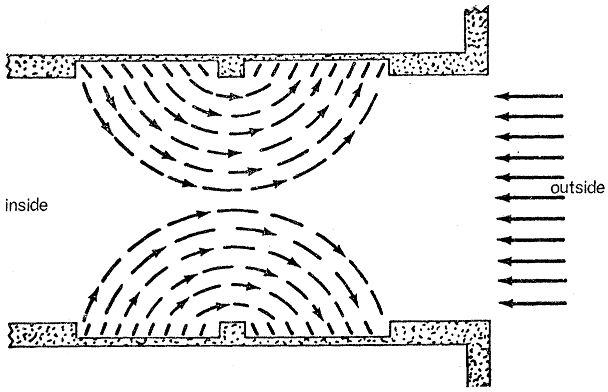


FIGURE 2. The Van-Kennel door—the earliest 'air door' (1904).

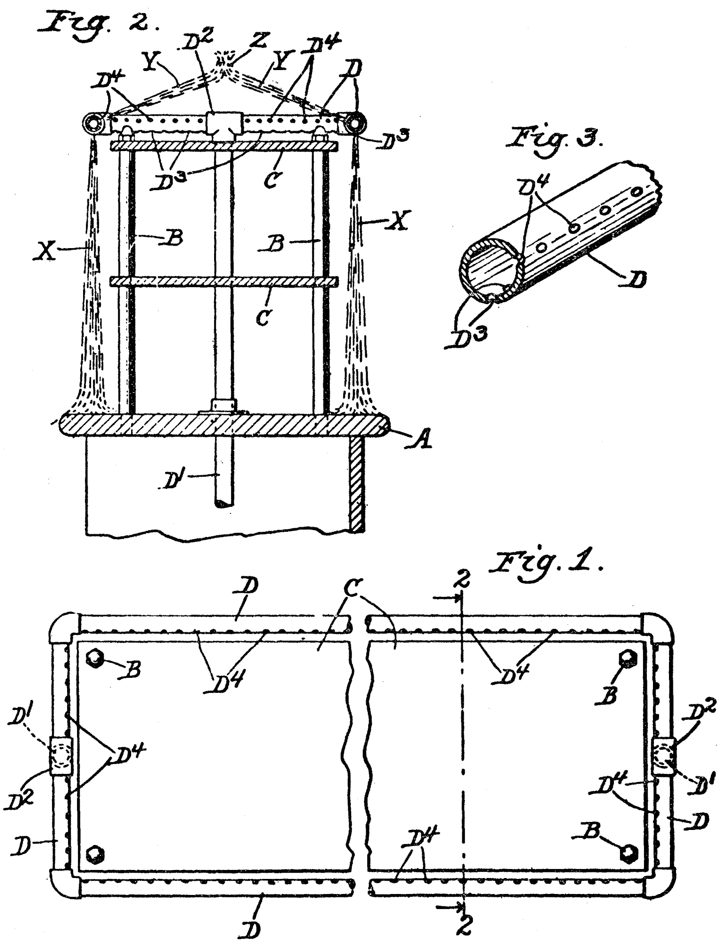


FIGURE 3. Witteborg's air-curtain enclosure.



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momentum of the jet and on the angle through which it can be turned. The momentum increases both with jet thickness and with speed, the magnitude per unit width of door being $j = \rho t V^2$. The energy flux of the jet (most of which is lost) is, again per unit width, $e = \frac{1}{2}\rho t V^3$. The ratio of

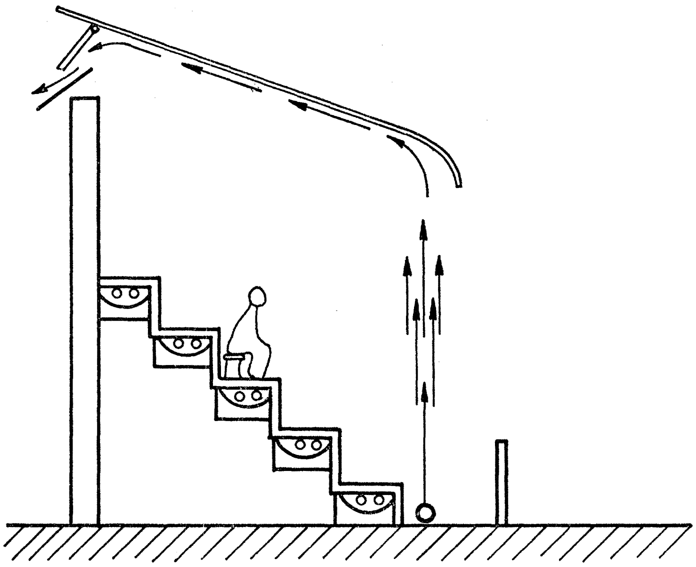

FIGURE 4. Moreau's air screen (1939).

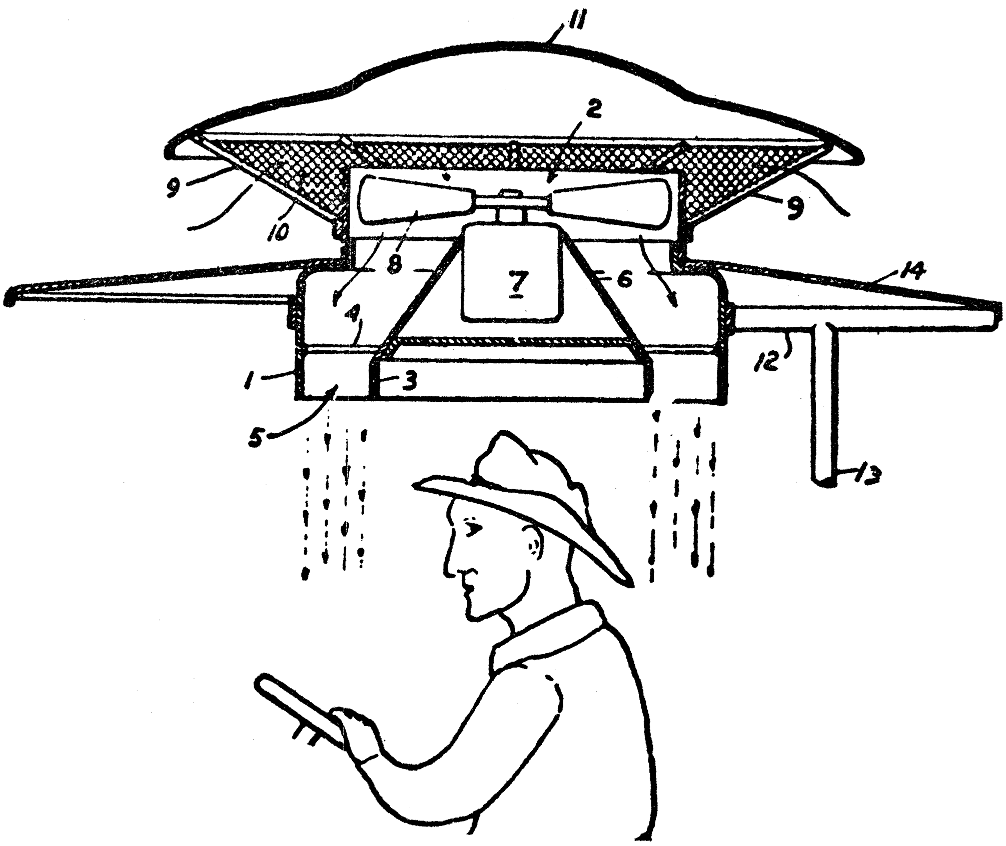


FIGURE 5. Morrison's air-curtain enclosure (1959).





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these is $e/j = \frac{1}{2}V$, and hence in this as in other applications of jets economy of energy points to the use of thick low-speed jets.

The air door, although probably the most important application of the air-curtain concept so far developed, is by no means the only one. Many ideas have been put forward, of which we give a few examples. In 1921 a U.S. patent was issued to E. G. Witteborg of Chicago for an air-curtain device to protect articles of food from insects and dust (figure 3). In this patent, Witteborg used the phrase 'curtain of air or sheet of air' and may have been the first to do so. In 1939, a French patent was issued to Henri Moreau for an air curtain to enclose a space whose atmosphere

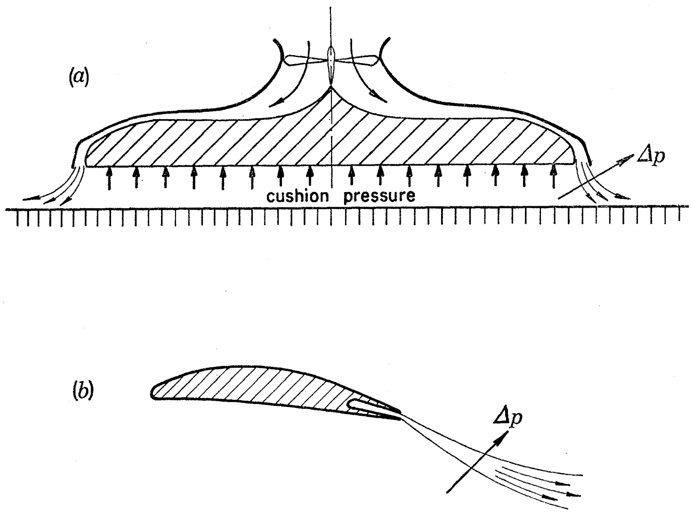


FIGURE 6. Applications of jet sheets to vehicle aerodynamics; (*a*) air cushion vehicle; (*b*) jet flap.

is to be controlled, for example the seats of a sports stadium (figure 4). An Australian patent application in 1957 by J. M. Morrison is for an air curtain to protect the driver of a tractor or other farm vehicle under extremely dusty conditions (figure 5). Professor I. W. Smith of the University of Toronto and a group of undergraduate students have experimented with an upwardly directed jet sheet issuing from the hood of an automobile to protect the windscreen from rain, in place of a conventional windshield wiper; and there are other examples in this vein. In his 1959 paper, Norton suggested the possibility, perhaps for the first time, that air curtains could be used as roofs for protection against rain, etc.

The common thread running through all these examples is concern with control of the environment in a defined space—and that is our main interest in this paper as well. We should, however, note that there are important applications of air curtains (jet sheets) to vehicle aerodynamics as well. There it is the stiffness property that is applied—the ability of the sheet to resist a lateral force. Two of these applications are illustrated in figure 6. One form of air-cushion vehicle (ACV or Hovercraft), shown in (*a*) uses the ability of an air curtain or jet sheet to contain a pocket or cushion of air at elevated pressure. This pressure acts against the bottom surface of the craft, providing support for it and its load, constituting a fairly efficient way of supporting the vehicle without any contact between it and the surface over which it rides. The second example is the airplane jet-flap shown in (*b*). The high-speed jet sheet provides an 'extension' of the airfoil itself in that it can sustain lift (pressure differential) through its 'momentum stiffness', while simultaneously providing jet thrust for propulsion.

## Technical and scientific problems in the use of air curtains

The conventional building structure controls a space by providing isolation of several kinds from the external physical environment, i.e. acoustic (noise), visual (sight), thermal (heat and cold), particulate (dust, insects), precipitation (rain and snow), and wind.

The air curtain, or jet sheet, cannot by its nature provide all of these. It is effectively transparent to both acoustic and electromagnetic radiation in the frequency bands of interest (i.e. to sound and light). Indeed, it may pose additional problems of unwanted noise emanating from its motors, blowers and ducts, and from the air curtain itself. It can, however, in principle be used to provide protection against all the other environmental factors mentioned. Indeed the successful use of air-curtain doors testifies to this, although that application does not pose difficulties nearly

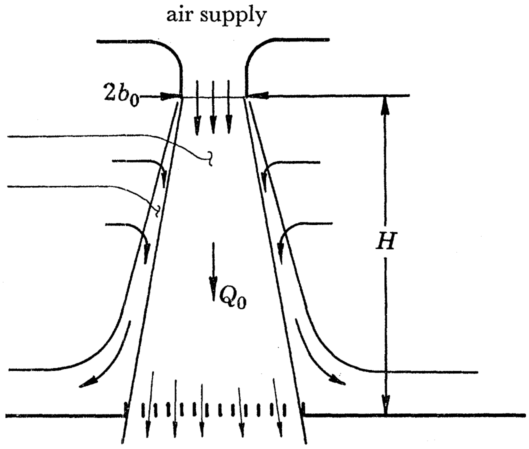


Figure 7. Process of heat transfer across an air curtain.

so great as those arising with air-curtain roofs or canopies, or with spaces where the air curtain is a large fraction of the total enclosing 'surface'. We discuss the problems posed under several headings:

### *Dust; insects; snow*

To isolate an interior space from these *in the absence of wind* requires air velocities of only a few feet per second and hence the power required and noise produced are small. This case may be said to present no serious problems of design, and if only protection from dust, insects and snow were needed, enclosures provided by air curtains alone would be quite feasible.

### *Heat and cold*

The major mechanism of heat transfer across air curtains appears to be one of entrainment, mixing and spillage, as illustrated in figure 7 (Hetsroni, Hall & Dhanak 1963). Here we have an air curtain separating warm and cold chambers at equal pressure. A volume rate of flow $Q_0$ issues from the jet nozzle and is recirculated through the return passage without further addition or subtraction of heat. Air is entrained into the jet from both sides and spilled off at the bottom as shown (the inner pair of lines shown encloses a constant volume flow $Q_0$. The air spilled into the warm side at the bottom is cooler than that which was entrained, and which it replaces, owing to turbulent heat transfer within the jet. Thus it is necessary to add heat to the space on the warm side of the curtain to maintain the temperature of the warm chamber constant, and conversely on the cold side. Hetsroni *et al.* by means of theory and experiments, have found a semi-empirical result for the heat transfer rate. It is valid only for relatively thin jets, and can be expressed as

$$h = 0.338 C_p \rho V \sqrt{(b_0/H)} \quad \mathrm{kW\,m^{-2}\,K^{-1}} \text{ (SI units)},$$

$$h = 290 C_p \rho V \sqrt{(b_0/H)} \quad \mathrm{Btu\,h^{-1}\,ft^{-2}\,{}^{\circ}F^{-1}} \text{ (imperial units)}.$$

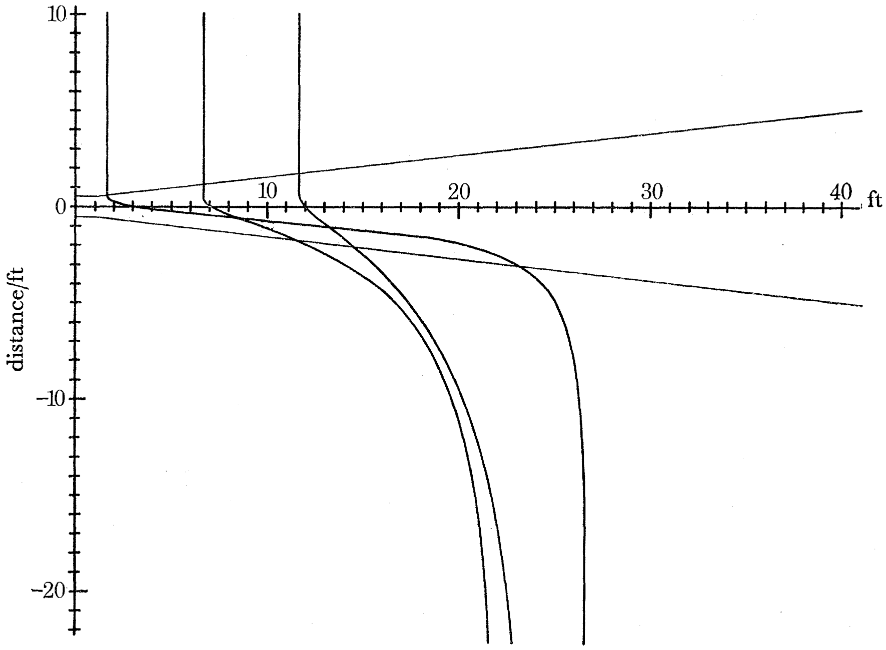


FIGURE 8. Computer trajectories of raindrops passing through an air curtain. Jet speed: 100 ft/s (30 m/s), jet thickness: 1.0 ft (0.3 m). Drop diameter: 1.5 mm.

This result is compatible with the observation by Sleight (1961) that heating and cooling loads per foot width of curtain are typically in the range 5000 to 50000 Btu/h (5 to 50 kW m$^{-1}$). These heat loads on air doors are quite comparable with, and may even be less than, those associated with the frequent opening and closing of a conventional solid door. The heat transfer in any particular case is obviously very much dependent on the particular geometry involved and on the ambient temperature and wind conditions, but the above equation can be expected to yield an order-of-magnitude estimate.

*Rain*

When an air curtain is to perform the function of a roof, canopy, or tent it must be able to keep the protected space free from rain. The basic interaction mechanism is illustrated in figure 8, which shows a horizontal jet and the trajectories of vertically falling raindrops. This problem is treated at greater length below—we simply remark here that high jet velocities are needed for this case, and hence, that more power, noise, and capital cost are entailed than for air doors.

*Wind*

The action of wind on a conventional air door has already been commented on above. Its main effect is to cause a pressure differential to exist across the curtain, which the latter can resist in accordance with its momentum stiffness. The curtain will 'break' at some critical wind condition and the design must be based on such a criterion. In more complicated cases, when the curtain constitutes a large fraction of the enclosure, and/or when it is not recirculated, as in figures 16 to 19, there is little that can be said in general about the shape of the air curtain itself and about the velocity fields within the protected spaces when external winds are present. Each individual case has to be studied on its own merits, with all the analytical and experimental methods of aerodynamics brought to bear. In this, as in other aspects of architectural aerodynamics, the flow fields occurring are so complex and so varied that theory unfortunately plays a rather minor part. Even experienced aerodynamicists are sometimes unable to predict in advance the main features, let alone the details, of the flow fields that typically occur in these situations. Thus model testing, mainly in wind tunnels, will inevitably be a principal research and design tool.

*Stability*

A comment on the stability of jet sheets is in order here. Thin jet sheets have a strong tendency to adhere to adjacent surfaces, as illustrated in figure 9 (the Coanda effect) and if there are two such surfaces present the jet may have difficulty in choosing to which one it should attach.

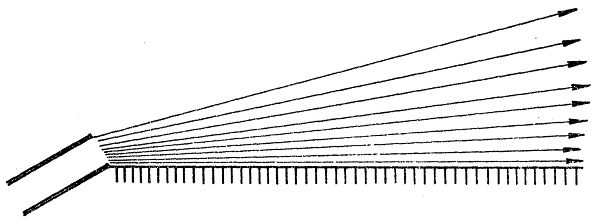

FIGURE 9. The Coanda effect.

Indeed a small change in the environmental conditions may cause it to flip from one to the other. In architectural applications where the jet is a large fraction of the structure the Coanda effect and the potential instability associated therewith must be carefully taken into account in choosing locations for air intakes, and in designing the shapes of all nearby surfaces. On the other hand, the Coanda effect can be put to good use as a control device, enabling the direction of a jet sheet to be altered. This feature is very effectively employed in many fluid flow devices in what is known as 'fluidics'.

*Noise*

We conclude this section with a comment on the noise produced by air curtains. As noted previously, noise will emanate from motors, blowers, ducts, and the air jet itself. Conventional acoustical treatment can be used to silence all but the last of these in the sorts of applications we envisage. The noise generated by the jet can be estimated by using Lighthill's theory in conjunction with experimental data. At distances of the order of 10 ft (3 m) from a 100 ft/s (30 m/s) jet of 1 ft (0.3 m) thickness the maximum intensity of the sound from the jet itself would be of the order of 60–70 dB. Whether this would be acceptable or not in any particular application depends entirely on the use to which the space is being put, and on the presence of other noises. However, this is a modest noise level, and would certainly not rule out air curtains of that order of speed.

## RESEARCH ON THE RAIN PROBLEM

It was evident from the beginning of our interest in air-curtain roofs that the two major problems are wind and rain, and that whereas the former is critically dependent on details of geometry the latter is susceptible to some generalized analysis. We therefore undertook at the Institute for Aerospace Studies some theoretical and experimental studies of raindrops passing through a horizontal jet (Goering & Zvilna 1969; Graham 1970). The theoretical work is described by Graham. In brief, he has carried out computer integration of the trajectories of water droplets falling through a jet sheet of realistic velocity profile (figure 8). The drops enter the jet from above at terminal velocity, experimental values for drag coefficients are used, and a criterion due to Taylor (1949) for shattering of the drops by the airstream is incorporated. The latter is a point of great importance, since small drops will pass through a jet unscathed, whereas large ones are broken up. If this were not so, much higher jet velocities would be needed to deflect the

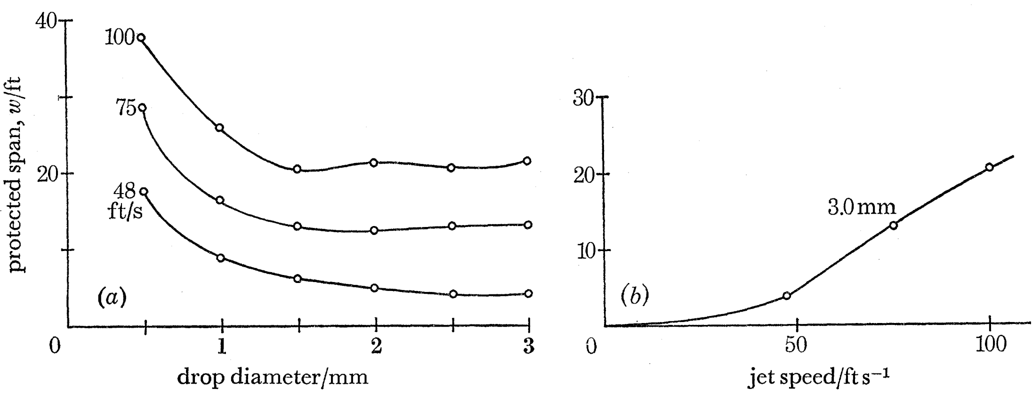


FIGURE 10. The dry span 20 ft (6 m) below the jet centre; (*a*) for various drop diameters at three different drop speeds, and (*b*) for varying jet speed for a 3 mm drop.

rain, since the largest drops, falling fastest, and having the largest ratio of mass/frontal area, would be the least deflected. The left-most trajectory shown in figure 8 is for a drop that breaks up—hence the crossing over of the trajectories. No cross-over was observed when the drops remained intact. The jet of the example is 1 ft (0.3 m) thick, uniform at the exit, and spreads as shown. Its exit velocity is 100 ft/s (30 m/s) corresponding to a jet power of 2.16 hp (160 kW) per foot run of jet. The protection afforded by this jet for drops of different sizes is as shown in figure 10*a* and the minimum dry width $w$ is shown in figure 10*b* against jet velocity.† Since jet power varies as the cube of velocity, the power required goes up rapidly with protected span.

To relate these results to protection from natural rain now requires only that we know, in addition to the above, the size of rain drops. Mason (1957) gives the estimate

$$1-F = \exp\left[-(x/a)^n\right],$$

where $F$ is the fraction of liquid water contained in drops of diameter less than $x$, and $a, n$ are experimental constants. Raindrops have a wide range of diameters, from nearly zero to several millimetres. The above equation shows however that the amount of water contained in the largest drops is small. Representative values of $a$ and $n$ corresponding to a moderately heavy rain (5 mm/h) are

$$a = 1.9\,\text{mm}, \quad n = 2.25.$$

With these numbers we find from the equation that 1 % of the liquid water is contained in those drops whose diameter exceeds 3.7 mm. Thus, although there are some very large drops, they contain relatively little of the falling water, and moreover these would break up on entering a

† Although drawn as smooth curves, $w$ is not a smooth function of $d$ and $V$ since the number of break-ups may differ from point to point. This accounts for the apparent anomaly in the 100 ft/s curve of figure 10*a*.



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high-speed jet, and be swept away by it. It can be concluded from the calculations that a protected span of the order of 20 ft (6 m) can be attained with a jet power of about 2.2 hp (162 kW) per foot width which corresponds to just over 0.1 hp per square foot (800 W $m^{-2}$) of protected area.

Graham's calculations showed that angling the jet upwards is of some benefit in deflecting the larger drops; apart from speed this angle was the only jet parameter he varied. There is little

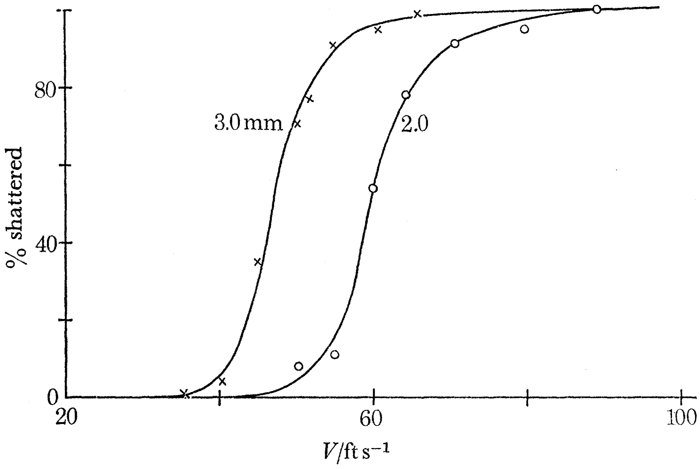


FIGURE 11. Effect of jet speed on drop break-up.

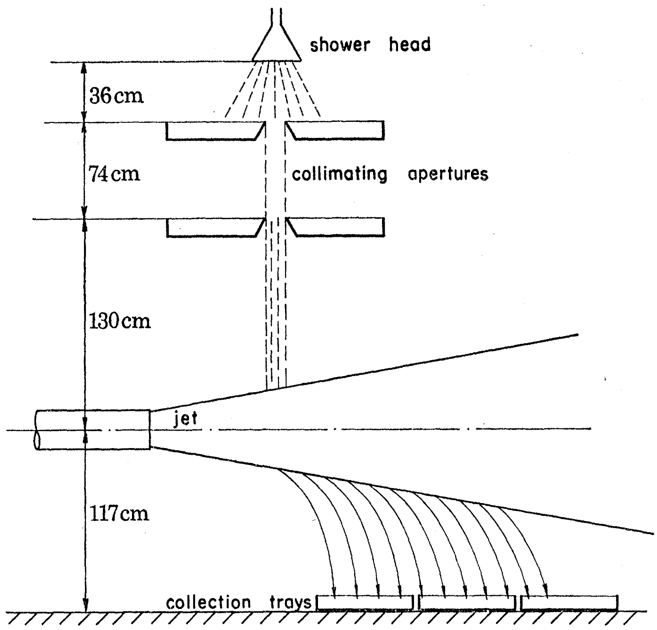


FIGURE 12. Diagram of the experiment on interaction of rain with a jet.

doubt that power savings can be effected by optimizing the jet thickness, its exit velocity profile, and its exit angle. The above-cited power is probably conservative. Calculations to investigate the effects of these parameters are planned for the future, but have not yet been carried out.

The experiments on horizontal jets performed at the Institute for Aerospace Studies were in two parts. In the first, droplets of milk (assumed to behave like water) were allowed to fall with terminal velocity into a jet, whilst being observed against a black backdrop under stroboscopic



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lighting. The jet issued from a 1 ft (0.3 m) square nozzle and had a variable speed. It was easy to observe whether the drop passed whole through the jet or was shattered. The percentage of drops shattered for each test condition in a large number of repetitions (100 at least) was observed

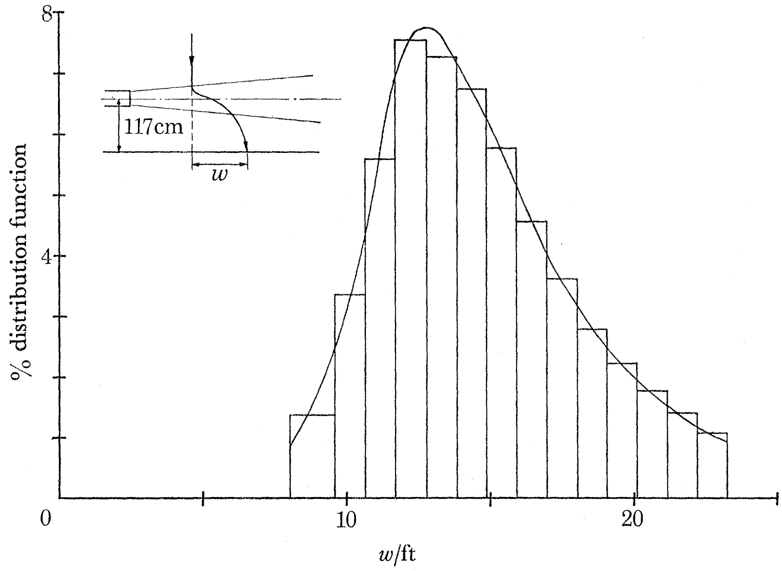


FIGURE 13. Measured distribution of water in the trays.

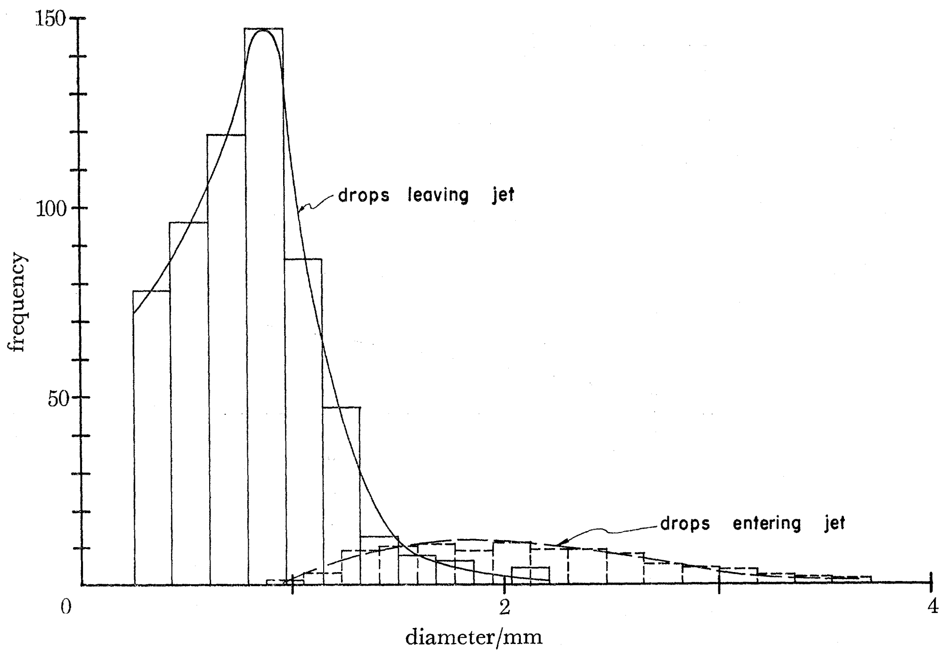


FIGURE 14. Measured distribution of drop diameter before and after interaction with the jet.

with the results shown on figure 11. 90 % of the 3 mm drops did not survive a jet speed of about 55 ft/s (17 m/s), and 90 % of the 2 mm drops a speed of about 70 ft/s (21 m/s). The speeds for 50 % likelihood of shattering are in good agreement with the critical speeds given by Taylor (1949). These experiments provide convincing verification that drops of diameter 2 mm or larger are readily shattered by a jet of practical speed.

The second experiment consisted of a simulation of rain falling into a jet. It is depicted schematically in figure 12. The 'rain' emanates from a standard shower-bath fixture, is collimated by two apertures to form a parallel beam, and after passing through the jet is collected in a set of trays 46 in (117 cm) below the jet centre. Measurements were made of the distribution of water in the trays and by photographic means of the drop-diameter distribution before and after entering the jet. A typical distribution of water downstream is shown in figure 13. The 'dry space' obtained is about $7\frac{1}{2}$ ft (2.3 m). It would of course be expected to be larger at greater distances below the jet (see figure 8). Figure 14 shows a typical result for the relative distributions of drop size before and after interaction with a jet of 90 ft/s (27 m/s). The major feature is the

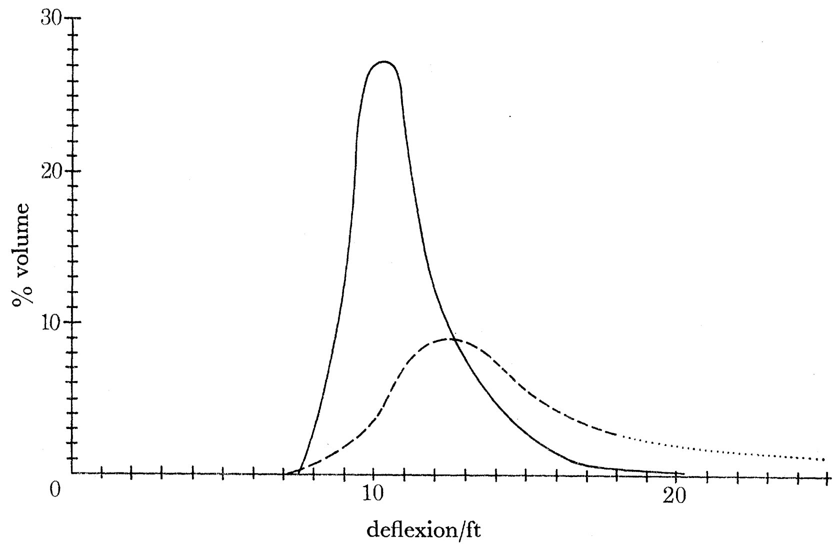


FIGURE 15. Comparison of measured (----) and predicted (——) distribution of water in the trays 46 in (117 cm) below the jet centre.

evident destruction of large drops and the production of large numbers of small ones. We repeat that this is an important phenomenon, for should the drops of 3 to 4 mm diameter pass through the jet intact then the power required to provide a given protected area would be much larger.

A comparison was made of the theory and experiments by applying the theory to one of the experimental situations. The measured distribution function of drop diameter entering the jet was used in conjunction with a set of computed trajectories. From these a prediction was made of the distribution of water in the trays, which could then be compared with that actually measured. The comparison is shown in figure 15. It can be seen that the theory predicts a more concentrated collection pattern than really occurs. This is because the calculation makes the conservative assumption that each time a drop breaks up (and it may do so several times in succession) it forms two equal but smaller drops. In fact, photographs show that they really shatter into many droplets (Lane & Green 1956). Thus the theory does not predict the generation of the large numbers of small drops that the experiment shows, and hence underestimates the downstream throw. What is more significant, however, is that it correctly predicts the dry area measured. Whether this would also be true for jets 10 to 20 ft (3 to 6 m) above the ground must await further experiments, since the variation of dry space with height depends on the angle of arrival of the drops at the trays—and this was not compared with the calculated values.

### The annular curtain

During the preparation of this paper it occurred to us that an annular jet directed upwards might have useful properties as a jet curtain, in view of the know tendency of such jets to coalesce. The situation is somewhat as illustrated in figure 16. Around the periphery of a disk of diameter $D$ there is an annular jet of thickness $t$. This jet coalesces and continues upwards as a single jet having the usual properties of a 'solid' jet. Immediately above the disk is an enclave R completely surrounded by the curtain. The air within R is of course in motion owing to entrainment and

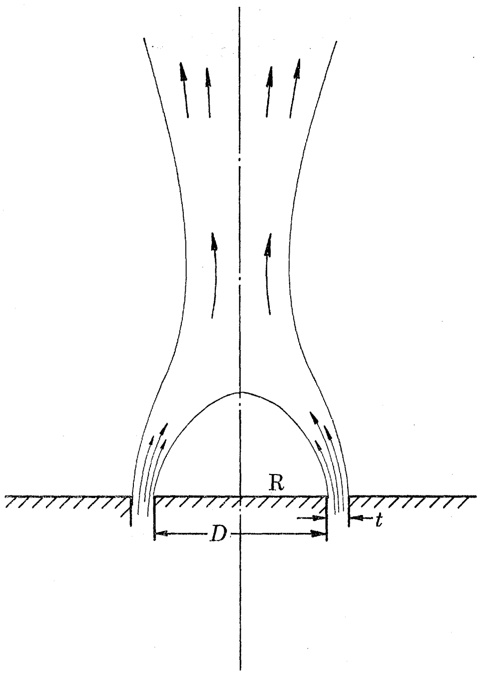


Figure 16. Configuration of an annular jet.

spillage by the inner surface of the annular jet. Although the illustration is for a vertical axisymmetric jet, it is clear that there may be advantages to be gained by using other planforms, and by imparting to the jet radially outward or circumferential velocity components. The former might be expected to be beneficial in reducing the induced flow speeds in R, and the latter, by imparting swirl to the jet (making it into a jet vortex) might be advantageous in throwing off the rain. We have found in some preliminary laboratory experiments that vertically-falling rain will in fact not penetrate into R provided that $t/D$ and $V$ exceed a critical pair of values that are mutually dependent. The jet power per unit area of protected space seems to be somewhat larger than that for the horizontal jet 'roof', but on the other hand theory indicates that it should, for very large systems, be roughly independent of the size $D$. That is, it should be about the same whether $D = 100$ ft or 1000 ft (30 or 300 m). It appears indeed that a whole town might in theory be accommodated within R! We have only just begun our study of this kind of air 'structure' and as yet can say nothing about the air velocities inside R, nor about the effect of side wind and driving rain. Needless to say, this jet configuration is an example of the ultimate in dynamic structures to which we have alluded—an enclosure with no visible structure at all. The prospects for its use are very intriguing and we invite other interested aerodynamicists to join in the research necessary to explore its characteristics and potential. One example of how it might be used is illustrated in figure 19.

## Potential uses of air-curtain enclosures

What are the possibilities for the future? We have, I think, fairly clearly shown that we have only scratched the surface of the scientific and engineering problems related to air-curtain enclosures. We have done even less in the way of conceiving how they might be applied to new solutions of old problems or, even more challenging, to the invention of totally new forms of environmental control that derive from the inherent properties of jet sheets themselves. This is not the point, we think, to be too constrained by limitations that appear serious, or even in-

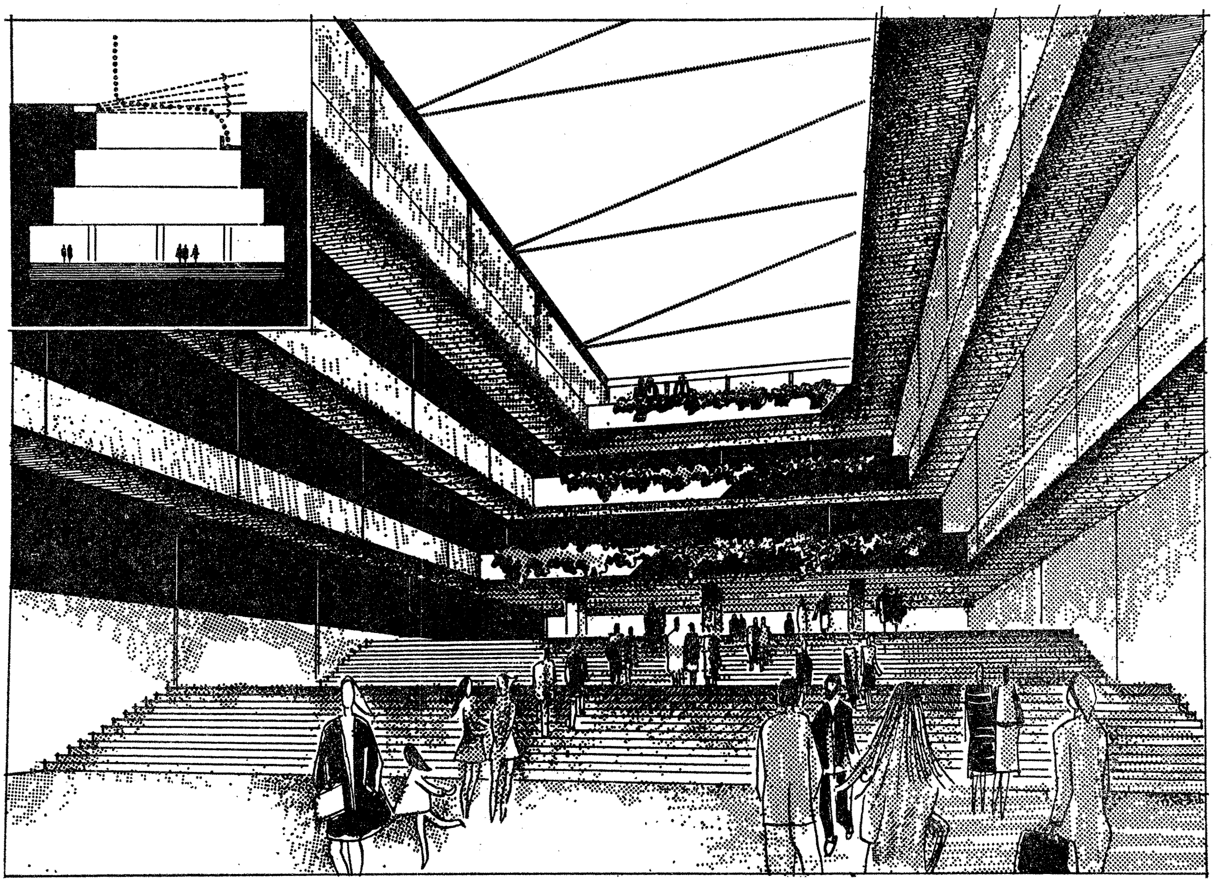

Figure 17. A hypothetical street or court protected by an air-curtain roof.

superable. Rather this is a time to let the imagination run free; for architects, town planners and others to say what they would like to have in the way of results and thus to put the challenge to science and engineering to produce the solutions.

The forms generated by conventional structures as we know them largely exclude the external environment. The dynamic structure has the capability to produce spaces that completely include all of the visual and acoustic environment, and which, under conditions of intermittent use become part of the 'natural' environment. Uses based on this aspect provide an opportunity to relate building form more closely to natural form. Some of our first studies might be related to outdoor spaces between buildings where we can temper the environment by providing shelter from precipitation, as suggested in figure 17—perhaps coupled with some radiant heating. We might also be thinking of making more habitable in the same way the civic spaces of a town or a



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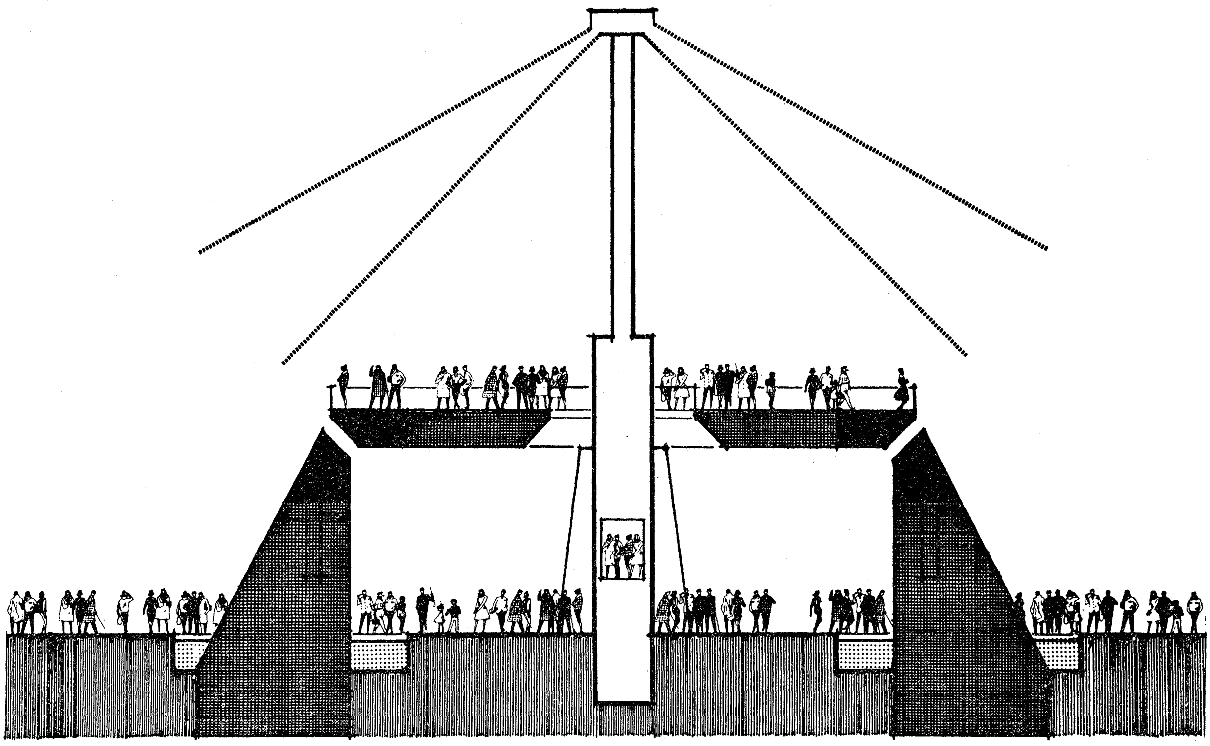

FIGURE 18. A hypothetical air-curtain shelter.

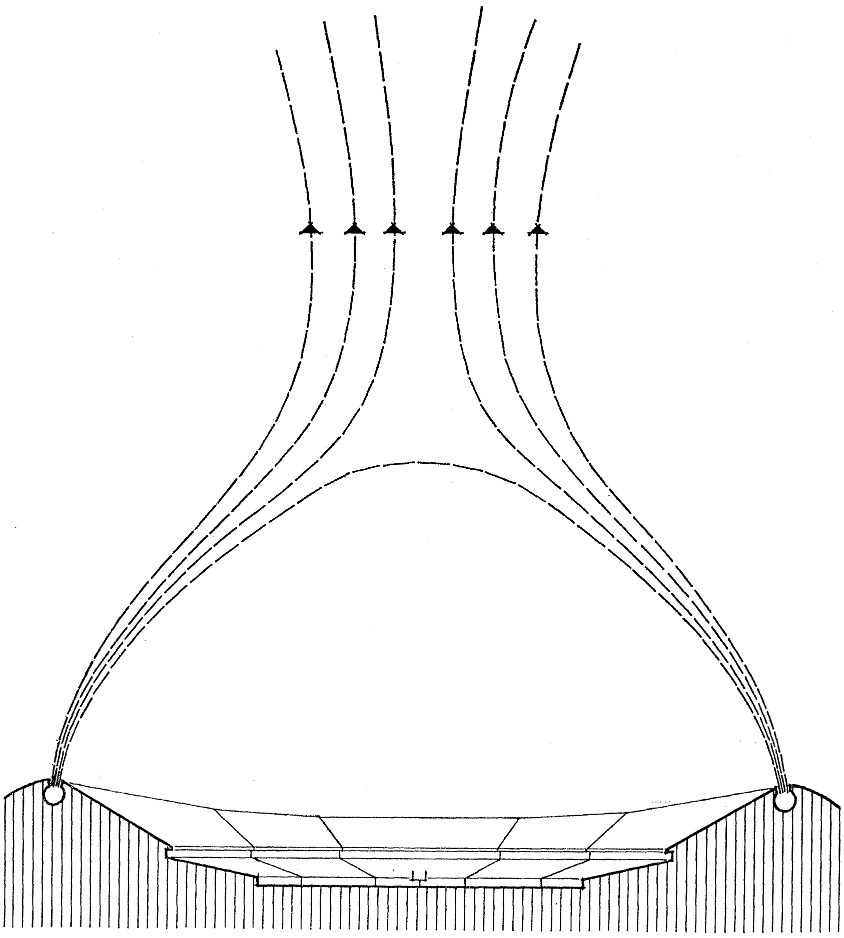

FIGURE 19. A hypothetical stadium under an annular air-curtain roof.



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town centre—perhaps even a significant street intersection. This approach seems to have certain advantages over the much discussed idea of covering a whole town with a light frame or pneumatic structure, since we have here the opportunity to eliminate the envelope at a moment's notice. To be able to walk in a pleasant downtown core and be free of inclement weather, yet to be able to see the whole environment as if out of doors is indeed an exciting prospect!

Among the possibilities we must include portable and temporary shelters; a construction-site shelter for example, used for a relatively short period of time, that permits unhampered movement of cranes or other large equipment would have a distinct advantage over any other type of temporary structure. One might imagine a truck or aircraft that carries supplies to a disaster area creating its own enclosure by using its own power plants as the structural generator.

In figure 18 we see a suggested application of a tent form of air roof over an exhibition or observation platform. Finally, figure 19 suggests a somewhat more ambitious application, where a large crowd needs to be protected for a short time. Here we have a stadium or amphitheatre with an air-curtain roof of rather heroic proportions utilizing the annular jet principle.

We remarked earlier that protection of the ground from snow in the absence of strong wind might be achieved with relatively little power. There are areas of the world where this possibility might be very attractive, as for example in the Arctic. One of the applications that comes to mind at once is the protection of airport runways, since the economic and other penalities of snow accumulation there are so high. However, where snow deposit is concerned, the aerodynamic problems may turn out to be rather more subtle and challenging than one might at first suppose. A glance at the Toronto landscape after a blizzard provides mute and ample testimony to the complexity of the patterns of snow deposit in an aerodynamic field.

The operative principle in considering air-curtain applications is to extend our lives to include more 'outdoor' space under conditions of increased comfort—to reduce the difference between 'outdoor' and 'indoor' while retaining protection against the inclement aspects of 'out of doors'.

The examples we have shown here are illustrative only, and do not of course represent engineered designs. Indeed they are presented in the light of our above-stated belief that we should not be bound just yet by our technological limitations, and in the hope if not the conviction that a concerted attack by scientists and engineers will push back those limitations.



## References (Etkin & Goering)

Drexler, A. 1955 *The architecture of Japan*, pp. 83, 87. New York: Museum of Modern Art.
Goering, P. L. E. & Zvilna, J. Dematerialization—towards dynamic structures. *Arch. Can.* **46**, no. 3, 21.
Graham, W. B. 1970 Jet-stream umbrella, B.A.Sc. Thesis, Engineering Science, University of Toronto, Toronto.
Hetsroni, G. Hall, C. W. & Dhanak, A. M. 1963 Heat transfer properties of an air curtain. *Trans. Am. Soc. Agr. Eng.* **6**, 328–334.
Lane, W. R. & Green, H. L. 1956 The mechanics of drops and bubbles, In *Surveys in Mechanics* (ed. G. K. Batchelor and R. M. Davies), pp. 163–212. Cambridge University Press.
Mason, B. J. 1957 *The physics of clouds*, appendix B. 1. Oxford: Clarendon Press.
Norton, W. 1959 Where to use a curtain of air. *Consulting Engineering*, March 1959, pp. 108–113.
Sleight, P. 1961 Curtains of air. *Compressed Air Magazine*, Oct. 1961, pp. 15–17.
Taylor, G. I. 1949 The shape and acceleration of a drop in high speed air stream, M.O.S. paper 6600/5278/49.