Performance of Siphonic Drainage Systems for Roof Gutters

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Report SR 463
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Contract

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Summary

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This report describes a research study on siphonic roof drainage systems, partly funded by the Construction Sponsorship Directorate of the Department of the Environment, and carried out in collaboration with the manufacturers and suppliers of three different proprietary systems.

In the first part of the report, the theory of siphonic systems is explained and descriptions are given of the products currently available in the UK. The similarities and differences between the systems in terms of components and design methods are discussed. Information on in-service performance is also given.

The second part of the report describes laboratory tests carried out at HR Wallingford on four separate siphonic systems. A test rig was constructed for the study and consisted of a 10m length of gutter installed about 6.5m above ground level and supplied with flow from a short section of roof. Each siphonic system consisted of two outlets and horizontal and vertical pipework with an overall length of about 28m. The flow capacities and pressures in the systems were measured and compared with the design predictions provided by the suppliers.

The final part of the report reviews the findings from the first two parts, and identifies key issues which specifiers and suppliers of siphonic systems should take into account so as to ensure satisfactory performance. Areas where the technology could be advanced by further research are also suggested.

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1 Introduction

A siphonic system draining a roof or gutter normally consists of grated outlets of a special design connected to a discharge point at or below ground level by pipework that is designed to flow full under specified rainfall conditions. By contrast, a conventional system generally consists of open outlets connected to vertical rainwater pipes that are designed to operate under atmospheric pressure with a continuous air core. The flow capacity of a conventional system is usually determined by the size of the outlets and by the depth of water above them; in the case of a gutter the driving head is of the order of 100 mm but on a flat roof it may be only about 30 mm. An equivalent siphonic system can have a significantly higher capacity because, if the pipework is enabled to flow full, the driving head becomes equal to the vertical height between the roof and the point of discharge; in many buildings this will be of the order of 10 m, ie two orders of magnitude greater than the driving head for most conventional systems.

Advantage can be taken of the intrinsically higher flow capacity of siphonic systems in several ways: by using fewer outlets; by using smaller diameter pipework; or by connecting more outlets to each vertical discharge pipe. Thus, for example, in a long valley gutter it may be possible to connect as many as ten or more outlets to a single collecting pipe and discharge the combined flow by means of one vertical pipe at the edge of the building. Since the pipework acts siphonically, the collecting pipe can be fixed horizontally just below the roof without the fall that would be required by a conventional pipe designed to flow part full. These features enable significant savings to be made in the construction of large industrial or commercial buildings. The need for vertical rainwater pipes inside a building can be eliminated, together with the provision of expensive below-floor drainage systems. This allows greater flexibility in the use of space within open-plan buildings and provides a means of meeting architects' requirements for large uncluttered areas in structures such as passenger terminals and sports arenas.

The advantages offered by siphonic systems can be clearly identified but, as with any new development, some caution is appropriate when experience is being gained. Firstly, siphonic systems operate on somewhat different principles from conventional systems and their characteristics need to be properly understood by their manufacturers and designers, by the people who specify them, and by the staff who install and maintain them. Secondly, siphonic systems represent a higher level of technology than conventional systems, and more care and precision are needed in both their design and installation. Thirdly, design standards and building regulations in the UK do not yet cover siphonic systems, although this should be partly remedied by the planned publication of a new European Standard (probably in 1997). Instead, manufacturers of siphonic outlets have developed their own design procedures and associated software packages, and remain responsible (either directly or through agents) for design and installation of the systems. As a result, most architects and drainage engineers are unable to carry out independent checks of designs presented to them and find it difficult to compare products or evaluate technical claims. The resulting degree of mystery associated with siphonic systems often acts as a disincentive to their use.

The purpose of the study described in this report was to provide independent information about the performance of siphonic systems and to give general recommendations about their design and use. The work consisted of the following two parts:

- a review covering the different siphonic systems available, the basis of their design procedures, the approximate number of installations in the UK, and information on in-service experience.

- independent tests on different designs of siphonic system using a specially constructed experimental facility at HR.

The project was funded by the Construction Sponsorship Directorate of the Department of the Environment (DOE) and by HR Wallingford. Substantial in-kind contributions were also made by three manufacturers/suppliers of siphonic systems who participated in the project; these companies were Engineering Services (Humber) Limited, Fullflow Systems Limited, and Sapoflow Limited in association with Sommerhein AB.

It should be mentioned here that the purpose of the review and the experimental work was to produce general information about siphonic systems and not to evaluate one type of manufactured system against another. The four systems tested were designed with different target flow capacities and used different sizes and lengths of pipe. The fact that one system had a higher capacity than another does not therefore mean that it was necessarily better designed or more efficient. This report is an open publication and the information it contains is therefore placed in the public domain. However, the report does not imply, nor should it be taken to imply, endorsement by DOE or HR Wallingford of particular siphonic systems. As explained above, the purpose of the study was to provide independent information for designers, users and manufacturers in order to improve understanding about the characteristics and performance of siphonic systems.

Chapter 2 of this report describes the theoretical basis of siphonic roof drainage systems, and Chapter 3 reviews the types of system commercially available and the extent of their use in the UK. The siphonic systems tested during the study are described in Chapter 4 and the test facility that was built for the study is described in Chapter 5. Details of initial calibration checks carried out with conventional outlets are given in Chapter 6, and Chapter 7 describes the installation and testing of four different designs of siphonic system. The results of the siphonic tests are discussed in Chapter 8, while more general features affecting the performance of siphonic systems are considered in Chapter 9. Finally, recommendations and key issues arising from the study are detailed in Chapter 10.

2 Theory for siphonic systems

Figure 1 shows a typical layout of a siphonic system draining a roof gutter. The outlets are connected by vertical tailpipes and angled junctions to a horizontal collecting pipe which conveys water to a vertical discharge pipe at the edge of the building. The system discharges into a manhole from which the water enters the pipes of the conventional site drainage system.

The flow conditions in a siphonic system vary considerably according to the rate of discharge. At lower flows, the water and air in the pipes remain distinct, with the water flowing along the invert of the horizontal pipes. The system therefore behaves in the same way as a conventional one, with the capacity controlled by the size of the outlets and the head of water above them.

At higher flows, junctions or bends may cause the pipes to flow full at some points and part-full at others. The behaviour of the air remaining in the pipes depends on the velocity and turbulence of the water flow; some air may remain above the water surface but be drawn along by the flow, or else it may become entrained into the water as bubbles. Different types of air-water flows are shown in Figure 2. Entrainment of air into bubbles is the most effective means of removing it from pipes.

If significant amounts of air continue to be drawn into the system through the outlets, it is unlikely that the pipes will be able to flow full along their whole length. Instead, parts of the system may prime and act siphonically on an intermittent basis. The instability of the flow can produce severe pressure fluctuations in the pipes and cause the water level on a roof or in a gutter to oscillate up and down. The design rules in British Standard BS 6367 (1983) for conventional roof drainage system are intended to avoid these dangers by limiting flow rates so that all pipes flow part full with pressures at or close to atmospheric.

The outlets used in siphonic systems are purposefully designed to restrict the entry of air and smooth the flow of water into the pipes. If a system is suitably sized, the high speed of the water removes the air present in the pipes more quickly than it can enter through the outlets. This causes the pipes to fill and flow full with a bubbly two-phase mixture of air and water. If the rate of run-off from the roof is higher than the flow rate through the pipe system, water will be stored in the gutter or on the roof and cause levels to increase around the outlets. This makes it harder for air to be drawn down into the outlets and enables the flow rate through the siphonic system to increase because less of the flow area is occupied by air bubbles. At some point, the depth of water at the outlets will be sufficient to cut off the supply of air completely so that the flow becomes 100% water. When this occurs, the flow rate is effectively equal to the maximum capacity for the system because the available head difference between the outlets and the point of discharge is being fully used by the flow in overcoming the hydraulic resistance of the pipes and fittings. Any further increase in flow rate through the system can only take place if there is a significant increase in the depth of water at roof level.

Flow conditions within a pipe system that is flowing full of water can be determined using Bernoulli's equation which is one of the fundamental equations in fluid mechanics. The equation can be used to describe the change in total energy that occurs along a streamline within a fluid as energy is lost in overcoming fluid resistance. The total energy of a fluid element consists of three components : the energy associated with its internal pressure; the kinetic energy due to its velocity; and the potential energy corresponding to its vertical elevation. Applying the equation between two points in a pipe system gives:

$$(p_1 + \frac{1}{2}\rho V_1^2 + \rho g z_1) - (p_2 + \frac{1}{2}\rho V_2^2 + \rho g z_2) = \Delta E_{12} \tag{1}$$

where ΔE_{12} is the energy lost between the upstream point 1 and the downstream point 2. Here p is the point pressure of the fluid, V is the corresponding point velocity, ρ is the density of the fluid, g is the acceleration due to gravity and z is the vertical elevation of the point. It is convenient in hydraulic applications to express the equations in terms of pressure head h (where $h = p/\rho g$):

$$(h_1 + \frac{V_1^2}{2g} + z_1) - (h_2 + \frac{V_2^2}{2g} + z_2) = \Delta H_{12} \tag{2}$$

where ΔH_{12} is the head loss between points 1 and 2 (= $\Delta E_{12}/\rho g$). If the volumetric flow rate is Q and the cross-sectional area of a pipe is A, Equation (2) can be written as:

$$\left(h_1 + \frac{\alpha_1 Q_1^2}{2gA_1^2} + z_1\right) - \left(h_2 + \frac{\alpha_2 Q_2^2}{2gA_2^2} + z_2\right) = \Delta H_{12} \tag{3}$$

The coefficient α allows for the effect of the variation in point velocity over the cross-sectional area of the flow. If the velocity distribution is completely uniform, α =1; the velocity distribution in a circular pipe with a fully-developed turbulent boundary layer corresponds to a value of about α =1.07. In practice, a value of α =1 is often assumed in hydraulic calculations because velocity profiles can be affected considerably by pipe fittings and the effect of the approximation is normally small and similar in magnitude to uncertainties in estimating the head losses. However, the effect of α can become more significant if the flow velocity and kinetic energy are high.

The head loss Δ H can be divided into two components, ie:

$$\Delta H = \Delta H_p + \Delta H_f \tag{4}$$

where ΔH_p is the loss due to the hydraulic resistance of the pipe walls and ΔH_f is the additional loss due to fittings such as bends, junctions, expansions and contractions. The ΔH_p component is determined from:

$$\Delta H_p = iL \tag{5}$$

where i is the energy gradient along the pipe (loss of head in m per m length of pipe) and L is the length of the section of pipe being considered. Currently the best equation for calculating the value of i is generally thought to be the Colebrook White equation :

$$\frac{1}{\sqrt{(2gDi)}} = -\frac{2.0A}{Q}\log_{10}\left[\frac{k_s}{3.71D} + \frac{2.51\nu}{D\sqrt{(2gDi)}}\right] \qquad (6)$$

in which ν is the kinematic viscosity of the fluid, D is the internal diameter of the pipe and k_s is its hydraulic roughness. Equation (6) is also known as the Prandtl-Colebrook equation. Values of k_s for different types of pipe are given in publications such as the flow tables produced by HR Wallingford & Barr (1994).

The head loss component due to pipe fittings is usually calculated from an equation of the type:

$$\Delta H_f = \frac{KQ^2}{2gA^2} \qquad (7)$$

where K is the head-loss coefficient for the fitting. Values of K may be obtained from manufacturers' data or from reference sources such as Idelchik (1986) or Miller (1990). When considering expansions or contractions, it is important to establish whether a quoted value of K is based on the upstream or downstream value of cross-sectional area. The full energy loss produced by a fitting such as a bend may not occur until some distance downstream, but for calculation purposes it is often assumed to be concentrated at the fitting itself.

With the information described above, it is possible to use the Bernoulli equation (3) to determine the limiting flow capacity of a siphonic system and to calculate the mean pressure and velocity at any point within the pipework. Equation (3) should be applied in a step-wise fashion to each pipe length or pipe fitting in turn. A suitable procedure for analysing a system consisting of a single outlet and discharge pipe is as follows:

(1) Make a first estimate of the likely flow rate Q in the system.

(2) Start at the downstream end of the system with section 2 at the exit point from the last pipe and section 1 at an appropriate point upstream (eg at the first bend, junction or change in pipe diameter).

(3) Most systems are designed on the assumption that the last pipe is able to discharge freely at atmospheric pressure (i.e. with $h_2 = 0$). Note that the flow has not lost its kinetic energy at this point so the value of A_2 should be taken as equal to the outlet area of the pipe.

(4) Calculate the head loss ΔH_{12} from Equations (4),(5) and (7) as appropriate.

(5) Use Equation (3) to calculate the pressure head h_1 at section 1, taking account of the change in level $z_1 - z_2$.

(6) Repeat the calculations for the next pipe length and continue upstream until the outlet is reached.

(7) The last calculation should treat the outlet as a fitting with a suitable value of loss coefficient, K_o, based on the cross-sectional area, A_2, of

the spigot connecting to the tailpipe. Since the water on the roof or in the gutter is relatively slow-moving, its kinetic energy is small enough to be neglected. This can be done by omitting from Equation (3) the term containing A_1 (ie equivalent to assuming $A_1 >> A_2$).

(8) Compare the head h_1 from the last calculation with the allowable depth of water, y_0, on the roof or in the gutter. If h_1 is positive and larger than y_0, repeat steps (2) to (7) with a lower assumed flow rate Q; conversely, if h_1 is negative, the value of Q should be increased.

(9) When h_1 agrees closely enough with y_0, the value of Q is equal to the limiting capacity of the siphonic system.

The above procedure can also be used for multi-outlet systems, with a separate estimate being made of the flow rate at each outlet. However, a method of allowing for the interactions between the different parts of the system is necessary to ensure that the individual estimates converge simultaneously towards the correct overall solution.

Although the individual calculation steps are straightforward, a computer program is required in practice to deal with the complex geometries of siphonic roof drainage systems. Other calculation procedures than the one described above can be followed; for example, it is possible to start from the outlets and work down through a system. Providing the theoretical basis is similar, the same results should be achieved but it is important to ensure that the head losses and kinetic energy changes at the upstream and downstream ends of the system are treated correctly.

Figure 3 shows the mean pressure distribution that might typically occur in the siphonic system in Figure 1 when it is operating at its limiting flow capacity with 100% water in the pipes; in this figure the pressure pattern in drainage line A-G is plotted with the horizontal axis showing distance along the pipework. Upstream of the outlet (point A'), the pressure head is equal to the depth of water in the gutter. As the flow accelerates into the outlet (point A"), the pressure falls below atmospheric in accordance with Equation (3). Within the tailpipe (points A" to B), the flow loses total energy due to the frictional resistance of the pipe, but the loss is exceeded by the change in vertical elevation so that the pressure becomes somewhat less negative. At the bottom of the tailpipe, the bend produces an additional head loss and this is shown in Figure 3 as a step change in pressure. In the horizontal pipe between points B and F, the pressure falls due to frictional losses and point losses caused by the junctions with the tailpipes from the other outlets. After point F, the pressure increases because the effect of the change in vertical elevation exceeds the frictional loss in the vertical pipe. Finally, the flow discharges from the system at point G with kinetic energy due to its velocity but at atmospheric pressure (ie h = 0). Although most siphonic systems exhibit this sort of pressure profile, changes in diameter along a pipe run can produce sudden local changes in pressure.

As a general rule, the lowest pressure in the type of system shown in Figure 1 will tend to occur at the top of the vertical discharge pipe (point F in Figure 3). According to Bernoulli's equation (3), there is no theoretical limit to how low the pressure might fall below atmospheric. However, water will cavitate and turn to water vapour at a pressure of about -10m water column below atmospheric pressure (at Standard Temperature and Pressure). This provides a practical limit below which it is impossible to go, and most siphonic systems are designed to ensure that pressures do not decrease below about -7 m or -8 m water column.

Potential problems of excess negative pressures are possible on buildings taller than about 15 m, and in such cases the layout and pipe diameters need to be considered carefully in order to prevent the above limits being exceeded. With any siphonic system, it is of course also necessary to ensure that the pipes are strong enough to resist the predicted negative pressures (with a margin to allow for fluctuations about the mean values).

3 Usage of siphonic systems in the UK

3.1 Outline history

The first siphonic roof drainage system was invented and patented by a Finnish consulting engineer Mr Olavi Ebeling in 1968, and promoted initially by a Swedish company Aeromotor. In conjunction with a Norwegian consulting engineer Dr Per Sommerhein, Ebeling designed the first major installation of siphonic systems for a turbine factory in Sweden in 1972.

The Scandinavian system (called 'UV System') was first brought to the UK in 1981 under licence agreement by a Danish company, Sapolite UK Ltd. Interest in the use of the system was slow to develop until in 1985/86 it was chosen by Foster Associates for the new Stansted Airport project. From this date, the rate of installation of siphonic systems in the UK has increased at a fairly steady rate. In 1992 the activities of Sapolite UK Ltd were taken over by Sapoflow Ltd which continues to market developments of the UV System. At least three different designs of outlet have been developed in Scandinavia: the original UV, the Super UV, and the latest UV-System type.

In about 1978 a Swiss company, Geberit AG, started to manufacture the UV type of outlet under licence, but a few years later changed to producing its own 'Pluvia' siphonic system. This system began to be sold and installed in the UK in about 1988 by a firm called Fullflow Systems Ltd. Geberit siphonic systems are now available in the UK from the Swiss company and agents, and a revised version of Pluvia has recently been launched with a new type of outlet and design software.

Another competing company in the UK was IMS Ltd which obtained siphonic outlets from Scandinavia but which has ceased trading. Siphonic systems using UV outlets manufactured in Finland are now being supplied by Wiljon Ltd.

In about 1992 Fullflow Systems Ltd ceased to be an agent for Geberit, and started to market outlets and software of its own design. The new system was developed with partial financial assistance from the Department of Trade and Industry, and the configuration of the outlets was developed by a consultant, Mr Peter Fraser.

Siphonic systems have also been developed independently in Germany by Dallmer and by AKO. The Dallmer 'Raindrain' system has been marketed in the UK by Engineering Services (Humber) Ltd. The AKO system is used particularly with cast-iron pipes but is believed not to be available in the UK.

This brief history of the development of siphonic systems is intended to give potential users an overview of the present market position but is inevitably far from complete. Links between companies have changed in complicated ways, and currently new suppliers and agents are entering the UK market and possible new systems are being developed.

Different companies have different ways of dealing with the four stages involved in the supply of a siphonic system which are:

- manufacture of the outlets
- manufacture of the pipes and fittings
- design of the systems
- installation of the systems.

One company may buy in the outlets and pipes from other sources but carry out the design and installation, another may manufacture the outlets and provide the design software, while another may carry out all four functions itself. No one method of working is necessarily superior to another but the key requirements are that:

- all components of the system (i.e. outlets, pipes, jointing methods, support rails, etc) should be fit for the purpose;

- the software package for sizing the pipework should be based on correct hydraulics principles and be validated for the components used;

- the designers should be experienced and have a proper understanding of the hydraulics and materials aspects;

- the installers should be reliable and well-experienced in working with the system.

3.2 Similarities and differences

3.2.1 Overall similarities

All siphonic systems are basically similar in terms of the physical principles that govern their performance (see Chapter 2). The two most important hydraulic requirements for a successful design are that:

(1) the system should be able to "self-prime" as the flow rate increases and thus enable the pipes to flow full from roof level to the point of discharge;

(2) the sizes of the pipework should be chosen so that, at the design flow rate, the overall head loss in the pipes and fittings connecting an outlet (in a gutter or roof) to the point of discharge does not exceed the difference in level between these two points.

Although all makes of siphonic system are governed by the same physical principles, there are certain differences between them in terms of construction and methods of design. These differences are described in the following Sections.

3.2.2 Outlet design

All current designs of outlet are similar in that they consist of a bowl projecting below roof or gutter level, an internal air baffle and an external leafguard. The main purpose of the leafguard is to prevent debris blocking the openings in or around the air baffle.

The depth of the bowl varies between designs. Some are shallow so as to minimize the amount of space required below roof or gutter level. Others are deeper and therefore require more space. In principle, a deeper bowl makes it easier to prevent air being drawn into the tailpipe, but this aspect of performance also depends on the design of the air baffle. In some examples, the greater depth of the bowl is used to produce a smoother entrance to the tailpipe, thus helping to reduce the amount of head loss caused by the outlet.

There are two main designs of air baffle. One type consists of a solid plate which causes the flow to enter the bowl through small openings between the plate and the sides of the bowl. Vanes are usually incorporated to help prevent swirling of water above the plate which would, otherwise, make it easier for air to be drawn in by the flow.

The other type of air baffle consists of a perforated plate or an inverted perforated cup over the inlet to the tailpipe. The perforated baffle appears to have two main functions: it increases the water depth in the bowl at low rates of flow, making it harder for air to be drawn down by the water; and it disrupts the formation of air-entraining vortices and helps prevent cyclic surging of the flow within the bowl.

The two types of air baffle may have some similarities to two classes of siphon that have been used for many years for dams and river regulation. "Blackwater" siphons are designed to be as efficient as possible at preventing the entrance of air and tend to exhibit an early but fairly sudden transition from part-full to full-bore flow and vice versa. "Air-regulated" siphons, by contrast, are designed to adjust more gradually by allowing a variable amount of air to be drawn in with the water at lower rates of low. The solid type of air baffle appears to be closer to the blackwater siphon in concept, and the perforated baffle may behave more like an air-regulated siphon. Although an air-regulated design should be smoother in operation than a blackwater one, it is necessary to ensure that it is effective at preventing the entry of air when required to operate at its maximum flow capacity. When the flow rate decreases at the end of a storm, the air-regulated type will tend to admit air more gradually back into the system and reduce pressure fluctuations occurring during the de-priming process.

Another important aspect of design is the method used for jointing an outlet to the gutter or to the membrane of the roof in which it is installed. The leafguard also needs to be fitted securely because, if this is not kept in place, the outlet is liable to become blocked by debris.

3.2.3 Pipes and fittings

The key hydraulic requirements for pipe and fittings used in siphonic systems are that:

(1) The components should be able to withstand the maximum expected positive and negative pressures;

(2) the joints should be air-tight and capable of being made to a consistent standard;

(3) the head loss characteristics of the pipes and fittings should be known and allowed for correctly in the design calculations;

(4) the support system should be capable of withstanding forces due to thermal expansion, flow-induced vibrations in the pipework and forces exerted by the flow at bends and other fittings.

The main types of pipe and fitting used in UK schemes are made from: high-density polyethylene (HDPE); unplasticized polyvinyl chloride (uPVC); and acrylonitrile butadiene styrene (ABS). Cast-iron pipes are also suitable and are more common in other countries such as Germany.

HDPE pipes may be jointed by means of electro-fusion or electro-welding techniques. In electro-fusion, a sleeve is positioned over the joint between two plain-ended pipes and welded to the pipes by passing electric current though a metal coil imbedded in the sleeve. This method is particularly convenient for making joints on site but the amount of current applied to the sleeve needs to be carefully controlled: too little and the joint may not be air-tight; too much and the pipe walls may melt and deform. Good results also depend on the sleeve and coil being manufactured to a consistent standard. In electro-welding, two plain-ended pipes are positioned either side of a metal plate and heated to a high temperature by passing an electric current through the plate; the plate is then withdrawn and the two pipes forced strongly together to make the joint. Although it is possible to use the equipment in the field, it is rather bulky and is more commonly applied by siphonic suppliers to pre-assemble lengths of pipes in the factory before delivery to site. It is also used by some suppliers to make their own special fittings such as large diameter mitred bends and reducers. The electro-welding technique produces joints with an internal bead. It is possible to remove the beads in straight lengths of pipe but not generally in curved fittings such as mitred bends. Removing the beads is time-consuming (and therefore expensive) and is not usually done. However, the presence of the beads can have a significant effect on the hydraulic resistance of the pipes. Intrusion of melted plastic into the bore of a pipe may also occur with electro-fusion sleeve joints.

uPVC and ABS pipes in siphonic systems are normally jointed using chemically-cemented spigot and socket joints, although 'O' ring compression joints are a possible alternative. The quality of cemented joints is dependent on the skill of the installer; some intrusion of cement into the pipe bore may occur, and it can be difficult to check the air-tightness of the joints under site conditions.

As mentioned above, the pipes in siphonic systems obviously need to be able to withstand the expected negative pressures. However, pipes are normally rated in terms of positive pressures, and information on their ability to resist negative pressures is not always available from their manufacturers. Under positive pressures, the walls of a pipe tend to deform symmetrically until the tensile strength of the material is exceeded. Under negative pressures, the walls tend to deflect inwards asymmetrically, leading to localised overloading and failure at considerably lower pressure differentials than apply under positive pressures. If pipes are jointed using 'O' rings or equivalent methods, it is also necessary to ensure that the joints will remain stable and airtight when subjected to negative pressures. It is, therefore, important that the performance of pipes and fittings used in siphonic systems should have been demonstrated by test under both negative and positive pressure conditions.

In order to minimize head losses, some but not all suppliers avoid the use of 90° bends, elbows or junctions. If a 90° change of direction is necessary, this may be achieved by using two 45° bends in series to produce, effectively, a longer radiused bend with a lower loss coefficient than standard manufactured fittings.

3.2.4 Computer design packages

Most but possibly not all UK suppliers of siphonic systems use proprietary computer packages to design the pipework. All the packages appear to be based on the application of Bernoulli's equation to determine the relationships between pressure, velocity and energy loss (see Equation (1)). Frictional losses at the pipe walls are calculated using the Colebrook-White resistance equation and an assumed value of pipe roughness, k_s (see Equation (6)).

Despite these overall similarities, there are some differences between the various design packages and the ways in which they are used. Some of them carry out the fundamental hydraulic calculations and provide detailed outputs of the flow conditions, but require the user to interpret the results and modify each design accordingly. Other packages can optimise the design automatically and produce other outputs such as costs and schedules of quantities, but these tend to give the user less information about the flow conditions. Some packages are dedicated to one type of outlet and make of pipe, while others are more flexible and allow the user to specify pipe diameters and loss coefficients. It is worth noting that head loss varies according to the fourth power of pipe diameter so it is very important to specify internal diameters accurately when designing systems; changing from one grade of pipe to another having the same nominal diameter but a different wall thickness could have a measurable effect on flow capacity.

Another area of difference concerns the losses at pipe fittings. One program inspected does not consider them individually but compensates by using a higher-than-usual value of k_s for the frictional losses at the pipe walls. This is less accurate and could lead to under-design if a system has a proportionately larger number of fittings than normal; also, adverse negative pressures at particular fittings may not be correctly predicted. Most other design packages assume fixed values of the loss coefficient, K, in Equation (7) for standard types of fitting, eg 90° bends, 45° bends, tee junctions, outlets, etc. Provided suitable values are chosen, this assumption will usually be reasonable because small differences between one make of fitting and another will often be insignificant compared with the effects of other uncertainties (eg interactions between fittings, value of k_s for the pipe material, etc). However, loss coefficients for tee junctions are harder to standardize because they can vary considerably depending on the ratios of the flow areas and flow rates and on the junction angle of the tee.

Most design packages carry out the hydraulic calculations on the assumption that the system is operating at its maximum capacity with all pipes flowing 100% full of water; this is the basis of the theory given in Chapter 2. However, one package permits systems to be designed for air-water mixtures provided the air content does not exceed 40%. It is believed that the calculations are carried out using Bernoulli's equation but treating the air-water mixture as a homogeneous bubbly liquid with a lower density than water. The behaviour of two-phase flows is complex and the following factors can be expected to be important:

- the considerable expansion of the air bubbles as the flow travels from regions of high pressure to low pressure in siphonic systems;
- the effect of the air on the frictional resistance of the pipes and fittings;
- the flow velocities and turbulence levels needed to prevent the air bubbles from coalescing to form distinct air and water phases.

3.2.5 Design criteria

Siphonic systems designed using the computer packages described in Section 3.2.4 are normally checked to ensure that they comply with five performance requirements. At the design rate of flow for a system, the following criteria need to be satisfied:

(1) maximum flow rate at each outlet should not exceed the rated capacity of the outlet (as specified by the manufacturer/supplier);

(2) maximum head loss between any outlet and the point of discharge should not be greater than the difference in level between those two points;

(3) minimum pressure at any point in the system should not be lower than a specified value (typically, -8m of water column (wc) below atmospheric pressure);

(4) minimum flow velocity at any point in the system should not be less than a limiting value (typically, 1m/s);

(5) maximum imbalance in pressures between outlets connected to a common discharge pipe should not exceed a certain limit (eg, 1m(wc)).

Most types of siphonic outlet are rated by their manufacturers/suppliers for maximum flow rates between about 10 l/s and 12 l/s, although at least one company produces a smaller outlet optimized for flow rates up to 6 l/s. The rating is normally determined by the need to prevent flow depths in gutters or on flat roofs exceeding specified limits (eg 30 mm, 35 mm or 50 mm). However, if the normal limit can be relaxed, most of the outlets are probably capable of accepting somewhat higher rates of flow without difficulty.

The limit on minimum pressure is intended to provide a margin of safety against possible collapse of the pipes and damage by cavitation resulting from vaporization of the water. The limit is normally compared with the values of mean pressure predicted by the design program, but these do not take account of the local pressure reductions caused by bends and turbulence in the flow. This factor is discussed further in Chapter 9.

Two different reasons for specifying a minimum velocity are sometimes given. One is to ensure that any debris entering a siphonic system will be transported easily through it and will not deposit and form blockages. The other reason given is to allow rapid entrainment of air in the pipes and to enable any such air to be transported in bubble-form through the system. Although both are important considerations, evidence from previous studies on these topics suggests that the water velocity needed to entrain air will usually be considerably higher than the self-cleansing velocity for prevention of blockages. The minimum flow velocity used in design should therefore be determined by the entrainment criterion (see also Chapter 9).

The question of the acceptable degree of pressure imbalance between outlets in a siphonic system is one of the key areas of difference between the various manufacturers and suppliers. Ideally, the head loss between roof level and the point of discharge should be the same for every outlet in a given system. However, this can be difficult to achieve because the flow from an outlet at the upstream end of the system has further to travel, and therefore tends to experience greater head losses, than an outlet at the downstream end. One solution is to use larger diameters of tailpipe for the outlets near the upstream end than for those near the downstream end so as to balance the overall head losses. However, this becomes more difficult in long systems with many outlets because the minimum velocity criterion prevents the use of tailpipes and collector pipes larger than a certain size. Also, the steps in available sizes of pipe may make it difficult to obtain an exact balance between outlets. Some designers may therefore choose to install orifice plates in some of the downstream outlets in order to increase the overall head losses and make them more equal to the losses at the upstream end of the system. However, other designers choose not to use orifice plates on principle, presumably because of concerns about possible blockages. Small changes in the diameter of orifice plates can have large effects on head loss so they need to be designed and installed accurately.

Siphonic systems do not have to be perfectly balanced in terms of head loss in order for them to operate satisfactorily. However, if an outlet has too much excess flow capacity it will tend to suck considerable amounts of air into the pipes; this can cause partial de-priming of the system and reduce the flow capacity of the outlets further upstream. There is no general consensus among the different suppliers about the acceptable degree of imbalance, but a typical figure for the maximum allowable difference in head loss between outlets in a given system is 1 m(wc).

Another approach adopted is to accept that there may be significant differences in flow capacity between the outlets draining a particular gutter, but to assume that water which cannot be accepted by outlets at the upstream end of the system will flow along the gutter to those outlets at the downstream end which have excess flow capacity. While there will certainly be some tendency for this to happen, studies have not yet been made of the effect of such a flow re-distribution on water levels along a gutter and of the time needed for it to occur; there may also be some effect on the speed with which a system primes and acts siphonically.

A variation on this approach is to accept an unbalanced design, but to assume that some of the outlets will continue to draw in significant quantities of air at the design rates of flow (ie, with no significant re-distribution of flow within the gutter). This allows a wider choice of pipework solutions to a given drainage problem. However, in order to design a system on this basis, it is necessary to be able to describe the flow characteristics of air-water mixtures correctly and to determine the separate flow rates of the two phases at all points within a system. This design approach is therefore considerably different from the others described earlier, all of which assume the pipes to be flowing 100% full of water under design conditions.

3.3 Extent of UK usage

Precise information on the number of siphonic roof drainage systems installed in the UK since 1982 is not available but it is estimated that the current total is of the order of 10 000. This figure is based on the definition of a "system" as consisting of all the outlets and pipework that discharge to ground level via a single discharge pipe; thus several separate systems may be used to drain a large building. The total number of systems installed throughout Europe is likely to be several times the UK figure.

The majority of siphonic systems in the UK have been installed in modern steel-framed buildings such as are commonly used for supermarkets, warehouses, offices and industrial purposes (see Plates 1 to 3). The advantages of siphonic systems for these types of building are considerable because they do not compromise the use of the internal space and avoid the need for individual rainwater pipes and below-floor drainage systems. As a result, siphonic systems now account for a significant part of this market, and are regularly specified by certain developers and owners (e.g. supermarket chains). Siphonic systems are also frequently used on specialized buildings such as football stadiums (e.g. Arsenal and Millwall) and airport terminals (e.g. Stansted and Heathrow) where there is a similar requirement for large unrestricted spaces. Siphonic systems are not usually considered for smaller commercial buildings and domestic housing where there are no difficulties in installing perfectly adequate conventional systems.

In Scandinavia, where siphonic systems originated and have been widely used, they are most commonly installed to drain flat roofs, which are often constructed in concrete and therefore intrinsically watertight. By contrast, it is more common in the UK for siphonic outlets to be installed in valley or parapet gutters that drain pitched metal roofs. With this type of construction, it is often difficult to ensure a watertight seal between the gutter and the roof along the entire length of the building. Thus, if the gutter should be overtopped in a heavy storm, there is a strong possibility that water could enter the building and cause serious damage or disruption. The differences between the UK and some other European countries in terms of construction techniques and also meteorological conditions were not initially fully appreciated and sometimes led to inappropriate choices of design rainfall intensity.

Although siphonic systems are now specified for a significant number of new projects, many architects and owners still prefer to use conventional systems. Reasons for this include:

(1) perceived doubts about the reliability of siphonic systems;
(2) unfamiliarity with the operating principles;
(3) difficulty of carrying out independent checks of the suppliers' designs;
(4) lack of coverage of siphonic systems by Standards and building regulations.

The first question will be discussed further in Section 3.4. The second problem will improve as more information and independent advice become available. However, the third problem is likely to remain a difficulty because the suppliers' design programs are complex and represent significant financial investments; careful training is also needed in their use. Concerning the last point, several systems have now obtained BBA accreditation, and a new European Standard is currently being prepared which will provide general performance criteria (but not design procedures) for siphonic systems.

3.4 In-service performance

A large majority of the siphonic systems that have been installed appear to have operated satisfactorily. However, it is known and also acknowledged by the industry that a certain number of failures have occurred in the UK and other countries. In this context, a failure is defined as an incident in which a building has suffered internal flooding due to a siphonic system not performing as expected; the flooding could be caused, for example, by a gutter overflowing, by collapse of a pipe due to excessive negative pressures, by leaks at joints or by lack of watertightness between an outlet and a gutter or roof membrane.

When considering the subject of failures, it is necessary to remember that conventional roof drainage systems also suffer a significant number of failures each year due to incorrect design, construction or maintenance. The design methods and criteria used for siphonic systems have developed with time as experience has been gained, so a failure now does not necessarily imply that current procedures are unsatisfactory.

Information on the number of failures of siphonic systems in the UK is difficult to obtain and verify, since it is a commercially sensitive issue for the manufacturers and suppliers involved. This review is, therefore, primarily based on seven separate cases in which HR Wallingford was asked to carry out design checks after flooding problems occurred. HR is also aware of at least another five cases but has only indirect knowledge of the reasons for these failures. It is not possible to estimate what proportion of the total number of failures these cases represent. However, it can be stated that the problems have not been restricted to any particular make of system.

The following causes of failure have been identified in the HR studies and in discussions with the suppliers and manufacturers of siphonic systems:

(1) Choice of too low a design rainfall intensity. [Strictly speaking, this is a 'failure' of specification and may often not be the responsibility of the supplier of the siphonic system.]

(2) Incorrect estimation of head losses in the system, resulting in a lower flow capacity than expected.

(3) Inadequate balancing of the system, leading to insufficient flow capacity at some outlets.

(4) Blockage of the outlets by debris, due to leafguards being removed or lost.

(5) Blockages within the pipework, probably due to a failure to seal off the siphonic system until all other construction work has been completed.

(6) Use of inadequate grades or types of pipe.

(7) Damage to pipes and joints, caused by flow-induced vibrations or thermal expansion.

(8) Too long a delay in priming of the siphonic action, leading to surcharging of the gutters.

(9) Insufficient flow capacity in the below-ground site drainage system, leading to surcharging of the siphonic system and a consequent reduction in flow capacity.

(10) Excessive negative pressures in the system, causing pipe collapse or damage by cavitation.

(11) Changes to the pipework layout made during installation, resulting in higher head losses than assumed in the design.

None of the cases investigated by HR suggests the existence of some unknown but fundamental problem affecting the performance of siphonic systems. Most of the failures were due to errors in the hydraulic design (causes (2) and (3) above), and could be explained satisfactorily in terms of the theory given in Section 2. One or two of the failures may have been due to poor maintenance or problems with the installation of the systems on site.

These findings indicate that it is very important for the designers of siphonic systems to have a good understanding of the principles involved. The computer packages are a vital tool in carrying out the complex calculations, but there is a danger that they may be used incorrectly if the results are not checked by an experienced design engineer.

Of the eleven possible causes of failure listed above, most can be avoided through correct application of existing information and expertise. However, there are two areas where further study would reduce uncertainties. The first issue concerns the degree of imbalance in a system (cause (3)) that can be allowed without compromising its overall performance. The second issue is the time needed for priming of the siphonic action to occur (cause (8)). This time is dependent on the size and layout of the pipework system and also on the value of minimum flow velocity specified (see Section 3.2.5). A method of reliably estimating the priming time is therefore needed.

4 Systems tested

As mentioned earlier, the second part of this research project involved the testing of siphonic systems. Following contacts with some of the major suppliers of siphonic systems in the UK, arrangements were made to test three different systems in HR's test rig: the Dallmer (Raindrain), the Sapoflow and the Fullflow systems.

The geometry of the outlets varies considerably from one system to another but basically they all comprise a leafguard, an air baffle and the outlet body or bowl connecting to a vertical length of pipe. Differences are also found in the materials used, which range from aluminium alloy and stainless steel to various types of plastic.

The Dallmer (Raindrain) outlet is shown in Figure 4 and Plate 4. It includes a thin perforated air baffle which is of smaller diameter than the bowl: the baffle smooths the entry of water into the bowl under siphonic conditions and restricts the formation of an air core. Both the perforated plate and the outlet bowl are made of a plastic material as is the leafguard; the clamp that fixes the polymer or bitumen roofing membranes to the gutter is made of stainless steel.

The Sapoflow outlet, shown in Figure 5 and Plate 5 includes a thin solid air baffle with alternate large and small flow-straightening vanes around its perimeter, a clamping ring with a gravel guard and a shallow outlet bowl. The baffle forces water to enter the bowl through small circumferential openings formed by the vanes. All the components of the outlet, including the leafguard, are either made of stainless steel or aluminium alloy.

The Fullflow outlet, shown in Figure 6 and Plate 6 is formed by a large, deep outlet bowl and a solid air baffle which forces the water to enter circumferentially and which has a streamlined shape on its underside. The outlet bowl also has a smoothly converging profile and is made of stainless steel; the leafguard and baffle are both made of a plastic material.

The differences between these systems reside mainly in the geometry of the outlets, but also in the approach adopted for the estimation of head losses in the system. In the design of the Dallmer system an overall pipe roughness coefficient, k, in the Colebrook-White equation is used for the calculation of head losses; local disturbances due to bends and other pipe fittings are not considered individually. The value of the roughness coefficient is chosen to take into account the friction losses and also the local head losses created by contractions/expansions, bends, junctions, etc. For this reason, relatively high values of k may be found in the design calculations. The Sapoflow and Fullflow design packages use separate coefficients to account for friction and local losses.

In all the three systems no use was made of orifice plates in the pipework to balance the flow but, instead, the diameters of the pipes were adjusted as necessary.

5 Test rig

5.1 General description

A new experimental rig was specially built at HR to accommodate the specific requirements of testing both siphonic and conventional drainage systems for roof gutters. These requirements were: (1) a sufficiently large head difference between the gutter outlets and the discharge point at ground level, i.e. a head drop of at least 5m so as to be representative of actual siphonic installations; (2) a section of sloping roof to produce appropriate flow conditions in the gutter; and (3) a system for producing a uniform flow distribution and run-off from the roof into the gutter.

The test rig, shown in Figures 7 and 8 and Plate 7, incorporated a pump capable of delivering a maximum flow rate of about 75 l/s to the gutter. The pump, which was installed on the ground level of the laboratory, lifted water from a sump to the main part of the experimental rig located on a balcony approximately 6.5m above ground level. For ease of testing, the pump could be switched on and off either from ground level or from the higher level of the rig. Two valves of different sizes were provided to control the flow from the pump, the smaller of which was used for lower flows or for fine adjustments.

A pipe manifold of 200mm diameter was installed above the section of roof to produce a uniform distribution of flow onto the gutter. It was designed to have a large number of small orifices, 12.7mm in diameter, so that the head loss at each orifice would be very much larger than the frictional loss caused by the flow along the manifold. Since the flow from the pump was introduced from one end of the manifold, the spacing of the orifices was made to vary along the length of the manifold to ensure a uniform inflow into the gutter along the whole of its length. A protective cowling was added to the manifold to prevent splashing and direct the flow smoothly onto the roof.

The roof was 10m long with a plan width of 1.17m and a slope of 1V:2H. The roof was made of sheets of plywood jointed to produce a smooth, plane surface, which discharged into a 12.0m long aluminium gutter with dimensions of 0.250m x 0.350m (height x width). A conventional outlet was provided at each end of the gutter and consisted of a 150mm diameter pipe (with a slightly radiused lip) connected directly to the sole of the gutter. The outlets discharged into the sump at ground level by means of two flexible hoses, thus completing the flow circuit. It should be noted that the roof was 10.0m long, so that the gutter projected 1.0m beyond the end of the roof at either end. When testing the siphonic systems, stop ends were installed to reduce the effective gutter length to 10.0m and prevent any water being drained by the two conventional outlets.

5.2 Measuring equipment

A 200mm diameter electromagnetic flowmeter was installed in the pipework to measure the flow rate from the pump. Checks of the flow in the gutter were occasionally made by using a miniature propeller meter which measures the flow velocity. The values of point velocity were then multiplied by the measured cross-sectional areas to give values of mean flow.

A total of six pressure tappings were drilled on the centerline of the sole of the gutter and connected to stilling wells to reduce oscillations of the water levels; these were measured with electronic point gauges with a repeatable accuracy of ±0.2mm. Figure 9 shows the location of the pressure tappings along the gutter.

The pressures in the pipework of the different siphonic systems tested were measured at three locations by means of diaphragm pressure transducers (Druck type PDCR 810). Due to the small wall thickness of the pipes, the transducers were screwed into plastic blocks glued to the outside of the pipes and carefully positioned so that their diaphragms were flush with the inside walls (see Plate 8). Values of fluctuating pressures were output by two metres, one giving the mean pressure and the other the root mean square (rms) value of the fluctuations about the mean (determined as the average value of the signal over a preset time).

Measurements of the air concentration in the flow at the point of discharge (under atmospheric pressure) from the siphonic system were taken using a Void-Fraction Meter (see Plate 9). The probe of the instrument has a small insulated wire tip which produces an electrical signal that is analysed electronically to determine the relative times that the tip is immersed in air and water; the ratio of the time in air to the total sampling time is equal to the point value of air concentration.

6 Tests with conventional outlets

Prior to the installation of the various siphonic systems, some tests were carried out with the gutter drained by the two conventional outlets (see Section 5.1 and Figure 7). The purpose of these tests was twofold: (1) to assess the general performance of the test rig and, if necessary, improve it by the introduction of small modifications; and (2) to check that the behaviour of the flow in the gutter was in accordance with the design assumptions contained in British Standard Code of Practice BS 6367 (1983) - Design of roofs and paved areas (see BSI, 1983).

The two conventional outlets were 150mm in diameter; the centres were located 0.150m from the ends of the gutter and were connected directly to the sole of the gutter. Each outlet drained a gutter length of 6.0m, but with inflow from the roof occurring only over the upstream 5.0m.

The procedure adopted in these preliminary tests was to increase the flow in small steps and measure the equilibrium water levels at certain fixed positions in the gutter. At the time of these initial tests, the water levels were measured directly using mechanical point gauges fixed to the sides of the gutter. They were positioned at sections 0.5m upstream of each outlet and at the mid-point of the gutter; in tests where a divide wall was introduced in the gutter, the measurements were taken at 0.10m from the wall.

Four different situations were considered in tests P1 to P4. Test P1 was carried out with both outlets in operation (the outlets were denoted D1 and D2, as shown in Figure 9). During the experiments it was observed that the flow separated from the square edge of the plywood roof and impacted on the centerline of the gutter, producing considerable splashing. It was therefore decided to round the edge of the roof to direct the flow towards the inside wall of the gutter. Test P2 was carried out after this alteration was made, with flow conditions similar to those in test P1. The rounded edge was adopted in all subsequent tests.

In both tests P1 and P2 the water level was measured 0.5m upstream of outlets D1 and D2 and at the mid section of the gutter. The results are shown in Table 1 where it can be seen that the capacity of the system formed by the gutter and two conventional outlets was between 50 and 60 l/s and, most likely, was just under 60 l/s. Although the mean water level in the gutter at mid section was still much below the top of the gutter, the waves generated by the turbulence in the flow caused intermittent spilling for Q=60 l/s. From Table 1 it can be seen that, for the same value of Q, the levels in the gutter were quite similar in tests P1 and P2. It should be noted that intermittent surging was observed at the outlets for some of the discharges tested. These small oscillations were likely to have been a result of the transition from weir to orifice flow and vice versa which occurred at particular flow rates.

Tests P3 was carried out with a divide wall positioned in the gutter near outlet D1 so that all the flow was drained through outlet D2. The results are presented in Table 2 where the capacity of outlet D2 is shown as being approximately half the combined capacity of the two outlets.

In the last test of this series, test P4, a divide wall was introduced at the mid section of the gutter and the water levels were measured on both sides of this wall at positions B1 and B2 (see Table 2), corresponding to the sections draining to outlets D1 and D2, respectively. The levels measured at positions B1 and D1 were generally slightly higher than at positions B2 and D2. This indicates the possibility that there was a small imbalance in the distribution of the flow along the roof with slightly more flow in the length draining to outlet D1. This imbalance was confirmed by checks carried out with a miniature propeller meter. It is also possible that the flexible hoses connected to the outlets were not equal in capacity, thus causing more backing up at one outlet than at the other.

It should be noted that the results of tests carried out with conventional outlets are not directly comparable with those of siphonic outlets because the layout and length of the pipework were considerably different in the two cases.

The results of tests P2 and P3 were compared with the design recommendations described in BS 6367 (1983), as mentioned earlier. The calculated water depths at the outlet and at the upstream end of the gutter are shown in Table 3, as well as the measured flow rate, and measured upstream and outlet water depths. This latter value was measured 0.5m from the outlet axis. In test P2, where the two outlets were in operation, the upstream depth was measured at the mid-section of the gutter and the flow was assumed to divide equally between the two outlets; in test P3 the length of the gutter that drained into the outlet was 11m (= 6m + 5m) and the upstream depth was therefore measured at the divide wall. It can be seen in Table 3 that the calculated and measured water depths are very similar for low and medium flows, but that they start to differ substantially for higher flows. At these flow rates the recommendations in the British Standard indicate that the flow through the outlets should be of orifice type. The water depths at the outlet were, therefore, calculated using the orifice-flow equation in BS 6367 which gives considerably higher water depths than the corresponding weir-flow equation. Observation of the flow characteristics pointed, however, to weir flow even at the higher flow rates. This behaviour may be attributed to a partial siphonic action produced by the pipework layout which could have induced weir flow at conditions where orifice-flow would normally have been expected.

7 Tests with siphonic systems

7.1 Conditions for installation

The three manufacturers of siphonic outlets that collaborated in the present research project were asked to design systems with a total capacity of the order of 25 l/s. The systems were required to consist of two outlets with tailpipes connecting to a length of horizontal collector pipe at balcony level and discharging back into the sump via a single vertical downpipe. The design flow rates could vary within the range 10 to 15 l/s per outlet to suit the particular requirements of the siphonic systems.

Stop ends were installed in the gutter to reduce its effective length to 10.0m (i.e. the same as the roof) and the siphonic outlets were installed at the quarter points (i.e. 2.5m from either end). Two square holes were cut in the sole of the gutter so that the outlets could be pre-attached to square plates that were then bolted to the sole.

An important condition was that the systems should be designed and installed according to the normal procedures of the suppliers without any additional factors of safety incorporated in the calculations. It was also required that short lengths of transparent pipe (supplied by HR) should be installed at four or five locations in each system to allow observation of the flow. The measurement of pressures was also carried out in these sections; for this purpose three of the transparent sections were fitted with special attachments for pressure transducers which were mounted flush with the internal walls of the pipes (see Section 5.2). The diameters of the transparent pipes were chosen to be as close as possible to those of the other pipes used by the suppliers but, due to the limited diameters commercially available, small contractions/expansions could not be avoided.

7.2 Description of systems tested

7.2.1 Dallmer system

The Dallmer (Raindrain) system was installed in the test rig as shown in the schematic diagram of Figure 10. With a total length of approximately 32m, the system incorporated five sections of clear pipe, three of which contained transducers for measurement of mean and fluctuating pressure (pipe nos. 6, 9 and 16). The characteristics of the pipes are also summarised in Table 4 which gives the external and internal pipe diameters, the pipe length and the angles of the bends. In this system both circular bends and elbows were used.

The system was designed for a total capacity of 24.2 l/s, with outlets R1 and R2 having predicted capacities of 10.8 l/s and 13.4 l/s respectively.

7.2.2 Sapoflow system

Sapoflow installed their first system (System no. 1) in the test rig as shown in the schematic diagram of Figure 11. The total length of the pipework was approximately 29m and incorporated four sections of clear pipe, three of which allowed the measurement of pressures (pipe nos. 5, 8 and 12). Table 5 shows the characteristics of the pipes, where it can be seen that both mitred bends and elbows were adopted.

System no. 1 was designed for a lower capacity than the others in this study and therefore used smaller diameter pipework; the design flow rate was 13.9 l/s, with 6.6 l/s drained by outlet R1 and 7.3 l/s by outlet R2. Therefore a second, higher capacity system was later installed and tested (System no. 2). The predicted flow capacity was 26.1 l/s, with 12 l/s being drained by outlet R1 and 14.1 l/s by outlet R2. Figure 12 shows a schematic diagram of Sapoflow system no. 2 and the description of the pipework is presented in Table 6.

7.2.3 *Fullflow system*

The Fullflow system installed in the test rig was designed for a total capacity of 26.9 l/s (with 13.1 l/s and 13.8 l/s at outlets R1 and R2 respectively), and had a pipework length of approximately 30m (see Figure 13). Unlike the other systems tested, the Fullflow outlet was mounted on a plate which was fixed on top of the sole of the gutter rather than under it. This arrangement produced a step of 2 to 3mm between the gutter sole and the level of the outlet. The system included five sections of transparent pipe, three of which had transducers for pressure measurements (pipes nos. 6, 9 and 17). Both elbow and mitred bends were used in the system, as can be seen in Table 7, where the characteristics of the pipework are described. Plate 10 shows the tailpipe connected to outlet R1.

7.3 Description of tests

Several different types of test were carried out to assess the performance of the siphonic systems: type 1, where each system was tested to determine its behaviour at a series of steady flow rates, increasing until the maximum capacity was reached; type 2, similar to type 1 but with the leafguards removed from the outlets; type 3, similar to type 2 but with the air baffles and the leafguards removed; type 4, similar to type 1 but with a divide wall splitting the gutter into two parts; and type 5 where the response of each system to simulated sudden rainfall was studied. In all but the type 5 tests, the flow rate was increased in small steps and kept constant until equilibrium conditions were achieved. In order to simulate storms of short duration in the type 5 tests, the pump valves were opened as quickly as possible so that the inflow rate to the gutter reached the required flow rate within about 3 to 9 seconds. Examples of the type 1 tests are shown in: Plate 11 (Dallmer system at Q = 10 l/s), Plate 12 (Sapoflow system at Q = 9.8 l/s) and Plate 13 (Fullflow system at 23.1 l/s).

In all but the type 5 tests, the water levels along the gutter were measured by means of point gauges in stilling wells connected to the pressure tappings in the gutter. Due to the short duration of the type 5 tests, the water levels were measured directly with a ruler. The values of mean and fluctuating pressures were also measured in all but the type 5 tests, where only mean values could be achieved due to the longer time required to read the rms values. Visual observations of the flow through the outlets and in the transparent sections of pipe were also made to identify the discharges at which the systems flowed full. Some measurements were also taken of the concentration of air in the flow just upstream of the exit from the vertical downpipe. Values of air concentration were obtained for tests type 1 and 2 with the exception of the Sapoflow system no. 2 (due to malfunctioning of the Void-Fraction Meter).

With each of the systems tested, the run-off entering the gutter did not divide equally between the two outlets because they had somewhat different flow capacities. This imbalance was due to outlet R1 having a significantly longer length of connecting pipework than outlet R2 (see Figures 10 to 13), though the adverse effect was reduced by the use of relatively larger pipes for R1. The suppliers of the siphonic systems tested had been asked to provide their design calculations showing the calculated capacity of each outlet. Using this information, a divide wall was positioned across the gutter so that the flow rate into each outlet was made to correspond to the design calculations. If the relative capacities of the outlets were correctly predicted, the water levels in the gutter either side of the divide wall should have been nearly equal. The results of all the tests are presented in Tables 8 to 27. Refer to Figure 9 for the location of pressure tappings 1 to 6.

A series of qualitative tests were also carried out to observe the effectiveness of the leafguards in preventing debris from entering the outlets. In these tests debris was scattered in the gutter before introducing the flow into the test rig (see Plate 14). The movement of the debris was then observed for various flow rates and the final position of the debris was recorded once the flow was turned off. Although it was not possible to determine whether or not all the debris had been kept out of the systems, it appeared that the leafguards were effective in preventing obstructions of the pipework. However, the leafguards became severely blocked, which resulted in a sharp rise of the water level in the gutter and the flow had to be turned off to avoid flooding. At the end of the test it was observed that the debris had gathered around the perimeter of the leafguards, apparently blocking them completely (see Plate 15).

8 Discussion of test results

Calculations were carried out by HR to determine the theoretical capacities of the systems tested and the values of pressure head along the pipework. These calculations were obtained from a numerical program especially written by HR for the assessment of siphonic roof drainage systems. The program was based on the theory given in Chapter 2 for systems flowing at their maximum capacity with 100% water. The Colebrook-White equation (Equation (6)) was used to determine the friction losses; local losses due to fittings such as bends, expansions and junctions were individually estimated for each fitting using published data (Idelchick (1986), amongst other sources) and information obtained from the suppliers of the systems.

As mentioned before, the suppliers of the systems tested were asked to provide design calculations so that a comparison could be made between the test results, the design calculations and HR's own calculations. The main purpose of HR's calculations was to check the suppliers' design calculations. So, for that reason, it was decided to make as much use as possible of the loss coefficients assumed in the design. However, in order to obtain a balanced solution, the flow was split differently between the two outlets. The values of the roughness coefficient, k_s, used in the HR's results were: 0.3mm (for the Dallmer system), 0.05 and 0.15mm (for Sapoflow systems nos 1 and 2, respectively) and 0.25mm (for the Fullflow system); all the pipes tested were HDPE.

A table was therefore produced (Table 28) comparing values of pressure obtained with the three different approaches at the sections monitored experimentally. The table also compares the flow rates achieved: the total flow capacity of the systems and the individual outlet capacities (only obtained in the calculations but not experimentally). It is important to remember that the four different systems were not designed to produce the same target value of flow capacity. Differences between the systems, therefore, reflect different choices of pipe size and types of fitting, and do not imply that one system has an intrinsically higher flow capacity than another.

An analysis of Table 28 shows that, in general, the total capacities of the systems were quite accurately estimated by the design calculations, as these agreed well with the laboratory tests. However, in two systems the suppliers' predicted capacities exceeded the measured values, with a maximum discrepancy of about

4%. For the purposes of this study, the suppliers calculated the capacities on the basis of the total available head, whereas in normal practice they may design systems to have a certain amount of reserve capacity (partly, because of the limitations imposed by the available steps in pipe diameter).

It should also be noted that the calculations can be strongly affected by the choice of pipe friction factors and local loss coefficients adopted, and this may explain differences between the design calculations and HR's theoretical results (this aspect was discussed earlier in Section 3.2.4).

Bigger discrepancies were found between the measured and calculated pressures. Of the three sections monitored in each system, the most negative pressures occurred, as expected, in the section of pipe just upstream of the vertical downpipe (ie Pipe 6 in the Dallmer and Fullflow systems, and Pipe 5 in the Sapoflow systems) - see Figures 10 to 13. In these sections the measured pressures (particularly in the Dallmer system) were found to be less negative than predicted by both the design calculations and HR's results. Although the head loss in the downpipe may have been underestimated, any such error would not alone be sufficient to account for the big differences observed in the Dallmer tests. One possible explanation is that the pressure transducer used in the tests was, in spite of the care in setting it flush with the internal wall of the pipe, protruding into the flow, thus measuring higher pressures. Measurements of pressure at the other two positions also show some differences when compared with the calculations. These differences are quite marked for the pipe sections immediately downstream of the junction in the case of the Dallmer, Sapoflow no 1 and Fullflow systems (pipes 9, 8 and 9 respectively). However, because of their location near the junctions, where the flow is greatly disturbed and subject to swirling, some variation in results is to be expected.

Tables 8, 13 and 23 show that the air concentration at the downstream end of the downpipes was no greater than 1% when the systems reached their capacity. This is an indication of the effectiveness of the air baffles in excluding air from the siphonic systems. The small amount of air measured is probably a mixture of air bubbles produced as a result of the turbulent inflow of water to the gutter and of air coming out of solution due to reductions in pressure within the pipework system.

Tests carried out with and without leafguards showed that they increased the water depths in the gutter (as expected), but in general terms they did not affect the ultimate capacities of the pipework systems. This applies to all the systems tested except for the Dallmer where a slightly higher capacity was achieved without the leafguard (compare Tables 8 and 9).

The effect of air baffles in the outlets on the system performance was also investigated. It was found to depend on the system in consideration. In the case of the Dallmer and the Sapoflow no 2 systems, removing the air baffle appeared to reduce the flow capacity to about 98% of the values with the baffle and leafguard in place. On the contrary, the capacities of Sapoflow no 1 and Fullflow appeared to increase (2% and 1%, respectively). However, oscillations of the flow were observed in the tests of Sapoflow system no 1 without the baffle. In all the cases, the pipes became full at lower flow rates when the air baffle was not present, which was an unexpected behaviour.

The tests with a divide wall (see Tables 11, 16, 21 and 26) were carried out so that the total flow entering the gutter would be divided between the two outlets in the same ratio as the predicted flow capacities (as given by the suppliers' calculations, see Table 28). Similar water depths on either side of the wall were therefore expected to be measured. The divide wall was positioned between tappings 4 and 5 but closer to tapping 4 in all the tests; because of this, figures in the tables do not allow definite conclusions to be drawn. However, additional measurements with a scale indicated that the levels were different by about 8% and therefore that the predictions of the relative flow capacities of the outlets were not completely accurate.

All the systems responded well to sudden increases in the flow rate and no hunting or instability was observed in the flow at the outlets; in some cases, however, the maximum water depths in the gutter were a little higher and the pressures somewhat more negative than those obtained in the equivalent steady-state tests. Higher water levels and more negative pressures are likely to have occurred due to inertial effects as the water in the pipes accelerated in response to the rapidly increasing flow rate.

9 Key issues for siphonic systems

9.1 General

The laboratory tests described in Chapters 4 to 8 show that the principles behind siphonic systems are valid, and that the maximum flow capacity of a system can be predicted satisfactorily using the theory given in Chapter 2 together with appropriate values for the loss coefficients of the pipes and fittings. However, the HR tests and the information reviewed in Chapter 3 show that siphonic systems differ from conventional roof drainage systems in certain key respects. These differences need to be clearly understood by both designers and specifiers, and are discussed in the following sections.

9.2 Integration of design

Siphonic systems represent a higher level of technology than conventional ones and therefore require correspondingly higher standards and skills in their design and installation. A siphonic system is a total product and all its components (outlets, pipes, joints and supports) need to work satisfactorily if the potential advantages are to be realized.

In a conventional system, the vertical rainwater pipes are designed to flow part full of water so there is no interaction between flow conditions at roof level and those below ground in the site drainage system. This is not the case with a siphonic system because, under design conditions, the full-bore pipes provide a direct connection between the two other components. Lack of capacity in the siphonic part will cause water levels to rise at roof level; similarly, if the below-ground system cannot accept all the discharge from the building, it may surcharge and reduce the head acting on the siphonic system, leading to backing-up of the flow at roof level.

Some building or roofing designers are under the impression that siphonic outlets are able to produce lower water levels in gutters than conventional outlets of similar size. This is not the case: the suction effect only begins inside the siphonic outlet and the normal laws of open-channel hydraulics still apply to the flow upstream of the outlet. Both siphonic and conventional outlets installed in fairly wide gutters will tend to prevent the gutters from discharging freely; this is equally the case with conventional outlets. It will therefore normally be necessary to design the gutters using the method given in Appendix B of BS 6367 (see BSI, 1983) for the condition of restricted discharge; also needed is information on the relationship for the outlet between flow rate and water depth in the gutter.

In summary, it is important that designers and installers of gutters, siphonic systems and site drainage systems should exchange information about their particular requirements. This is not always straightforward because the three systems are often the responsibilities of different sub-contractors. It is therefore necessary that the organization having overall responsibility for the project should ensure satisfactory co-ordination between these sub-contractors.

9.3 Design rainfall intensity

The choice of design rainfall intensity is a very important matter for any type of roof drainage system. It should be decided on the basis of an economic balance between the cost of the system and the cost of possible flooding damage that might occur during the life of the building if the system were to overflow; note, that designing for absolute security is normally not feasible and some degree of flooding risk must be accepted.

A siphonic system, because of its hydraulic characteristics, will tend to be more sensitive than a conventional one to increases in rainfall intensity. As an example, consider first a conventional design in which the outlets are sized to operate with a water depth of 100mm in the gutters. If the rainfall intensity were to be 10% greater than the design figure, the outlets would be able to deal with the extra flow if the water depth in the gutters could safely increase by about 7mm. Consider now an equivalent siphonic system sized to make full use of the 7m height of the building at the design rainfall intensity (ie, with no flow capacity in reserve). If the design rate were to be exceeded by 10%, the water depth in the gutter would need to increase by about 1.5m in order for the system to be able to pass the higher rate of flow; in most cases, this would obviously not be possible.

This difference between the two types of system needs to be understood clearly. The siphonic design is not "unsafe" because, if designed satisfactorily, it will deliver the level of performance required by the specifier, but usually with only a little in reserve (unless the designer has built-in a significant factor of safety). Any error made in selecting an appropriate value of design rainfall intensity is, therefore, more likely to become apparent with a siphonic system than with a conventional one. Designers of buildings thus need to consider carefully the degree of security against flooding that they require, taking into account the type of roof construction and the consequences of possible flooding.

One way of catering economically for very rare storm events is to install overflows in gutters or on flat roofs. The overflows may discharge from the building at a high level or into a separate conventional or siphonic system. Overflow weirs installed at either end of a long gutter can provide early warning of possible flooding problems, but they will rarely have sufficient flow capacity to prevent the gutter being overtopped in the middle sections remote from the overflows.

In some instances it has been argued that storage effects enable a siphonic system to be safely designed for a lower flow rate than the design rate of run-off from the roof. Although BS 6367 recommends that design rainfall intensities should normally be determined assuming a duration of 2 minutes, it needs to be appreciated that these events will usually be parts of longer storms having somewhat lower mean intensities. In most cases the volume of storage in a gutter and the associated siphonic pipework will be significantly less than the volume of rainwater in the whole storm. As a result, the amount of attenuation due to storage effects will usually be too small to justify a reduction in the design rainfall intensity for the system, whether it be siphonic or conventional. The recommendation in BS 6367 is therefore valid that each component of a rainwater system should be designed to cater for a flow rate equal to its contributing catchment area multiplied by the chosen value of rainfall intensity.

9.4 Negative pressures

As explained in Section 3.2.5, low pressures in siphonic systems need to be considered for two different reasons. The first reason concerns the structural strength of the pipes to resist negative pressures. Pipes collapse more easily than they burst because negative pressures tend to accentuate any asymmetries in the pipe walls and lead to a "buckling" mode of failure. Secondly, cavitation damage to the internal walls of the pipes may occur if the pressures are too low.

Cavities are formed in a liquid when the pressure at a point falls close to the vapour pressure of the liquid. The value of vapour pressure depends on the temperature of the liquid; when water boils at 100°C, the vapour pressure is equal to 1 bar absolute pressure (i.e. 1 atmosphere). However, at a temperature of 15°C, the vapour pressure is only about 0.017 bar absolute, so cavitation will not occur until the local pressure falls to about 0.98 bar below atmospheric (equivalent to a negative pressure head of about -10.0 m of water column (wc) at sea level).

Cavitation damage is not caused by the formation of the cavities but by their collapse. If cavities move to points of higher local pressure, they tend to implode violently and can exert extremely high impact forces on adjacent solid surfaces. Concentrated impact pressures as high as 15000 atmospheres have been measured, which serves to explain how cavitation is able to cause serious damage to even very strong materials such as stainless steel. More flexible materials such as polyethylene tend to resist cavitation damage better than metals and other more rigid plastics.

The conditions needed for cavitation to occur can be determined from the value of the non-dimensional cavitation index, σ, for the pipe or fitting. This quantity may be defined as:

$$\sigma = \frac{p + p_a - p_v}{\frac{1}{2}\rho V^2} \tag{8}$$

where p is the mean static pressure (relative to atmosphere) at which cavitation first occurs, p_a is the absolute value of the atmospheric pressure (e.g. 1 bar = 10^5Pa), p_v is the vapour pressure of the liquid, ρ is the density of the liquid and V is the mean velocity of the liquid; consistent units (e.g SI) must be used throughout. In the case of water, it can be convenient to express Equation (8) in terms of pressure head, h:

$$\sigma = 2g\left(\frac{h + h_a - h_v}{V^2}\right) \tag{9}$$

where g is the acceleration due to gravity and the subscripts have the same meanings as above.

The higher the value of σ that a pipe fitting has, the more easily will it cavitate. Cavitation bubbles are able to form in a flowing liquid when $\sigma > 0$ because turbulence and separation eddies give rise to fluctuations that reduce the local instantaneous pressure from the mean value, p, down to the vapour pressure, p_v. Equations (8) and (9) show that the cavitation potential of a particular fitting becomes greater if:

- the flow velocity is increased;
- the temperature is raised (leading to an increase in p_v and h_v)
- the mean static pressure is lowered;
- the value of atmospheric pressure is reduced (e.g. by the effects of altitude).

As an example, experiments by Tullis (1981) show that a particular type of 90° bend with a nominal diameter of 75mm will begin to cavitate when $\sigma = 2.37$ and start to suffer damage when $\sigma = 2.13$. If the flow velocity in the bend were V = 3m/s, cavitation damage could occur if the mean pressure at that point were lower than h = -9.0m(wc) (assuming atmospheric pressure of 1 bar and water at 15°C). If the flow velocity were increased to V = 6m/s, damage could occur if the pressure was lower than -6.1m(wc).

The above example indicates that a fixed value of minimum pressure (e.g. - 8m (wc)) may not always be an appropriate design criterion for siphonic systems. Instead, it is recommended that a minimum value of cavitation index, σ, should be applied based on the most critical type of fitting used in the system. This alternative criterion would be straightforward to implement in computer packages, and would take proper account of the combined effects of low pressure, high velocity, altitude and water temperature.

9.5 Balancing of systems

As explained in Section 3.2.5, there can be difficulties in achieving equal flow capacities for outlets at the upstream and downstream ends of long siphonic systems. As a result, some suppliers have developed different criteria for the acceptable degree of imbalance in a system and for the amount of air (if any) that can be allowed to be drawn in under design flow conditions.

Although it does not appear to have been used yet, one straightforward way of avoiding these difficulties would be to accept that outlets in a siphonic system will not have equal flow capacities and to adjust the spacings between them accordingly. Thus, an outlet with lower capacity at the upstream end of the system would be required to drain a smaller area of roof than an outlet with higher capacity at the downstream end. This would allow more flexibility in the choice of pipe sizes, although some iteration in the design process might be necessary because the exact locations of the outlets could not initially be specified. Some education of architects and roofing contractors might also be necessary to convince them that outlets do not have to be spaced at regular intervals. The main advantage of this approach is that it would remove an area of present uncertainty from the design calculations. Systems could be sized to flow 100% full of water under design conditions with no imbalances in pressure and with good confidence that this situation would be achieved in practice.

9.6 Priming of siphonic action

The time taken for a system to prime and act siphonically is an important factor that cannot yet be reliably predicted. The four systems tested in the HR experiments (see Chapters 4 to 8) primed quickly and responded with little delay to rapid changes in flow rate. However, it is known that problems have occurred with some designs, and that the time for priming to take place can be significantly affected by variations in pipe size and layout.

More study is needed to understand and quantify the physical processes involved in the priming of a siphonic system. The main requirement is that enough air must be removed from the pipes to enable them to flow full-bore, either with 100% water or, at lower rates of flow, with a mixture of water and air bubbles. The HR tests showed full-bore flow occurred when the flow rate of water exceeded about 70% to 90% of the maximum capacity of the system. However, this limit is a function of the water velocity and is likely to vary from one design to another. Until all the pipework from outlet to discharge point is flowing full-bore, the system cannot make complete use of the available head provided by the height of the building.

Since rainwater systems in the UK are designed for 2-minute storm events, it is suggested that a suitable performance requirement for speed of priming might be as follows: siphonic systems shall be designed so that the discharge from a system is able to vary from zero to the maximum capacity of the system in 60 seconds or less. It is not feasible to impose such a requirement at the present time because a quantitative method of predicting the speed of priming is not yet available. However, it is possible to identify the following features which help or hinder the priming process:

(1) Outlet design. The air baffle and bowl need to be shaped so that the entry of air into the pipework is restricted as much as possible even when depths of water in the gutter or on the flat roof are small. The head loss produced by the baffle should not be too large because, otherwise, it may reduce the initial flow capacity of the outlet when it is operating in a non-primed state and, thereby, increase the time needed for the system to fill and prime.

(2) Minimum flow capacity. If the velocity of water in a pipe is too low, it will not be able to entrain air into the flow or prevent bubbles rising to form air pockets along the soffits of the pipes. If the latter happens, the siphonic action is reduced and there is a risk of slug flows developing and causing large pressure fluctuations.

An experimental study by Volkart (1982) on flow in steep pipes showed that air entrainment will not occur until:

$$V > 6.0 \left(\frac{gA}{P}\right)^{½} \quad (10)$$

where A is the cross-sectional area of the flow and P is the wetted perimeter of the pipe. For a circular pipe flowing half-full, the minimum entrainment velocity given by Equation (10) varies from V = 2.1m/s in a 50mm diameter pipe to V = 3.6m/s in a 150mm diameter pipe. Similar values of 2-3m/s for the entrainment velocity were found by May et al (1991) in laboratory research on aeration systems for dam spillways. Siphonic systems will prime and run full much more quickly if the air in the pipes is entrained in the form of bubbles than if it is dragged along by the surface of the flowing water. For these reasons, it is considered that a minimum design velocity of 1m/s or less (as used by many manufacturers and suppliers) may not always be sufficient to ensure rapid priming of siphonic systems. The experimental evidence described above suggests that, in long lengths of horizontal pipe, a minimum velocity of the order of 2m/s (under design conditions) may be necessary to ensure good air entrainment and rapid removal of air.

(3) Vertical tailpipes. The tailpipe connecting an outlet to a horizontal collecting pipe (see Figure 1) is an important factor determining the ability of a siphonic system to respond to rapid increases in flow rate. The mini-system formed by the outlet and tailpipe up to the point where it joins the horizontal collector pipe can be designed to act independently of the rest of the system during the early stages of filling. Rapid priming of this mini-system can be achieved if the water dropping down the tailpipe accelerates sufficiently to produce a strong hydraulic jump sealing the entry to the collector pipe. This jump can have two beneficial effects: it removes the air from the tailpipe very rapidly and also prevents it being replaced by air from the collector pipe. Once primed, the tailpipe produces a strong suction effect at the outlet even if the rest of the system is not yet acting siphonically. Another advantage is that the high rates of inflow from the tailpipes help to remove

tailpipes help to remove the air from the collector pipe more quickly and reduce the time needed for the whole system to prime. The above discussion also highlights the problems that may arise if the tailpipes are oversized (in an effort to minimize head losses) or if they consist of a small vertical drop and a long length of nearly horizontal pipe connecting to the collector pipe. In such cases, the initial flow capacity of the tailpipe is very limited so the filling and removal of air from the system may occur much more slowly. In order to ensure that a system will be able to prime rapidly, it is suggested that two separate design checks should be made. Firstly, the design flow rate into an outlet should be determined in the normal way assuming the whole system to be acting siphonically. Secondly, the mini-system formed by each outlet and its tailpipe should be checked to ensure that, when acting siphonically, it can deal with the rate of flow entering the outlet but with armospheric pressure existing in the horizontal collector pipe.

A separate but related issue concerns the breaking of the siphonic action at the point of discharge into the below-ground site drainage system. This is best achieved by discharging the siphonic system into a vented manhole, which should be large enough to provide some stilling and prevent high velocity flow jetting directly into the outgoing drainage pipe. A direct connection should not be made between the siphonic pipework and ordinary drainage pipes because the latter may be subjected to negative pressures which they are not able to withstand. Some designers add a sudden expansion section at the downstream end of the siphonic system to ensure a clean breaking of the siphonic action; this duplicates, but in a less effective way, the effect of the manhole.

The pipework from the building to the first manhole should be included in the hydraulic design of the siphonic system. Two extreme cases need to be considered. In the first, it should be assumed that the water level in the manhole is at the soffit level of the incoming siphonic pipe; this will give the lowest possible value of pressure in the siphonic system. In the second case, it should be assumed that the manhole is surcharged up to ground level; this will give the minimum possible flow capacity for the system. Arrangements should be made to ensure that the manhole cannot surcharge above ground level; this may be done by using a grated cover for the manhole.

9.7 Construction and maintenance

Siphonic systems need to be installed precisely in accordance with the design drawings because small changes in layout or pipe size can have large effects on flow capacity. Sometimes, changes on site are unavoidable but if this happens the hydraulic design calculations should be re-checked and action taken to remedy any shortfall in performance.

Regular maintenance of all rainwater drainage systems is necessary to prevent blockage by leaves and other debris. In the case of siphonic systems, it is important to ensure that the leafguards are in place and are regularly cleaned, otherwise the outlets or pipework may become clogged, leading to the risk of design water depths in gutters or on flat roofs being exceeded. Many owners of buildings are unaware that they are drained by siphonic systems. The maintenance manuals given to owners therefore need to explain this and stress the need for regular maintenance.

10 Conclusions

10.1 Theory and usage of siphonic systems (Chapters 2 and 3)

(1) Siphonic systems have considerably higher flow capacities than conventional roof drainage systems because their design enables them to make full use of the pressure head provided by the height of buildings.

(2) Siphonic systems now account for a significant proportion of new roof drainage systems in the UK and other parts of Europe. It is estimated that of the order of 10 000 systems have so far been installed in the UK and that the worldwide total is likely to be several times this figure.

(3) Siphonic systems are mainly used in large commercial and industrial buildings because they can eliminate the need for internal downpipes and allow more flexible use of internal spaces. These advantages also make them suitable for special buildings such as airport terminals and sports stadiums.

(4) Various proprietary systems are available but they all work in accordance with the same physical principles. However, there are differences between some of them in terms of outlet design, choice of pipe material and method of support.

(5) Nearly all systems are designed using computer packages which are based on solutions of the Bernoulli energy equation and the Colebrook-White resistance equation. The design packages differ somewhat in the degree of automation provided and in the values of the loss coefficients for certain types of pipe and fitting. Some packages also differ in terms of the degree of imbalance allowed between outlets in a given system and in the amount of air (if any) that is assumed to be carried by the flow.

(6) Failures of siphonic systems have occurred in the UK and elsewhere. Of the cases studied by HR Wallingford, all the failures were attributable either to errors in design or to problems caused by blockages occurring during or after construction. None of the cases indicated a fundamental flaw in siphonic systems but did highlight the importance of designers and installers adhering to established procedures and principles of good practice.

10.2 HR experimental study (Chapters 4 to 8)

(1) Preliminary tests carried out with the gutter in the HR rig drained by two conventional outlets showed very good agreement with the design recommendations for gutter capacity given in BS 6367 (1983), particularly for low and medium flow rates.

(2) Four different siphonic systems were studied experimentally and calculations were also carried out by HR to determine their theoretical capacities and values of pressure head along the pipework. In general, it was found that the total capacities of the systems were satisfactorily estimated by the design calculations. The estimation of pressure heads was found to be less accurate: the measured pressures were generally less negative than predicted by both the design calculations and HR's theoretical results; this suggests that the design methods will tend to err on the conservative side in terms of negative pressures.

(3) Measurements of the air concentration at the downstream ends of the downpipes indicated that only a very small amount of air (not greater than 1% in volume) was present in the systems tested when they reached their ultimate capacities; this may have been caused by dissolved air coming out of solution within the systems.

(4) Although a tendency for an increase in capacity was observed for one system when the leafguards were removed, the presence of leafguards generally appeared to have little influence on the ultimate capacities of the systems.

(5) Qualitative tests showed that the leafguards tested appeared to be very efficient in preventing debris from entering the outlets. However, the collection of debris around the perimeter of the leafguards resulted in a sharp rise of the water level in the gutter and therefore highlighted the need for frequent maintenance of roof drainage systems.

10.3 Key issues (Chapter 9)

(1) Siphonic systems represent a higher level of technology than conventional systems and need higher standards and skills in their design and installation. It is important that the designers of gutters and site drainage systems take necessary account of the requirements and performance characteristics of siphonic systems.

(2) Specifiers of all types of roof drainage system need to consider carefully the degree of flooding risk that is acceptable and establish the requirements of the owners, users and insurers of the buildings. Siphonic systems can be accurately designed to achieve given levels of performance but will normally have limited extra capacity in reserve. The choice of an appropriate value of design rainfall intensity is therefore very important.

(3) More attention should be given to the cavitation potential of different types of pipe fitting when determining the lowest value of negative pressure to be allowed in a design. The pipes and joints used must also be capable of withstanding the negative pressures.

(4) A suggested method of avoiding pressure imbalances in siphonic systems is to vary the positions of the outlets so that the roof areas drained correspond to the calculated flow capacity of each outlet.

(5) Further research is needed to establish suitable values of minimum flow velocity for siphonic systems. Also needed is a quantitative method of predicting the time needed for a system to prime and act siphonically. Features that assist rapid priming are described in Section 9.6. A standard design of discharge chamber should be developed to ensure a satisfactory interface between the siphonic system and the site drainage system.

(6) The effects on flow capacity of any changes made on site during the installation of siphonic systems need to be evaluated and action taken to remedy any shortfall in performance. Owners of buildings need to be made aware of the maintenance requirements of siphonic systems.

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Tables

Table 1 Results of tests P1 and P2

Test P1 - Two outlets D1 and D2; sharp edged roof

Total flow Q l/s	Water depth in gutter (m)			Observations
	D1	mid section	D2	
6.3	0.029	0.044	0.027	
15.0	0.046	0.070	0.048	
19.9	0.051	0.081	0.053	
30.0	0.068	0.108	0.067	
40.0	0.082	0.130	0.082	
50.0	0.096	0.145	0.095	
60.0	-	0.168	-	Intermittent surging at the outlets

Test P2 - Two outlets D1 and D2; round edged roof

Total flow Q l/s	Water depth in gutter (m)			Observations
	D1	mid section	D2	
6.3	0.028 0.037	0.041	0.030	Small oscillations at outlet D1
15.2	0.050	0.073	0.051	
20.0	0.060	0.087	0.055	
29.8	0.068 0.073	0.104	0.066	Small oscillations at outlet D1
39.8	0.075	0.124	0.078	
50.0	0.091	0.148	0.094	
60.0	0.084	0.166	0.106	Waves reach top of gutter

Table 2 Results of tests P3 and P4

Test P3 - Outlet D2 only; round edged roof

Total flow Q l/s	Water depth in gutter (m)		Observations
	at wall	D2	
6.0	0.060	0.039	
6.4	0.071	0.042	
15.2	0.114	0.070 0.084	Oscillations at outlet D2
20.1	0.130	0.082 0.102	Oscillations at outlet D2
27.6	0.161	0.100	Waves reach top of gutter at mid-section

Test P4 - Two outlets D1 and D2; divide wall at mid section; round edged roof

Total flow Q l/s	Water depth in gutter (m)				Observations
	D1	B1	B2	D2	
6.3	0.029 0.039	-	0.043	0.030	Oscillations at outlet D1
15.2	0.053	0.074	0.074	0.049	
20.2	0.067	0.089	0.082	0.056	
29.8	0.068 0.080	0.106	0.100	0.064	Oscillations at outlet D1
39.8	0.084	0.129	0.119	0.076	
50.0	0.096	0.155	-	0.088	

Table 3 Comparison between tests with conventional outlets and BS 6367 (1983)

Test no.	Measured			Calculated using BS 6367	
	Q_{outlet} (l/s)	y_{outlet} (mm)	y_u (mm)	y_{outlet} (mm)	y_u (mm)
P2	3.15	30.0+	41	27.9	45.1
	7.60	50.5+	73	50.2	79.8
	10.0	57.5+	87	60.3	90.4
	14.9	66.0+	104	78.7	118
	19.9	76.5+	124	136*	204
	25.0	92.5+	148	215*	322
P3	5.0	39.0	60	38.0	64.4
	6.4	45.0	71	44.8	73.9
	15.2	77.0	114	79.8	129
	20.1	92.0	130	139*	208
	27.6	100	161	262*	392

+ Average of depths at outlets D1 and D2

* BS 6367 predicts orifice-type flow at outlet

Table 4 Dallmer system - details of pipework

Pipe No.	Diameter (mm)		Length (mm)	Angle (°)	Notes
	ext. Ø	int. Ø			
1	126	115	500	-	Transparent pipe
2	110	100	400	-	
B1	110	100	400	90	Circular bend
3	110	100	1900	-	
B2	110	100	400	90	Circular bend
4	110	100	4150	-	
B3	110	100	400	90	Circular bend
5	110	100	220	-	
B4	110	100	350	45	Circular bend
6	126	115	500	-	Transparent pipe and pressure transducer
7	110	100	280	-	
B5	90	83	400	90	Circular bend
8	90	83	6370	-	
9	115	103	500	-	Transparent pipe and pressure transducer
10	90	83	630	-	
11	90	83	2360	-	
B6	90	83	360	90	Circular bend
12	90	83	320	-	
13	115	103	500	-	Transparent pipe
14	90	83	370	-	
B7	90	83	360	90	Circular bend
15	90	83	5920	-	
16	115	103	500	-	Transparent pipe and pressure transducer
17	90	83	650	-	
B8	-	55	380	90	Elbow bend
18	-	55	400	-	
R1	-	-	-	-	Outlet
J1			130	30	Junction
19	-	55	130	-	
B9	-	55	240	45	Elbow bend
20	-	55	973	-	
B10	-	55	330	90	Elbow bend
21	-	55	410	-	
R2	-	-	-	-	Outlet

Table 5 Sapoflow system no. 1 - details of pipework

Pipe No.	Diameter (mm)		Length (mm)	Angle (°)	Notes
	ext. Ø	int. Ø			
1	75	68	515	-	Transparent pipe
2	75	70	920	-	
B1	75	70	-	45	Elbow bend
3	75	70	4650	-	
B2	75	70	-	2 x 45	Elbow bends
4	75	70	750	-	
5	110	99	580	-	Transparent pipe and pressure transducer
6	75	70	250	-	
B3	75	70	-	2 x 45	Elbow bends
7	75	70	5275	-	
8	90	81	580	-	Transparent pipe and pressure transducer
9	75	70	3840	-	
B4	75	70	-	2 x 45	Elbow bends
10	75	70	950	-	
B5	75	70	-	2 x 45	Elbow bends
11	75	70	6495	-	
12	75	68	500	-	Transparent pipe and pressure transducer
13	75	70	400	-	
B6	75	70	-	2 x 45	Elbow bends
14	75	70	110	-	
B7	56	50	-	120	Det. A
15	56	50	470	-	
R1	-	-			Outlet
J1	56	50	-	45	Junction
16	56	50	1920	-	
B8	56	50	-	2 x 45	Elbow bends
17	56	50	580	-	
R2	-	-	-	-	Outlet

Table 6 Sapoflow system no. 2 - details of pipework

Pipe No.	Diameter (mm)		Length (mm)	Angle (°)	Notes
	ext. Ø	int. Ø			
1	110	103	500		Transparent pipe
2	110	103	1130		
B1	110	103	-	45	Elbow bend
3	110	103	4450		
B2	110	103		2 x 45	Elbow bends
4	110	103	930		
5	115	103	500		Transparent pipe with pressure transducer
6	110	103	250		
B3	110	103		2 x 45	Elbow bends
7	110	103	5240		
8	110	103	500		
J1	110	103	860	45	Junction
9	90	84	3850		
B4	90	84		2 x 45	Elbow bends
10	90	84	1450		
B5	90	84	-	2 x 45	Elbow bends
11	90	84	6180		
12	90	83	500		Transparent pipe with pressure transducer
13	90	84	680		
B6	90	84		45	Elbow bend
14	90	84	130		
B7	63	59	-	2 x 45	Elbow bends
15	63	59	640		
R1	-	-	-	-	Outlet
16	75	70	1600		
B8	63	59	130	2 x 45	Elbow bends
17	63	59	640		
R2	-	-	-	-	Outlet

Table 7 Fullflow system - details of pipework

Pipe No.	Diameter (mm)		Length (mm)	Angle (°)	Notes
	ext. Ø	int. Ø			
1	126	115	500	-	Transparent pipe
2	110	101.4	700	-	
B1	110	101.4	60	2 x 45	Mitred bend
3	110	101.4	1820	-	
B2	110	101.4	60	2 x 45	Mitred bend
4	110	101.4	4280	-	
B3	110	101.4	60	2 x 45	Mitred bend
5	110	101.4	600	-	
6	110	103	500	-	Transparent pipe and pressure transducer
7	110	101.4	450	-	
B4	110	101.4	60	2 x 45	Mitred bend
8	110	101.4	6100	-	
9	115	103	500	-	Transparent pipe and pressure transducer
10	110	101.4	540	-	
J1	110	101.4	240	45	Det A
11	110	101.4	2550	-	
B5	110	101.4	60	2 x 45	Mitred bend
12	110	101.4	420	-	
13	115	103	500	-	Transparent pipe
14	110	101.4	360	-	
B6	110	101.4	60	2 x 45	Mitred bend
15	90	83	150	-	
16	90	83	6170	-	
17	90	83	500	-	Transparent pipe and pressure transducer
18	90	83	430	-	
B7	90	83	130	90	Elbow bend
19	90	83	140	-	
B8	90	83	130	90	Det B
20	90	83	290	-	
21	75	69	130	-	
R1	-	-	-	-	Outlet
B9	75	69	130	45	Det A
22	75	69	850	-	
B10	75	69	130	90	Elbow bend
23	75	69	420	-	
R2	-	-	-	-	Outlet

TABLE 8 - DALLMER SYSTEM

Q (l/s)	Water depth in the gutter (m)						Pressure (mean) (m)			Air Concen-tration (%)	Observations
	1	2	3	4	5	6	Pipe 6	Pipe 16	Pipe 9		
6.9	0.030	0.028	0.030	0.029	0.023	0.027	-	-	-	-	Pipes flowing part full
7.2	0.032	0.029	0.031	0.030	0.024	0.029	-	-	-	-	Pipes flowing part full
10.6	0.039	0.035	0.039	0.038	0.032	0.037	-	-	-	-	Pipes flowing part full
18.7	0.057	0.054	0.061	0.061	0.058	0.063	-2.54	-0.28	-	-	Pipes flowing full
19.9	0.061	0.058	-	0.065	0.063	0.066	-2.72	-0.33	-	-	Pipes flowing full
22.1	0.068	0.065	0.073	0.073	0.071	0.075	-3.18	-0.48	-	0.7	Pipes flowing full
22.9	0.073	0.070	0.075	0.078	0.077	0.081	-3.21	-0.48	-	-	Pipes flowing full
23.6	-	-	-	-	-	-	-3.31	-0.29	-1.68	0.3	Unsteady levels in the gutter (water level rising)

TABLE 9 - DALLMER SYSTEM WITHOUT LEAFGUARDS

Q (l/s)	Water depth in the gutter (m)						Pressure (mean) (m)			Air Concentration (%)	Observations
	1	2	3	4	5	6	Pipe 6	Pipe 16	Pipe 9		
6.9	0.030	0.025	0.028	0.027	0.020	0.025	-	-	-	-	Pipes flowing part full
10.6	0.035	0.032	0.035	0.035	0.026	0.032	-	-	-	-	Pipes flowing part full
18.7	0.052	0.049	0.058	0.058	0.055	0.064	-2.66	-0.09	-1.50	5	Pipes flowing full
22.1	0.066	0.061 0.063	0.072	0.071 0.072	0.070 0.071	0.075 0.076	-3.15	-0.26	-1.64	1	Pipes flowing full. Steady, oscillating water levels in the gutter.
23.6	0.075	0.072	0.082	0.082	0.082	0.086	-3.31	-0.29	-1.68	-	Pipes flowing full. Steady, oscillating water levels in the gutter

TABLE 10 - DALLMER SYSTEM WITHOUT PERFORATED PLATES

Q (l/s)	Water depth in the gutter (m)						Pressure (mean (m) (rms			Air Concen-tration (%)	Observations
	1	2	3	4	5	6	Pipe 6	Pipe 16	Pipe 9		
10.6	0.039	0.034	0.037	0.037	0.030	0.035	-	-	-	-	Pipes flowing part full
13.7	0.045	0.039	0.043	0.043	0.035	0.042	-	-	-	-	Pipes flowing part full
16.2	0.050	0.045	0.050	0.050	0.044	0.050	-2.71 0.081	0.04 0.044	-1.14 0.030	9.5	Pipes flowing full
18.7	0.057	0.054	0.061	0.060	0.058	0.063	-2.58 0.045	-0.07 0.027	-1.48 0.017	5	Pipes flowing full
22.6	-	0.066	0.076	0.075	0.074	0.079	-3.23 0.018	-0.23 0.018	-1.54 0.015	0.6	Pipes flowing full
22.9	-	-	-	-	-	-	-	-	-	-	Unsteady levels in the gutter (water level rising)

TABLE 11 - DALLMER SYSTEM WITH DIVIDE WALL

Q (l/s)	Water depth in the gutter (m)						Pressure (m) (mean (rms			Air Concentration (%)	Observations
	1	2	3	4	5	6	Pipe 6	Pipe 16	Pipe 9		
6.9	0.032	0.030	0.034	0.033	0.021	0.024	-	-	-		Pipes flowing part full
7.3	0.034	0.031	0.035	0.034	0.022	0.026	-	-	-		Pipes flowing part full
10.6	0.041	0.038	0.043	0.042	0.029	0.034	-	-	-		Pipes flowing part full
18.7	0.058	0.055	0.062	0.062	0.058	0.062	-2.71 0.024	-0.28 0.019	-1.66 0.17	5	Pipes flowing part full
19.9	0.061	0.057	0.064	0.064	0.068	0.072	-2.92 0.016	-0.31 0.014	-1.52 0.020	3	Pipes flowing full

TABLE 12 - DALLMER SYSTEM
SIMULATION OF SUDDEN RAINFALL (TIME TO REACH Q WAS 5s APPROXIMATELY)

Q (l/s)	Water depth in the gutter (m)						Pressure (mean) (m)			Observations
	1	2	3	4	5	6	Pipe 6	Pipe 16	Pipe 9	
18.7	0.060	0.060	0.068	0.067	0.067	0.075	-2.77	-0.29	-1.60	No abnormalities were observed in the system
22.9	0.090	0.085	0.080	0.080	0.070	0.075	-	-	-	No abnormalities were observed in the system. Mean pressures were similar to those of "normal" test.

The test was performed with two outlets of the type shown in Figure 4, with spigot diameters of 75mm connecting to tailpipes with 55mm id.

TABLE 13 - SAPOFLOW SYSTEM NO 1

Q (l/s)	Water depth in the gutter (m)						Pressure (m) (mean (rms			Air Concen-tration (%)	Observations
	1	2	3	4	5	6	Pipe 5	Pipe 12	Pipe 8		
4.0	0.027	0.026	0.026	0.026	0.022	0.025	-	-	-	-	Pipes flowing part full
6.2	0.033	0.031	0.032	0.032	0.028	0.032	-	-	-	-	Pipes flowing part full
8.2	0.039	0.036	0.038	0.037	0.034	0.037	-	-	-	-	Pipes flowing part full
10.2	0.043	0.041	0.043	0.043	0.039	0.043	-2.19 0.22	-0.19 0.04	-1.01 0.09	7	Pipes flowing full
12.3	0.049	0.047	0.050	0.049	0.046	0.050	-2.72 0.21	-0.31 0.04	-1.37 0.10	2.9	Pipes flowing full
13.9	0.055	0.052	0.056	0.056	0.053	0.057	-3.08 0.15	-0.41 0.03	-1.57 0.06	1	Pipes flowing full
14.3	-	-	-	-	-	-	-	-	-	-	Unsteady levels in the gutter (water level rising)

TABLE 14 - SAPOFLOW SYSTEM NO 1 WITHOUT LEAFGUARDS

Q (l/s)	Water depth in the gutter (m)						Pressure (m) (mean (rms			Air Concen-tration (%)	Observations
	1	2	3	4	5	6	Pipe 5	Pipe 12	Pipe 8		
4.0	0.027	0.026	0.026	0.026	0.022	0.025	-	-	-	-	Pipes flowing part full
6.2	0.032	0.030	0.031	0.036	0.026	0.029	-	-	-	-	Pipes flowing part full
8.2	0.036	0.035	0.037	0.036	0.031	0.036	-	-	-	-	Pipes flowing part full
10.2	0.040	0.039	0.041	0.040	0.036	0.041	-2.17 0.21	-0.14 0.04	-1.00 0.10	-	Pipes flowing full
12.3	0.045	0.042	0.046	0.046	0.042	0.047	-2.71 0.15	-0.30 0.03	-1.00 0.06	-	Pipes flowing full
13.9	0.050	0.047	0.054	0.052	0.050	0.055	-3.07 0.13	-0.42 0.02	-1.56 0.04	-	Pipes flowing full
14.3	-	-	-	-	-	-					Unsteady levels in the gutter (water level rising)

TABLE 15 - SAPOFLOW SYSTEM NO 1 WITHOUT PLATES

Q (l/s)	Water depth in the gutter (m)						Pressure (m) (mean (rms			Air Concentration (%)	Observations
	1	2	3	4	5	6	Pipe 5	Pipe 12	Pipe 8		
4.1	0.027	0.026	0.026	0.026	0.023	0.025	-	-	-	-	Pipes flowing part full, levels oscillating in the gutter
6.2	0.033	0.032	0.032	0.032	0.028	0.030	-	-	-	-	Pipes flowing part full
8.3	0.040	0.038	0.039	0.039	0.035	0.039	-	-	-	-	Pipes flowing part full
9.8	0.050	0.043	0.044	0.044	0.040	0.044	-2.01 0.10	-0.11 0.03	-0.91 0.06	-	Pipes flowing full
12.3	0.057	0.050	0.053	0.052	0.049	0.053	-2.62 0.02	-0.19 0.00	-1.21 0.02	-	Pipes flowing full
13.3	0.061	0.053	0.057	0.056	0.054	0.057	-2.85 0.02	-0.24 0.00	-1.39 0.02		Pipes flowing full
14.2	0.056	0.056	0.060	0.060	0.058	0.061	-3.02 0.01	-0.29 0.00	-1.46 0.01	-	Pipes flowing full
14.5	-	-	-	-	-	-				-	Unsteady levels in the gutter (water level rising)

TABLE 16 - SAPOFLOW SYSTEM NO 1 WITH DIVIDE WALL

Q (l/s)	Water depth in the gutter (m)						Pressure (m) (mean (rms			Air Concentration (%)	Observations
	1	2	3	4	5	6	Pipe 5	Pipe 12	Pipe 8		
4.0	0.030	0.029	0.031	0.030	0.020	0.023	-	-	-	-	Pipes flowing part full
6.2	0.036	0.034	0.035	0.035	0.027	0.030	-	-	-	-	Pipes flowing part full
8.3	0.040	0.039	0.040	0.041	0.032	0.036	-	-	-	-	Pipes flowing part full
10.2	0.045	0.043	0.045	0.045	0.036	0.040	-2.18 0.12	-0.31 0.03	-1.08 0.05	-	Pipes flowing full
12.3	0.050	0.047	0.051	0.051	0.042	0.046	-2.73 0.03	-0.35 0.01	-1.38 0.03	-	Pipes flowing full
14.0	0.054	0.053	0.057	0.057	0.053	0.057	-3.08 0.01	-0.43 0.00	-1.59 0.01	-	Pipes flowing full
14.3	-	-	-	-	-	-	-	-	-	-	Unsteady levels in the gutter (water level rising)

TABLE 17 - SAPOFLOW SYSTEM NO 1
SIMULATION OF SUDDEN RAINFALL (TIME TO REACH Q WAS 3s APPROXIMATELY)

Q (l/s)	Water depth in the gutter (m)						Pressure (mean) (m)			Observations
	1	2	3	4	5	6	Pipe 5	Pipe 12	Pipe 8	
8.1	0.034	0.037	0.038	0.038	0.038	0.038	-1.51	-0.10	-0.81	No abnormalities were observed in the system; water levels in the gutter a little higher than in "normal" test
10.4	0.034	0.041	0.047	0.047	0.042	0.045	-2.23	-0.19	-1.04	No abnormalities were observed in the system; water levels in the gutter a little higher than in "normal" test
14.0	0.054	0.050	0.057	0.057	0.058	0.059	-3.05	-0.41	-0.79	No abnormalities were observed in the system.

The test was performed with two outlets of the type shown in Figure 5, with spigot diameters of 2" BSP connecting to tailpipes with 50mm id.

TABLE 18 - SAPOFLOW SYSTEM NO 2

Q (l/s)	Water depth in the gutter (m)						Pressure (m) (mean (rms			Observations
	1	2	3	4	5	6	Pipe 5	Pipe 12	Pipe 8	
5.1	~0.025	0.026 0.027	0.031 0.032	0.030 0.032	0.030 0.032	0.032 0.034	-	-	-	Pipes flowing part full. Intermittent priming of the outlets, considerable noise.
10.2	~0.034	0.032	0.036	0.036	0.030	0.036	-	-	-	Pipes flowing part full. Intermittent priming of the outlets, considerable noise
12.5	~0.039	0.038	0.041	0.042	0.035	0.042	-	-	-	Pipes flowing part full
18.4	~0.050	0.049	0.055	0.055	0.051	0.058	-	-1.47 +0.11	-	Pipes flowing part full
20.0	~0.055	0.050	0.056	0.057	0.051	0.060	-	-1.57 +0.10	-	Smaller diameter pipes flowing full
23.1	~0.060	0.058	0.066	0.066	0.061	0.070	-3.90 +0.08	-2.07 +0.04	-3.23 +0.04	Pipes flowing full
24.0	~0.062	0.057	0.065	0.066	0.061	0.069	-4.12 +0.07	-2.16 +0.04	-3.42 +0.02	Pipes flowing full
25.0	~0.067	0.061	0.070	0.070	0.066	0.074	-4.27 +0.06	-2.24 +0.03	-3.53 +0.02	Pipes flowing full
26.0	-	-	-	-	-	-	-	-	-	Pipes flowing full. Unsteady levels in the gutter (water level rising)

TABLE 19 - SAPOFLOW SYSTEM NO 2 WITHOUT LEAFGUARDS

Q (l/s)	Water depth in the gutter (m)						Pressure (m) (mean (rms			Observations
	1	2	3	4	5	6	Pipe 5	Pipe 12	Pipe 8	
5.1	~0.023	0.026	0.021 0.029	0.029 0.031	0.026 0.031	0.026 0.032	-	-	-	Pipes flowing part full. Intermittent priming of the outlets, considerable noise.
10.2	~0.031	0.031	0.036	0.036	0.028	0.025	-	-	-	Pipes flowing part full. Intermittent priming of the outlets, considerable noise
12.5	~0.037	0.036	0.041	0.041	0.034	0.042	-	-	-	Pipes flowing part full
18.4	~0.045	0.043	0.052	0.051	0.044	0.055	-	-1.46 +0.15	-	Pipes flowing part full
20.0	~0.055	0.046	0.054	0.054	0.047	0.058	-	-1.52 +0.07	-	Small diameter pipes flowing full
23.1	~0.056	0.053	0.064	0.064	0.059	0.069	-3.88 +0.11	-2.02 +0.07	-3.22 +0.05	Pipes flowing full
24.0	~0.060	0.054	0.064	0.064	0.058	0.068	-4.12 +0.08	-2.14 +0.04	-3.40 +0.03	Pipes flowing full
25.0	~0.062	0.056	0.066	0.066	0.061	0.071	-4.24 +0.07	-2.25 +0.05	-3.50 +0.02	Pipes flowing full
26.0	-	-	-	-	-	-	-	-	-	Pipes flowing full. Unsteady levels in the gutter (water level rising)

TABLE 20 - SAPOFLOW SYSTEM NO 2 WITHOUT PLATES

Q (l/s)	Water depth in the gutter (m)						Pressure (m) (mean (rms			Observations
	1	2	3	4	5	6	Pipe 5	Pipe 12	Pipe 8	
5.1	~0.022 ~0.024	0.021 0.022	0.022 0.023	0.023	0.017 0.018	0.021 0.022	-	-	-	Pipes flowing part full. Intermittent priming of outlets, considerable noise.
10.1	~0.035	0.031	0.035	0.035	0.028	0.035	-	-	-	Pipes flowing part full. Intermittent priming of outlets, considerable noise
12.6	~0.038	0.036 0.035	0.040 0.039	0.040	0.033	0.041	-	-	-	Pipes flowing part full.
15.1	~0.045	0.039	0.044	0.045	0.037	0.046	-	-0.78 +0.06	-	Smaller diameter pipes flowing full
18.3	~0.052	0.047	0.052	0.055	0.049	0.057	-	-0.94 +0.08	-	Smaller diameter pipes flowing full
20.0	~0.056	0.050	0.057	0.058	0.053	0.061	-	-1.17 +0.09	-	Smaller diameter pipes flowing full
23.0	~0.060	0.056	0.062	0.063	0.058	0.067	-3.26 +0.15	-1.32 +0.14	-2.57 +0.10	Pipes flowing full
24.9	~0.068	0.058	0.065	0.067	0.061	0.070	-3.66 +0.12	-1.52 +0.10	-3.73 +0.11	Pipes flowing full

TABLE 21 - SAPOFLOW SYSTEM NO 2 WITH DIVIDE WALL

Q (l/s)	Water depth in the gutter (m)						Pressure (m) (mean (rms			Observations
	1	2	3	4	5	6	Pipe 5	Pipe 12	Pipe 8	
5.0	~0.023	0.022 0.025	0.014 0.023	0.022 0.028	0.023 0.035	0.023 0.035	-	-	-	Pipes flowing part full. Intermittent priming of the outlets, considerable noise.
10.2	~0.039	0.036 0.037	0.040	0.041 0.042	0.030 0.034	0.037 0.043	-	-	-	Pipes flowing part full. Intermittent priming of the outlets, considerable noise
12.5	~0.043	0.042	0.046	0.048	0.033	0.040	-	-	-	Pipes flowing part full
18.5	~0.058	0.054	0.061	0.062	0.048	0.056	-	-1.63 +0.05	-	Smaller diameter pipes flowing full
20.1	~0.063	0.058	0.065	0.066	0.051	0.060	-3.06 +0.15	-1.73 +0.05	-2.50 +0.05	Pipes flowing full
23.2	~0.070	0.063	0.072	0.072	0.056	0.065	-3.90 +0.05	-1.76 +0.02	-2.98 +0.02	Pipes flowing full
25.0	~0.073	0.066 0.069	0.076 0.077	0.075 0.078	0.060 0.064	0.070 0.072	-4.33 +0.07	-1.77 +0.03	-3.58 +0.03	Pipes flowing full. Some instability in the water levels in the gutter.
26.0	~0.076	0.087	0.077	0.078	0.060	0.070	-4.46 +0.05	-2.41 +0.05	-3.68 +0.06	Pipes flowing full. Some instability in the water levels in the gutter.
28.0	-	-	-	-	-	-	-	-	-	Pipes flowing full. Unsteady levels in the gutter (water level rising).

TABLE 22 - SAPOFLOW SYSTEM NO 2
SIMULATION OF SUDDEN RAINFALL (TIME TO REACH Q WAS 6 TO 9s APPROXIMATELY)

Q (l/s)	Water depth in the gutter (m)						Pressure (mean) (m)			Observations
	1	2	3	4	5	6	Pipe 5	Pipe 12	Pipe 8	
20.0	0.108 0.055	0.080 0.050	0.085 0.062	0.085 0.062	0.090 0.060	0.075 0.065	-4.57	-1.82	-3.76	→ Levels before priming → Levels after priming
25.0	0.100 0.065	0.120 0.075	0.110 0.055	0.110 0.055	0.100 0.070	0.110 0.075	-4.64	-2.48	-3.78	→ Levels before priming → Levels after priming

The test was performed with two outlets of the type shown in Figure 5, with spigot diameters of 2" BSP connecting to tailpipes with 59mm id.

TABLE 23 - FULLFLOW SYSTEM

Q (l/s)	Water depth in the gutter (m)						Pressure (m) (mean (rms			Air Concentration (%)	Observations
	1	2	3	4	5	6	Pipe 6	Pipe 16	Pipe 9		
5.0	0.027	0.024	0.026	0.025	0.022	0.023	-	-	-	-	Pipes flowing part full.
8.0	0.033	0.029	0.032	0.032	0.027	0.028	-	-	-	-	Pipes flowing part full. Intermittent priming of the outlets.
10.1	0.037	0.033	0.036	0.036	0.030	0.034	-	-	-	-	Pipes flowing part full. Intermittent priming of the outlets.
12.6	0.042	0.037	0.041	0.041	0.035	0.041	-0.99 +0.16	-	-	38	Pipes flowing part full. Intermittent priming of the outlets.
18.7	0.050	0.046	0.052	0.052	0.045	0.055	-2.06 +0.12	-0.37 +0.02	-1.32 +0.04	3.6	Pipes flowing intermittently full.
20.0	0.052	0.047	0.055	0.054	0.047	0.057	-2.25 +0.12	-0.40 +0.02	-1.44 +0.03	2.5	Pipes flowing full.
23.1	0.056	0.052	0.061	0.060	0.053	0.064	-2.78 +0.07	-0.52 +0.01	-1.75 +0.02	1.2	Pipes flowing full.
24.0	0.058	0.054	0.061	0.062	0.055	0.065	-2.94 +0.05	-0.54 +0.02	-1.85 +0.02	<1	Pipes flowing full.
26.7	0.066	0.060	0.070	0.069	0.064	0.072	-3.33 +0.01	-0.65 +0.01	-2.12 +0.01	<1	Pipes flowing full.
27.3	-	-	-	-	-	-	-	-	-	-	Pipes flowing full. Unsteady levels in the gutter (water level rising)

TABLE 24 - FULLFLOW SYSTEM WITHOUT LEAFGUARDS

Q (l/s)	Water depth in the gutter (m)						Pressure (m) (mean (rms			Air Concen-tration (%)	Observations
	1	2	3	4	5	6	Pipe 6	Pipe 16	Pipe 9		
5.0	0.028	0.024	0.026	0.025	0.022	0.023	-	-	-	-	Pipes flowing part full.
8.0	0.033	0.029	0.032	0.032	0.027	0.030	-	-	-	-	Pipes flowing part full. Intermittent priming of the outlets.
10.1	0.037	0.032	0.036	0.036	0.031	0.035	-	-	-	-	Pipes flowing part full. Intermittent priming of the outlets.
12.6	0.041	0.036	0.041	0.041	0.034	0.041	-0.99 +0.16	-	-	38	Pipes flowing part full. Intermittent priming of the outlets.
18.7	0.049	0.043	0.051	0.051	0.043	0.054	-2.06 +0.12	-0.37 +0.02	-1.32 +0.04	3.6	Pipes flowing intermittently full.
20.0	0.050	0.045	0.054	0.053	0.045	0.058	-2.25 +0.12	-0.40 +0.02	-1.44 +0.03	2.5	Pipes flowing full.
23.1	0.054	0.050	0.060	0.059	0.052	0.064	-2.78 +0.07	-0.52 +0.01	-1.75 +0.02	1.2	Pipes flowing full.
26.7	0.064	0.058	0.068	0.067	0.062	0.069	-	-	-	<1	Pipes flowing full.
27.3	-	-	-	-	-	-	-	-	-	-	Unsteady levels in the gutter (water level rising)

TABLE 25 - FULLFLOW SYSTEM WITHOUT PLATES

Q (l/s)	Water depth in the gutter (m)						Pressure (mean (m) (rms			Air Concen- tration (%)	Observations
	1	2	3	4	5	6	Pipe 6	Pipe 16	Pipe 9		
5.0	0.028	0.023	0.022	0.024	0.020	0.019	-	-	-	-	Pipes flowing part full.
8.1	0.035	0.029	0.032	0.032	0.027	0.030	-	-	-	-	Pipes flowing part full.
10.0	0.038	0.032	0.035	0.036	0.031	0.034	-	-	-	-	Pipes flowing part full.
12.6	0.042	0.036	0.040	0.040	0.034	0.039	-1.09 +0.21	-	-	-	Pipes flowing part full.
18.7	0.050	0.043	0.050	0.050	0.041	0.052	-2.00 +0.14	-0.31 +0.03	-1.25 +0.04	-	Pipes flowing intermittently full.
20.0	0.051	0.045	0.052	0.052	0.043	0.056	-2.19 +0.12	-0.32 +0.02	-1.36 +0.03	-	Pipes flowing full.
23.2	0.055	0.050	0.058	0.057	0.049	0.062	-2.73 +0.08	-0.44 +0.05	-1.68 +0.04	-	Pipes flowing full.
25.7	0.061	0.053	0.063	0.063	0.054	0.063	-3.15 +0.02	-0.57 +0.02	-1.99 +0.01	-	Pipes flowing full.
26.8	0.063	0.057	0.067	0.067	0.061	0.069	-3.31 +0.01	-0.61 +0.01	-2.10 +0.01	-	Pipes flowing full.
27.8	-	-	-	-	-	-				-	Pipes flowing full.

TABLE 26 - FULLFLOW SYSTEM WITH DIVIDE WALL

Q (l/s)	Water depth in the gutter (m)						Pressure (m) (mean (rms			Air Concen-tration (%)	Observations
	1	2	3	4	5	6	Pipe 6	Pipe 16	Pipe 9		
5.1	0.029	0.026	0.028	0.028	0.021	0.022	-	-	-	-	Pipes flowing part full
10.2	0.039	0.036	0.040	0.040	0.030	0.035	-	-	-	-	Pipes flowing part full
12.8	0.043	0.040	0.046	0.046	0.034	0.042	-	-	-	-	Pipes flowing part full
14.8	0.046	0.043	0.049	0.049	0.037	0.045	-1.34 +0.19	-	-	-	Pipes flowing intermittently full
20.1	0.054	0.052	0.060	0.060	0.043	0.056	-2.33 +0.13	-0.51 +0.03	-1.49 +0.05	-	Pipes flowing full
24.0	0.061	0.057	0.067	0.067	0.050	0.064	-2.99 +0.05	-0.59 +0.02	-1.92 +0.02	-	Pipes flowing full
26.8	0.075	0.069	0.077	0.077	0.055	0.065	-3.34 +0.02	-0.65 +0.01	-2.13 +0.01	-	Pipes flowing full
27.3	-	-	-	-	-	-	-	-	-	-	Unsteady levels in the gutter (water level rising)

TABLE 27 - FULLFLOW SYSTEM
SIMULATION OF SUDDEN RAINFALL (TIME TO REACH Q WAS 6 TO 9s APPROXIMATELY)

Q (l/s)	Water depth in the gutter (m)						Pressure (mean) (m)			Observations
	1	2	3	4	5	6	Pipe 6	Pipe 16	Pipe 9	
19.0	0.054	0.054	0.056	0.056	0.051	0.056	-2.85	-0.43	+0.13 ↕ -1.82	No abnormalities were observed in the system; initial pressures generally more negative and water levels a little higher than in "normal" test.
19.7	0.056	0.051	0.059	0.051	0.052	0.060	-2.23	-0.41	-1.41	No abnormalities were observed; water levels a little higher than in "normal" test.
26.7	0.078	0.078	0.081	0.081	0.078	0.081	-3.40	-0.71	+0.11 ↕ -2.17	No abnormalities were observed; pressures more negative and water levels higher than in "normal" test.

Note : Two values of pressure refer to maximum and minimum pressures recorded.

The test was performed with two outlets of the type shown in Figure 6, with spigot diameters of 75mm connecting to tailpipes with 69mm id.

Table 28 Comparison of experimental and predicted results

System	Ultimate flow capacity (l/s)			Pressures (m)		
(A) Dallmer	Q_1	Q_2	Q_T	Pipe 6	Pipe 9	Pipe 16
(A.1) Tests	-	-	22.9-23.6	-3.21	~ -1.66	-0.48
(A.2) Dallmer calcs	10.8	13.4	24.2	-4.57	-1.87	-0.47
(A.3) HR calcs	9.74	13.6	23.3	-4.36	-2.00	-0.68
(B1) Sapoflow No 1				Pipe 5	Pipe 8	Pipe 12
(B1.1) Tests	-	-	13.9-14.3	-3.08	-1.57	-0.41
(B1.2) Sapoflow calcs	6.60	7.30	13.9	-3.31	-1.99	-0.75
(B1.3) HR calcs	6.09	7.66	13.8	-3.56	-2.13	-0.45
(B2) Sapoflow No 2				Pipe 5	Pipe 8	Pipe 12
(B2.1) Tests	-	-	25.0-26.0	-4.27	-3.53	-2.24
(B2.2) Sapoflow calcs	12.0	14.1	26.1	-4.62	-3.72	-2.12
(B2.3) HR calcs	12.2	14.1	26.4	-4.42	-3.50	-1.88
(C) Fullflow				Pipe 6	Pipe 9	Pipe 17
(C.1) Tests	-	-	26.7-27.3	-3.33	-2.12	-0.65
(C.2) Fullflow calcs	13.1	13.8	26.9	-3.74	~ -3.16	~ -0.41
(C.3) HR calcs	13.6	14.2	27.8	-3.63	-2.22	-0.70

Note: Q_1 and Q_2 correspond to the flow capacities of outlets 1 and 2, respectively

Figures

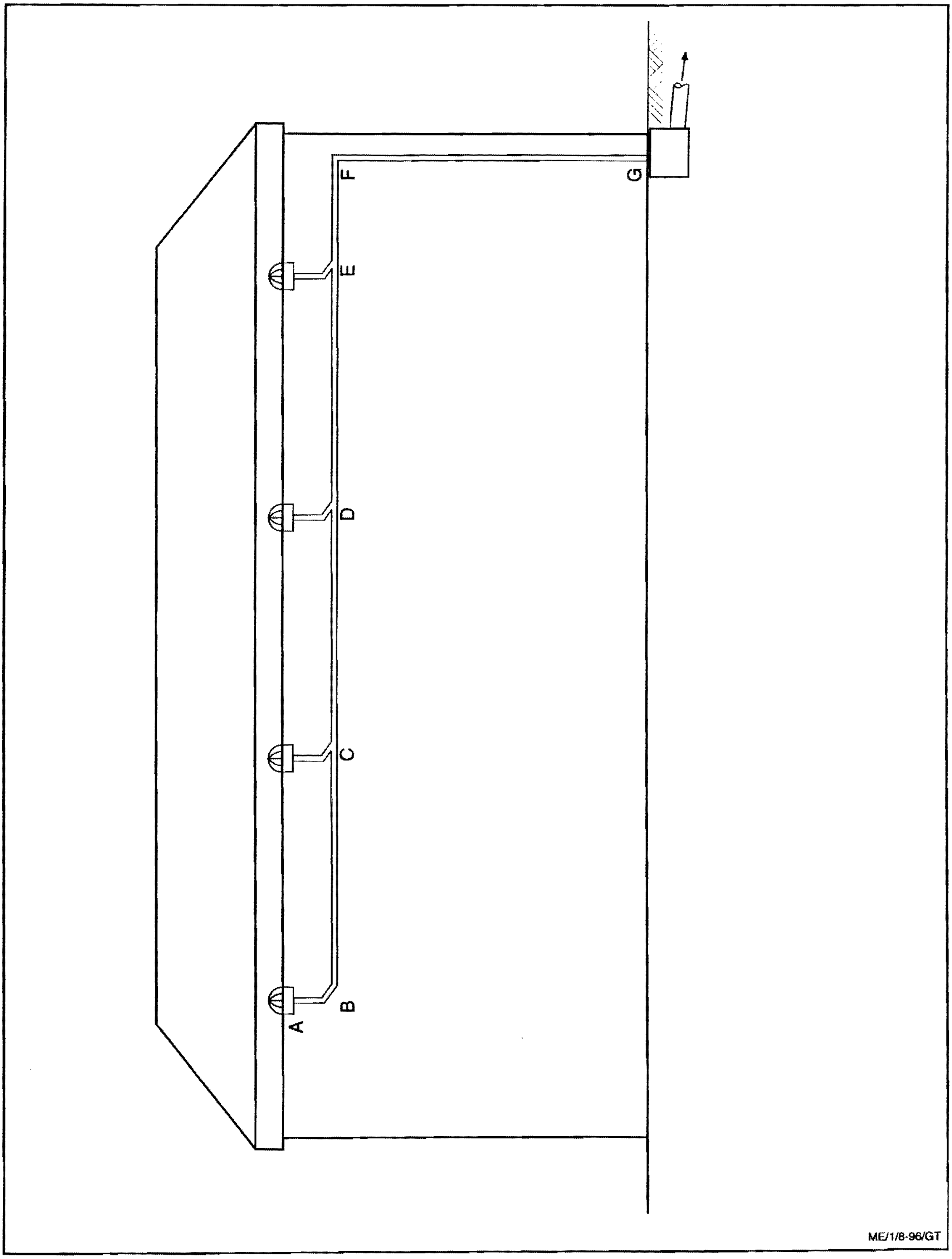

Figure 1 Typical layout of a siphonic system

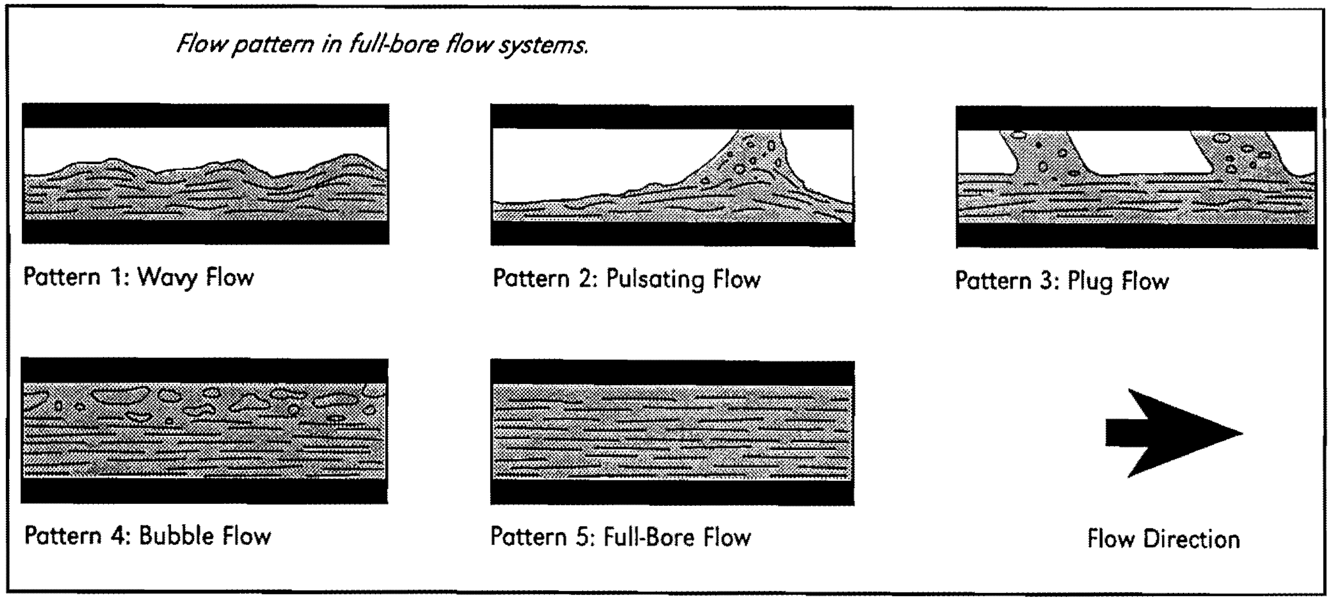

Figure 2 Types of air-water flow (courtesy of Sommerhein AB)

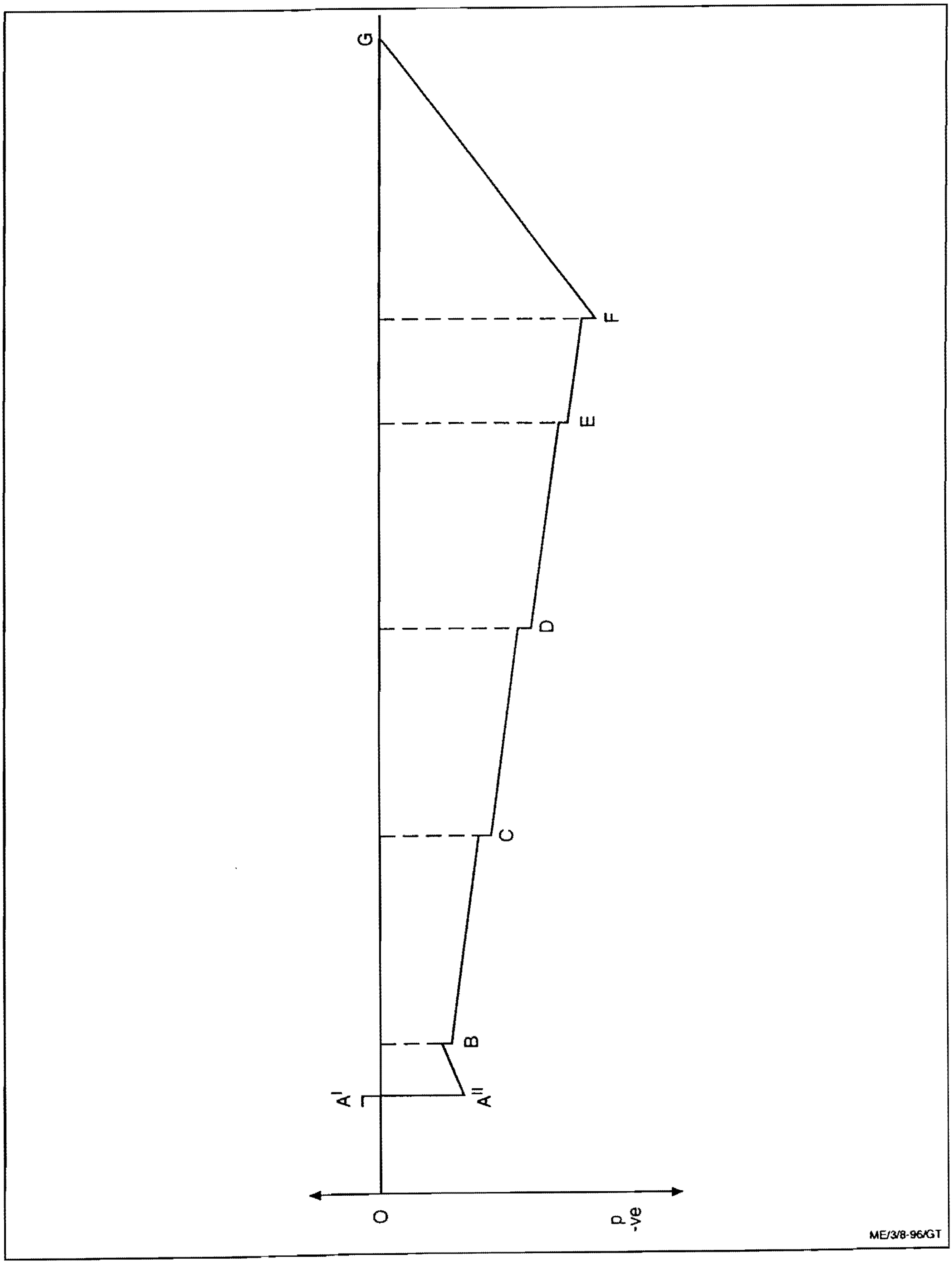

Figure 3 Typical pressure pattern in a siphonic system (see Fig 1)

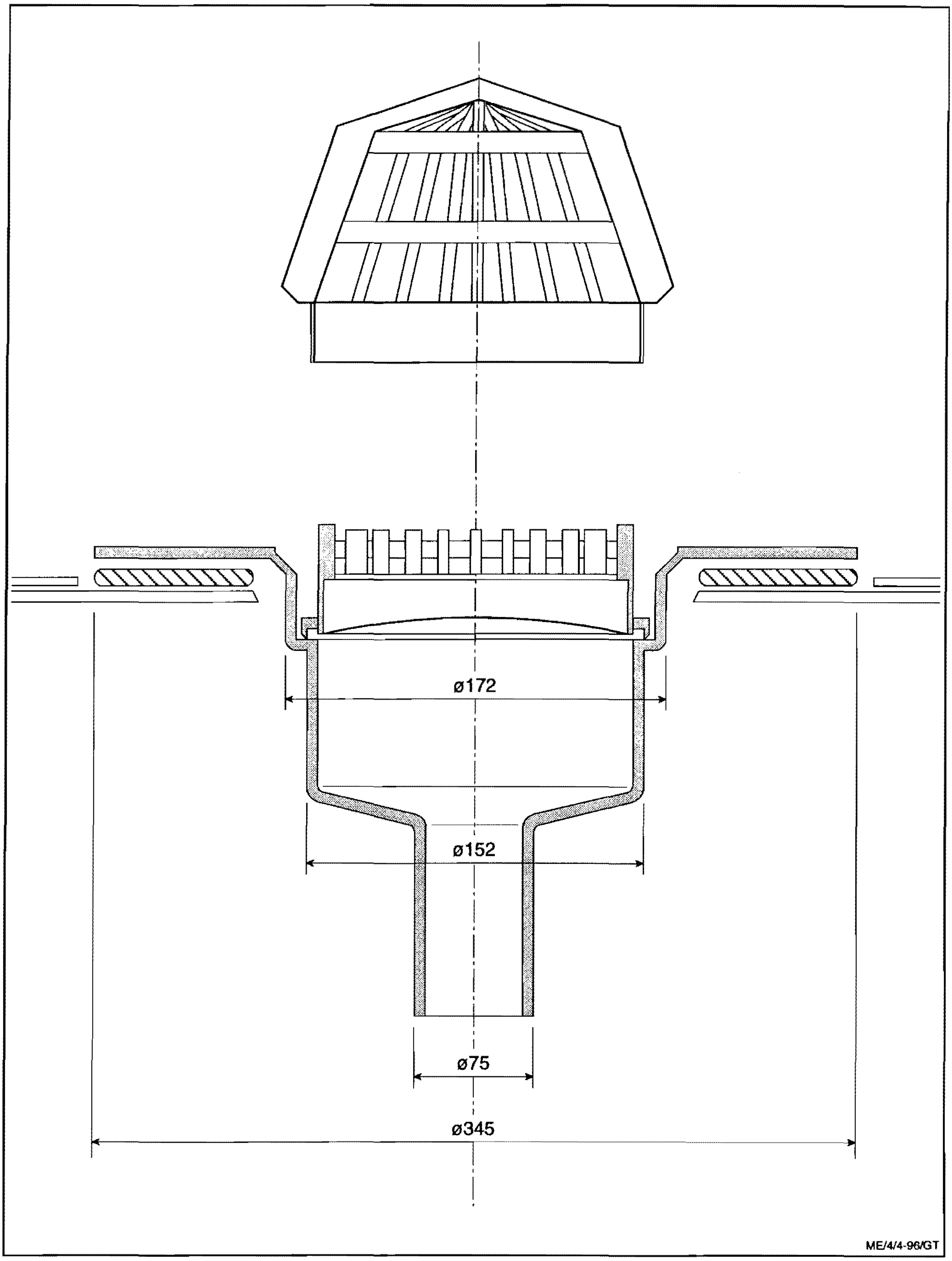

Figure 4 Schematic diagram of Dallmer (Raindrain) outlet

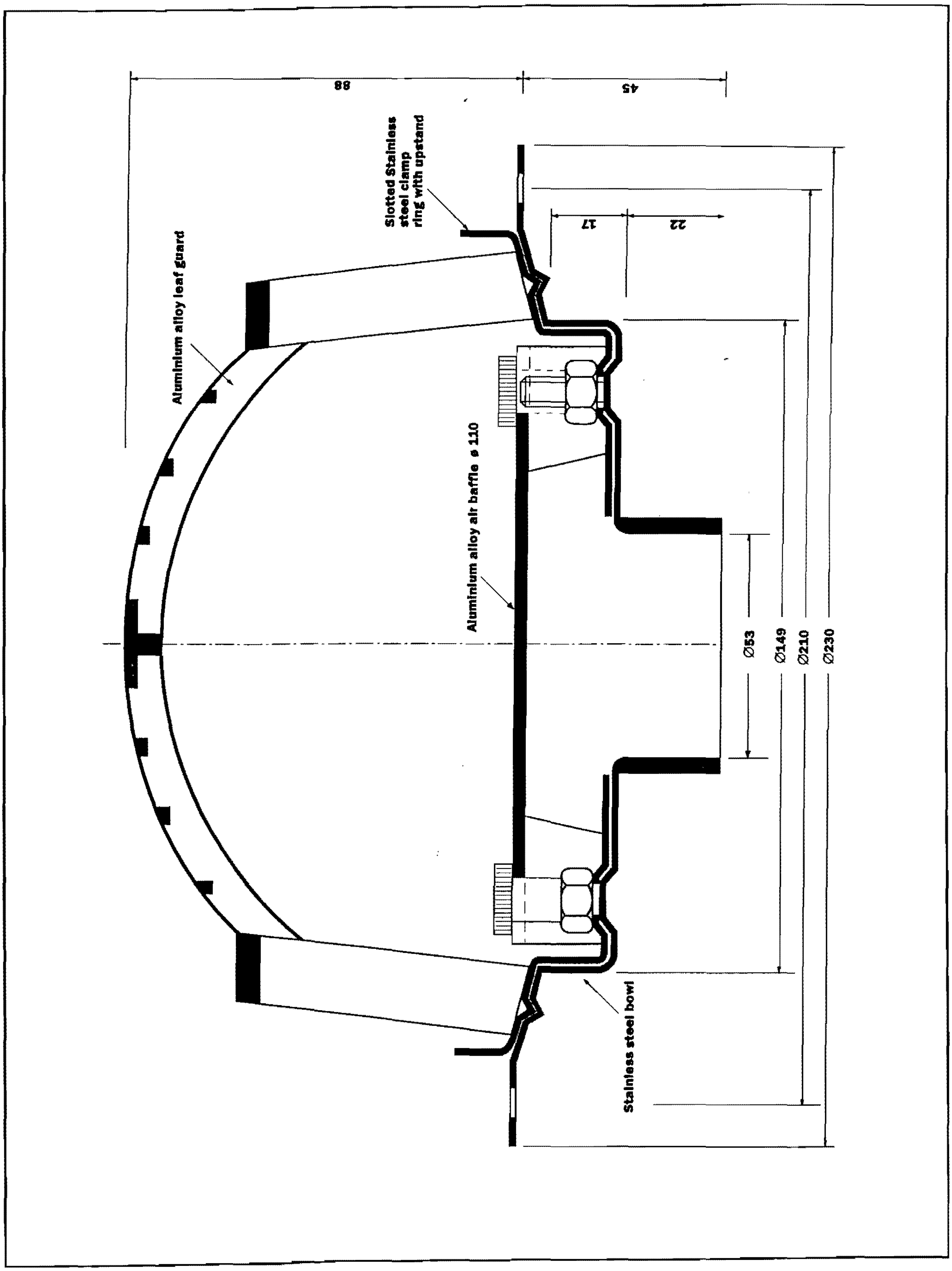

Figure 5 Schematic diagram of Sapoflow outlet

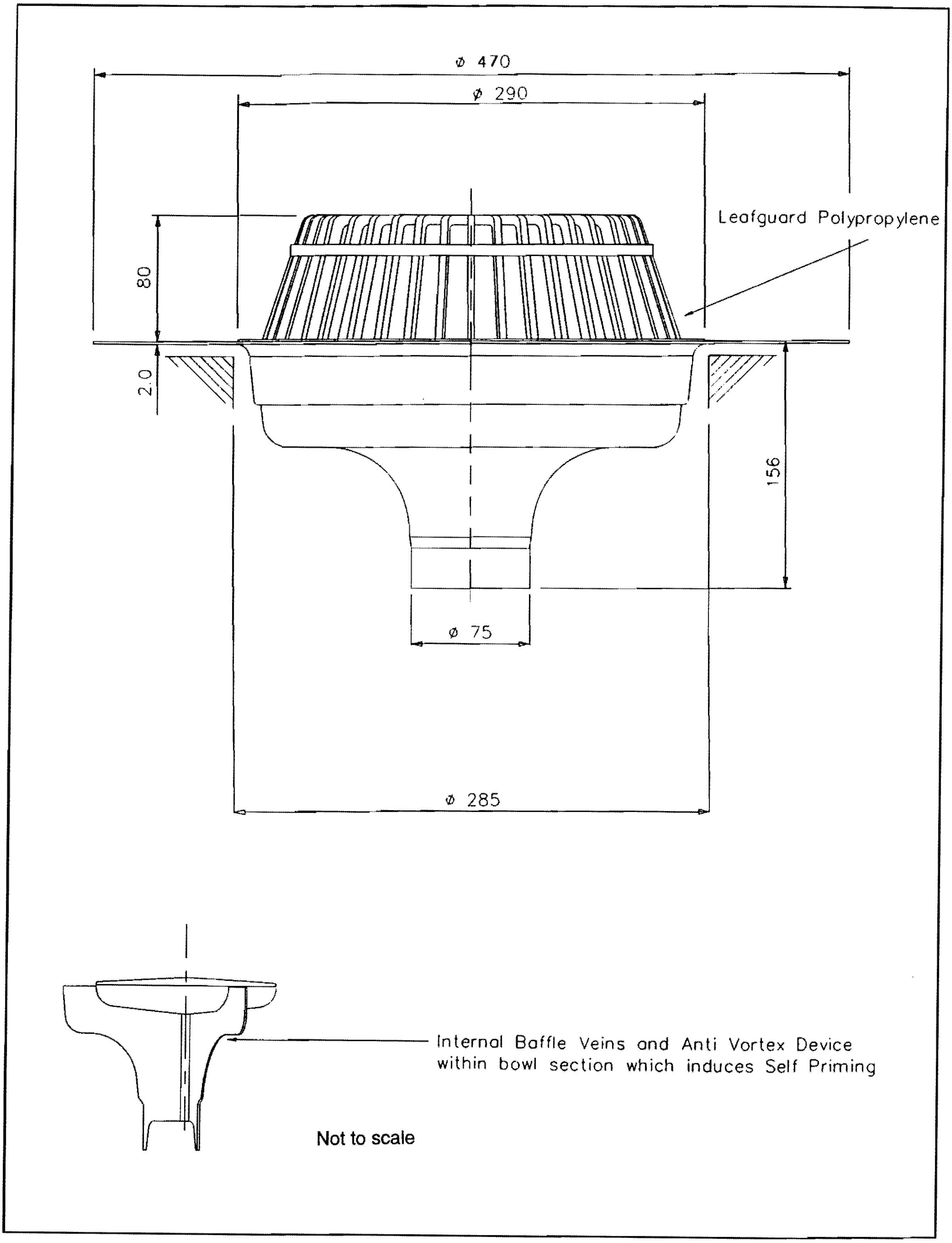

Figure 6 Schematic diagram of Fullflow outlet

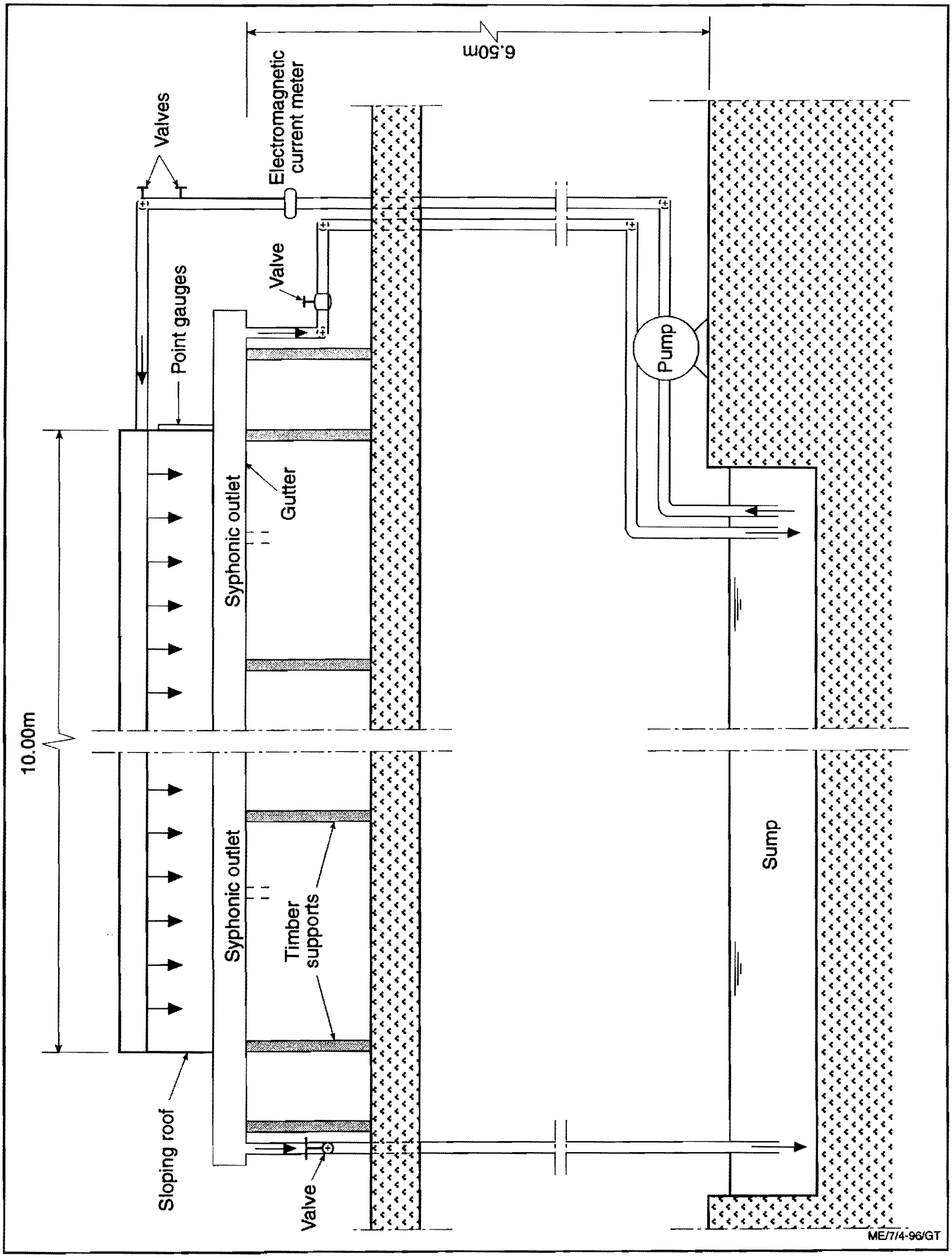

Figure 7 Test rig - front view

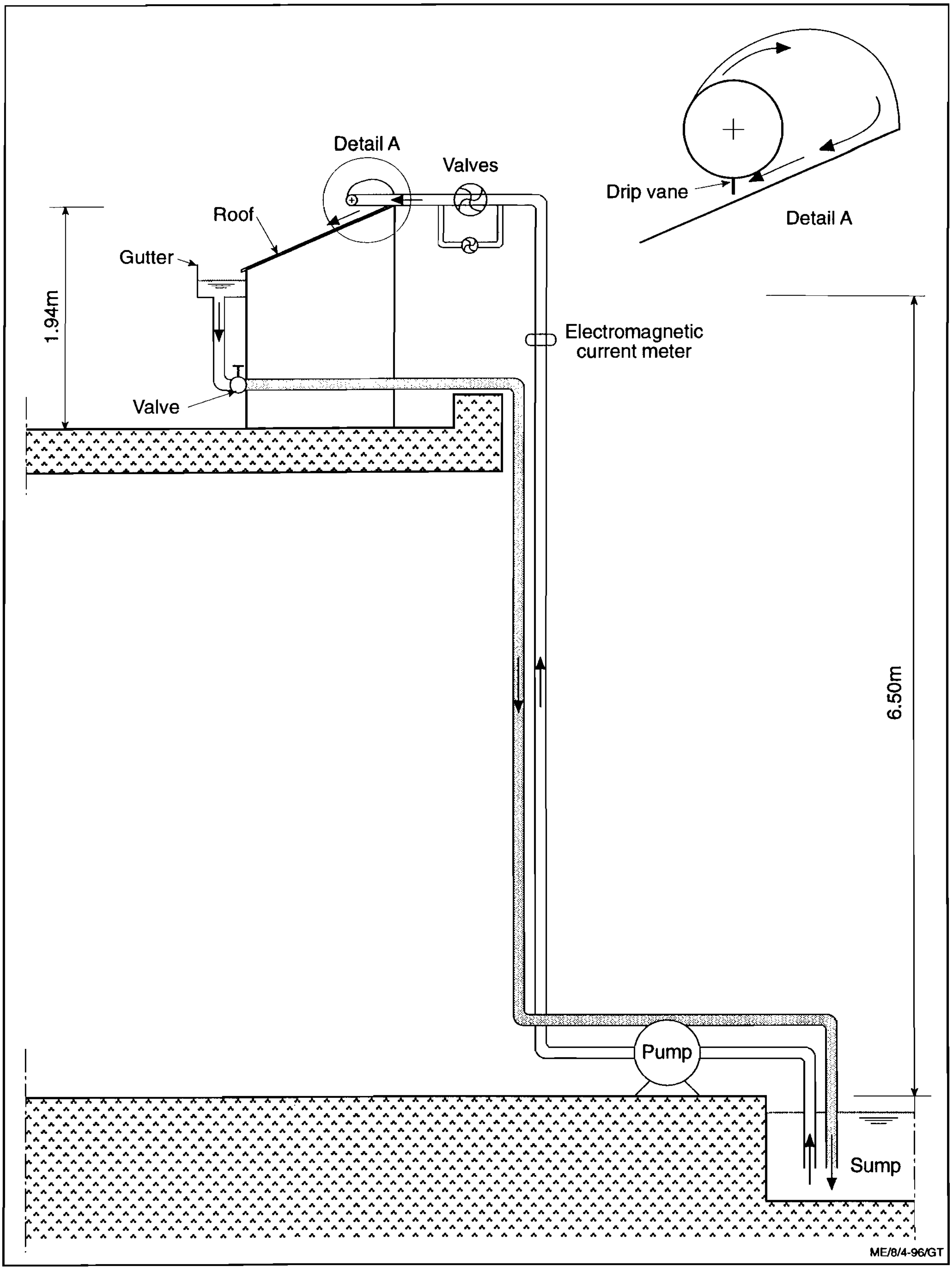

Figure 8 Test rig - side view

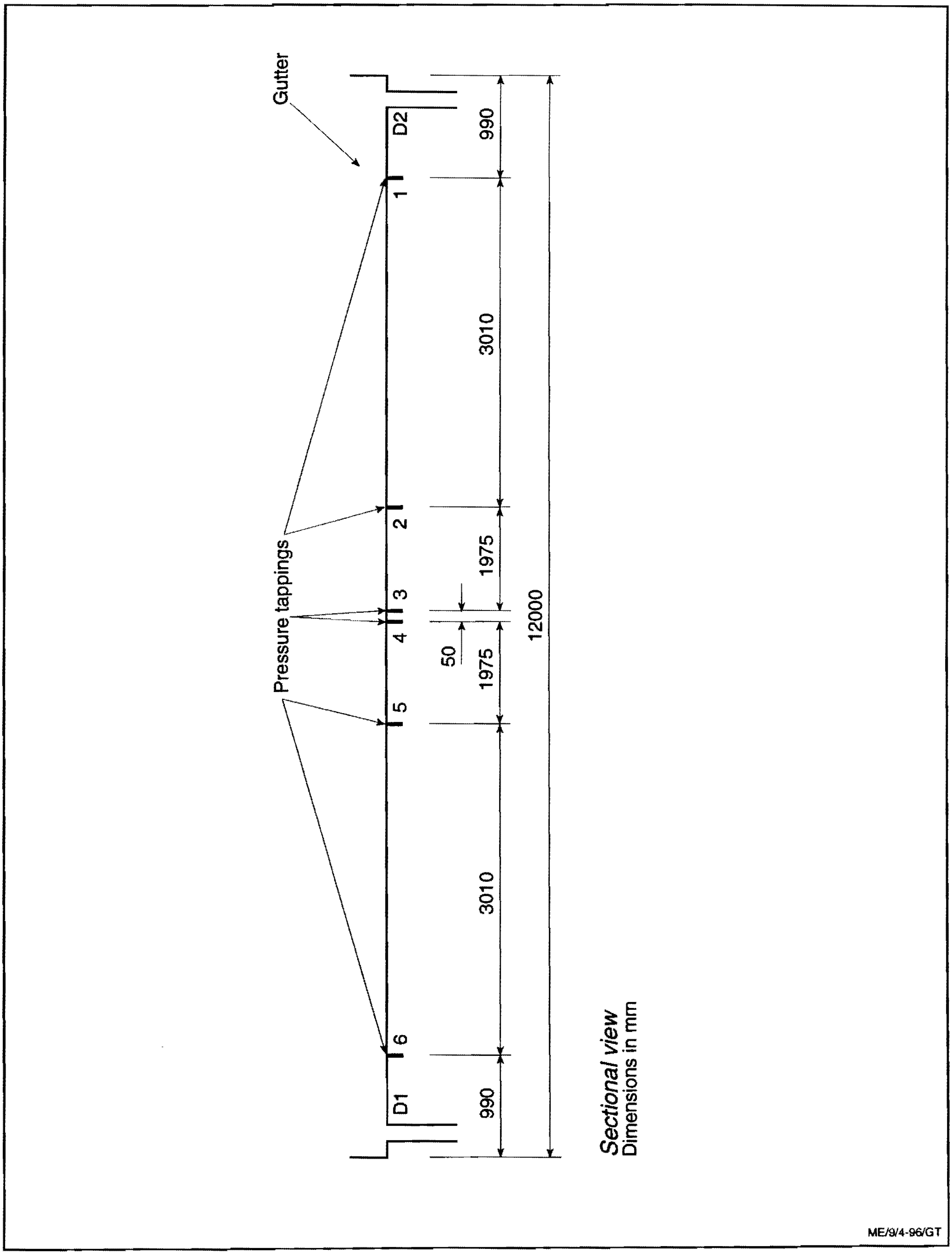

Figure 9 Location of pressure tappings

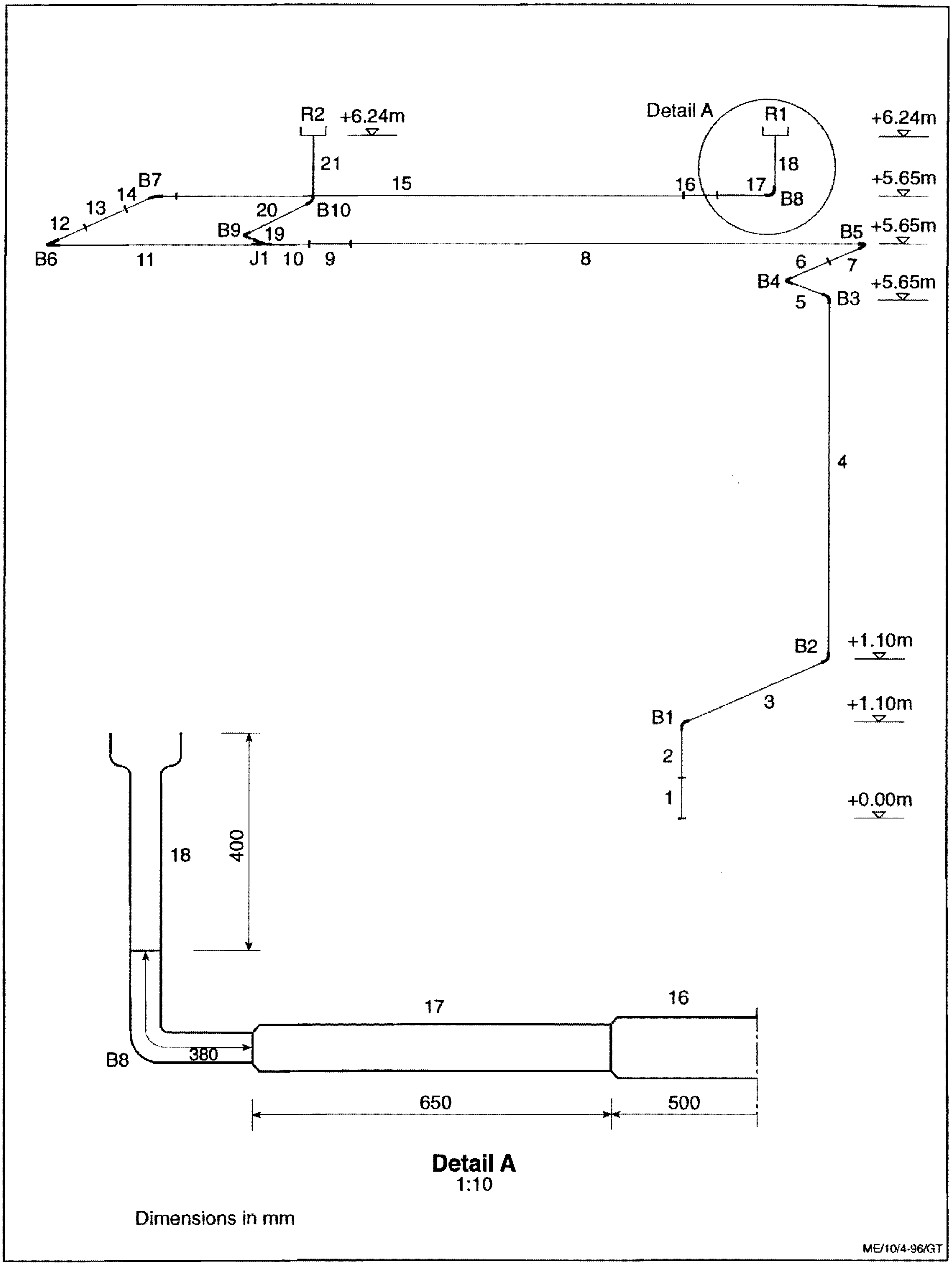

Figure 10 Schematic diagram of Dallmer system

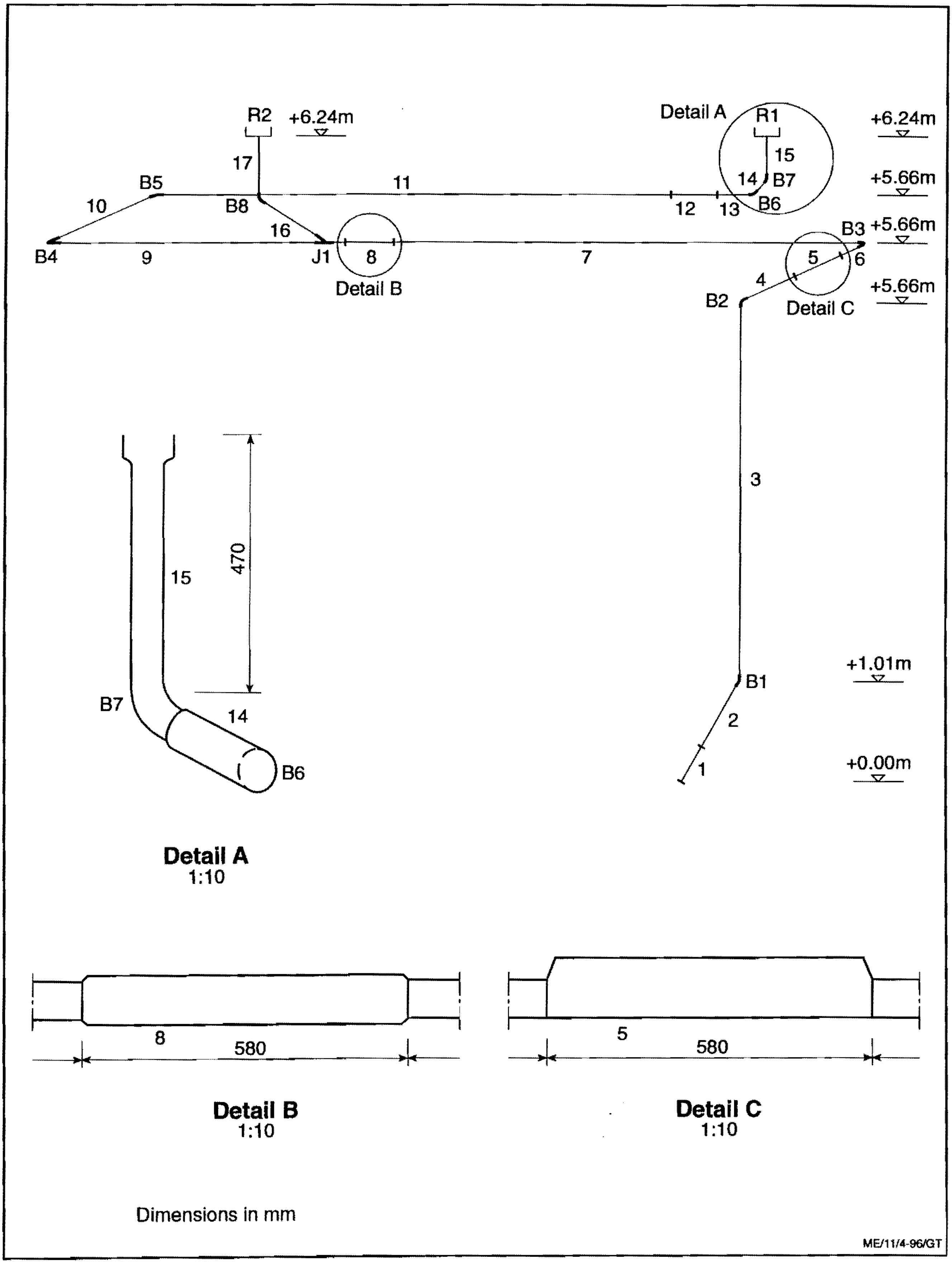

Figure 11 Schematic diagram of Sapoflow system No. 1

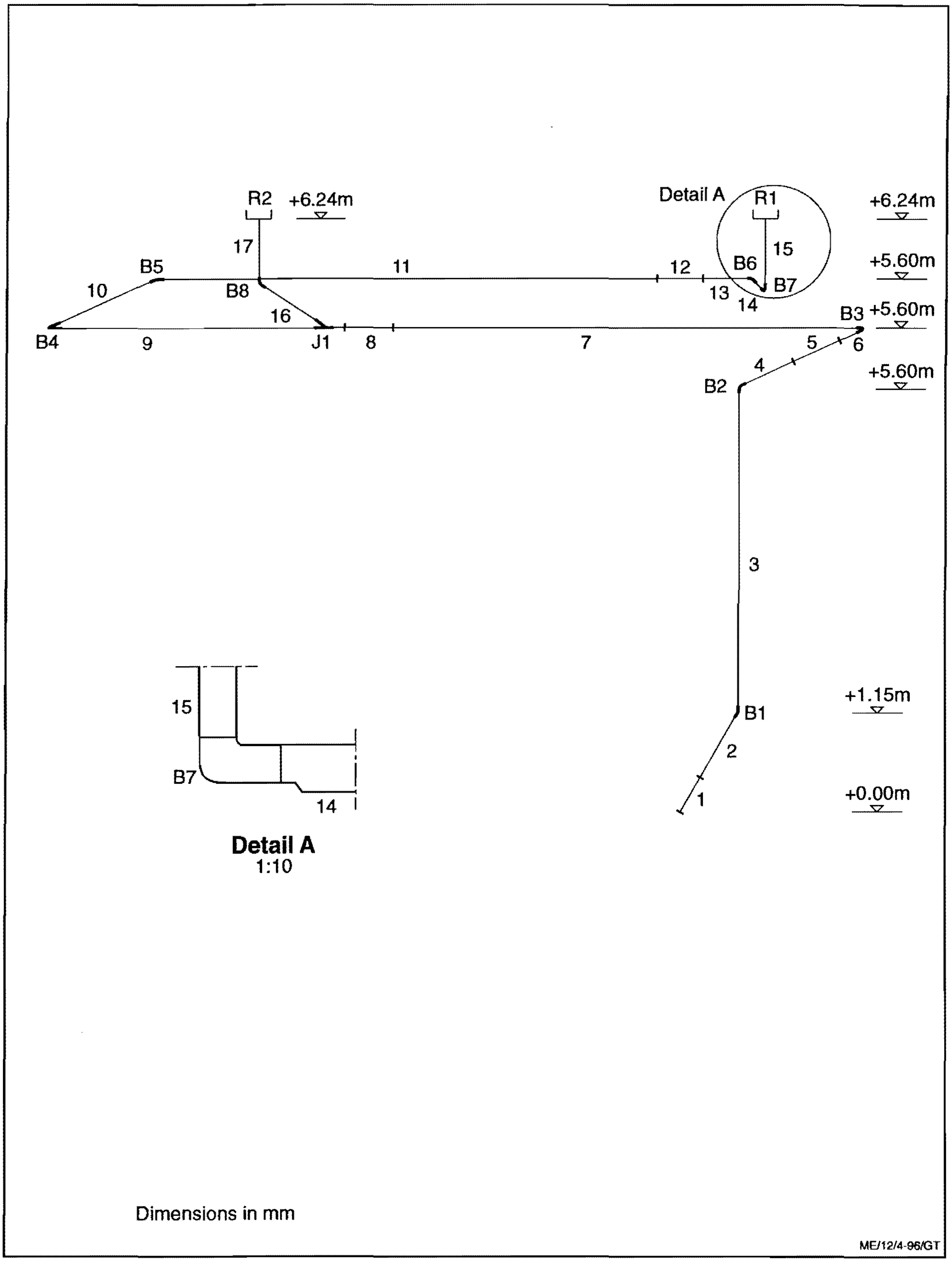

Figure 12 Schematic diagram of Sapoflow system No. 2

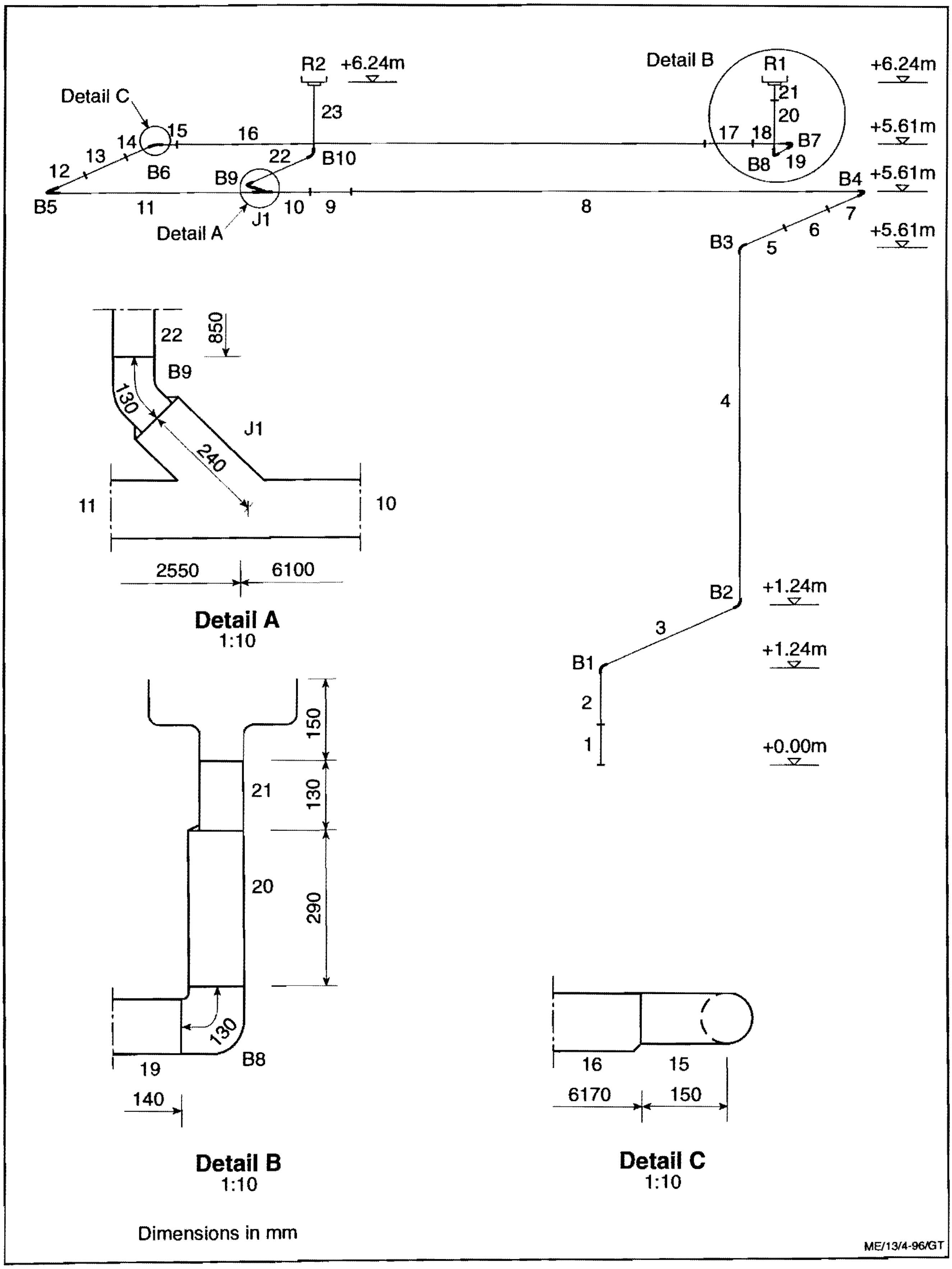

Figure 13 Schematic diagram of Fullflow system

Plates

Plate 1 Installation of siphonic system in a building

Plate 2 Tailpipe connecting outlet to a collector pipe

Plate 3 Siphonic outlet in a valley gutter

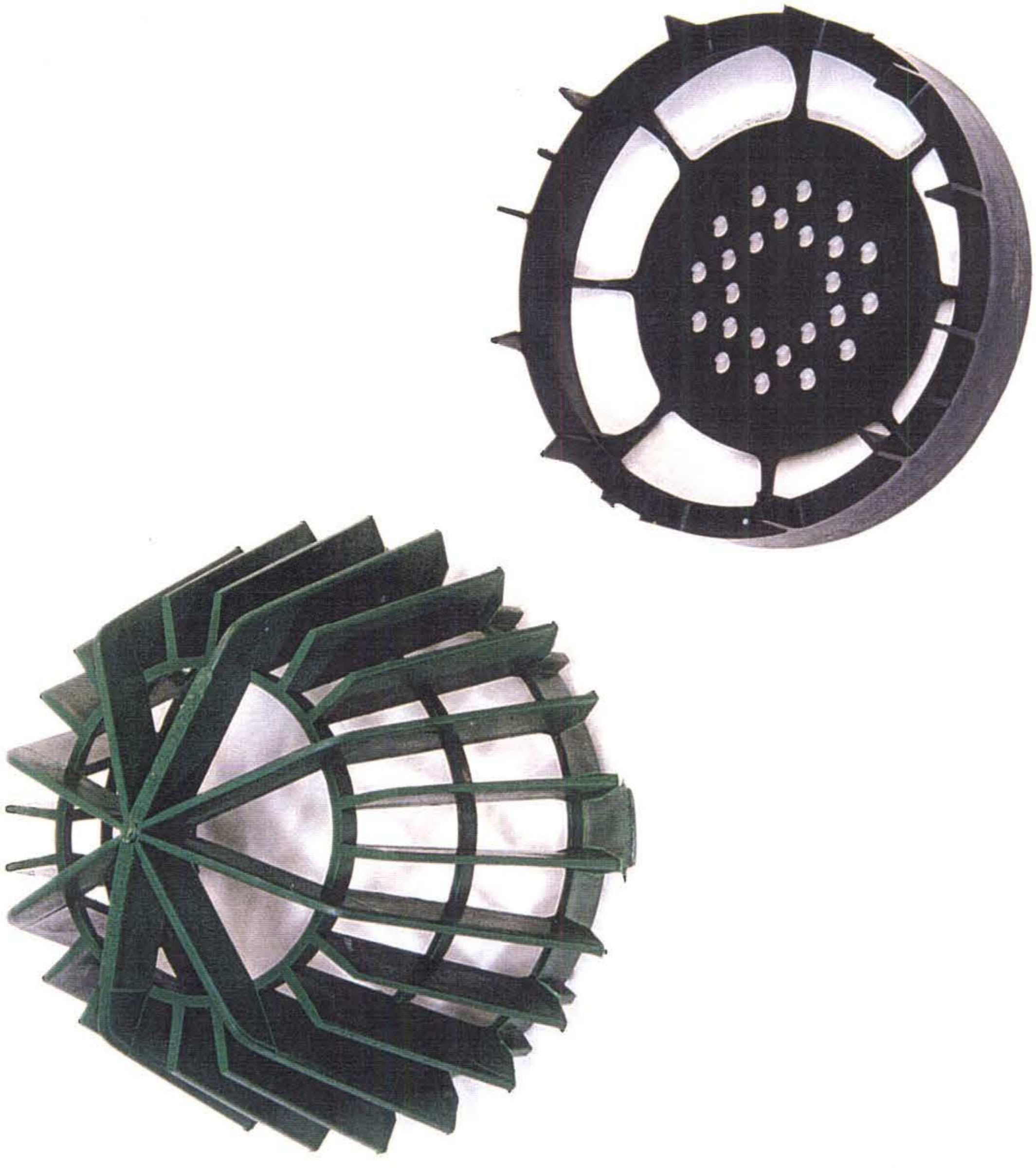

Plate 4 Dallmer leafguard and plate

Plate 5 Sapoflow outlet

Plate 6 Fullflow outlet

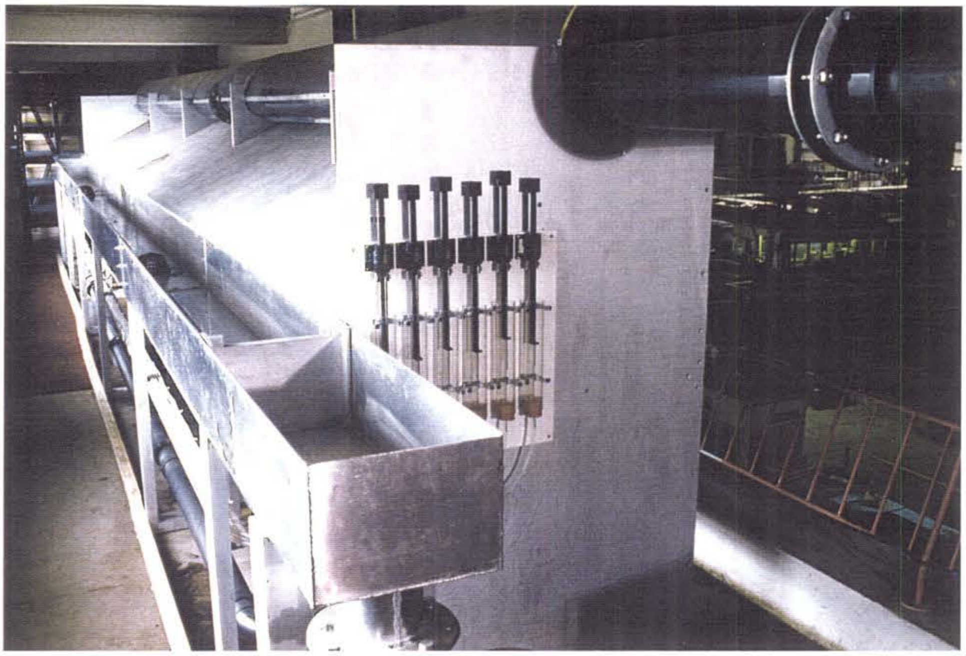

Plate 7 View of test rig

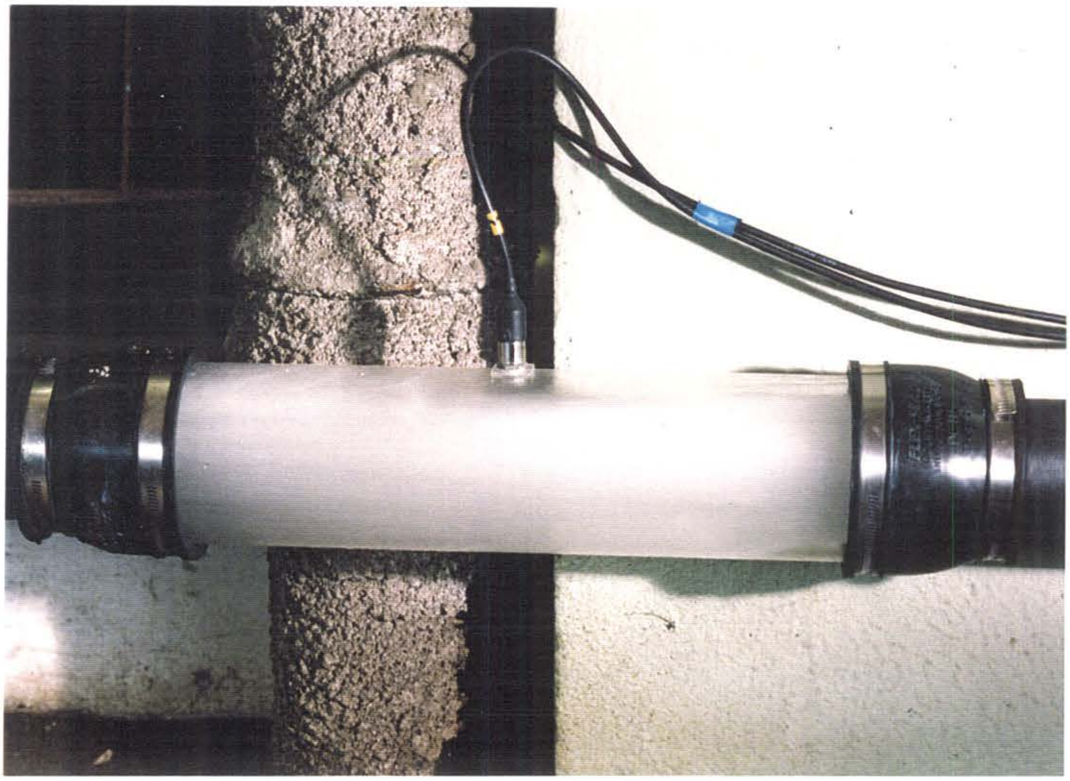

Plate 8 Pressure transducer

Plate 9 Air void meter

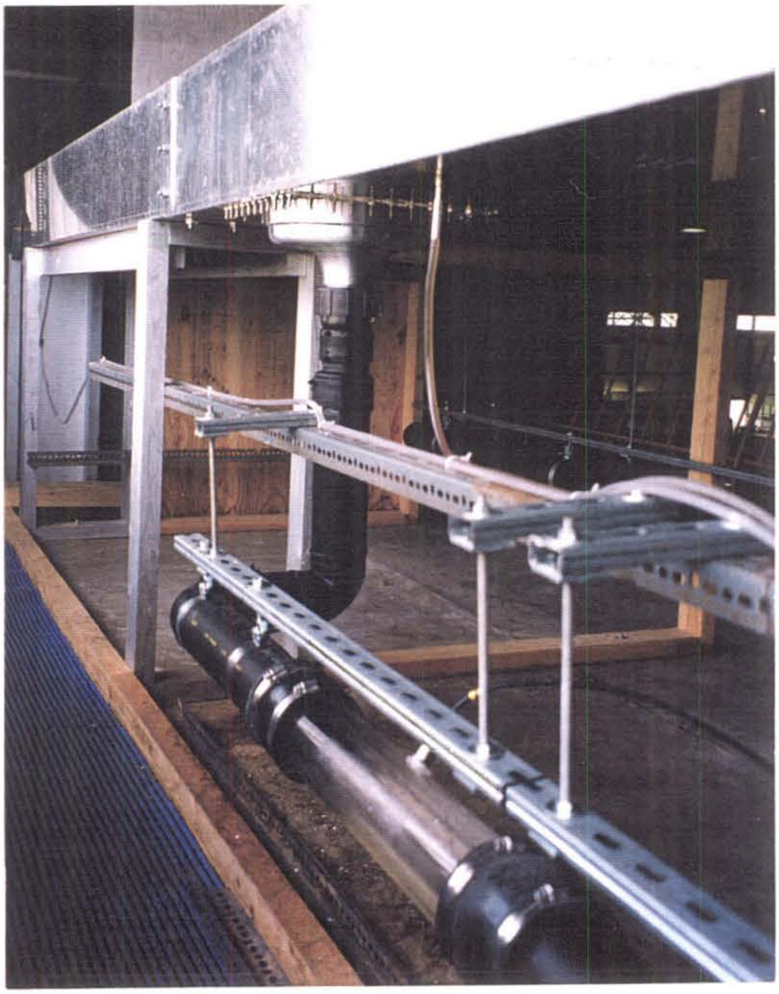

Plate 10 Fullflow tailpipe at outlet R1

Plate 11   Test of Dallmer system at Q = 10 l/s

Plate 12 Test of Sapoflow system at Q = 9.8 l/s

Plate 13 Test of Fullflow system at Q = 23.1 l/s

Plate 14 Test with debris in the gutter (beginning of test)

Plate 15 Test with debris in the gutter (end of test)