FURTHER TESTING OF SOLAR WATER HEATING SYSTEMS

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EXECUTIVE SUMMARY

In 2001 the Energy Monitoring Company conducted a study for the DTI which compared the amount of energy eight modern solar water heating systems could produce over an average year. The approach adopted followed closely the recommendations of a feasibility study previously commissioned by the DTI. It consisted of operating all eight systems side by side on an outdoor test rig, with each subjected to the same hot water run off profile each day over a period of about six months. The systems were operated under the same climate conditions and the project provided an accurate measure of their operation under the most realistic conditions possible.

In appraising those tests two questions arose. The first was how the results obtained related to those of other tests carried out to International Standards. The second was whether an alternative mode of operation, in which auxiliary energy was applied directly to the solar cylinder, would cause a significant reduction in output.

In the first of the two trials described in this report two of the systems, a flat plate manufactured by AES and an evacuated tube system from Riomay, were retested in accordance with ISO Standard 9459-2: Outdoor test methods for system characterisation and yearly performance prediction of solar-only systems. Whilst constraints imposed by the existing facility meant that there were minor deviations from the requirements of that standard, the impact of these has been comprehensively assessed and in all cases found to be minimal.

The ISO tests provide an estimate of the annual output which can be expected from a system. Depending on the incoming cold water temperature assumed those predictions were between 5% below and 10% above those obtained in the previous study. It is concluded that the original side by side test method provided results compatible with those obtained from tests to the ISO Standard. The ISO calculation method also allows the impact of reduced hot water demand on system performance to be determined. This has been done for both systems, and the performance of the Riomay evacuated tube system has been found to be more robust in the face of reducing daily load.

In the original tests the systems were treated as solar only systems, in which the solar cylinder acts as a preheat vessel for a second cylinder, to which auxiliary energy is applied to 'top up' the hot water supply on dull days. The second trial described in this report explores the effect of integrating auxiliary heating with the solar cylinder on the performance of the same two systems.

For the evening run off schedule used in the previous work, and with optimal control of auxiliary energy input, the solar contribution from the AES flat plate system is reduced by only 7% and that of the Riomay evacuated tubes remains unchanged. In this mode of operation a preheat cylinder is no longer installed and total system losses are therefore reduced. The magnitude of this reduction has been calculated using an extension to the ISO annual calculation method, and found to be larger than the reductions in solar performance. Thus for this highly optimised heating strategy the systems give a larger net benefit when operated in this mode. However, while it provides the required amount of hot water in the evening, this particular test schedule does not necessarily guarantee that any hot water is available early in the morning. This is unlikely to be acceptable in a real installation, and some additional auxiliary energy will almost inevitably be used to remedy the situation. This in turn will result in reduced solar benefit from the system. The results obtained suggest that the Riomay evacuated tube system would be more robust in the face of changes to the heating schedule, but neither system can be guaranteed to continue to give the maximum possible output once more intrusive auxiliary heating schedules are introduced. Operation of the systems in preheat mode removes this potential source of performance degradation, and will be more robust in real applications.

CONTENTS

1 INTRODUCTION

In 2001 the Energy Monitoring Company conducted a study for the DTI which compared the amount of energy eight modern solar water heating systems could produce over an average year [1].

The approach adopted for that work followed closely the recommendations of a feasibility study previously carried out for the DTI by ESD [2]. It consisted of operating all eight systems side by side on an outdoor test rig, with each subjected to the same hot water run off profile each day over a period of about six months. This was considered the most appropriate method: the systems were operated under the same, realistic, climate conditions covering the full range of solar geometries and the same load patterns. The tests provided an accurate measure of the operation of the systems under the most realistic operating conditions possible, but at the same time ensured that all the systems were tested under identical conditions. For the first time it was possible to make a fair and transparent comparison of the performance of eight systems, covering a range of technologies.

In appraising the results from those tests two questions arose. The first was how the results obtained related to the results of other tests carried out to International Standards such as the relevant ISO Standard [3]. The goals of such a standard are rather different from those of the previous study. Tests on different systems cannot necessarily be carried out under identical climatic conditions, and the test method must therefore be guaranteed to give comparable results when different systems are tested under different climatic conditions.

Section 2 of this report outlines the criteria which were used to select two systems from the eight originally tested. Section 3 describes tests carried out on those two systems in accordance with the ISO Standard, and includes a detailed comparison with the results obtained in the previous study.

In the original tests the systems were treated as solar only systems, in which the solar cylinder acts as a preheat vessel for a second cylinder, to which auxiliary energy is applied to 'top up' the hot water supply on dull days. The second question to arise from those tests was whether was whether an alternative mode of operation, in which auxiliary energy was applied directly to the solar cylinder would cause a significant reduction in output.

Section 4 contains details of further tests carried out on the same two systems using an integrated source of auxiliary energy to top up the contents of the solar cylinder directly on dull days. Once again the performance of the systems is compared back to that measured during the original tests carried out without integrated auxiliary heating.

2 SELECTION OF SYSTEMS FOR TEST

The ISO Standard lays out exacting conditions under which tests should be conducted, and to test all eight systems in that detail would be a major experimental effort. The second round of testing, where auxiliary heating is integrated with the solar cylinders, amounts almost to a repeat of the tests carried out previously and again the effort required to test all eight systems would be large.

In view of these considerations it was clear that the available resources would not permit further testing to be carried out on all eight systems. Instead, two systems were selected from the eight previously tested. To make this selection a series of criteria was developed:

- the systems chosen should demonstrate the two principal technologies represented among the original eight systems: flat plate collectors and evacuated tubes

- in order that the conclusions of this limited phase of testing could be generalised the systems chosen should not employ technologies which are not typical of the bulk of the collector market

- the systems chosen for further testing should be ones which have a significant market share

- the systems chosen should be from the middle of the performance range observed in the previous tests.

A total of six flat plate collectors had been included in the previous trial. Of these the ZEN, which is a drainback system, and the Solartwin, which is a PV powered low flow system, were considered technologically exceptional and therefore excluded from the next round of testing. The fact that the Solartwin system could not be included was regrettable, as the low flow technology which this system uses makes the integration of auxiliary heating with the solar cylinder particularly interesting. Of the remaining systems, those manufactured by Filsol and AES have the largest market share. The Filsol system was the overall leader in the previous trials, whilst the AES system was close to the middle of the performance range. For these reasons the AES system was chosen as the most representative for further testing.

The choice of an evacuated tube system was much simpler. Of the two systems originally tested one manufacturer declined to participate in any further experimental work, leaving only the system supplied by Riomay as a candidate for the second round of tests.

3 TESTS CARRIED OUT TO THE ISO STANDARD

In this section we describe the tests carried out to the ISO Standard 9459-2: Outdoor test methods for system characterisation and yearly performance prediction of solar-only systems [3].

3.1 Summary of the test method

The test method described in ISO Standard 9459-2 consists of three types of test. In the first the system is preconditioned by circulating cold water through it and operating mixing pumps, and then operated from 6 hours before solar noon to 6 hours past solar noon. At this stage a run off is made, the volume of which is a minimum of three times the volume of the system solar cylinder. This test is to be carried out on at least six occasions, over a range of solar radiation levels and inlet water temperatures. From these results the energy output of the system is parameterised in terms of solar radiation level, mains water temperature and external air temperature.

The remaining two tests are carried out once only. The first determines the degree of mixing which occurs during run off. The solar cylinder is filled with hot water and mixed. A run off is then made and the resulting delivery temperature profile used to determine the degree to which incoming cold water mixes with the contents of the tank during run off.

The final test determines the heat loss from the solar cylinder. This is done by again filling the cylinder with hot water and mixing it. The solar cylinder is then allowed to cool over a period of between 12 and 24 hours, and is then mixed again. The heat loss coefficient is estimated from the mixed tank temperatures at the start and finish of the test and the average temperature of the air around the cylinder during the test. In general, two such tests may be needed, one with the collectors connected to the store and one with them isolated. Both of the systems tested here use non-return valves to ensure this isolation when the circulation pumps are not running, and hence only one heat loss test was required.

In order to extrapolate the performance of the systems to a full year the ISO Standard lays out a detailed modelling routine, which consists of a series of calculations carried out for each day of the year:

- the output of the system is estimated from solar radiation, mains water temperature and external air temperature
- the final temperature distribution in the tank is calculated
- the impact of the desired run off is determined

- the amount of energy remaining in the tank is estimated, and assumed to be evenly distributed throughout its volume

- the degree of cooling which occurs overnight is estimated and the starting tank temperature for the following day calculated.

3.2 Modifications required to the test rig

A number of minor modifications were required to implement the tests described above. The ISO Standard requires that a volume of water equal to three times the capacity of the solar cylinder or sufficient to reduce the inlet-outlet temperature difference to less than 1K, whichever is the larger, be run off on each test day. The solar cylinders are of volume approximately 165 litres, and the cold water storage tanks used in each test rig have a capacity of only about 420 litres. Changing the storage tanks for larger ones would have been a major undertaking, and it was acknowledged from the outset of the work that the volume of water run off would thus be slightly less than required. A full assessment of the impact of this, and other more minor deviations from the requirements of the standard, is given in Section 3.5.1.

3.2.1 Mixing arrangements

The standard requires that the solar tank is flushed and then mixed to a uniform temperature before each test is started at 6 hours before solar noon. To this end a pump and solenoid valve were installed around each of the solar cylinders. The purpose of the solenoid valve is to inhibit natural circulation through the pump during the period that the test is in progress.

The standard further requires that during the early morning flushing/mixing cycle the pump which powers the collector loop is also operated. To this end changeover mains relays were installed which allowed the solar pumps to be run under the control of a timeswitch.

Finally, the specification also calls for a highly uniform cold water delivery temperature. In the standard it is assumed that this will be achieved either by using an in-line temperature controller or by mixing from hot and cold water tanks. The existing test rig configuration provides cold water from cold water storage tanks. Mixing pumps were installed in these tanks to ensure temperature uniformity, and the tanks were heavily insulated to ensure that the temperature of their contents did not vary between the flushing of the systems in the morning and the evening run off.

3.2.2 Run off metering

The previous study used one of two run off sequences. In the first water was drawn from each system in a single 150 litre evening run off. In the second the run off was distributed through the day, with 60 litres in the morning, 30 litres at lunch time and a further 60 litres in the evening. To implement these schedules, and to ensure that exactly the same amount of water was drawn from each system, a series of calibrated metering tanks each with a maximum capacity of 150 litres was provided.

The ISO test schedule requires that a much larger volume of water is run off, and the existing metering tanks would not have been able to accommodate this. The tanks were therefore dispensed with, and the flow meters mounted in the supply to the solar cylinders were used to determine the flow through each system.

3.2.3 Cold water bleed valve

The ISO Standard requires that a bleed valve is installed to allow water which may have been heating or cooling in the pipework to the solar cylinder to be bled from the system shortly before the run off. The standard requires that this is done without any water being lost from the cylinder itself. To guarantee this, the valve was installed upstream of the non return valve which stops water flowing backwards out of the cylinder into the cold water supply tank. This strategy has the disadvantage that it results in a very small amount of water (about 0.05 litres) heated by conduction from the tank being left around the main temperature probe. This produces a small temperature 'spike' at the beginning of each run off, as the probe takes a few seconds to register the temperature of the incoming cold water. The error associated with this is assessed in Section 3.5.1.

Figure 3.1 shows the test rig modified as described.

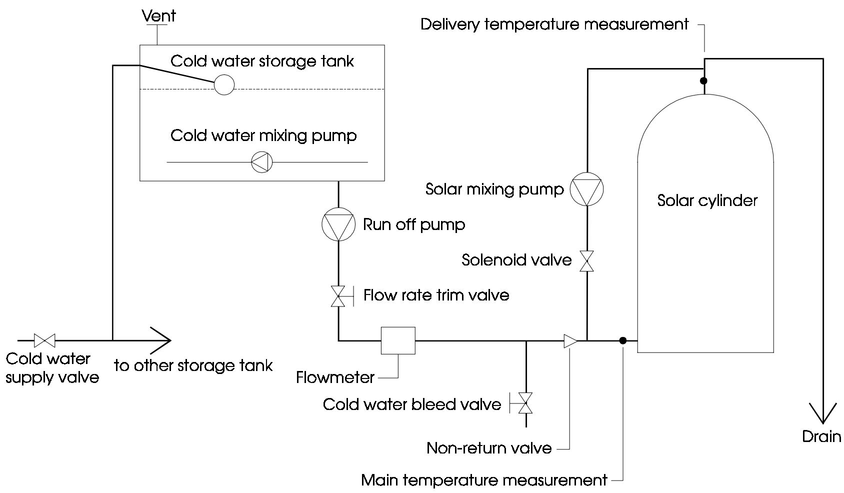

Figure 3.1: Test rig modified to carry out ISO tests

3.2.4 Collector covers

To allow the collectors to be conditioned to the test starting temperature they are covered prior to mixing. To achieve this hinged wooden shutters were constructed for each of the collectors under test. For the AES system these were hinged at the bottom and folded downwards, out of the line of sight of the collector, during the tests. For the Riomay system, however, such a mounting arrangement would have meant that the shutter support would have significantly overshadowed the lowest tube on the array. For this system the shutters were therefore hinged at the top, and opened upwards. Once again, when opened there was no overshadowing of the array.

3.2.5 Equipment enclosure temperature control

In the previous tests the sheds in which the solar tanks and their ancillary equipment were housed were assumed to represent airing cupboards within a dwelling, and their temperatures were controlled to a representative level using small heaters.

The ISO Standard assumes a single ambient air temperature for all parts of the system, thus implicitly assuming that all equipment is housed at the same temperature as the collectors. Thus the thermostatically controlled heaters were turned off, and small ventilation fans installed in both sheds. These ran continuously throughout the testing period.

3.3 Modifications required to instrumentation

A few minor modifications were required to the instrumentation associated with the test rig to fulfil the requirements of the ISO Standard. These relate primarily to additional climate data: the standard requires that both wind speed and diffuse radiation are measured. These measurements are for reporting purposes only, and they are not used in the analysis.

Finally, minor modifications were required to the data acquisition software to incorporate calibration data for some sensors. This was necessary to achieve the higher temperature measurement accuracy specified in the ISO Standard.

3.3.1 Wind speed measurement

The ISO Standard requires that the wind speed across the front face of the collectors is measured. This was achieved by installing a Vector Instruments A100 series anemometer in the plane of the collectors, with the centre line of its rotor approximately 100mm above the surface of the collectors.

The anemometer has a cut in speed of $0.1ms^{-1}$ and an accuracy of ±5%.

3.3.2 Diffuse radiation measurement

The standard further requires that diffuse radiation is measured in the plane of the collectors. A Kipp and Zonen CM5 solarimeter fitted with a shadow ring was used for this measurement. The performance of the CM5 is slightly inferior to that of the CM11 used to measure the total radiation incident on the collectors. One of its most significant shortcomings is the fact that it has a significant tilt error. To minimise the impact of this the instrument was calibrated against the CM11 in the plane of the collectors before use.

3.3.3 Accuracy of temperature measurements

The absolute accuracy required of temperature measurements is ±0.1°C, and the same figure also applies to the calculated difference between the incoming main temperature and the temperature at which hot water is delivered. This is significantly better than that specified for the previous tests, which was the standard Class A Platinum resistance thermometer accuracy of ±0.15°C at 0°C rising to ±0.35°C at 100°C.

All of the sensors used on the test rig had previously been checked by placing them together in a stirred waterbath alongside a UKAS calibrated Quartz thermometer. As expected, they had been found to be within the accuracy band originally specified.

That calibration data revealed that the sensors associated with the AES system were in fact well within the revised ±0.1°C specification. One of the sensors used on the Riomay installation however had an error which rose to ±0.2°C at higher temperatures. A simple correction was derived from the calibration data and incorporated into the data analysis software in order to bring the measurements from this sensor within the required accuracy band.

3.3.4 Collector flow rate measurement

If a flow meter is not already installed in the collector loop, the standard requires a suitable meter be inserted. The AES system already incorporated a flow tube which gave a satisfactory indication of flow. However the Riomay system did not, and a Kent water flow meter was duly plumbed into the collector loop.

3.3.5 Modifications to data format

The way in which data was recorded was chosen in order that a common format could be used for all parts of the tests to the ISO Standard. To this end, the temperatures of the hot and cold probes were added to the values recorded every five minutes.

The data format is outlined in detail in Appendix A.

3.4 Test sequence

Table 3.1 summarises the sequence of operations involved in carrying out a test. The manual interventions required, which consist of covering and uncovering the collectors and operating the cold water bleed valve, are also shown.

The exact time at which solar noon occurs varies over the course of a year. At the time these tests were carried out it was within five minutes of local noon. The times shown in the table assume that solar noon occurs at exactly 12:00.

	Cold water supply valve	Cold water mixing pump	Run off pump	Solar mixing pump and collector loop pump
Fill cold water tanks	3:00 ON			
	7:00 OFF			
Mix cold water tanks		4:00 ON		
		7:00 OFF		
Flush system			5:05 ON	
			5:20 OFF	
Mix system				5:25 ON
				5:55 OFF
6:00 - Covers removed				
Mix cold water tank		16:55 ON		
		17:55 OFF		
17:55 - Bleed valve opened briefly				
Water draw off			18:00 ON	
			18:45 OFF	
19:00 - Covers replaced				

Table 3.1: Sequence of actions required on a test day

3.5 Data Analysis

The analysis of the data gathered during the tests is carried out in three stages. First it is necessary to determine whether the way in which the test was carried out fulfilled the requirements laid out in the standard, and to assess the impact of any deviations. Then, performance parameters are derived from the measurements taken. Finally, these parameters are used in conjunction with climate data and a calculation method specified in the standard to estimate the annual performance of the system.

3.5.1 Compliance with requirements of the standard

The standard lays out detailed criteria for many aspects of the tests. In this section the data gathered is inspected to determine whether these have been fulfilled.

The first such criterion is for the quality of system mixing before the test is carried out. The standard requires that the difference between the temperatures measured at the top and bottom of the tank is less than 1°C for a period of at least 15 minutes. Figure 3.2 shows these temperatures over the whole of the 30 minute mixing period, and also shows the 1°C acceptance criterion.

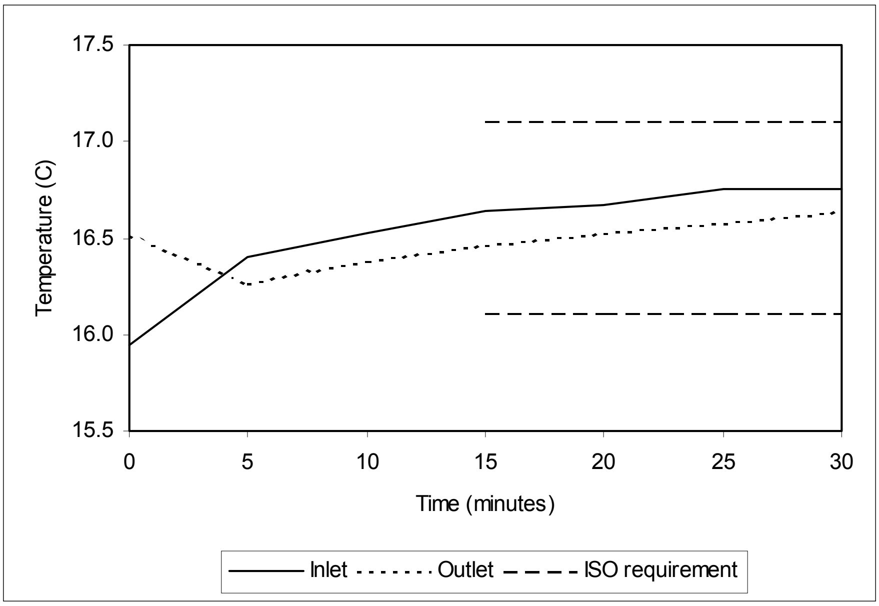

Figure 3.2: Mixing of solar tank before start of test

It is clear from the figure that the required degree of mixing is being readily achieved.

During the evening run off the standard requires that the flow through the system is constant at 600 ± 50 litres/hour. Figure 3.3 shows the flow during each minute of the sample run off, and indicates that it is well within these limits, which are also shown on the figure.

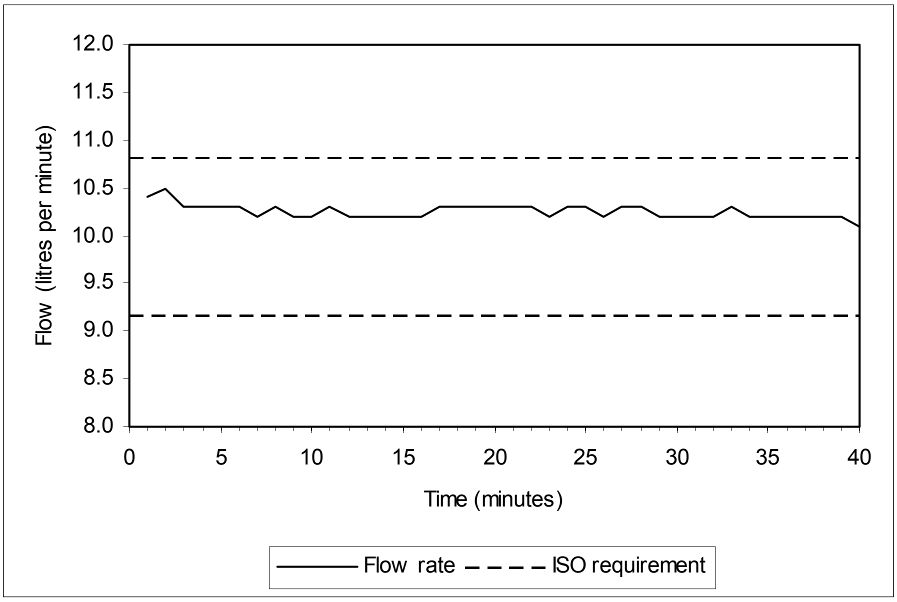

Figure 3.3: Flow rate during run off

Once again it is clear that the criterion specified in the standard is being satisfied.

Figure 3.4 shows the main and delivery temperature measurements recorded at 5 second intervals over a sample run off.

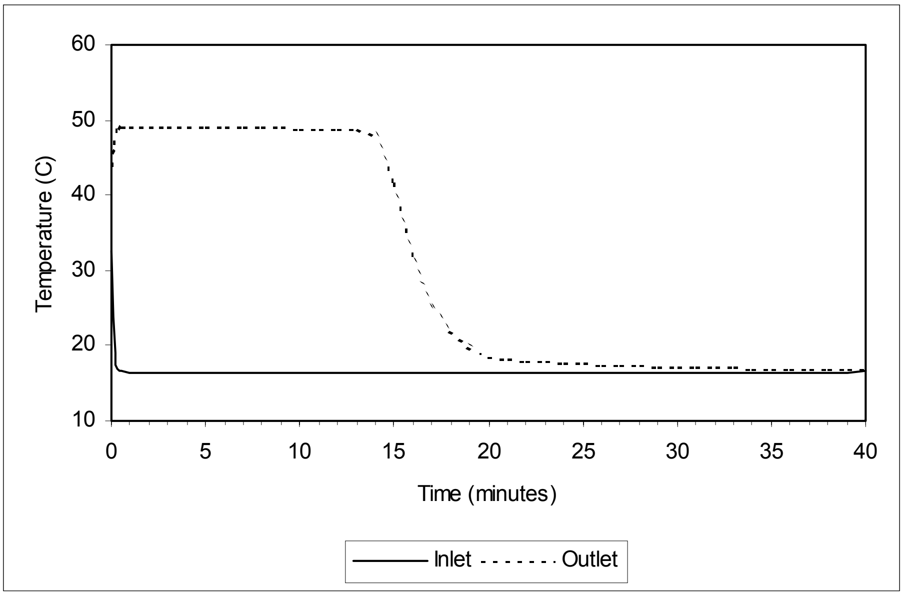

Figure 3.4: Inlet and outlet temperatures recorded during run off

The figure shows that at the beginning of the run off both sensors take a small amount of time to equilibrate. In the case of the inlet temperature sensor this effect is made more pronounced by the decision to insert the cold water bleed valve before the associated non-return valve. This results in a small pocket of warm water being left around the inlet temperature sensor. However, the volume of that water is very small (approximately 0.02 litres). It is replaced by incoming cold water within less than a second from the start of the run off, and the error introduced is absolutely minimal. Much more significant is the error introduced by the time constant of the sensor. This is approximately five seconds, and as result the sensor takes approximately 15 seconds to reach the temperature of the incoming cold water. The effect of this is still minimal: for the example shown it introduces an error of approximately 0.03°C in the determination of the average inlet temperature during run off. One reason that the effect can be so easily observed is that temperature measurements have been made every five seconds. The standard only requires that measurements are made every 15 seconds, and in this situation the effect would go almost unnoticed.

The standard requires that the main temperature drifts by less than 0.2°C over the course of the run off. During the course of the run off the temperature is allowed to fluctuate by up to ±0.25°C, but the overall drift must remain less than 0.2°C. Figure 3.5 shows the inlet temperature measured during the run off together with this criterion, and indicates that, once the initial sensor settling time has elapsed the requirements of the standard are easily achieved.

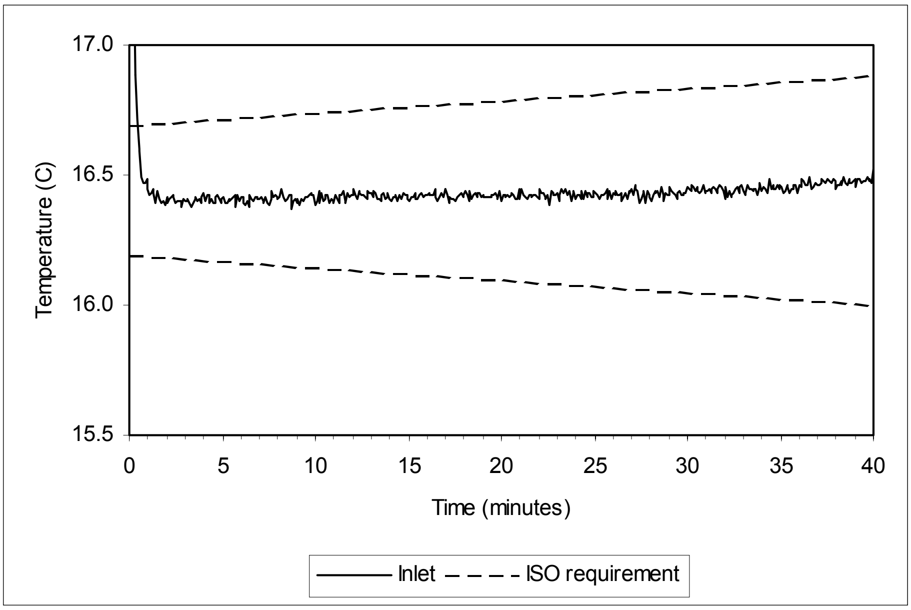

Figure 3.5: Inlet temperature during run off

As well as confirming that the inlet temperature was steady over the course of the run off, Figure 3.5 confirms retrospectively that the temperature of the water that the system was flushed with in the morning (shown on Figure 3.2) was extremely close to the main temperature used for the run off.

The test schedule requires that the volume of water run off from the system three times its capacity, or sufficient to reduce the difference between inlet and outlet temperatures to less than 1K, whichever is the greater.

We have already seen that the run off volume used here is insufficient to meet this requirement. Figure 3.6 shows the inlet and outlet temperatures recorded during the last five minutes of the run off.

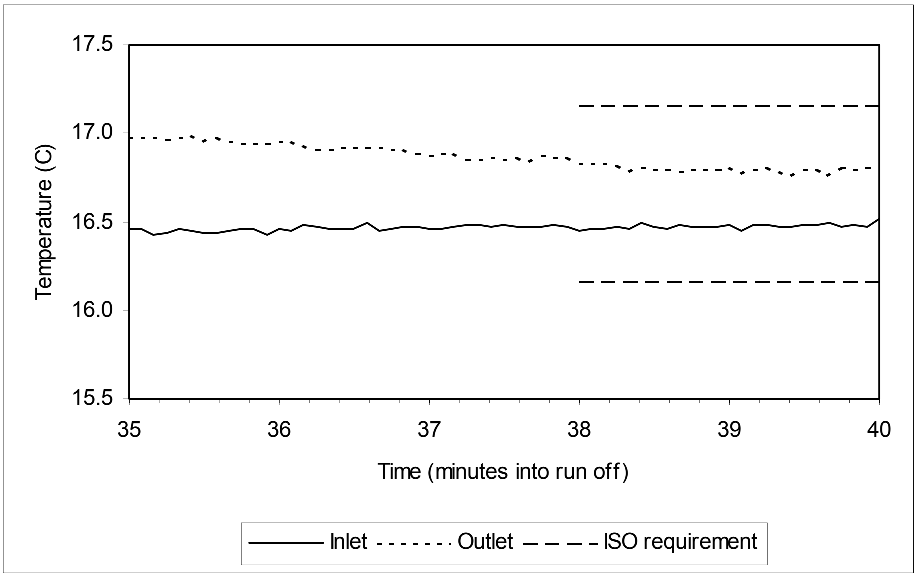

Figure 3.6: Inlet at outlet temperatures at close of test

The figure confirms that although a slightly reduced run off volume has been used the temperature difference has been reduced to a value well within 1K. More importantly, this figure allows the error introduced by violating the run off volume requirement to be estimated.

Over the last minute of the run off the inlet temperature averaged 16.48°C, and the outlet temperature 16.80°C, a temperature difference of 0.32°C. In order to comply exactly with the requirements of the standard a volume of 500 litres should have been run off. In fact only 411 litres were used, a shortfall of 89 litres. Under the most pessimistic assumption, that the temperature difference remained at 0.32°C, this additional water would have added approximately:

$$89 \times 0.32 \times 4.18 = 119 \text{ kJ}$$

to the energy output of the system. The output on this day was 23.19MJ. We conclude that the error in estimated system output introduced by the reduced run off volume is of the order 0.5%.

The final minor deviation from the requirements of the standard relates to the range of differences between the mains inlet and ambient air temperatures explored in the tests. The standard requires that at least two days data should be obtained with differences 9K larger than on other days. In fact only one day was obtained with a difference of 6.8K, followed by a second at 5.7K. This has no impact on the values of the parameters determined, but does result in a small increase in the uncertainty associated with those parameters.

3.5.2 Derivation of ISO test parameters

A program was written to process the raw data, and generate the daily totals and averages required to derive the test results. In addition, the program implemented some of the conformity checks which were presented graphically in the previous section, providing confirmation that the test conditions were satisfactory on each test day.

The analysis described in the standard consists of modelling the daily output of the system in terms of solar radiation and the difference between external ambient and water inlet temperatures. The data is summarised by an equation of the form:

$$Q = a_1 H + a_2 (T_a - T_{main}) + a_3$$

where:

Q is the daily system energy output

a_1, a_2 and a_3 are the model parameters

T_a is the daily external temperature over the period 6:00am to 6:00pm

T_{main} is the temperature of the inlet water.

In addition to this the standard also requires that a similar equation for the maximum temperature rise is derived, and this yields a further three parameters b_1, b_2 and b_3. This model is not used in the prediction of annual system performance, and has not been developed here.

When fitting multiple parameters of this type it is vital that the variables driving the system (in this case H and $T_a - T_{main}$) are not themselves highly correlated. In this situation it becomes impossible to separate out their individual effects, and the parameters can no longer be estimated with confidence [4]. The test rig used here does not actively control T_{main} and there is therefore a risk that this type of unwanted correlation could emerge. Figure 3.7 shows the relationship between solar radiation and $T_a - T_{main}$ for the AES system over the test period.

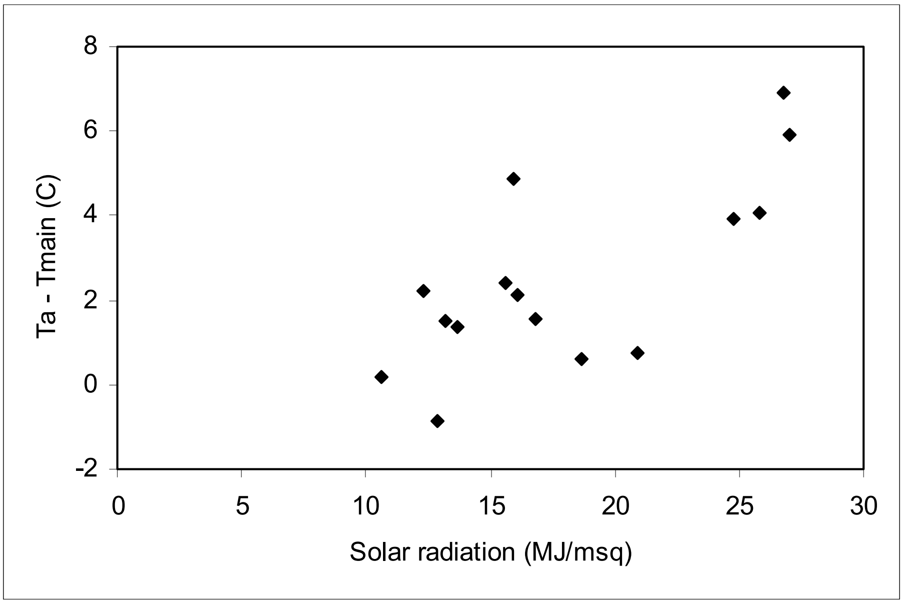

Figure 3.7: Relationship between solar radiation and T_a-T_{main} over test period

The type of linear dependence between the driving quantities which would cause problems estimating the parameters would be evidenced on Figure 3.7 by the points falling along a straight line. The figure confirms that this is not the case, and that the required model parameters can be safely estimated using linear regression.

Linear regression was also used as a tool to determine when testing should stop. The standard lays out certain requirements for the levels of solar radiation and T_a-T_{main} which must be experienced during the test, and stipulates that a minimum of six days data must be collected. In fact it took ten days to achieve the desired range of conditions. At this stage a regression was carried out to generate estimates of all three parameters and their 95% confidence intervals. This process was continued for a further six days, and Figure 3.8 shows how the most important parameter a_1, which relates system output to solar radiation level, and its 95% confidence interval evolved over that period.

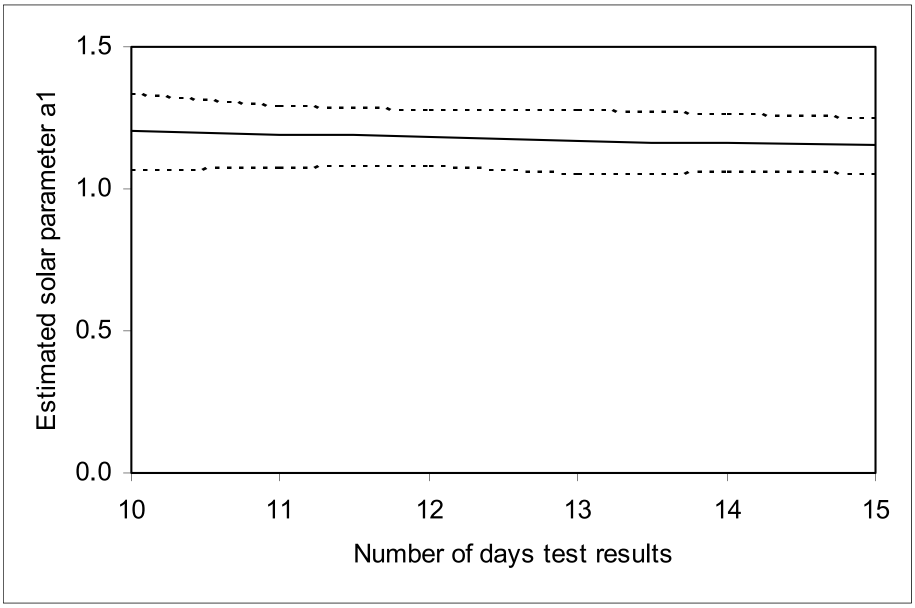

Figure 3.8: Evolution of the parameter a_1 and its 95% confidence interval

At the end of the fifteenth day of testing the experiment was concluded. Table 3.2 summarises the results of the final regressions for each of the systems tested.

	AES system	Riomay system
a_1	1.156±0.087m^2	0.948±0.049m^2
a_2	0.766±0.223MJK^{-1}	0.315±0.122MJK^{-1}
a_3	0.754±1.268MJ	1.869±0.677MJ

Table 3.2: Performance parameters

The equation which has been used to model the measured results does not have a convenient representation as a two dimensional graph. If the output of the system is represented by height then the equation can be considered to describe a plane above the surface which contains the solar and T_a-T_{main} axes. This interpretation allows further insight into the problems associated with a linear relationship between solar and T_a-T_{main}: if the points on Figure 3.7 fell on a line the plane would tilt on this knife edge, making its exact location hard to determine.

It is, however, difficult to visualise the quality of the model fit in three dimensions. Instead the effects of the two independent variables can be examined separately, by projecting the measurements onto a surface containing the energy output axis and the independent variable in question.

Figure 3.9 shows this projection for the solar radiation axis and confirms that, as expected and as seen in all previous tests, there is a strong relationship between incident solar radiation and system output, and also that the linear model used in the prescribed analysis is appropriate.

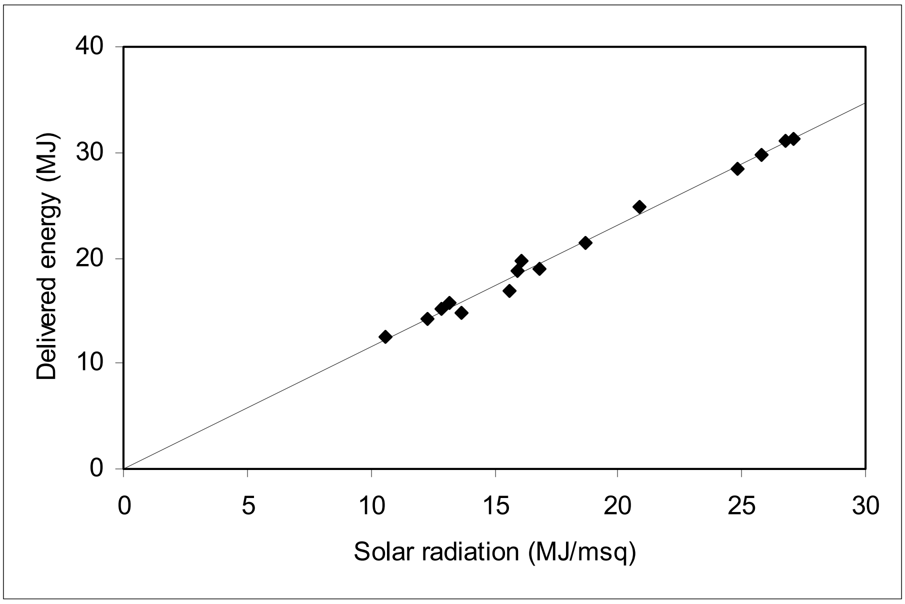

Figure 3.9: Projection of system performance onto solar axis

Figure 3.10 shows the corresponding plot showing the dependence of system output on T_a-T_{main}.

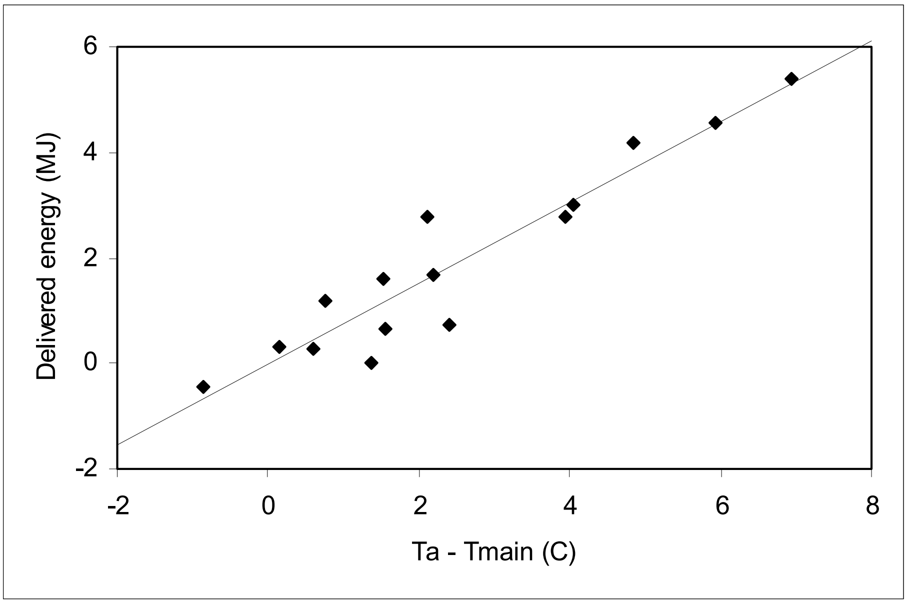

Figure 3.10: Projection of system performance onto T_a-T_{main} axis

The quality of the fit to the model at first appears significantly worse, but it is important to note that the scale of the y-axis is considerably enlarged from that of Figure 3.9. This is a consequence of the fact that T_a-T_{main} has a much smaller influence on system performance than solar radiation, and errors associated with this aspect of the model are therefore much less significant.

The standard states that these intermediate results should not be used to make statements about system performance. However, it is informative to compare these results directly with those obtained in the previous round of testing. In that work a two parameter model was fitted to the daily system output:

$$Q = A0 + A1\ H$$

where:

A0 and *A1* are the model parameters.

Table 3.3 shows the results obtained in the previous study.

	AES	Riomay
A0	0.10 ± 0.57MJ	0.94 ± 0.48MJ
A1	1.148 ± 0.036m^2	0.950 ± 0.032m^2

Table 3.3: Performance parameters from previous study

By far the most important parameter is the response of the system to solar radiation, a_1 for the ISO tests and A1 for the previous tests. It is reassuring to see that the values obtained from the two tests are extremely close to each other for both systems.

The previous work did not consider the effect of incoming main temperature, and there is therefore no parameter which corresponds directly to a_2. There are two ways in which the temperature of the incoming cold water can affect the energy output of the systems. The first is that as water is circulated through the collectors its temperature will tend to move towards ambient temperature. The second is that as the water stands in the storage tank its temperature will again tend to move towards ambient. If we consider the situation where there is no solar radiation, then if the entire contents of the tank moved to ambient temperature over the course of a day the energy gain per degree of T_a-T_{main} (in other words the expected value of the parameter a_2) would be approximately:

$$160 \times 4.18 = 670\ kJK^{-1} = 0.67\ MJK^{-1}$$

This value compares closely with that obtained from the test on the AES system. The Riomay system, however, shows only about half this value, reflecting the fact that the evacuated tube collectors have a much lower thermal conductivity to ambient.

The parameters a_3 and A0 represent the output of the system when the incident radiation and, in the case of a_3, T_a-T_{main} are zero. For the AES system, both tests indicate that this parameter cannot be distinguished from zero. In the case of the Riomay system both tests indicate a small positive value, but with large uncertainties. When the uncertainty bands are taken into account the two parameter estimates overlap.

The next piece of analysis required is the generation of normalised run off profiles. The profiles are required for two days, the first of which will be used to predict system performance for solar radiation levels in the range 8 to 16MJm^{-2}, and the second for radiation levels 16 to 25MJm^{-2}.

To generate these profiles the tank volumes must be known accurately. They were measured by emptying each tank, and then filling them with water which was weighed as it was added to the tanks. The results of this measurement are shown in Table 3.4.

	AES	Riomay
Volume	167.2 litres	162.4 litres

Table 3.4: Measured tank volumes

Each profile consists of a series of values which summarise the amount of energy provided as each tenth of the tank volume is run off. The generation of the integrated energy output as a function of run off volume is simple: indeed it has already been done in order to produce the daily performance data analysed above. On the July 18th the total radiation received by the collectors was 12.3MJm^{-2} and this day is therefore ideal for the production of the first profile required. On July 11th the corresponding radiation level was 20.9MJm^{-2}, ideal for the generation of the second profile. Figure 3.11 shows the cumulative energy delivered by the AES system over the course of the run off on July 18th, as a function of volume flow.

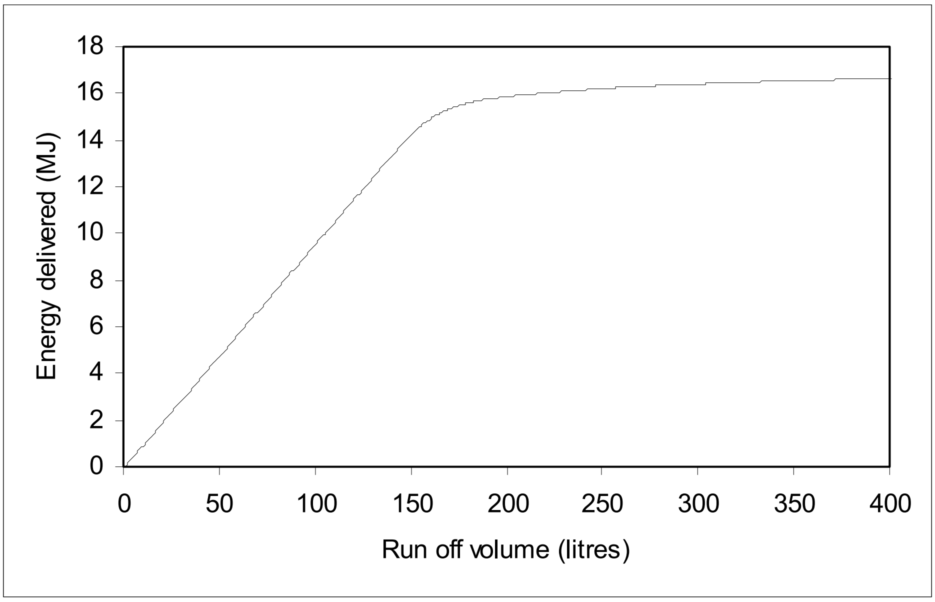

Figure 3.11: Cumulative energy delivered during run off

Because the measurements of run off flow and temperature were taken at regular time intervals rather than regular flow intervals there is no guarantee that values will be obtained which lie exactly on the one tenth tank volume increments required. This is easily solved by using an interpolation process to derive the values at the points required, and Figure 3.12 shows these superimposed on the original profile.

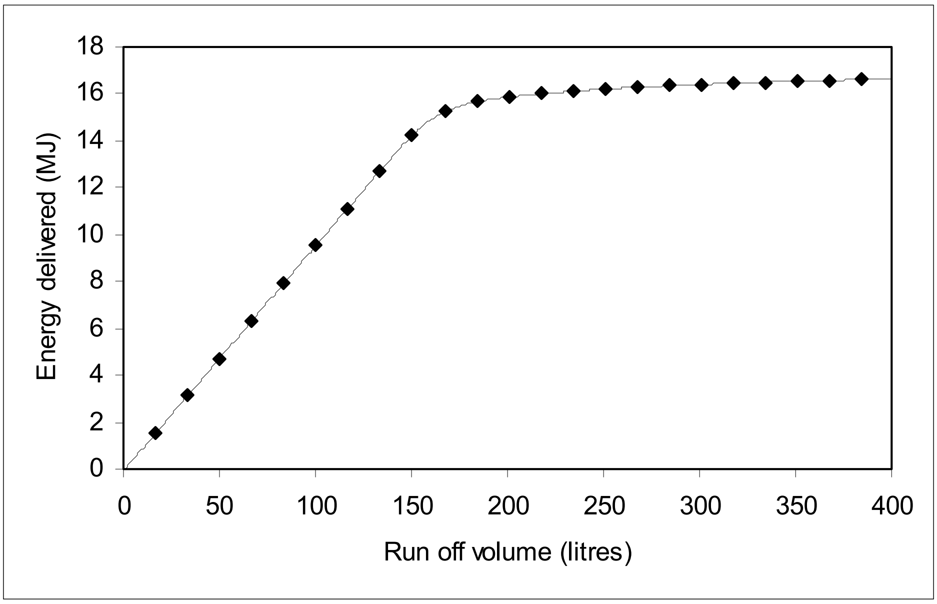

Figure 3.12: Interpolated points on energy profile

Two further steps are required to convert the profile to the form required. The first is to difference the points shown on the figure to provide values which indicate the amount of energy present in each part of the run off, rather than the cumulative value. Finally, the profile is normalised so that the values tabulated add up to unity. The resulting profile is shown on Figure 3.13.

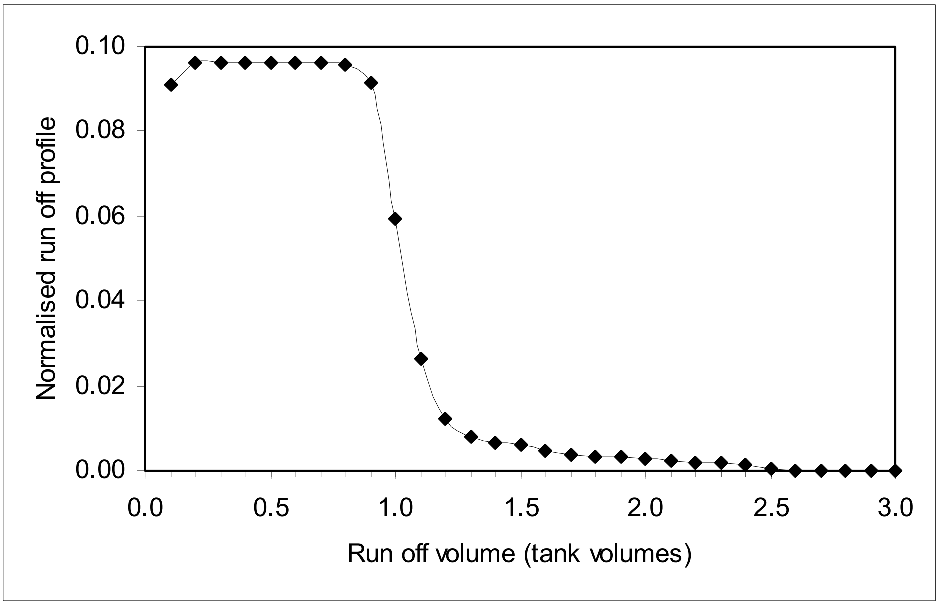

Figure 3.13: Normalised run off profile

Table 3.5 shows the numerical values of the points on both profiles for both systems.

Volume (tanks)	AES		Riomay	
	8-16MJm^{-2}	16-25MJm^{-2}	8-16MJm^{-2}	16-25MJm^{-2}
0.0 – 0.1	0.0911	0.0928	0.0887	0.0903
0.1 – 0.2	0.0962	0.0976	0.0927	0.0922
0.2 – 0.3	0.0964	0.0979	0.0927	0.0917
0.3 – 0.4	0.0962	0.0978	0.0928	0.0922
0.4 – 0.5	0.0962	0.0975	0.0926	0.0918
0.5 – 0.6	0.0962	0.0975	0.0925	0.0914
0.6 – 0.7	0.0962	0.0974	0.0923	0.0916
0.7 – 0.8	0.0956	0.0971	0.0907	0.0913
0.8 – 0.9	0.0914	0.0941	0.0756	0.0843
0.9 – 1.0	0.0592	0.0614	0.0457	0.0537
1.0 – 1.1	0.0262	0.0246	0.0271	0.0299
1.1 – 1.2	0.0122	0.0090	0.0160	0.0178
1.2 – 1.3	0.0079	0.0057	0.0115	0.0111
1.3 – 1.4	0.0067	0.0048	0.0103	0.0089
1.4 – 1.5	0.0059	0.0043	0.0097	0.0078
1.5 – 1.6	0.0047	0.0038	0.0089	0.0069
1.6 – 1.7	0.0037	0.0033	0.0084	0.0065
1.7 – 1.8	0.0033	0.0027	0.0078	0.0062
1.8 – 1.9	0.0031	0.0022	0.0073	0.0058
1.9 – 2.0	0.0028	0.0019	0.0069	0.0055
2.0 – 2.1	0.0025	0.0017	0.0064	0.0051
2.1 – 2.2	0.0021	0.0016	0.0061	0.0048
2.2 – 2.3	0.0017	0.0014	0.0056	0.0045
2.3 – 2.4	0.0016	0.0012	0.0052	0.0042
2.4 – 2.5	0.0007	0.0007	0.0049	0.0039
2.5 – 2.6	0.0000	0.0000	0.0014	0.0006
2.6 – 2.7	0.0000	0.0000	0.0000	0.0000
2.7 – 2.8	0.0000	0.0000	0.0000	0.0000
2.8 – 2.9	0.0000	0.0000	0.0000	0.0000
2.9 – 3.0	0.0000	0.0000	0.0000	0.0000

Table 3.5: Run off profiles
(Values may not sum exactly to unity due to rounding effects)

The analysis of data from the two one day tests is very much more straightforward. The production of a normalised output curve from the results of the mixing test follows exactly the process described above for the normalised draw off profiles, and as expected, produces a slightly sharper discharge curve. Figure 3.14 shows this result for the AES system.

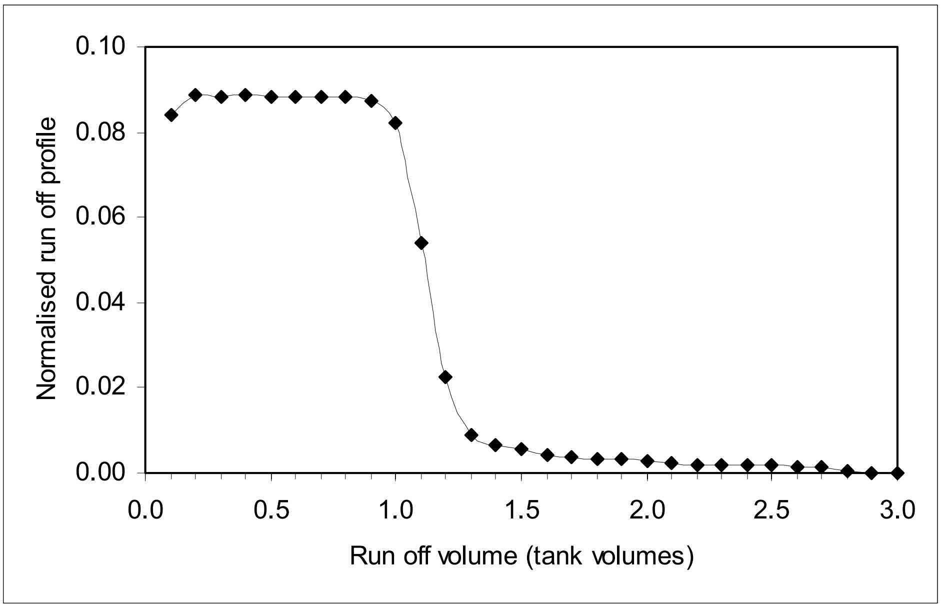

Figure 3.14: Normalised mixing profile from stratification test

Table 3.6 contains the results for the two systems.

Volume (tanks)	AES	Riomay
0.0 – 0.1	0.0967	0.0933
0.1 – 0.2	0.0990	0.0942
0.2 – 0.3	0.0988	0.0937
0.3 – 0.4	0.0986	0.0935
0.4 – 0.5	0.0987	0.0937
0.5 – 0.6	0.0984	0.0934
0.6 – 0.7	0.0982	0.0932
0.7 – 0.8	0.0978	0.0933
0.8 – 0.9	0.0965	0.0920
0.9 – 1.0	0.0691	0.0720
1.0 – 1.1	0.0245	0.0336
1.1 – 1.2	0.0080	0.0148
1.2 – 1.3	0.0034	0.0065
1.3 – 1.4	0.0024	0.0042
1.4 – 1.5	0.0020	0.0036
1.5 – 1.6	0.0016	0.0033
1.6 – 1.7	0.0014	0.0031
1.7 – 1.8	0.0011	0.0029
1.8 – 1.9	0.0010	0.0027
1.9 – 2.0	0.0008	0.0025
2.0 – 2.1	0.0006	0.0023
2.1 – 2.2	0.0005	0.0022
2.2 – 2.3	0.0004	0.0020
2.3 – 2.4	0.0004	0.0019
2.4 – 2.5	0.0001	0.0018
2.5 – 2.6	0.0000	0.0004
2.6 – 2.7	0.0000	0.0000
2.7 – 2.8	0.0000	0.0000
2.8 – 2.9	0.0000	0.0000
2.9 – 3.0	0.0000	0.0000

Table 3.6: Normalised mixing test profiles
(Values may not sum exactly to unity due to rounding effects)

The remaining stage in the data analysis is the determination of the tank heat loss coefficients. These are determined by examining the temperatures during the mixing periods at the start and finish of that particular test. The tank heat loss coefficient is then estimated from:

$$U_s = \frac{\rho c_p}{\Delta t} \ln\left[\frac{t_i - t_{as(av)}}{t_f - t_{as(av)}}\right]$$

where:

U_s is the required coefficient

ρ and C_p are the density and specific heat capacity of water, here evaluated at the mean of the initial and final water temperatures,

V_s is the volume of the tank, from Table 3.4

Δt is the duration of the test

t_i and t_f are the initial and final water temperatures

$t_{as(av)}$ is the mean temperature around the tank over the course of the test.

Deriving the required values from the measurements taken during the test is straightforward. For example, the temperature at the start of the test on the AES system was 65.22°C, and over a period of 18 hours it fell to 55.01°C Over that period the mean temperature in the shed housing the tank was 19.33°C. Inserting these values into the above equation yields a tank heat loss coefficient of 2.72WK^{-1}. The table below summarises the results for the two systems.

	AES	Riomay
U_s	2.72WK^{-1}	2.48WK^{-1}

Table 3.7: Measured tank heat loss coefficients

3.5.3 Climate data generation

To carry out the extrapolation to annual performance, daily values of total incident solar radiation, external temperature averaged between 6:00am and 6:00pm and between 6:00pm and 6:00am, and cold water main temperature are required.

The previous work used monthly totals of solar radiation based on 20 year average values [5] to predict system output. This data cannot be used directly for the ISO calculation. An hourly climate data file for Kew was obtained. This contains values of global and diffuse solar radiation measured on the horizontal. The thermal simulation program SERI-RES was used to generate the corresponding values on a plane facing due south, but inclined at 30°.

The hourly data used for this process related to one particular year, whereas the monthly totals used previously were long term year averages. Because of this the hourly values obtained for each month did not sum exactly to those used previously. To produce estimates of performance which can be compared to those of the previous study this situation was remedied by generating a series of scaling factors to be applied to all of the hourly values in each month to bring the totals into line with those used previously.

A sample program for carrying out the annual extrapolation process forms an appendix to the standard. This program accepts external temperature values averaged over 24 hours, and assumes that the average value throughout the day is 2.5°C above this value, and the average at night 2.5°C below. This assumption has been adopted in the analysis conducted here, meaning that only daily average external temperatures need be generated for the calculation process. This is readily achieved from the hourly Kew data. External temperature did not play a part in the extrapolation process used in the previous study and there is therefore no need to check for 'backward compatibility'.

Finally, the ISO calculation method requires the incoming cold main temperature. This does not normally form a part of meteorological data records, and the program supplied as part of the standard proposes one way in which it can be generated, by assuming a sinusoidal profile over the year with mean value equal to the mean external temperature, and amplitude specified by the user. This is an approximation of the type normally used to predict ground temperature, and is therefore equivalent to the assumption that the cold water supplied to the systems is at the temperature of the cold main coming into the building. The calculation proves to be quite sensitive to the exact assumption used, and further discussion of this is presented in the next section.

3.5.4 Extrapolation to annual performance

Armed with the performance parameters from Section 3.5.2 and the climate data generated as described in Section 3.5.3 the calculation procedure described in the standard can be implemented. A small Windows application has been created which accepts as input a climate data file (which includes the corrections needed to bring solar radiation into line with the values used in the previous study) and a file containing the test results for a particular system. The user is free to adjust the volume drawn off from the system each evening, and to choose between two algorithms for the calculation of the temperature of the incoming cold water supply.

The systems tested would normally be supplied from a cold water storage tank located in the roofspace of a house. In this situation cold water brought in from the main is held in surroundings whose temperature is determined by a complicated relationship which includes external temperature, the rate of ventilation in the loft, solar radiation incident on the surface of the roof and local wind speed. The extent to which the water in the tank adopts the temperature of its surroundings depends on how long it remains there, and on how well the tank is insulated.

It is clear from this that any estimate of the temperature of the cold water entering the solar system will be an approximation. Here we look at two cases, corresponding to the two extremes of behaviour which might be observed:

- in the first the transfer of heat to the water in the cold storage tank is assumed to be high, and that water is assumed to come to the external air temperature, averaged over the day, and

- in the second it is assumed that no transfer of heat occurs to the cold water storage tank, and that the temperature of the water remains close to the temperature at which it came into the building. In this case the algorithm used in the program appended to the ISO Standard provides a good estimate of incoming main temperature.

Referring back to the equation which defines the ISO test parameters in Section 3.5.2 reveals that in the first case the parameter a_2, which summarises the effect of differences between the mean daytime temperature and incoming main temperature, will make no contribution to the predicted performance. In this case, given that the remaining two parameters are close to those predicted previously, the estimated output will also be expected to be close to previous predictions.

Table 3.8 shows the annual predictions obtained for both incoming water temperature algorithms, together with the values which were derived in the previous project.

	AES	Riomay
ISO calculation ($T_{main} = T_a$)	4229MJ	3935MJ
ISO calculation ($T_{main} = T_{ground}$)	4913MJ	4277MJ
Previously derived values	4447MJ	3995MJ

Table 3.8: Extrapolated annual performance

As predicted, the results for the first cold water temperature algorithm are close to those of the previous study. For the AES system the prediction using the first algorithm is 5% below the previous value, and with the second algorithm 10% above. For the Riomay system the results are even closer to those obtained previously, at 1.5% below for the first cold water temperature algorithm and 7% above for the second.

The annual extrapolation method defined in the standard includes a detailed treatment of the way in which unused energy is stored overnight by the system. The energy remaining in the cylinder is calculated, and from the resulting temperature the overnight heat loss is found. This then allows the starting temperature for the next day to be estimated. To retain compatibility with the previous work the values shown in Table 3.8 were calculated assuming that 150 litres was drawn from each system each evening. Because this is close to the capacity of the solar cylinders there is little energy left over after the run off, and this part of the calculation is not heavily exercised in the results presented.

The fact that the calculation treats the storage of energy overnight in a detailed way, and that all the parameters required for this have been determined experimentally, means that the method can be used with confidence to determine the impact of reduced run off volumes, a facility which the analysis used in the previous trials did not provide. Figure 3.15 shows the results for the two systems, using the first of the two cold water temperature algorithms.

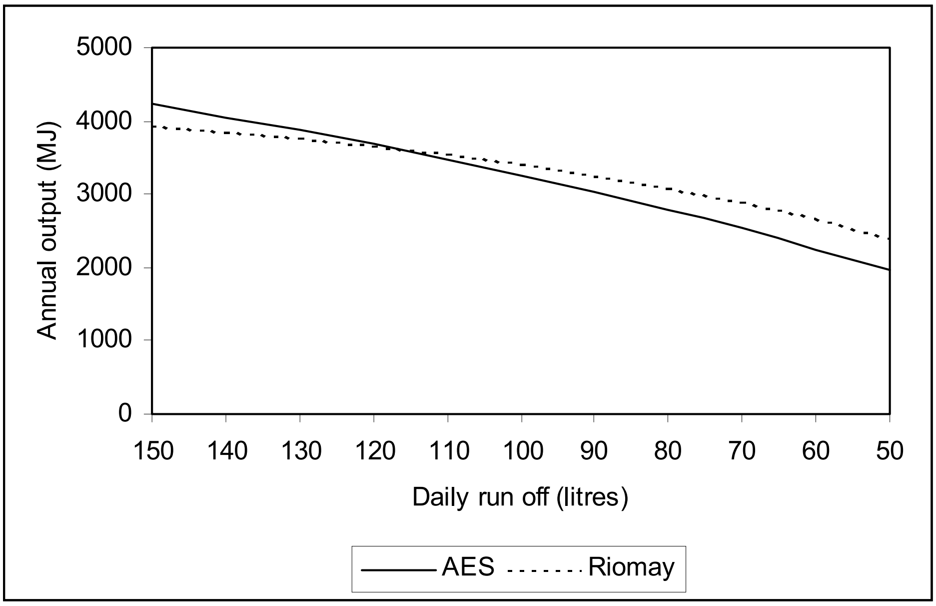

Figure 3.15: Impact of reduced run off volume on system performance

The figure shows that the Riomay evacuated tube system is more robust in the face of reduced run off volume, and that if the volume of water used each day falls below about 120 litres its performance actually overtakes that of the AES flat plate system. The reason for this lies with its reduced heat loss to ambient temperature. When some hot water is left in the tank overnight the collectors operate at a higher temperature the following day. This has a greater impact on the performance of the flat plate collectors, and explains the shape of the curves shown.

4 TESTS WITH INTEGRATED AUXILIARY HEATING

The second set of tests described in this report explored the extent to which integrating auxiliary heating with the solar cylinder affects the solar benefit delivered.

4.1 Summary of the test method

To facilitate direct comparison of results, the test method used followed that of the original study closely. However, each system was equipped with an auxiliary heat source, in the form of an immersion heater, with which on dull days could be used to bring the temperature of the solar tank up to the required level. To make the results of the tests comparable with the previous study the same functional requirement was placed on each system: to deliver 150 litres of water at 55°C at 6:00pm each evening.

It is clear that, if used unwisely, integrated auxiliary heating could seriously reduce the effectiveness of the solar collectors, and hence the solar benefit. In the most extreme case, if the auxiliary heater simply held the contents of the solar cylinder permanently at or above the required setpoint, there would be a very marked decrease in the amount of solar energy collected. In the tests described here the auxiliary heat source was switched on at 4:00pm and thermostatically controlled. It was switched off immediately before the run off, at 5:59pm. Whilst this operating schedule provides the required amount of hot water at 6:00pm, it does not necessarily guarantee that hot water is available early in the morning. This is unlikely to be acceptable in a domestic installation, and some auxiliary energy will almost inevitably be used to remedy the situation. This in turn will result in higher collector operating temperatures during the day, and reduced system output. The schedule used here should therefore be regarded as highly optimised.

These comments are reflected in the ISO Standard which relates to the testing of systems with integrated auxiliary heating [6]. The run off schedule specified there requires that 30% of the load is imposed early in the morning. Using this profile, however, would not have provided results which could be compared to those from the previous study.

The previous tests assumed that the solar system would act in preheat mode. The solar cylinder would be installed ahead of the existing hot water cylinder, effectively increasing the temperature of the inlet water to that cylinder. Before conducting or analysing the results of the tests it is important to consider the energy flows which occur in solar preheat systems and those with integrated auxiliary heating. Figure 4.1 shows the preheat configuration.

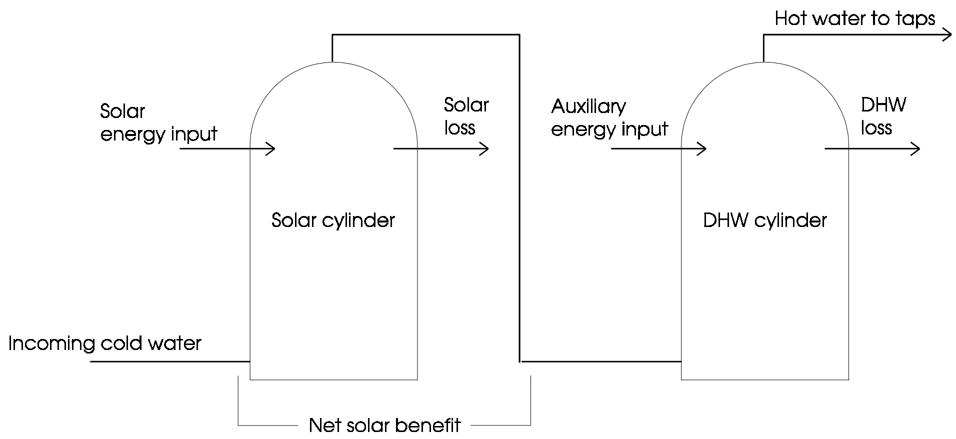

Figure 4.1: Energy flows in solar pre-heat configuration

The figure shows that the addition of the solar preheat cylinder also introduces an additional cylinder loss. The net benefit of the system is given by the output of the solar collectors minus these losses. As expected, this can be evaluated simply by measuring the inlet and outlet temperatures of the solar cylinder: if the solar system was not present the DHW cylinder would receive its supply at the incoming cold water temperature. Thus the monitoring approach taken in the previous work, where the inlet and outlet temperatures of the solar cylinder and associated flow were measured, accounted for solar cylinder losses and gave the correct measure of solar benefit.

In the case of a system where the functions of the solar and DHW cylinders are combined, an integrated auxiliary installation, the situation is not so straightforward. Figure 4.2 shows the relevant energy flows.

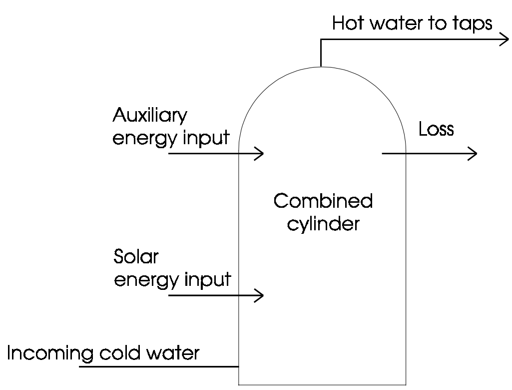

Figure 4.2: Energy flows in integrated auxiliary configuration

Now the benefit provided by the solar system is simply its output: no additional tank losses have been introduced by its installation as no extra tank has been installed.

One approach to determining the solar benefit is to measure the collector output directly by inserting a flow meter and flow and return temperature probes into the collector loop. However, this approach has the drawback that it no longer accounts for utilisation issues. It also requires modification to the collector loop. An alternative method would be to use a different data analysis, in which the reduction of auxiliary energy is estimated as a function of solar radiation. This analysis, however, runs into numerical problems on dull days, when the solar contribution being estimated is a relatively small difference between two large numbers.

Neither of the alternative approaches described could be considered directly comparable with the original study. The heat loss coefficient of both solar cylinders has already been measured as part of the ISO test sequence. The approach finally adopted was to carry out the tests exactly as before, and then estimate the eliminated tank loss using this information.

4.2 Modifications required to the test rig

The test regime followed very closely that used in the previous work, and only minor modifications were required to the original test rig configuration to carry out the tests.

4.2.1 Installation of auxiliary heater

A 2.5kW electric immersion heater was installed in each of the solar tanks. Solid state relays allowed the heaters to be controlled by the data loggers which also recorded the performance of each system.

4.2.2 Control temperature measurement

In a realistic situation the installed immersion heaters would most likely be controlled by a thermostat, mounted in the pocket which forms an integral part of the heater. For the tests described here it was acknowledged that such thermostats would not provide an adequate level of accuracy or quality of control. At the same time, however, it was felt that the temperature sensing arrangement used should be representative of the types of controls normally employed in such applications.

To satisfy the twin requirements of accurate control and representative sensing a dummy immersion heater thermostat was manufactured, which consisted of a Class A Platinum resistance temperature sensor encapsulated at the end of a conventional thermostat. This was connected to the data acquisition system, and its reading used to implement a simple ON/OFF control strategy which was executed every five seconds. In this way good control to an accurately defined setpoint was obtained, but the sensing point was representative of the way in which temperature would be sensed in a real system.

4.3 Modifications required to instrumentation

One addition was required to the instrumentation, in the form of an electrical power meter to measure the amount of auxiliary energy used. This in turn necessitated a change to the format in which data from the tests was recorded.

4.3.1 Auxiliary energy metering

The energy consumed by the immersion heater was measured using a power meter supplied by Northern Design. This meter measures voltage and current consumption and integrates their product to provide a measure of total energy consumption. The meter also provides a measure of VA consumption, and hence of the power factor of the load. This facility was not used in this trial.

To measure the immersion heater power the meter was equipped with a 60:5A current transformer, but the cable to the heater was wound through the transformer four times, giving an effective ratio of 15:5A. The voltage across the heater was sensed at the heater terminals, eliminating errors due to voltage drops along the power cable.

To provide adequate measurement resolution the meter was configured to provide 1 pulse per 10 Watt hours of consumption. The meter has a basic accuracy of ±1%.

4.3.2 Modifications to data format

The only modification required to the data format used in the previous tests was the addition of the energy consumed by the immersion heater to each five minute record.

The resulting data format is described in detail in Appendix B.

4.4 Test sequence

The test schedule followed closely that used for the single run off tests in the earlier work. Table 4.1 summarises the sequence of events required to complete a days testing.

	Cold water supply valve	Auxiliary heater	Run to 150 litres	Metering tank drain valves
Fill cold water tanks	15:45 ON			

	17:45 OFF			
Top up temperature		16:00 ON		
		17:59 OFF		
Run off				17:45 OFF
			18:00 ON	
			18:30 OFF	
				18:45 ON

Table 4.1: Sequence of actions required for a days testing

Data was collected using this sequence for a total of approximately six weeks.

4.5 Data Analysis

The data analysis carried out follows very closely that used in the original study [1].

4.5.1 Derivation of performance parameters

Following the discussion above, Figure 4.3 shows the net daily benefit of the AES system, defined as hot water supplied minus auxiliary energy input, as a function of incident solar radiation.

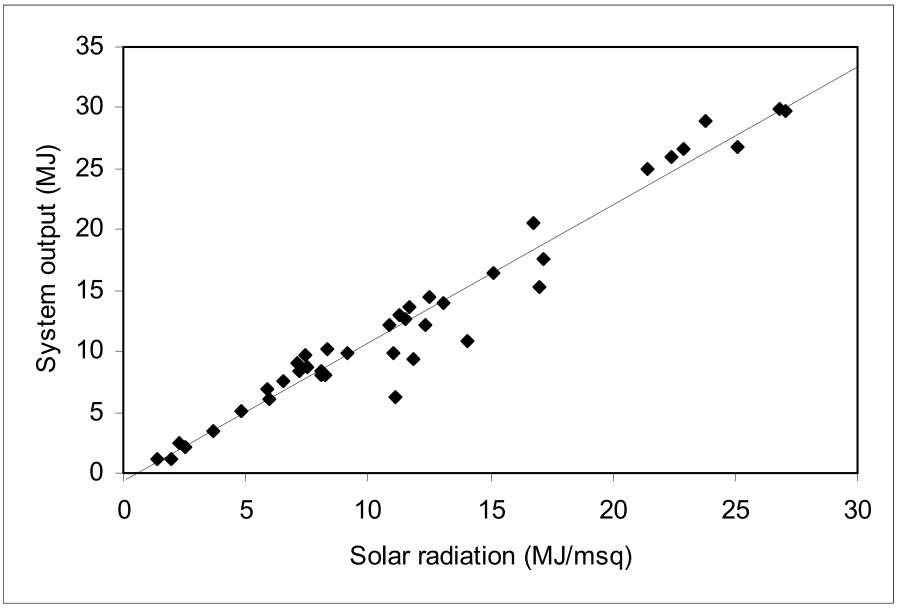

Figure 4.3: Net benefit from AES system as a function of solar radiation

The two performance parameters A0 and A1 can be readily derived from this data. Table 4.1 shows the results for both the AES and Riomay systems.

	AES	Riomay
A0	-0.72 ± 1.06MJ	0.04 ± 0.64MJ
A1	1.134 ± 0.077m^2	1.029 ± 0.051m^2

Table 4.1: Performance parameters with auxiliary heating

To interpret these results they must be compared with the parameters obtained previously when the systems were operated without auxiliary heating. Table 4.2 summarises those results.

	AES	Riomay
A0	0.10 ± 0.57MJ	0.94 ± 0.48MJ
A1	1.148 ± 0.036m^2	0.950 ± 0.032m^2

Table 4.2: Performance parameters from solar-only operation

Comparing the figures in Tables 4.1 and 4.2 reveals that for the AES system neither test produces a value of A0 which is significantly different from zero. The value of the more important parameter A1 is seen to have decreased very slightly, although within the uncertainty bands shown it cannot be said to have changed. In the case of the Riomay system the A0 parameter is also indistinguishable from zero when integrated auxiliary heating is used. For this system however the value of A1 actually increases slightly, although once again the width of the uncertainty bands is larger than the change observed.

4.5.2 Extrapolation to annual performance

Armed with the revised performance parameters it is a simple matter to re-calculate the expected annual benefit from each system when operated with integrated auxiliary heating. Table 4.3 shows the results, and also summarises the figures obtained previously for solar-only operation.

	AES	Riomay
With integrated auxiliary heating	4151MJ	4017MJ
In solar preheat operation	4447MJ	3995MJ

Table 4.3: Extrapolated annual performance

As expected from the direct comparison of the performance parameters the table shows that the performance for the AES system falls only slightly, by less than 7%. The performance of the Riomay system is essentially unaffected.

Consideration of the mechanism by which the reduction in performance occurs reveals why this should be the case. When an auxiliary energy source is integrated with the solar cylinder its operation has the effect of raising the temperature at which water is fed to the collectors. This in turn increases the heat loss from the collectors to ambient, reducing their net output. The lower heat loss associated with the evacuated tubes means that they are much less sensitive to the temperature of the store from which they operate, and hence that they do not show the reduction in performance seen for the flat plate system.

It must be stressed that these results rely on a properly timed and controlled input of auxiliary energy. In this respect a solar preheat system remains the more robust option.

4.5.3 Evaluating solar tank loss

The ISO calculation method implemented in Section 3.5.4 provides a way of estimating the annual loss from a solar cylinder. The method already calculates the overnight heat loss from the solar cylinder by assuming an exponential temperature profile as the system cools. This information is then used to estimate the temperature of the water in the solar cylinder at the start of the following day. The method then calculates the energy added to the cylinder over the course of the day, and hence the energy available for the evening run off. The temperature immediately prior to that run off can be readily found from this value. In order to generate an estimate of the tank heat loss over the day it is necessary to estimate its average temperature. This requires that a temperature profile is assumed. The most obvious assumption, that the temperature increases linearly throughout the day, is equivalent to assuming a uniform solar input from 6:00am to 6:00pm, clearly not realistic. Instead the solar input has been assumed to be sinusoidal, and the corresponding temperature response calculated from that. Figure 4.4 shows a sample temperature profile, generated using this assumption.

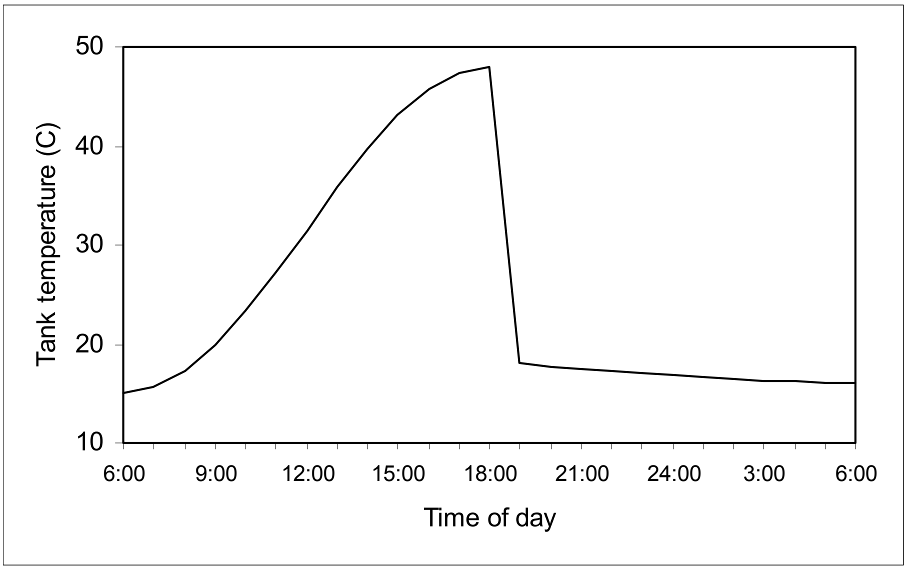

Figure 4.4: Sample tank temperature profile

Using this profile and the measured tank heat loss coefficient the amount of energy lost from the tank over the course of the day can be found. This is then added to the calculated overnight heat loss to give the overall loss.

Table 4.4 shows the values calculated for the two systems using the two algorithms for the incoming water temperature, T_{main}.

	AES	Riomay
($T_{main} = T_a$)	684MJ	635MJ
($T_{main} = T_{ground}$)	546MJ	478MJ

Table 4.4: Estimated annual tank heat losses

These heat losses are significant compared to the overall benefit obtained from the systems, at between 12 and 16% of the overall gain from the systems. In the case where the incoming water is assumed to be at ground temperature there are periods when the temperature of the water in the tank is below ambient, and thus a net heat gain to the tank. This offsets some of the losses incurred when the system is working, and accounts for the reduced losses shown when this assumption is adopted for incoming cold water temperature.

Most significant, however, is the fact that these losses, which are being eliminated from the system by the integration of auxiliary heating with the solar cylinder, are in this case larger than any reduction in solar performance. Thus for the highly optimised heating strategy used here the systems actually give a larger net benefit when operated in this mode. However, as pointed out this is a highly optimised operating schedule, and is unlikely to be implemented in a real application. From the results seen here it can be surmised that the Riomay evacuated tube system will be more robust in the face of changes to the heating schedule, but neither system can be guaranteed to continue to give the maximum possible output once more intrusive auxiliary heating schedules are introduced. Operation of the system in preheat mode removes this potential source of performance degradation, and will generally be preferable.

5 CONCLUSIONS

In 2001 the Energy Monitoring Company assessed eight solar water heating systems for the DTI. This report has described two further trials. These were carried out on two of the eight systems originally tested: a flat plate collector manufactured by AES and an evacuated tube system from Riomay.

In the first trial the systems were tested according to ISO Standard 9459-2: Outdoor test methods for system characterisation and yearly performance prediction of solar-only systems. It was acknowledged from the start of these tests that due to constraints imposed by the existing test rig, which was originally designed to carry out tests to a different schedule, the work carried out here would not fully comply with the requirements of the standard. However, the impact of these deviations has been assessed, and in all cases found to be minor.

Like the previous tests, the ISO method provides parameters summarising the response of the system to solar radiation and the output under zero radiation conditions. To within the joint uncertainty bands, these are the same as those generated previously. The ISO tests also provide information on the sensitivity of the systems to inlet water temperature, on stratification and tank heat loss. None of these parameters, however, is intended for direct interpretation. Instead they are used as input data for a calculation method which yields the annual system output which can be expected from the system.

The result of this calculation turns out to have a significant sensitivity to the temperature attributed to the incoming water supply. For the systems tested here that water would normally be drawn from a cold water storage tank. Two assumptions have been explored. In the first heat transfer to the contents of the storage tank is assumed to be high, and the resulting solar system inlet water temperature has been taken to be the same as the daytime air temperature. In this situation the ISO calculation returns annual performance predictions which are 5% and 1.5% less than those obtained previously for the AES and Riomay systems respectively. Under the alternative assumption that heat transfer to the cold storage tank is minimal and the incoming water remains at the temperature of the ground the outputs of both systems increase slightly, and the predictions are 10% and 7% above those obtained previously.

The ISO calculation method incorporates a detailed determination of the amount of energy stored by the system from day to day. This in turn allows the impact of reduced hot water demand on system performance to be determined. This has been done for both systems, and the performance of the Riomay evacuated tube system has been found to be more robust in the face of reduced daily load.

In the second trial the impact of integrating auxiliary water heating with the solar cylinder was explored.

For the evening run off schedule assumed in the previous work (and indeed in the ISO testing described above) the solar contribution of the AES flat plate system is reduced by only 7% and that of the Riomay evacuated tube system is unchanged. This difference in relative performance is understandable, as the lower heat loss associated with the evacuated tubes means that they are less sensitive to the temperature of the store from which they operate.

In this mode of operation the elimination of a preheat tank removes the heat loss associated with a preheat cylinder. The tank loss which would occur from this cylinder has been calculated using an extension to the ISO annual calculation method. These losses, which are being eliminated from the system by the integration of auxiliary heating with the solar cylinder, are larger than the changes in solar performance observed. Thus for the highly optimised heating strategy used here the systems actually give a larger net benefit when operated in this mode. However, it must be stressed that this is a highly optimised schedule. Whilst it provides the specified amount of hot water at 6:00pm, it does not guarantee that any hot water is available early in the morning. This is unlikely to be acceptable in a domestic installation, and some auxiliary energy will almost inevitably be used to remedy the situation. This in turn will result in higher collector operating temperatures during the day, and reduced system output.

The results obtained suggest that the Riomay evacuated tube system will be more robust in the face of changes to the heating schedule, but neither system can be guaranteed to continue to give the maximum possible output once more intrusive auxiliary heating schedules are introduced. Operation of the system in preheat mode removes this potential source of performance degradation, and will generally be a more robust configuration.

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APPENDIX A: ISO TEST DATA FORMAT

The disk which accompanies this report contains all of the data gathered during the project. This Appendix describes the format of the data gathered during the testing to the ISO Standard.

A1 Meteorological data

The meteorological data collected during the project is in a file called ISOMET.TXT. It consists of five minute records of global and diffuse solar radiation level in the plane of the collectors, wind speed across the collectors and external air temperature.

Solar radiation and wind speed have been measured every five seconds, and the results averaged over fifteen minute periods. The averages are recorded on a preceding time step basis: the value recorded with time stamp 15:00:00 is the average from 14:55:05 through to 15:00:00. External ambient temperature was measured every fifteen minutes and recorded directly.

Table A1 describes how the values on each line, which are delimited by tab characters, are interpreted.

Entry	Quantity	Units
1	Date	DD/MM/YYYY
2	Time	HH:MM:SS
3	Global solar radiation	Wm^{-2}
4	External air temperature	°C
5	Wind speed	ms^{-1}
6	Diffuse solar radiation	Wm^{-2}

Table A1: Format of recorded ISO meteorological data

A2 System performance data

Data from each system have been placed in a separate file. The files are named using the following convention:

ISO N . TXT

where:

ISO indicates that the file contains data from the ISO tests, N is the system identifier:

1: AES

2: Riomay

The data format is summarised in Table A2.

Entry	Quantity	Units
1	Date	DD/MM/YYYY
2	Time	HH:MM:SS
3	Record identifier (=0 for 5 minute record or 1 for run off data)	
Record type 0		
4	Electricity consumption	Wh
5	Shed temperature	°C
6	Water supply temperature	°C
7	Water delivery temperature	°C
Record type 1		
4	Water supply temperature	°C
5	Water delivery temperature	°C
6	Water volume flow	litres

Table A2: Format of system data files

A3 Dates of data used in analysis

The file ISODATES.TXT contains two lists of dates. The first contains the days which were used to derive the daily performance of the systems, and the second contains the dates of the data used to generate the normalised run off profiles.

APPENDIX B: INTEGRATED AUXILIARY TEST DATA FORMAT

The disk which accompanies this report contains all of the data gathered during the project. This Appendix describes the format of the data gathered during the tests carried out with integrated auxiliary heating.

B1 Meteorological data

The meteorological data collected during the project is in a file called AUXMET.TXT. It consists of five minute records of global and diffuse solar radiation level in the plane of the collectors, wind speed across the collectors and external air temperature.

Solar radiation and wind speed have been measured every five seconds, and the results averaged over fifteen minute periods. The averages are recorded on a preceding time step basis: the value recorded with time stamp 15:00:00 is the average from 14:55:05 through to 15:00:00. External ambient temperature was measured every fifteen minutes and recorded directly.

Table B1 describes how the values on each line, which are delimited by tab characters, are interpreted.

Entry	Quantity	Units
1	Date	DD/MM/YYYY
2	Time	HH:MM:SS
3	Solar radiation	Wm^{-2}
4	External air temperature	°C

Table B1: Format of recorded ISO meteorological data

B2 System performance data

Data from each system have been placed in a separate file. The files are named using the following convention:

AUX N . TXT

where:

AUX indicates that the file contains data from the integrated auxiliary test, N is the system identifier:

1: AES

2: Riomay

The data format is summarised in Table B2.

Entry	Quantity	Units
1	Date	DD/MM/YYYY
2	Time	HH:MM:SS
3	Record identifier (=0 for 15 minute record or 1 for run off data)	
Record type 0		
4	Auxiliary electricity consumption	Wh
5	Parasitic electricity consumption	Wh
6	Shed temperature	°C
Record type 1		
4	Water supply temperature	°C
5	Water delivery temperature	°C
6	Water volume flow	litres

Table B2: Format of system data files

B3 Dates of data used in analysis

The file AUXDATES.TXT contains a list of the dates from which data was used in the final analysis.