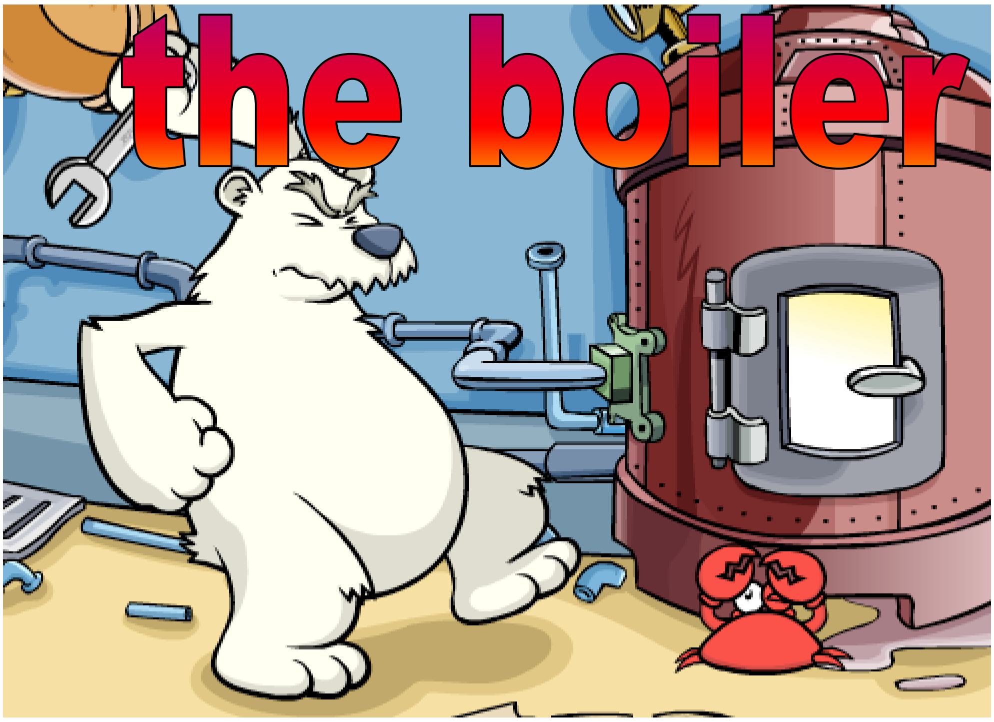
Don't blame the boiler



until you have read this

Report from analysing the performance of the heating system in 64 churches in the Lichfield Diocese

Contents

Church heating study report

Introduction

All the churches in Lichfield Diocese were invited to take part in a study of the effectiveness of their heating controls in Autumn 2016. About 70 churches replied asking to be included and 64 actually took part and received a report. In view of the number of replies and the limited number of temperature loggers I could justify purchasing, I sent out one logger to most churches to record the temperature in the building for one week. During the previous two winters I had researched and developed methods for analysing the temperature records (logged every 6 minutes) using additional data from pipe temperatures and electricity used by boilers (all the early research was on systems with water-filled radiators), and was able to apply the results of this research to the data from week-long recording of building temperature patterns.

Summary

The churches included in the study are a self-selected set that in general have particular problems or concerns about their heating. Hopefully therefore, it is not a representative sample of all churches in the diocese. The observations from the study show why churches had reason to be concerned:

- In 45% of the churches the greatest rate of heating (which is in the first hour) was less than 1 degree per hour, and lower in subsequent hours

- In 32% of the churches the total amount by which the temperature of the church was raised by the heating system was less than 5 degrees, and in 78% less than 8 degrees. These levels would be acceptable in churches where the temperature was kept at a minimum of say 10 degrees, or were used most days, but not in churches used only once or twice a week where the starting temperature is likely to be below 5 degrees in cold weather.

- Most (89%) of the churches had timer controls, but only 5 had any form of programmable thermostat. It was common for just one person to know how to operate the controls and in only one instance of the churches I visited, was there any kind of written instruction about how to do this (it began with "Step1. Pray")

- Eleven of the churches had overhead radiant heaters as the main source of heating – in most cases the Wardens reported that congregations complained about the intensity of the heat on their heads and the lack of heat at their feet.

- A number of churches had been operating with a continuous minimum temperature in the range 15 to 18 degrees, in the belief that this was recommended practice. The recommended value is actually 12 degrees which has been found to give the best preservation of the internal fabric and objects. In situations where the church is not in use everyday, even this level is uneconomic; a more suitable temperature being 8-9 degrees which would still have the benefit of limiting the range of temperature variation.

The individual results are shown in Appendix 2. I have also attached a set of case studies (referenced in the text below) to illustrate the various conclusions and recommendations made to churches.

The initial objective of the study had been to look for ways to get greater efficiency through **better use of the control systems,** and where such systems were in place, I was able to offer suggestions that included:

- Reducing the minimum (base) temperature set for periods when the building was not in use (Case Study 1)

- Bringing the boiler on earlier (or setting a higher in-use temperature) on a day that was the first of a sequence of days of use, so that the increase in temperature on that day would be carried forward to later days (Case Study 2)

- Lowering the in-use temperature set, in cases where the heating system was unlikely to reach that temperature, or where the loss of heat from the building was such that the heating system was taking several hours to add the last degree. (Case Study 3)

- Operating the controls to achieve a more consistent (though in some cases lower) experience of temperature for regular users. (Case Study 4)

- Over-riding any form of "intelligence" in the controller, because none of the controllers I looked at was suitable for a church environment (e.g. the heating rate in most churches is much lower than that expected by the automated system). (Case Study 5)

For the other **churches without** (or not able/willing to use) **time and temperature controls**, I looked for ways to make improvements that might be affordable. I was not wholly comfortable about this approach because I am not a "heating expert". Fortunately the diocese has a very experienced (volunteer) Heating Advisor to the DAC and I was able to make some visits with him. I took the precaution of recommending, where appropriate, that churches should seek his advice before considering any physical changes that might require a Faculty. Predictably, he is now overloaded with work.

The changes I have recommended that these churches consider include:

- In churches where the capacity of the boiler to generate heat was greater than the capacity of the emitters (radiators) to give out heat (Case Study 6), to experiment with:

  - raising the water temperature set on the boiler,
  - adding radiators or convector radiators,
  - increasing the flow rate of the circulating water, and
  - removing shelves and other covering from radiators.

  I have modelled the effect of increasing the rate of heat output on total energy consumption. The results indicate that, in very broad terms, a 10% increase in heat output (with a consequential reduction in heating up time) would result in an overall reduction of about 10% in total energy used. (Appendix 1)

- In churches with multiple tandem boiler installations, that the church gets professional advice from a qualified Heating Engineer about ways to avoid the configuration dropping to a single boiler operation as soon as the circulating water reached the set temperature (Case Study 7)

- In churches with a "froststat" that is designed to keep the temperature of the church above a set minimum during periods when the building was not in use, I have suggested that they use it to get the temperature up to a suitable starting level for a period of 4 hours before the heating comes on fully. This period is based on published research that building fabric temperature lags about that time behind the air temperature, and this is confirmed by my analysis of data from one church. (Case Studies 8 and 4)

- In churches that are used most days of the week but only for part of the day, the starting temperature when the heating might need to come on varies with the time since the previous heating period. For this situation, I prepared an example chart that would enable the church to work out how long in advance of the time of each period of use the heating would need to be put on. (Case Study 9)

I have tried to collect more data from the churches with **overhead radiant heaters** but without much success. I followed a design for a "radiant thermometer" from a university research project and measured radiant as well as air temperature. Somewhat frustratingly the two readings were almost identical. I plan to continue this research next winter because I think radiant heaters could be an appropriate solution for a number of churches, especially those in rural locations without access to mains gas supplies, if the heaters can be installed at a higher level in the building thus reducing the differential between upper and lower body radiant heat experience. (Case study 10)

I have illustrated the above and some of the analysis methods I have used in a **set of case studies which follow**, based on the reports I wrote for individual churches.

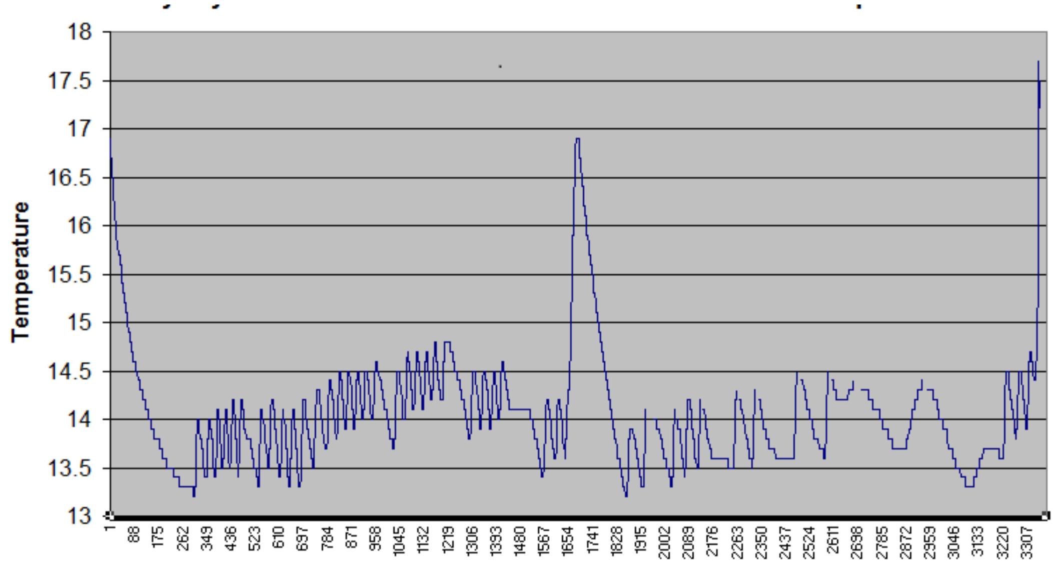
Appendix 1 contains a technical report about my initial research that underpins the work reported here. I am more than happy to share the methods with others, but anxious not to labour this aspect in this report.

Appendix 2 gives a summary of the characteristics of each of the churches included in the study and the recommendations I made, together with a couple of summary charts showing the distributions of initial heating rate and overall temperature gained.

John Polhill
Environmental Officer
Anglican Diocese of Lichfield
August 2017

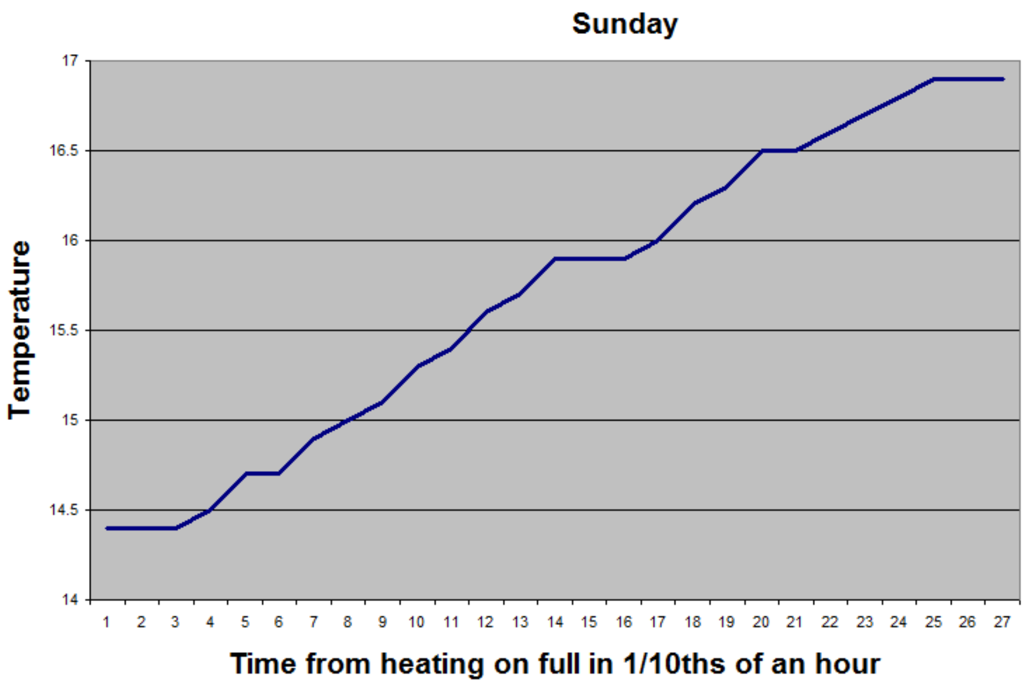
Case study 1 – Reducing base temperature

A temperature recorder was placed in the church from 19th March to 2nd April 2017. The recorder logs temperature every 6 minutes. The results are shown below.



The heating appears to run at a setting of 14 degrees when the church is closed and then 17 degrees or higher for services and other events

Taking just the period the boiler was on and plotting it in more detail, shows the following.



Key points from the results in these charts are:

- The heating adds about 1.3 degrees per hour when it first comes on. The range of results from other churches is mainly 0.3 to 3.0 degrees per hour, so this church is in the middle of the range.

- The heating rate falls (to about 0.9 degrees per hour) as the temperature rises. This happens because the amount of heat lost from the building to the outside is proportional to the difference in temperature between inside and outside. The heating at this church is not on long enough to approach the maximum - there is evidence from fitting the formula that it could get the temperature up to about 20 degrees if left on longer, though the time taken to add each degree will increase.

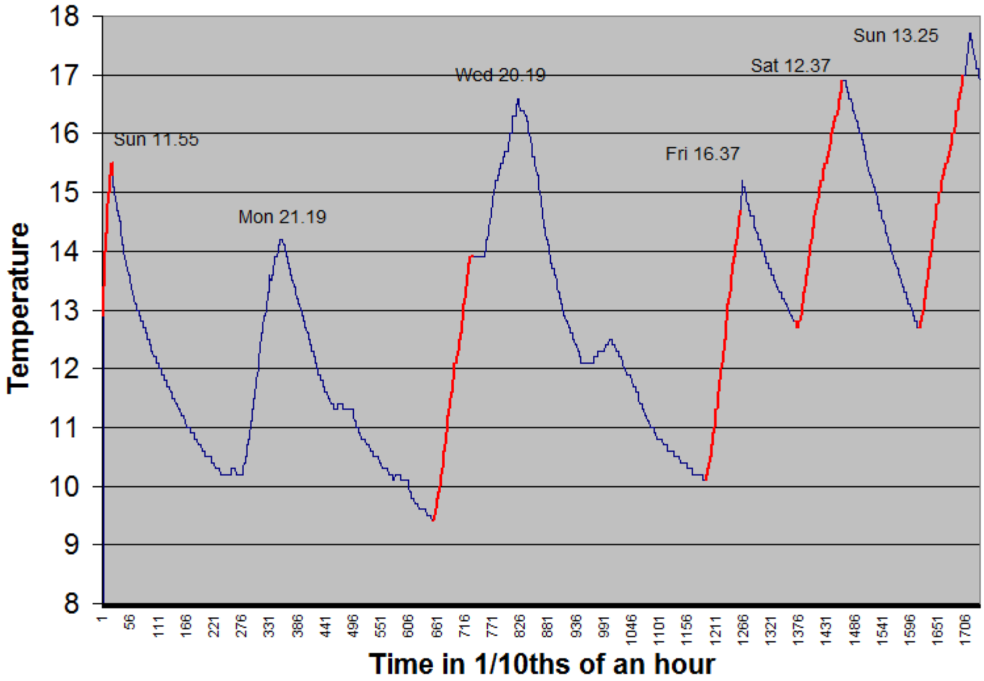
- Looking at the sections of the graph for weekdays, the "sawtooth" pattern shows the thermostat bringing the heating on and off for short periods to keep the temperature of the building to within about 0.25 degrees of the set value (assumed to be 14 degrees). The length of the periods of rising temperature can be used to estimate the percentage of time the boiler is "ON". In the first week the boiler is on for about 33% of the time to hold this temperature, during the second week, when the weather was warmer, the percentage drops to about 20%. It may be that the church had received specific professional advice to retain the building at 14 degrees to dry it out.

  The normal recommended temperature to preserve the fabric is 12 degrees. It is likely that the heating bill would be reduced by as much as 40%* if the church were to use this lower temperature setting. This estimate is derived from the theory model that the time the boiler needs to be on is directly proportional to how far the set building temperature is between the unheated temperature and the maximum increase in temperature achievable.

  ** [The calculation goes like this. The Sunday observations indicate that the temperature would have dropped to about 11 degrees if the heating were turned off (during this colder period), and the range achievable by the heating is about 9 degrees. So to maintain 12 degrees the heating would only have to be on 11% of the time – one ninth of the time for each degree above 11. This means that the boiler would have to be on 165 hours at 11% and 2.5 hours (plus an additional 2.5 hours to get up from the lower starting temperature) on full to heat up for the service – a total of 23 hours equivalent fully on. Currently the boiler is on 165 hours at 33% and the 2.5 hours for the service – a total of 57.5 hours. So, for this day, the saving would be 100 * (57.5 – 23)/57.5 = 60%. These readings were taken in mid-March, and might be around the average for the heating period; 40% seems a conservative estimate of the overall saving.]*

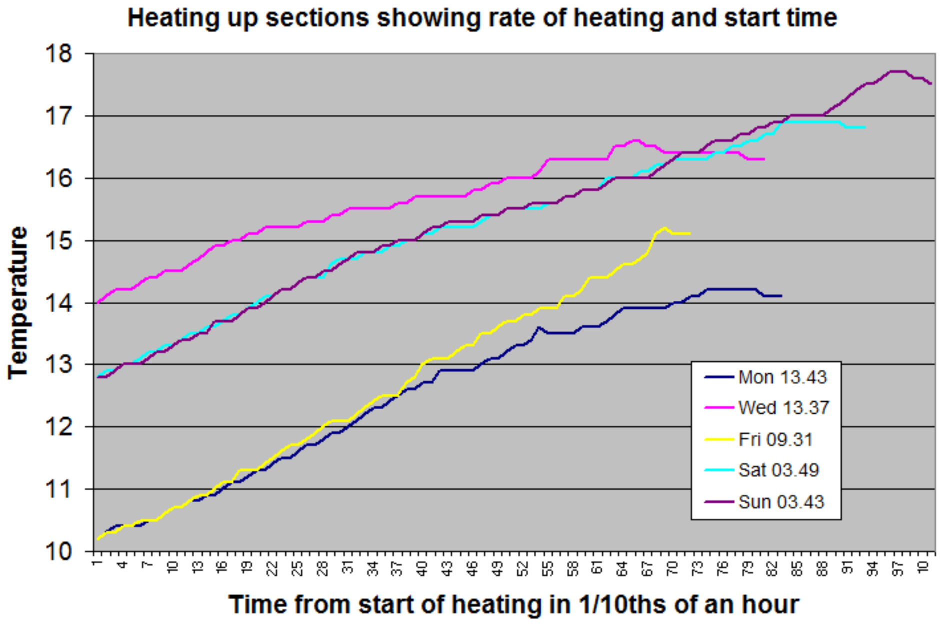
Case study 2 – Exploiting a sequence of days with heating on

A temperature recorder was placed in the church from 26th February to 5th March 2017. The recorder logs temperature every 6 minutes (tenths of an hour). The results are shown below with the times of peak temperatures and the periods when the heating was scheduled to be on coloured red.



The observations show that the heating was on additionally on the Monday from 13.45 to 21.30 and on the Wednesday afternoon from 13.30 to 20.20.

Taking just the heating-up sections of the graph and plotting them on the same chart from their starting point gives the following comparison.



From these two charts the following observations can be made:

- The initial heating-up rate is up to 0.6 degrees per hour. The range I have observed in most other churches is 0.3 to 3.0 degrees per hour, so this church is toward the lower end of the range

- However, even after 5 hours of the heating being on, the heating rate can be still 0.4 degrees per hour – two thirds of the initial rate. It is normal for the heating rate to fall as temperature rises. This shows that the heating system is capable of raising the temperature substantially further.

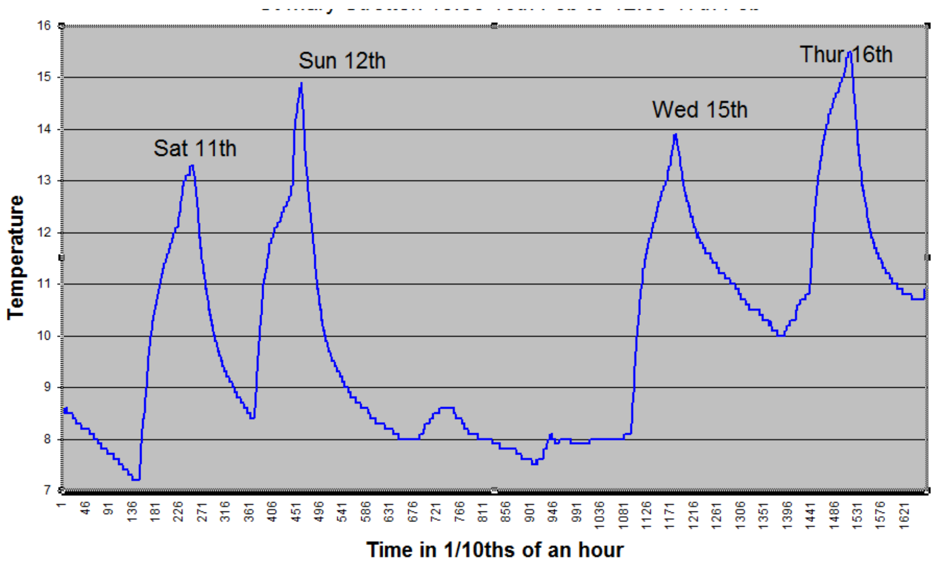
- The six differently coloured lines on the second graph are roughly parallel (though their slope does vary somewhat, possibly due to variations in the outside temperature, and also the different amount of heat added by varying sizes of congregation). This pattern indicates that the amount the temperature will have risen after a given heating time is the same, so the temperature actually reached is dependent on the starting temperature.

- So, if the building is cold when the heating comes on, it will be colder at the end of the heating period, than if the starting temperature had been higher, and to reach a given in-use temperature, the heating would need to come on sooner.

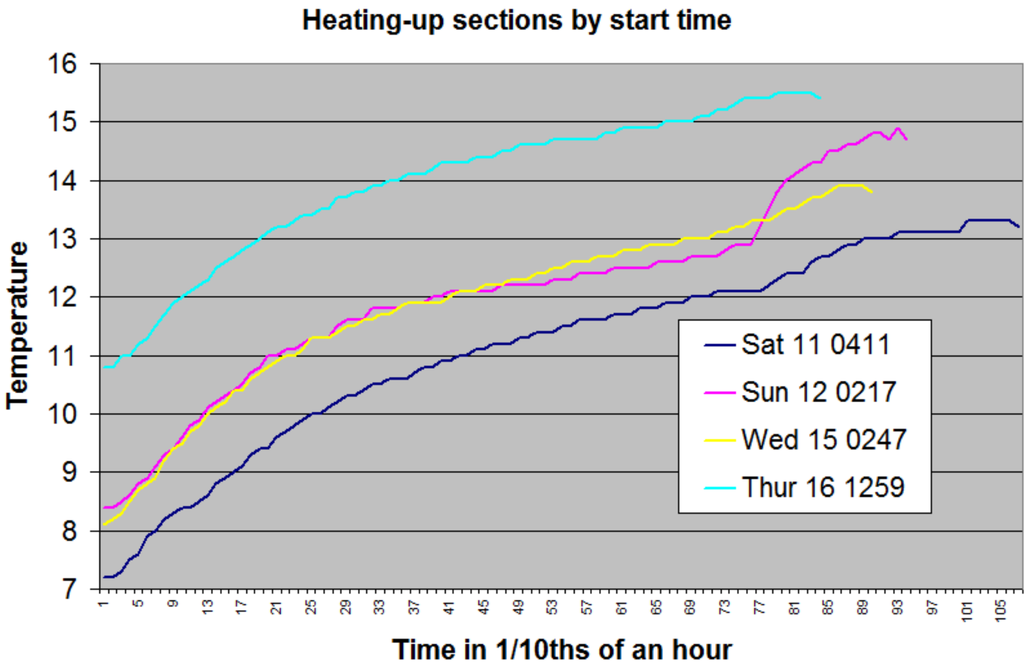
- Looking at the parts of the first graph that are periods of cooling, it appears that the building temperature is still falling when the heating comes back on for the days when the heating has been on during the previous day – this is particularly true for the Wednesday afternoon, Saturday and Sunday. So, in weeks where the heating is on for three consecutive days (as on Friday to Sunday in the week studied) it could be that if the heating had been set to come on two hours earlier on Friday, thereby adding almost a degree to the temperature reached on that day, this gain would have carried through to Saturday and then to Sunday - three for the price of one!.

Case study 3 – Avoiding diminished returns

A temperature recorder was placed in the church from 10th to 17th February 2017. Observations were taken every 6 minutes. The results are shown below:



Taking just the sections of the graph when the heating was on (temperature rising) and superimposing them (curves labelled by the start time):



From these graphs one can make the following observations:

- The initial heating rate when the boiler first comes on is about 1.3 degrees per hour. The range of values I have found in other churches is 0.3 to 3.0 degrees per hour so this church is in the middle of that range

- The heating-up curves are almost parallel showing that the way the church heats up is dependent on the starting temperature

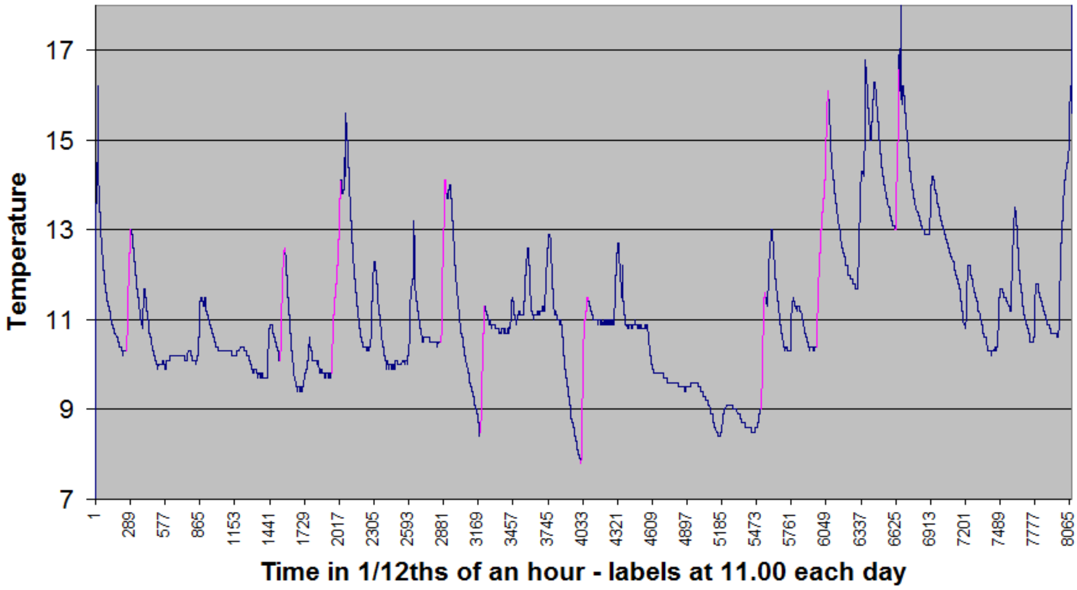
- Heating appears to come on about 7 hours before the scheduled event. On some events (like the Sunday Service) the arrival of people adds up to one degree to the temperature. Most churches show this effect, which is dependent on the size of the congregation. It is not clear why the heating curve for the Sunday Service falls a little below the others for the 3 hours before the Service, by about 0.5 degrees.

- The curves all level off (after allowing for the effect of the congregation) to about 5 – 5.5 degrees above the starting temperature.

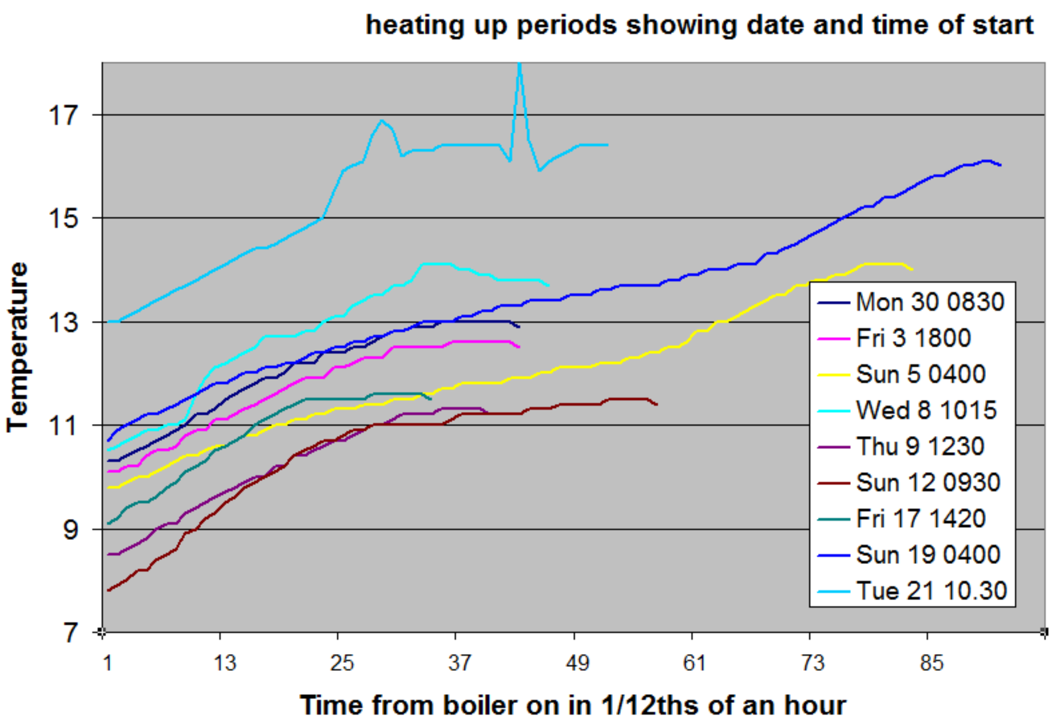
- It is not worth trying to increase the in-use temperature by putting the boiler on earlier, because adding the last 0.5 degree already takes about 4 hours. It seems that using a frost-stat to keep the temperature above, say, 8 degrees, would have enabled the Wednesday heating to reach its 11 degrees 4 hours earlier, though this would have incurred some extra energy to maintain the minimum temperature. The best approach would be to experiment by increasing the minimum temperature in steps whilst monitoring the effect on temperature and the amount of time the boiler was running. This can be achieved by using a logger for room temperature and another for the temperature of the flow pipe from the boiler.

Case study 4 – getting more consistent temperatures for users

A temperature recorder was place in the church from Thursday 29th January to Thursday 26th February 2017. The recorder logged the temperature every 5 minutes.



Taking the 9 heating periods coloured in pink, and plotting the data in more detail, superimposing the heating portions of the data, we have:



The two "humps" in the top curve for Tuesday 21st will be the result of the presence of congregations for the two funerals held that day. Observations from other churches show that congregations can add up to two degrees to the building temperature. The effect can also be seen in the curves for the two Sundays at about five and a half hours from the heating coming on (viz 09.30)

The points of significance from the data include:

- Each of the heating periods shows a gain of about 1 degree in the first 1.5 hours of the heating being on – a rate of 0.7 degree per hour. Observations from most other churches lie on the range 0.3 to 3.0 degrees per hour – so this church is toward the lower end of the range.

- The heating curves are mainly parallel. This means that the temperature tends always to rise by the same number of degrees, with the end temperature therefore depending on the start temperature. This is shown on the first chart by the two cold nights in the middle of the recording period.

- The curves on the second chart for the Sundays tend to show a lower rate of temperature increase than the others – might this be because doors are left open to welcome people for the services.

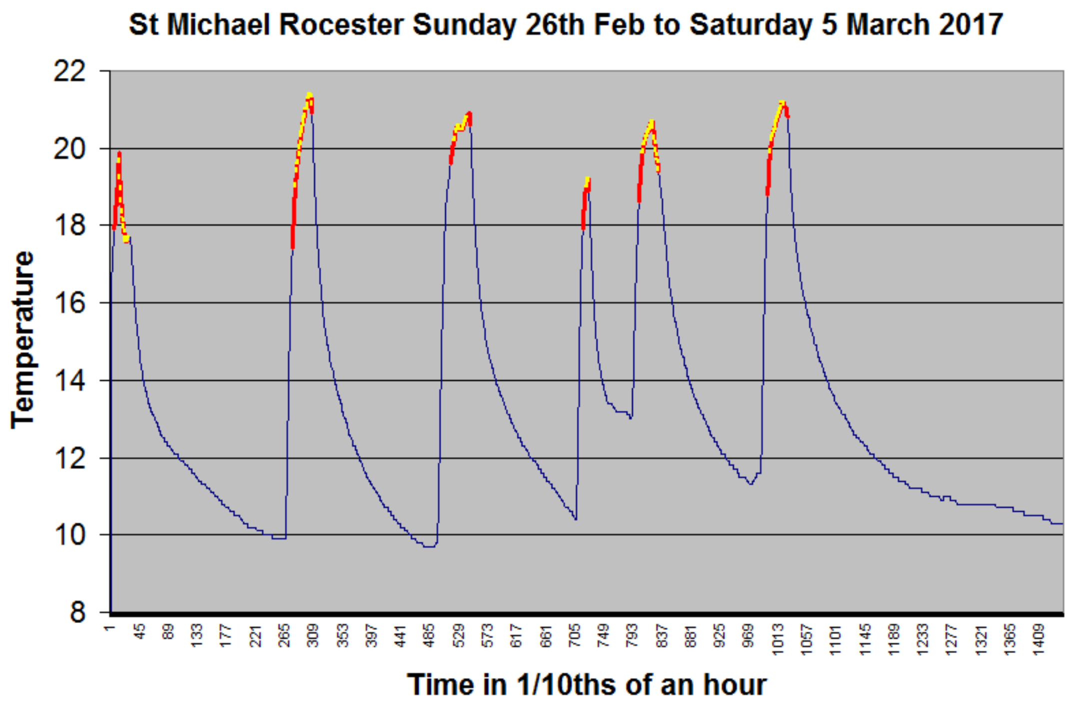
- After the initial steep start the curves bend over and, without the effect of the congregation arriving, would eventually level off to a maximum value.

- Another consequence of the heat loss is that, in the later stages of heating, the rate of temperature gain is quite low – for example, the yellow curve only gains one degree in the second 2.5 hours (rate of 0.4 degrees per hour).

- To get the church warmer (or to a more consistent temperature which might be more advantageous), especially during a cold spell when the starting temperature would be lower, the most cost-effective approach would appear to be to use a "frost stat" to bring the heating on at a low level for 3-4 hours before the normal heating period, making the start temperature always say, 12 degrees, and give time for the building to have reached this temperature. The result would be that the temperature would have got up to 17 degrees consistently when the congregation starts to arrive, and to 19 when the people have contributed their 2 degrees. The best way to achieve this, in terms of controls, would be to replace the timer with a programmable thermostat, which would allow the church to set up to six periods of each day with a different temperature. Not everyone finds these easy to use, and if the church has patterns of use that vary from week to week, the need to re-set the programme can be a chore.

Case study 5 – "intelligent" controls may not be appropriate in a church building

A temperature recorder was placed in the church from 26th February to 5th March 2017. The recorder logs temperature every 6 minutes (a tenth of an hour). The results are shown below with, in red the times the heating was set to be "ON", and in dotted yellow, the times the church was in use.

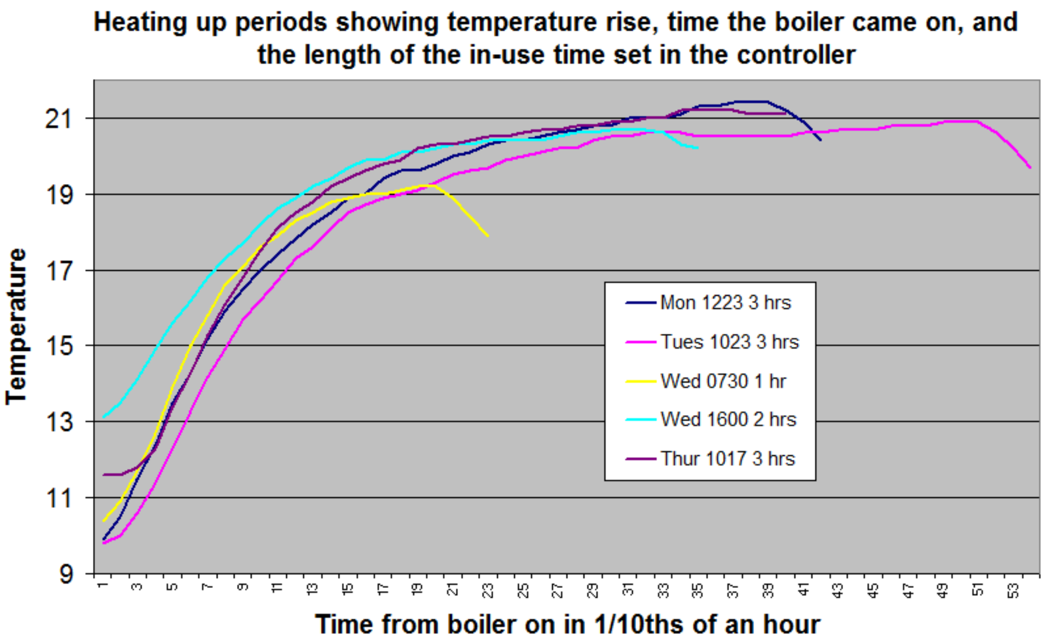


The Heatmiser controller interprets the times given to it as the times the church is required to be at the set temperature and calculates from its own analysis of previous heating periods, the time the boiler should be turned on to get the church up to the required in-use temperature (20 degrees for this church). You can see (might need to zoom in) that the temperature of the church at the start of the time requested (red line) varies between 17.5 and 19.5 degrees, whereas the temperature at the start of the time the building was actually in use varies only between 19 and 20 degrees.

In the quotation from the heating system installer, the assumption being made is that the building will be held at 16 degrees when not in use and 20 degrees when in-use. This would mean that the heating system had to raise the temperature by the same 4 degrees each time and the "intelligent" controller can work out quite quickly how long this needs to be. However, keeping the building at 16 degrees all the time would be prohibitively expensive – the heating would have needed to be on about 60% of the time during the not in-use periods for the week covered by this survey. I'm guessing that, from experience, the church had discovered that giving the controller a start time of 30 minutes before the actual start gives a pretty good outcome, and this is confirmed by the temperature records.

I have studied a few other churches with similar controllers and the evidence is that they do not perform well in churches where no "night temperature" has been set. I think this is because they are not able to cope well with varying temperature at the time the boiler needs to come on. The scheme this church has adopted works quite well because their heating system is very effective and heats the building in less than two and a half hours from 9 degrees. In churches that take 12 hours or more to heat up, the variation in starting temperature would be just too much for the automatic system to cope.

Taking just the heating-up sections of the graph and plotting them on the same chart from their starting point gives the following comparison.



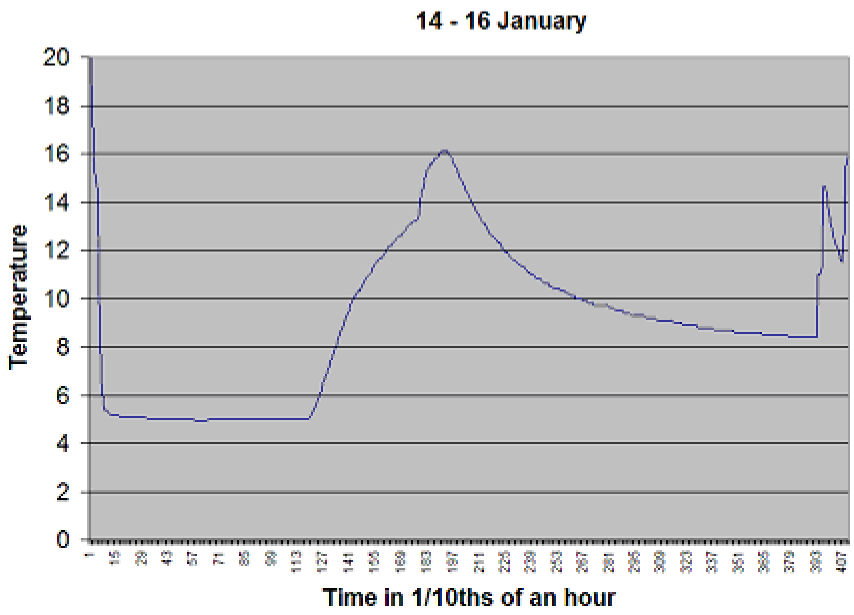
From this chart the following observations can be made:

- The initial heating-up rate is in the range 6 to 8 degrees per hour. The values I have observed in other churches are from 0.3 to 4.0 degrees per hour, so this church is a long way above the rest.

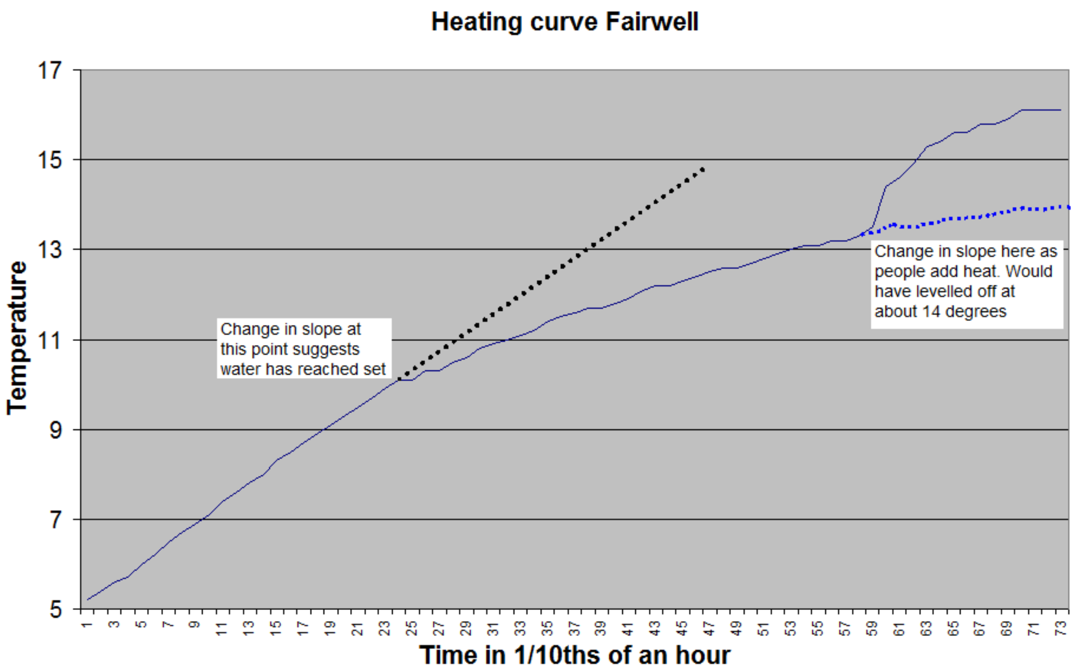
- The temperature recorded goes up to 21 degrees on most occasions. The sensors used by the automated systems do often seem to under-estimate building temperature by about a degree. The manual gives instructions to the installer about how to re-calibrate this, so if the church wished, the temperature could be held at 20 degrees, as intended. This might save 5 to 10 percent of the heating bill, but the church would be that much colder.

Case study 6 – insufficient emitter capacity

A temperature logger was placed in the church by the Priest's desk on Saturday 14th January 2017 and removed on the following Monday. The complete temperature recording for this period is:



And expanding the heating up section of the curve shows:



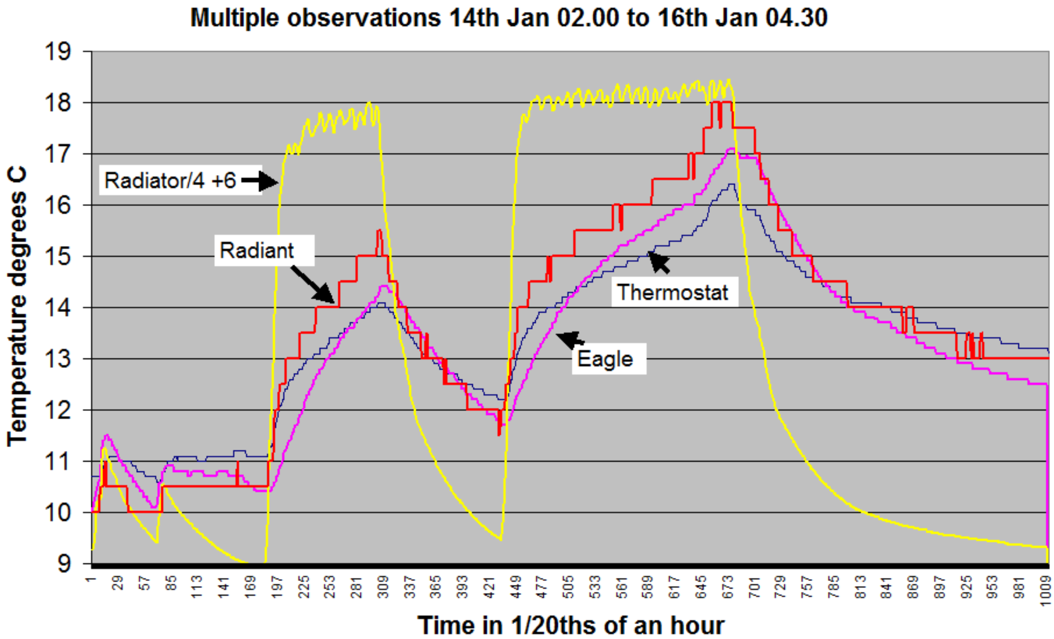
The graph shows that the arrival of the congregation adds about two degrees to the temperature, without them it would have levelled off at about 14 degrees. So the heating system has added 8.6 degrees in 7.2 hours – an average of 1.2 degrees per hour. However, in this case the curve is in two sections; for the first 2.3 hours the temperature rises in a straight line at 2.1 degrees per hour. At this point there is a marked change in the slope of the line and it becomes a curve of diminishing slope toward the 14 degree limit. This pattern is present in a number of churches and I have researched it carefully. The evidence shows that the change takes place at the point where the boiler has heated up the water to the set temperature and so turns off until the returning water has cooled (because heat is being given off from the radiators). The boiler then alternates between on and off to keep the water at the set temperature.

The change in slope suggests that the boiler is on only about 60% of the time once it has heated up the water. This means that it has some spare capacity which could be used to heat additional radiators or a radiator replaced by a fan assisted convector. Increasing the heat output would reduce the time the boiler needed to be on, or enable the temperature to go higher – if the boiler could run at 80% capacity, the maximum temperature would increase from 14 degrees to about 16 degrees (18 with the congregation present).

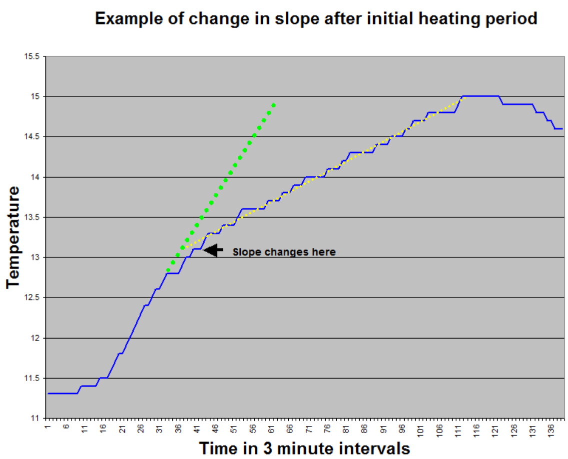
Any such changes would need a Faculty and should be carried out by a competent contractor with careful assessment of the location of new heating elements.

Case study 7 – effect of tandem boilers

The temperature was recorded continuously in the period 10 to 17 January 2017 with temperature loggers in two locations in church (one by the sensor for the thermostat and the other on an eagle lectern), a third on a radiator to measure water temperature, and an experimental recorder to measure radiant heat. These four sets of observations are superimposed in the chart below, with the water temperature scaled to the same range as the other readings. At the point 18 degrees on the chart, the water temperature would have been observed as 48 degrees - the actual temperature was probably about 53 degrees because the logger sensor is not in direct contact with the radiator surface.



From previous observations, I had examined the shape of the heating curve in some detail (for 28th December stating at 10:30).



This shows a pattern that is quite common in church heating systems. The slope of the curve changes quite sharply at around 13 degrees, and 1.5 hours after the boiler comes on.

In churches where I have been able to check this, the change occurs at the time when the water in the system reaches the maximum temperature set in the boiler (in a domestic system this might happen within 20 minutes!). After this point the boiler reduces its output to that which the emission devices (radiators) are capable of giving off. A conventional boiler turns itself on and off; a condensing boiler reduces the gas flow to match the level of energy required. The change in slope indicates that after the "elbow" point, the boiler is running at about 35% of capacity.

From this set of graphs we learn that:

1. Radiant heat has a small but measurable effect.

2. The fabric at the thermostat (on a central pillar) is warmer than the air at the eagle lectern position at the start but lower at the peak (as we would expect I think because the fabric takes longer to change temperature than the air)

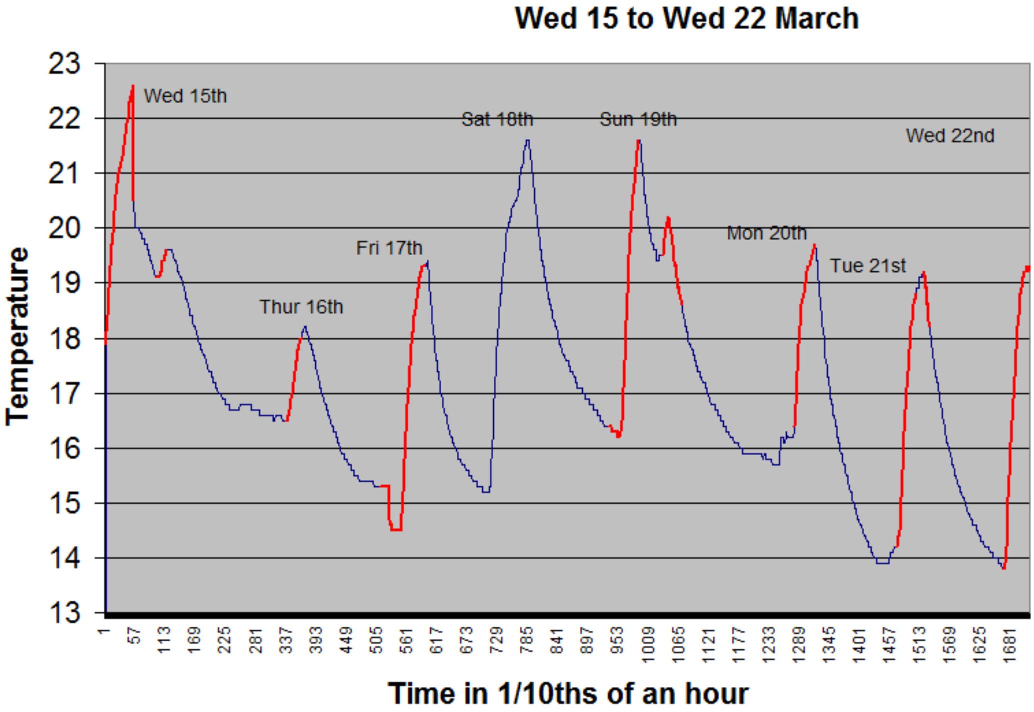
3. The zigzag on the radiator graph tells us how much the boiler is on when the radiator temperature has stabilised - it's roughly 60% of the time. If all the radiators are on for these periods then there is still spare capacity in the boiler. This would mean that the church could put up the boiler temperature to get more rapid heating. This would normally result in reduced overall energy consumption. Ten degrees on the boiler temperature would put boiler usage up to 76% and reduce heating up time for a 6 degree gain by one hour. With further use of the temperature loggers the church could experiment with the settings and measure the effect.

6. There is a difference between the estimate of boiler utilisation from the air temperature graph (35%) and the zigzag of the radiator temperature (60%). The chart with multiple curves confirms that the change in the slope of the air temperature graph is at the moment when the water temperature reaches the set value.

The boiler arrangement for the church is a tandem system. I have studied this arrangement elsewhere and discovered that it is common to set one boiler at a slightly higher temperature. This is intended to avoid both boilers coming on and off for short periods once the water has reached the set temperature. A consequence of this is that cool water passing through the "idle" boiler mixes with heated water from the active one reducing the temperature of the flow into the radiator system. It also would explain the difference in estimates of boiler utilisation, and would confirm the estimate of 35% utilisation of total boiler capacity (within the accuracy of the measurements).

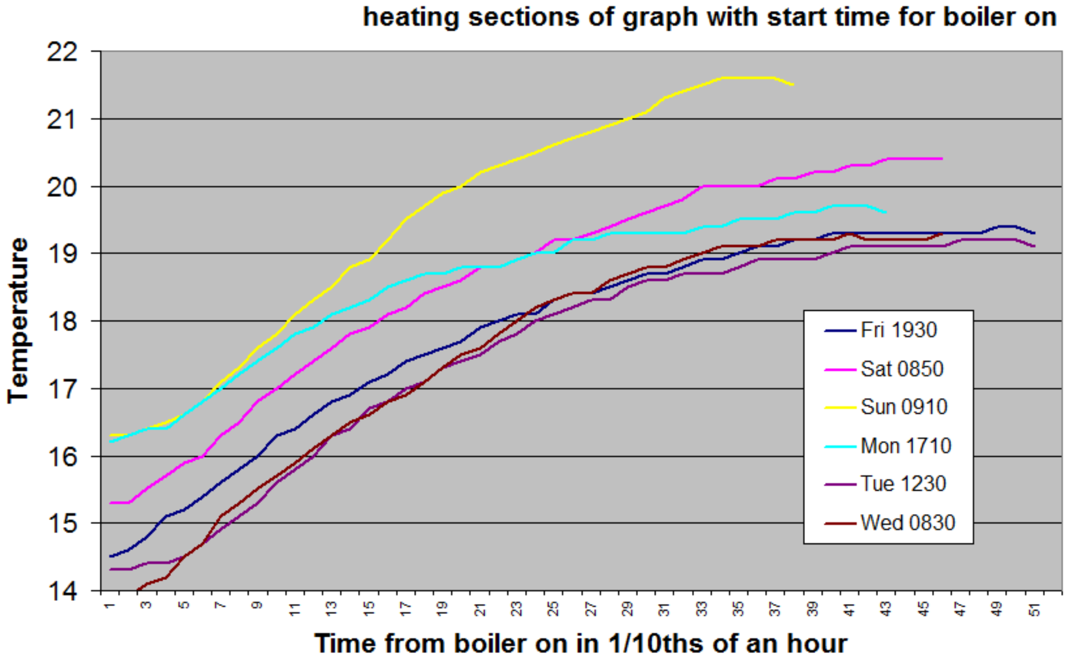
Case study 8 – use of a frost stat to preheat the building

A temperature recorder was placed in the church from 15th to 22nd March 2017. The recorder logs temperature every 6 minutes. The results are shown below with the periods the boiler was scheduled to be on coloured red.



There are some minor differences between the times the temperature was rising (indicating the boiler was on) and the schedule I was given by the church. There was evidently also an additional event on the Saturday (? wedding). I have used the observed times in the analysis.

Taking just the heating-up sections of the graph and plotting them on the same chart from their starting point gives the following comparison.



It looks as if the Monday users (turquoise curve) turned the heating off after about 45 minutes of their session (1 hour 45 minutes from boiler start). I omitted the curve for Thursday which is much lower than the others because the heating was only on in an extension.

From these two charts the following observations can be made:

- Between 2.5 and 4 hours from the heating coming on, the temperature rises by only one degree (0.6 degrees per hour), and it appears that by 4 hours the heating is close to the maximum achievable increase of five degrees above the starting temperature.

- The six differently coloured lines on the second graph are closely parallel. This shows that the amount the temperature will have risen after a given heating time is the same, so the temperature actually reached is dependent on the starting temperature. The line for Sunday (in yellow) and Saturday (pink/red) gain about half to one degree more than the others. This is likely to be the effect of the congregation /wedding party being present.

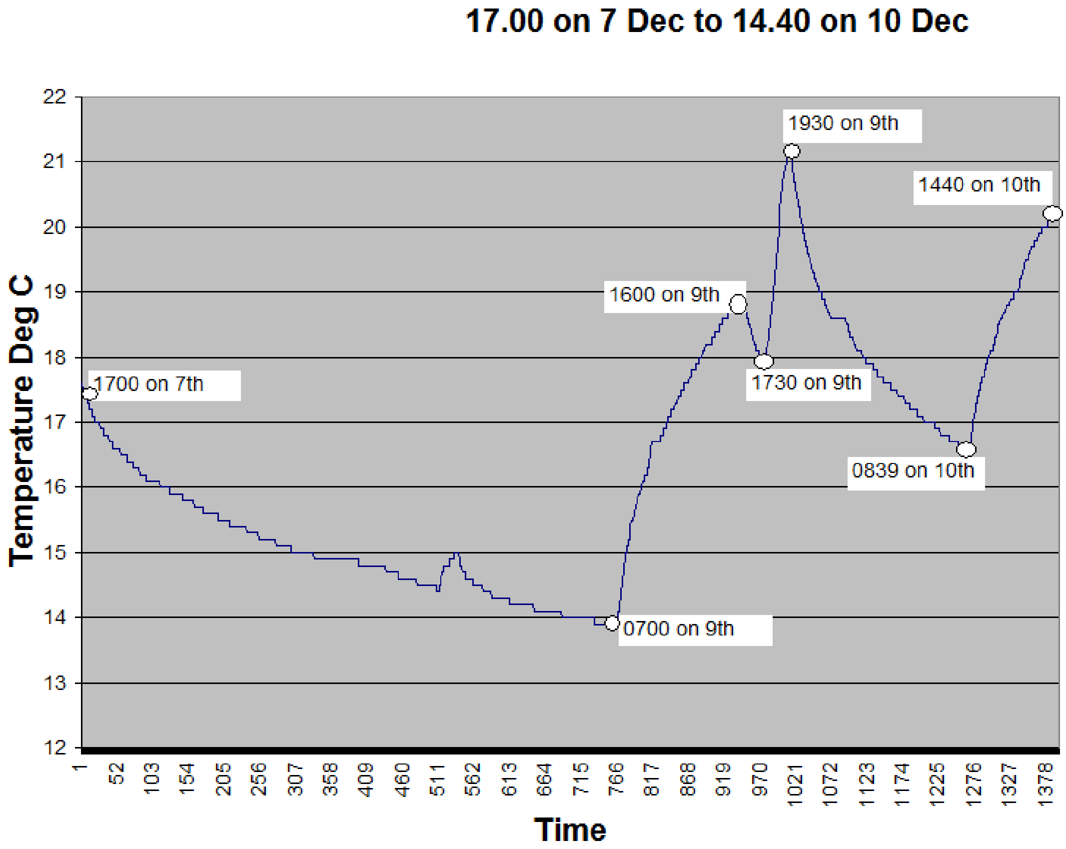
- So, normally, if the building is cold when the heating comes on, it will be colder at the end of the heating period, than if the starting temperature had been higher, and to reach a given in-use temperature, the heating would need to come on sooner, but there is little point in starting more than four hours before, because the rate of heating will have levelled off.

The simplest way the church could respond to these characteristics would be to follow the method used by some churches that use a "frost stat" controlling the boiler to keep the building above some minimum temperature (say 15 degrees) so that when the heating comes on they can make sure that it will start from at least this temperature. This would give a more even temperature experience for users. This might use more fuel, but the church could counter-balance this by reducing the time the heating is on full, because the building itself will be warmer, and the congregation will feel warmer.

It would be important to monitor the effect of any change (for example, by taking gas meter readings) because estimates based on heating theory are not always realised in practice.

Case Study 9 – using a chart to estimate times to put heating on

This report is based on records of the temperature in the church from 17.00 on Wednesday 7th December 2016 to 14.40 on Saturday 10th December.



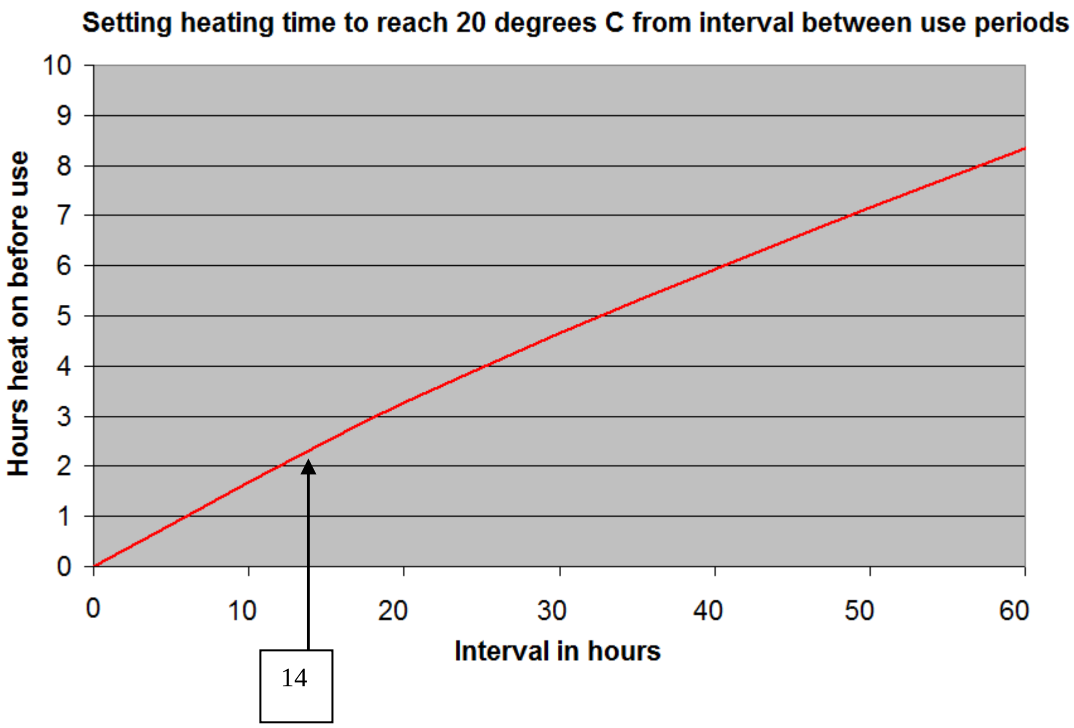
On the 9th the section of cooling between 1600 and 1730 may have been because doors were left open, and the subsequent rapid heating, the presence of lively Scouts!

The two heating periods for which there are observations (9th and 10th December) show similar shapes of curve – starting quite steeply and then curving over toward the end of the heating period. This is exactly what would be expected – as the internal temperature rises, more of the heat generated by the heating system is lost to the fabric and the outside, until a point would be reached at which the heat put into the building is exactly balanced by the heat loss.

By fitting a curve of suitable formula to the observations I have estimated that this balance point (highest temperature that could be reached) would have been at 20.5 degrees on the 9th and 23.0 degrees on the 10th. In both cases this is 6.5 degrees above the temperature when the heating came on. Again this pattern is consistent with other churches for which I have observations.

The two sections of <u>cooling</u> curve (from the start of observations and from the evening of the 9th to the morning of the 10th) are essentially sections of the same curve that levels off at around 14 degrees C, showing that the core of the building fabric probably stays at this temperature most of the time with the heating schedule used.

From these curves it is possible to calculate how the church would cool down and heat up (when the boiler starts) between periods when the building is in use. The method uses the Microsoft Excel Solver Add-on to find the time the boiler would need to start up, for a range of time intervals, and fits a curve to the results. The calculation would be different for each in-use temperature – I used 20 degrees Centigrade. The results can be read off from the graph below.

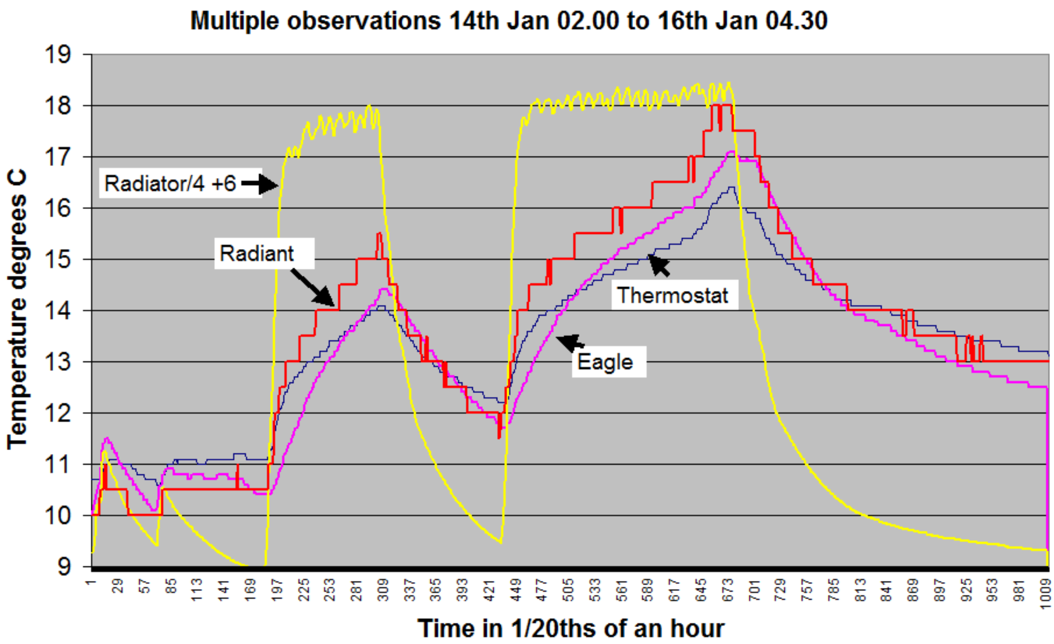


As an example, if the building is used until 2100 one day and is required again at 11.00 the next day, the total interval is 14 hours. Going up from 14 hours on the bottom axis hits the red line at about 2.3 hours, so the heating would need to be put on at 2 hours 20 minutes before 11.00 – that's 0840. The chart is based on some assumptions so it would probably be wise in practice to start a bit sooner. This kind of chart would enable the church to programme the timer for each week to match the usage pattern and so use the boiler time as effectively as possible. I could have added other lines to the chart for different in-use temperatures.

Case study 10 – radiant heaters and radiant temperatures

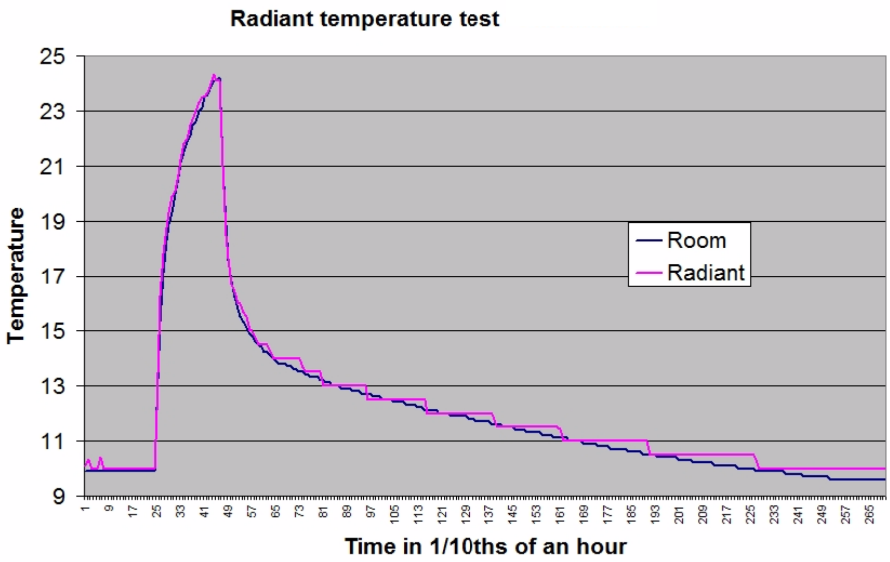
Recordings were made in the period 10 to 17 January 2017 with temperature loggers in two locations in church (at the location of the thermostat and on an eagle lectern), a third on a radiator to measure water temperature, and an experimental recorder to measure radiant heat. The radiant recorder is made by painting a copper sphere (from a cistern float valve) matt black and placing a temperature data logger inside it – the design was here (http://www.scielo.cl/pdf/rconst/v15n3/art06.pdf) . The church has a water-filled radiator heating system.

The four sets of observations are superimposed in the chart below, with the water temperature scaled to the same range as the other readings. At the point 18 degrees on the chart, the water temperature would have been observed as 48 degrees - the actual temperature was probably about 53 degrees because the logger sensor is not in direct contact with the radiator surface.



From this data we might conclude that radiant heat has a small but measurable effect. However I repeated the experimental use of the radiant temperature recorder in another church that had radiant overhead heating. Here the normal air temperature logger and the experimental radiant logger were in the same position with the air temperature logger shielded from the direct effect of the radiant heaters.

The two sets of recordings are plotted together in the chart below – the steps in the curve for the radiant logger occur because the recorder used for this purpose logs temperature in 0.5 degree steps.



I concluded that the results from the other church were a reflection of the radiant logger having been placed in a different location within the church from the air temperature loggers, and not necessarily from a difference between air and radiant temperatures.

I plan to conduct some controlled experiments with a slightly modified radiant recorder to determine whether the recorder can actually recognise radiant temperature as distinct from air temperature, with the objective of being able to measure the heating experience of the users of churches that have overhead radiant heaters.

Appendix 1 – Experience of modelling church heating systems

One of the elements of "conventional wisdom" in church circles is that no two churches are the same". This is certainly true of the heating systems in Anglican churches in particular because of the age of many of the buildings. The characteristics of the building structure, the heating systems installed, the heating controls available and building usage patterns vary widely. In a comprehensive and authoritative article on "Thermal comfort in UK churches" Mark Ramsden quotes from a BRE report that:

> *'in the case of "a large heavyweight building with a slow acting system used intermittently" there is a" fundamental problem with measuring a value of anything that may be used sensibly to control the heating system". There was "no single temperature measurement that could be regarded as typifying the state of the building". The suggestion is made that a thermostat on the wall,* as used in *most churches is "unlikely to represent anything of value for controlling the system". '*

I am not a heating engineer nor particularly a statistician, but I do have some years of experience of building computer models of things varying from blast furnaces to bus maintenance garages. It occurred to me that it might be possible to construct a general model of how church heating systems operate and to calibrate this model by taking measurements in a specific building and then to use this building-specific model to test alternative ways of managing its heating system.

During the winters of 2015 and 2016, I had the opportunity to work with nine churches in the Lichfield Anglican Diocese (following a diocesan project to create Environmental Action Plan for 30 churches), in which heating management emerged as a particular concern. Since the churches "self-selected", the nine do not constitute a formally representative sample, but they do in practice cover a range of building types, heating systems and patterns of usage. From the results of this work I have concluded that there is a way to produce informative analysis that can be applied to create more cost-effective systems. The method involves:

- Collecting appropriate measurements by using low-cost data logging equipment (I used a "Minilogger" temperature recorder from Mindsets with a USB connection to extract the data – they cost about £20)
- Building a computer (spreadsheet) model to match the observations
- Applying the model to test the effect of alternative heating management (and design) options on the comfort of users and the cost of fuel.

An outline of the method and example results follows.

*   *   *   *   *

1. <u>Collecting data</u>

Setting up a model is a tussle between what you want to measure, what you can measure and what you can, in practice control. The Treasurer want to know how much fuel is used but, for example, it isn't practical to take readings from a gas meter every minute for 24 hours (one meter would have requited the observer to lie down in some scrub next to a busy main road!). The users are interested in the room temperature, but church heating systems using radiators typically raise the temperature by between 0.2 and 1 degree centigrade per hour, so we need to know about how the heat rises over a period of many hours, so that the timing controls can be set appropriately. I tried a number of approaches to find the best way to monitor temperature and energy used.

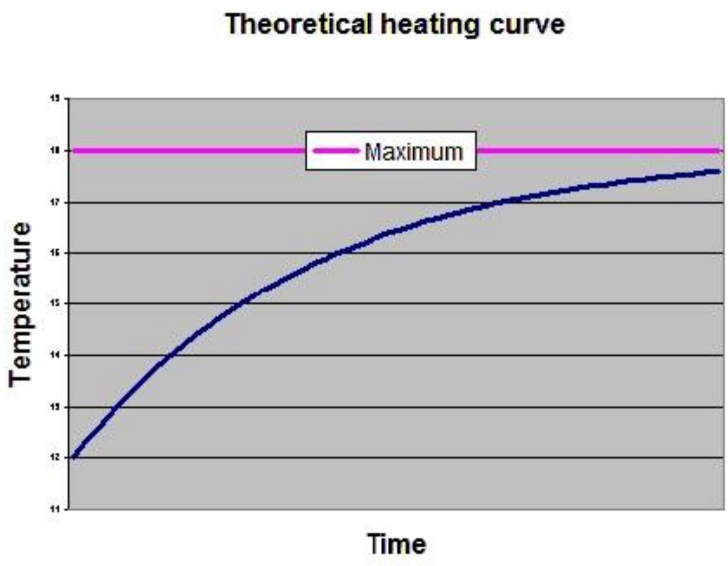
a) Modelling temperature

The purpose of having a mathematical model of the way the heating behaves, is that changes to the heating programme can be evaluated without conducting actual live experiments (on systems that start up in the early hours of the morning!). I found that it is possible to construct a formula for the way temperature changes with time and to find values for the constants (parameters) in the formula that replicated the way each of the individual heating systems worked.

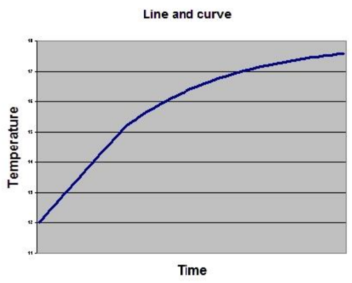
In order to model a system it is usually best to start from the theory and use actual observation to get values for the various constants that make up a formula. For situations where the outside temperature and the heat input to the building are reasonably constant, the theoretical formula that connects building temperature with time is:

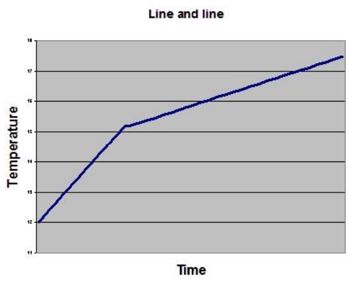
$T_I = a.e^{bt} + c$ where T_I is the internal temperature of the building at time t
a, b, and c are constants, and e is a special number that turns up in lots of situations where things change.

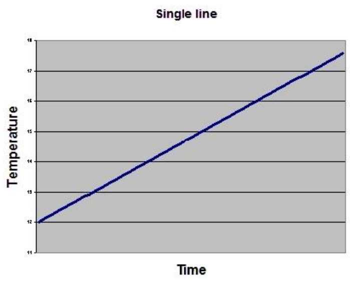
When the boiler is running and the building is heating up, a and b are both negative, and the formula as a graph would be a curve rising steeply at first and then levelling off over time to the value c.



However, when we plot the measurement of temperature against time for the actual recordings taken in the churches there appear to be three distinct patterns:

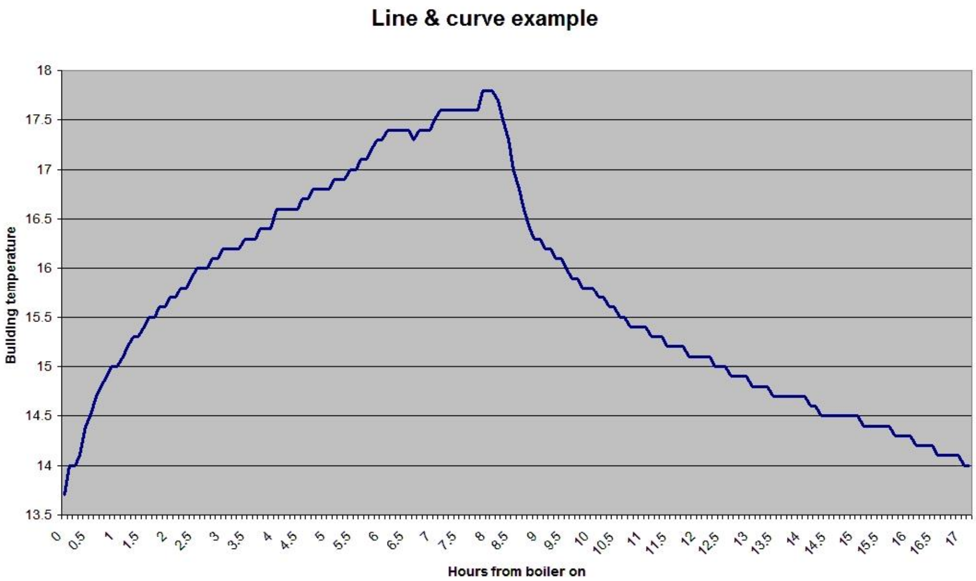


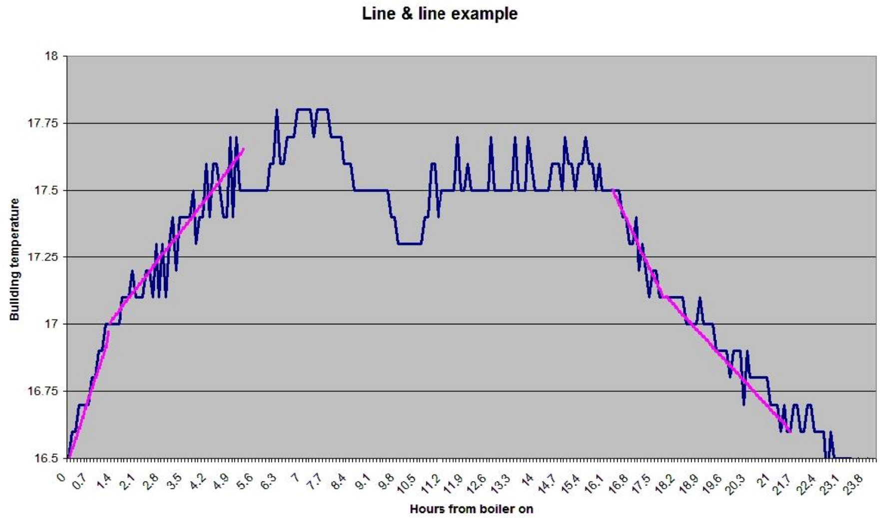


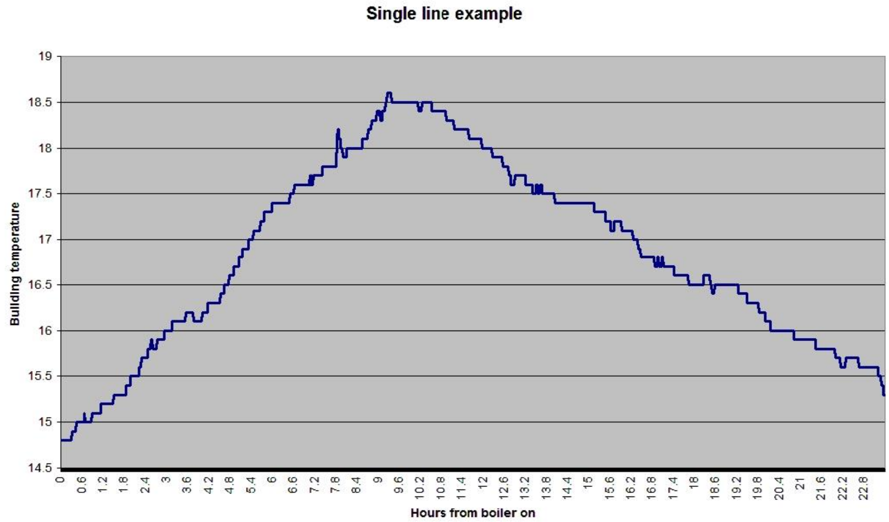


In the churches where the graph changes slope (either from a straight line to a curve, or to another straight line) I looked at other data I had collected to try to discover the reason for the change. It was clear that the change takes place at the moment when the circulating water reaches the temperature set at the boiler (typically after 45 to 60 minutes). I have discussed this phenomenon with a few people without finding a convincing explanation. Fortunately, it doesn't affect the results I was looking for, and I have simply retained the change in the models. If someone is looking for a research project …

The following three graphs, one for each shape of curve, from churches that exhibited the shape, show the measurements taken and the lines and curves fitted to the observations.

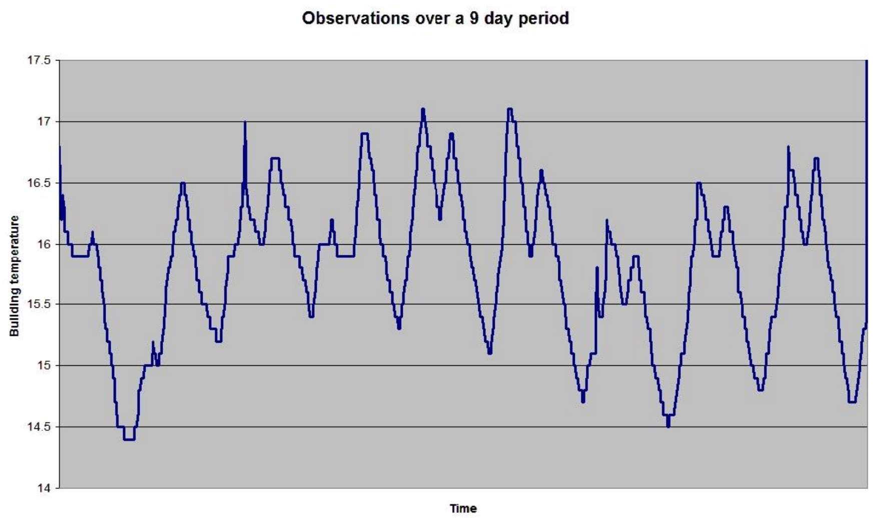






The curves for cooling follow a very similar pattern, falling steeply at first and then levelling off, and churches where the heating curve has an elbow, mostly also have an elbow in the cooling curve.

In this church (graph below) which is open most days, you can see that the heating and cooling graph sections are not identical for all the cycles – not least because doors are opened to let people (and cold air) in, and these people then give off heat. However, most importantly, I have been able to check that the curved portions of the graph are part of the same underlying curve and do not depend on the temperature at which the curved portion begins.



My conclusion is that by recording the building air temperature for one or two heating and cooling cycles, it will be possible to calibrate a model of how the building responds to the heating system and to use this to predict the effect of changes to the heating controls. However, to complete the analysis fully, to include estimates of the effect of such changes on total heating costs (energy usage) it is necessary to have information about how the boiler is operating.

b) Modelling heating fuel consumption

There are two ways that boilers operate. Conventional gas and oil boilers and electric heaters run at full capacity until the water or radiator surface reaches a set temperature and then turn off completely until this temperature has dropped by a set amount (typically in the range 0.5 to 5.0 deg C), and then come on again. By contrast, modern condensing boilers are designed to run at full capacity until the circulating water has reached the set temperature and then “modulate” the fuel flow to keep the water at this temperature – rather like the accelerator on a car. The effectiveness of this facility varies a good deal with the quality of the boiler and the temperature setting.

I found that the simplest and most reliable way to estimate fuel consumption is from the difference between the temperature of the water pipe leaving the boiler (flow) and that entering the boiler (return) and that the data can be collected by placing a small battery-powered USB logger (looks like a data stick) on top of the pipe where the metal is exposed. The energy being put into the water is proportional to the temperature difference between return and flow, and the proportion can be calibrated because all boilers come on at full capacity when they first start up. I was able to confirm from recordings of electrical consumption by the boilers that the time lag between the boiler starting up and the flow temperature starting to rise is roughly the same as the time to the temperature dropping when the boiler turns off (I had originally hoped to use electrical consumption of the boilers to estimate fuel consumption, but this doesn’t work for all boilers and I had too many problems with the monitoring equipment).

c) “Comfort” rather than temperature

Ramsden's research includes detailed examination of how people experience warmth and the sources of this. His research (and that of others) suggests that people experience comfort as a combination of the temperature of the air and also of the radiant heat that reaches their bodies. The radiant heat can come from a number of sources including the fabric of the building, sunshine coming through windows, the bodies of other people and the surface of heating equipment. Assessments of the relative contribution to comfort of the two sources vary from equality to radiant being three times more important. Radiant heat can be measured by a "globe thermometer" which is basically an ordinary thermometer (or data logger) placed in the centre of a black metal sphere. I plan to experiment with this, but meanwhile have used some indications from Ramsden's research to explore the possible effect of using comfort rather than just air temperature on the analysis.

2. <u>Calibrating the model</u>

a) Temperature

In most churches I took readings over a period of 7 to 14 days to give me a number of heating and cooling cycles and also some variation in weather and external temperatures. For each church I selected a heating cycle where the range between initial room temperature and maximum (at the end of the heating period) was as great as possible and where there was minimum evidence of interference from external door being opened and large groups of people using the building – one church appeared to have had a particularly exciting New Year's Eve event! The advantage of starting from a heating cycle with a large range (min to max) is that the model will not have to make estimates much outside of the observed data where it might not properly represent the real relationship.

I then used the least squares method to get the best fit for straight line and curved sections of the heating and cooling curves of temperature against time. This is easy to do with the "Solver" function in Microsoft Excel, though it does sometimes need a bit of help to get a solution in the right area. The solution gives the values of the parameters a, b and c in the exponential formula and the slope of a linear section as degrees change per unit time.

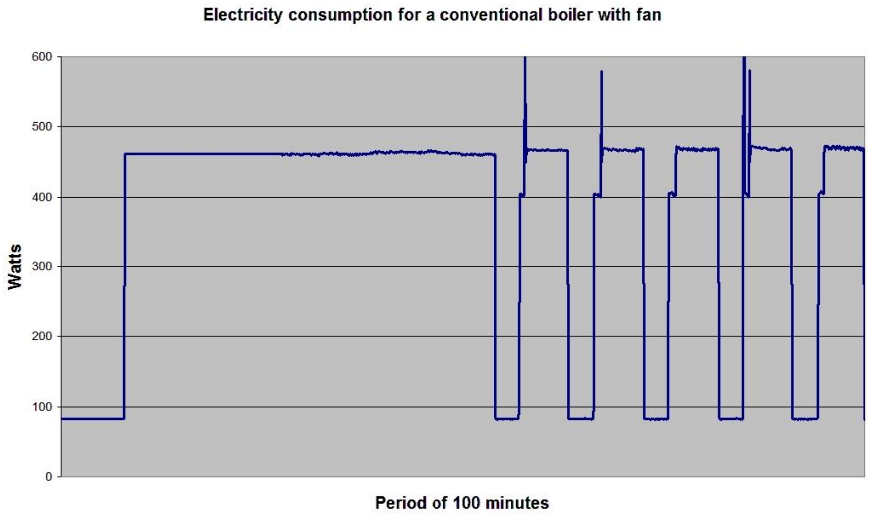
b) Fuel

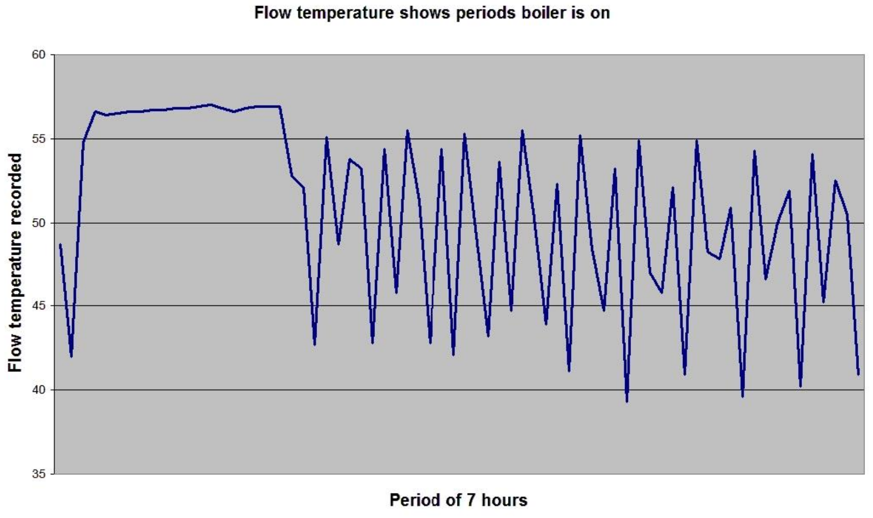
I have good data on water temperature for two churches with conventional boilers and one with an industrial grade condensing boiler. For the conventional boilers it is only necessary to use the flow temperature to detect when the boiler is "on" and to calculate the level of fuel usage as a percentage of maximum from the percentage of time the flow temperature is rising.

There are theoretically three states the boiler can be in:

i. Boiler fully on heating up the water to the set water temperature
ii. Boiler partly on because the radiators are at the set water temperature and cannot give off all the heat the boiler is capable of producing
iii. Boiler partly on because the room temperature has reached the value set on the room thermostat.

The graphs below show observations for the churches with **conventional** boilers: the first is for the electricity consumption of a gas boiler in a church that has no room thermostat and only has two possible states (luckily for me, this boiler has a fan that blows air into the combustion chamber and so the electricity consumption shows clearly the on/off states); the second shows the flow temperature for a church that has a room thermostat and shows states (i) and (iii).

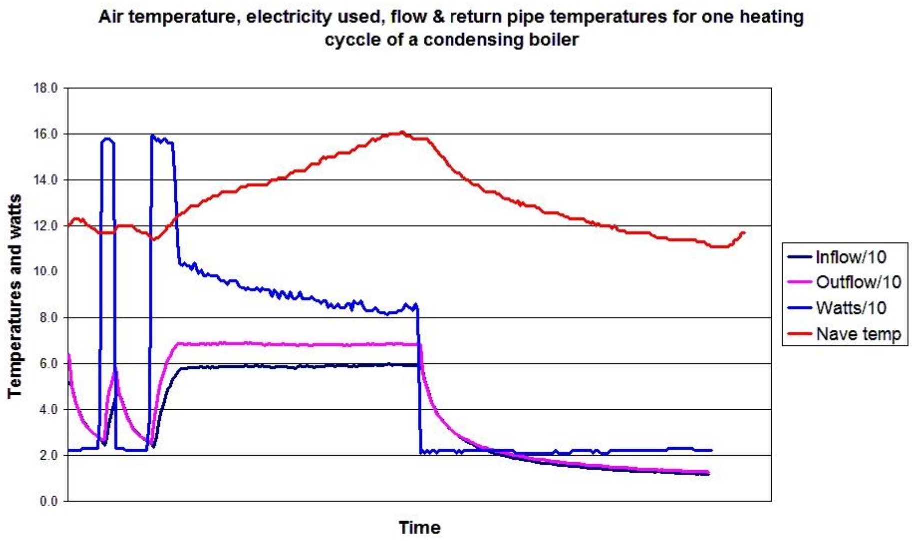




In both cases the proportion of time the boiler is on is constant during states (ii) and (iii) – the variation in upper and lower flow temperatures during state (iii) is because the moment of recording the temperature (every six minutes) comes at different times in the cycle for each reading. In future work I will use shorter recording intervals.

The value for boiler percentage in state (iii) – around 50% - gives a value for the current setting on the thermostat. The percentage for other thermostat settings can be estimated from this because the energy used will be proportional to the difference between room temperature and external air temperature.

The situation for the **condensing** boiler is potentially more complex, because of the possibility that the degree of modulation (reduction in gas flow) will vary during state (ii). For this church I have concurrent measurements for both water temperatures and electricity use by the boiler. The graph below shows these recordings together with that of room temperature – the water temperatures and electricity consumption have been scaled so that the graphs fit on the same chart.



The readings show that the difference in water temperature drops from the value when the boiler is running at full capacity to 79% when the set temperature is first reached, and to 71% just before the boiler is switched off by the time control. A similar effect is present in the electricity readings but the percentages here are 60% and 46% respectively. It was this evidence that led me to abandon using electricity consumption to estimate fuel use. The 79% to 71% reduction recorded by the water temperatures may be partly explained from the increase in air temperature so that less heat is passed into the air as the difference between air and radiator temperatures falls. I decided that this was an unnecessary complication and used the figure from the end of the heating period only to represent energy usage in state (ii).

This church does have a room thermostat, but the temperature never reached the set value! There are readings for maintaining the minimum air temperature at 12 deg C where the boiler runs fully for a series of short periods and so the percentage of time the boiler is on at this temperature can be used to estimate the value for other temperatures as for the conventional boiler examples.

3. Applying the model

There are three levels at which results from the monitoring can be analysed and applied:

- Examining the raw data
- Experimenting with different settings of the boiler temperature, timer/room temperature controls

- Evaluating minor changes to the heating system itself.

a) The raw data

Without observations of the building temperature churches have no real idea about how the heating system is behaving. Some were astonished to find that the temperatures set on the simple or programmed thermostat were not being achieved.

One church had installed a quite sophisticated domestic programmable room thermostat which had some special features designed to make the heating more effective. These features assumed that the room would heat up at several degrees per hour, and made minor adjustments to make sure the room would be at exactly the set temperature at the set time. For a system that was struggling to achieve one degree in three hours these features were at best irrelevant and at worst put the boiler into a rapid cycling mode turning it on and off every few minutes.

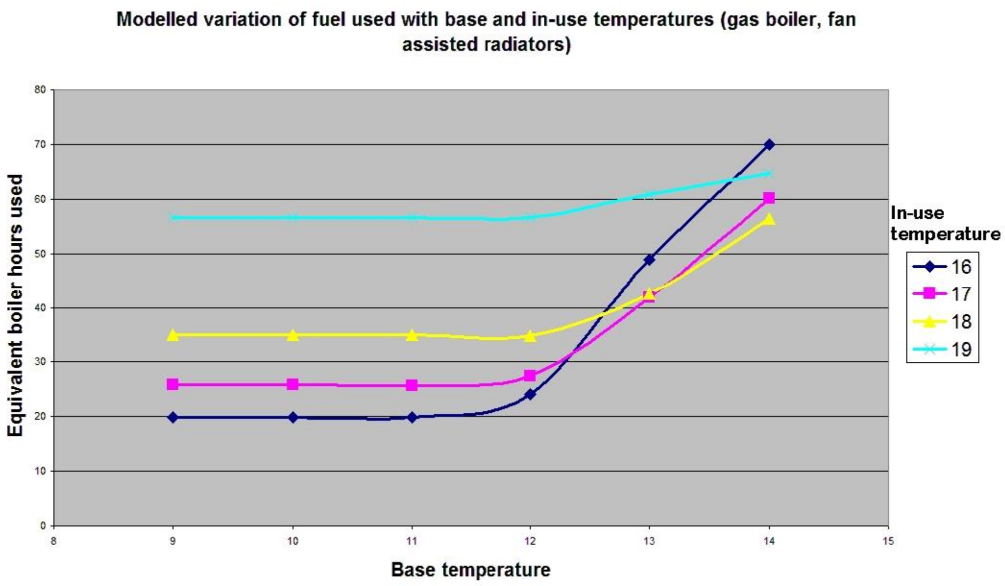
In other churches the thermostats were in places where the air did not circulate - behind some flags, in the middle of a pillar, in a corridor separate from the open church. One church had a heating system that consisted of large cast iron pipes running in deep ducts around the church, some of which had been carpeted over. It took 90 minutes from the boiler coming on before the church began to warm up at all, and three hours after the boiler had turned off before the church began to cool down.

None of the churches with condensing boilers had been advised that the way the boilers work to get extra efficiency over conventional boilers, has no effect if the return water temperature is above 45 – 50 degrees centigrade.

There are reasonable explanations for all of these issues but it would have been difficult to expose their effect with any precision without the observations, and it has been possible mostly to make simple adjustments that made better use of the heating.

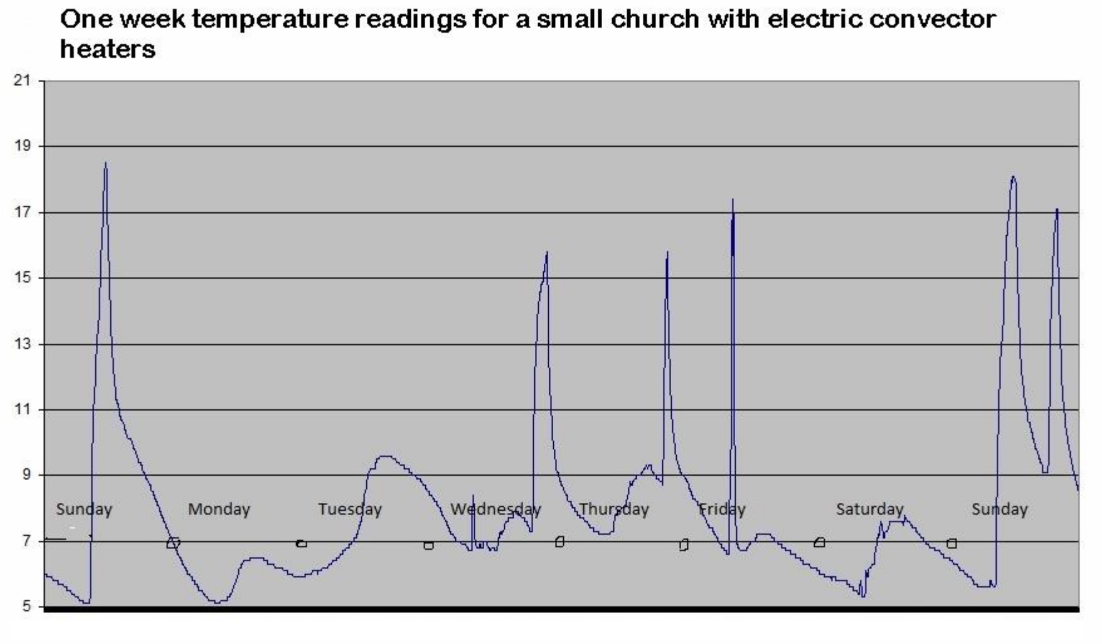
b) changing settings

I have given two examples, in some sense at opposite ends of a scale: one is a large stone built town church used most days with twin commercial condensing gas boilers controlled by a timer clock and room thermostat controls. Its set room temperature range was from 12 to 19 degrees centigrade, gaining about 0.5 degrees per hour after the water had reached the set temperature of 70 deg C. In practice, the in-use temperature set was rarely achieved. The graph below shows the estimated total boiler hours run during a week plotted against the minimum (base) temperature, and for different settings of maximum (in-use) temperature. The model works out the time the boiler would need to come on in order for the building to reach the set temperature for the beginning of each period the building was in use. The boiler is then off until the temperature has dropped to the base, and the model uses the estimated boiler utilisation to hold the base temperature, repeating this sequence for each heating cycle.

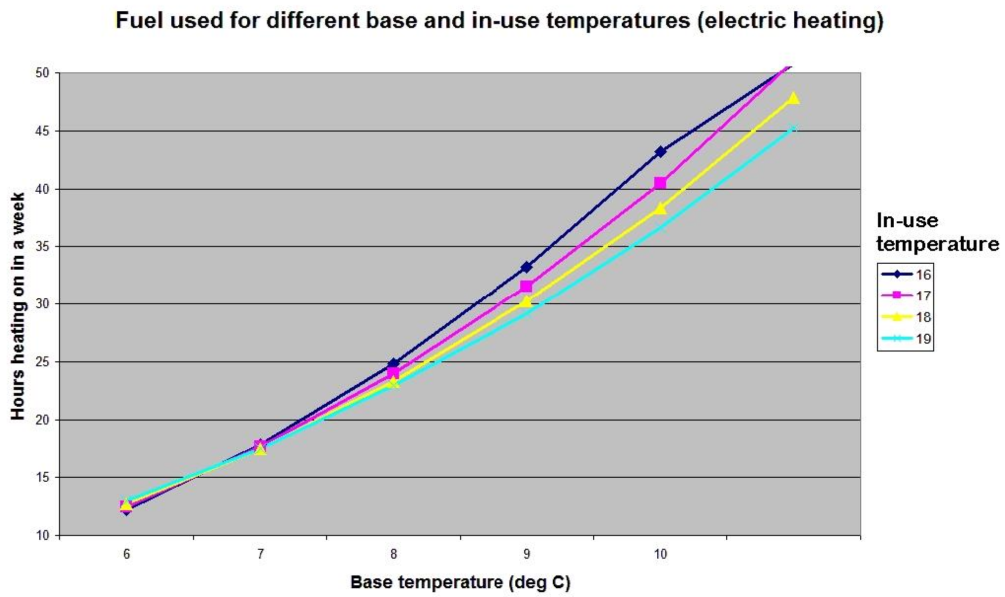


It is evident from the graph that changing base temperature has little effect on fuel used up to 12 deg C regardless of the in-use temperature setting. This accords rather well with the recommendation that, for the sake of preserving the fabric of churches (stone, wood and cloth) the building should be kept above 12 deg C, and that changes in temperature should be slow to reduce the effects of condensation. The fact is that in this church, the heating was on so regularly that the temperature did not drop below 12 degrees between heating cycles anyway because of the way the fabric retains heat. The chart does show the cost in fuel consumption of keeping the church above this natural base temperature, and of increasing the in-use temperature setting.

By contrast I have also included a small, brick built church with electric heaters placed along the walls. The heaters are rather like oil-filled radiators but with flat surfaces. There is only a time control. The church has steel window frames, single glazed. It is used several times a week for short periods. The observations were taken in January when the outside temperature was between 2 and 5 degrees centigrade, but with sunshine on some days. The temperature was recorded on a data logger suspended in the centre of the church about eight feet above the floor. Observations for the week are shown below.



The heating cycles for this church do seem to vary – it is possible that an additional fan heater was used for the Thursday and Friday events and this may explain the very sharp rise and fall of temperature. I used the curve for the first Sunday as the basis for the model because this is consistent with the observations for the Wednesday and the following Sunday. The model results for fuel use at different base and in-use temperatures is shown below.



In this example, the fuel used is proportional to the base temperature because the heating and cooling periods are very short and the base temperature would have to be held for most of the week. For higher base temperatures, the higher in-use temperatures actually result in a reduction in fuel usage over the week because the extended cooling period reduces the time the base temperature is held.

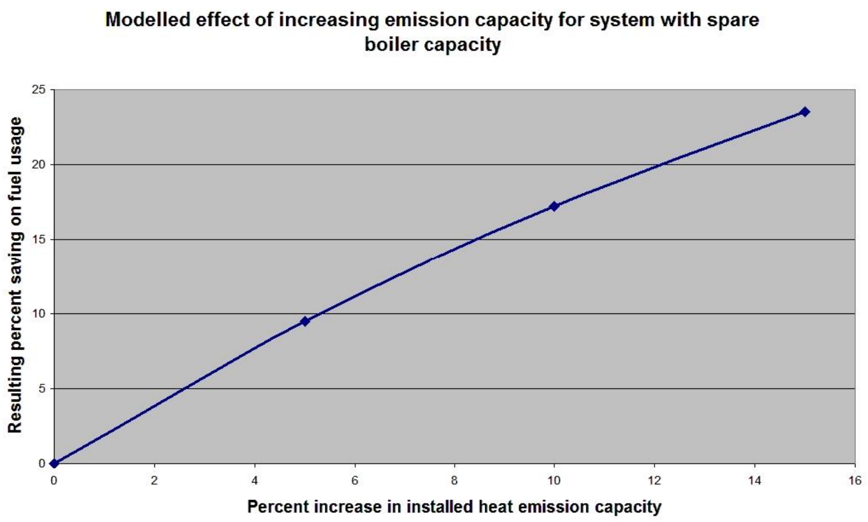
c) Changing emission capability

For several of the churches it was evident that the capacity of the boiler to produce heat exceeded the capacity of the emission equipment (radiators etc) to give out heat. A consequence of this difference is that it takes longer for the building to heat up, and it is possible that the extra fuel used during more rapid heating would be less than that saved by having the boilers on for a shorter time, leading to a net saving in fuel, or a higher in-use temperature at the same fuel consumption.

The options that might have been available to churches I visited included:

- Increasing the maximum water temperature setting (for a conventional boiler)
- Reducing the maximum water temperature setting (for a condensing boiler)
- Cleaning dirt off the fins on “gilled” pipe
- Removing various items that had been stored in a way that covered up radiators
- Removing radiator shelves and other cabinets that restricted the heat output of radiators
- Adding one or two fan assisted convectors on separate circuits
- Replacing banks of 6 inch diameter iron pipe with radiators.

I have modelled the effect of increasing the effective emission capacity of the heating system for one church in which the boiler ran at 70% capacity after the water reached the set temperature. The graphs shows the percent reduction in total heating cost for various levels of increase in emission capacity. This church has since removed shelving above the radiators. The church did not have any control on building temperature. The net effect of the increase in emission capacity has been to increase the temperature for periods of use by about one degree without any increase in gas consumption.



Appendix 2 – Summary of individual church characteristics

				Heating type								Control type									Recommendations					
Seq	Church type	Visit	Size	Boiler	Rads	Pipes	Air Convectors	Store	Radiant E finned	U/floor	Under Pew	On/off	Timer	Thermo stat	Prog Therm	Min temp	Max temp	Days in use	Max rate deg/hr	Range degrees	Heat Advisor	Temp	Convec tors	Pre heat	Prog Therm	Bigger pump
1	Stone	y	l	2	y				y				y					4	0.7	6.5						y
2	Stone	y	m	1	1							y	y			15		2	0.3	3.5			y			
3	?		m	y	?	y							y					2	0.4	4	y	y				
4	Stone	y	s						y				y					1								
5	Brick modern		m																							
6	Brick/stone	y	m	y	y								y					2	1.1	5.5		y	y			
7	Stone	y	s	y	y								y					1	2.1	8			y			
8	Stone		m	y	y								y	y		11		2	1.5	4						
9	Brick																		2.7	4.5						
10	Brick			y	?								y					5	0.9	7.5					y	
11	Brick		m	y	y								y					4.5	0.5	4	y					
12	Stone	y	s	y	y								y					2	4	13						
13	Brick			y	y								y					5	2	6.5			y		y	
14	Stone	y	m	3	y								y					2	1	6						
15	Brick	y	m	y	y								y					3.5	2.4	10			y			
16	Brick	y	s						y		y		y					1	0.2	2						
17	Stone		m	y	y								y					2	4	11	y		y			
18	Stone	y	l	2	y										y	11		7	0.5	5	y	y				
19	Brick	y	m	y			y						y					5								
20	Brick	y	m	y	y								y	y				7	1.5	6.5			y			
21	Stone	y	l	y	y								y					7	1	13					y	
22	Stone		s					y	y			y						2.5	0.5	3						
23	Stone		m	y	y								y					1.5	1		y					
24	Stone		s	y		y					y		y					2	0.5	4	y					
25	Stone		l										y					6	0.7	8						
26	Stone		m	y	y								y		y	13		3	0.4	5	y	y				
27	Stone		m	y	y								y					6.5	3.2	6		y			y	
28	Brick		l						y																	
29	Stone	y	m	y	y		y						y				21	7	1							

Seq	Church type	Visit	Size	Heating type								Control type									Recommendations					
				Boiler	Rads	Pipes	Air Convectors	Store	Radiant E finned	U/floor	Under Pew	On/off	Timer	Thermo stat	Prog Therm	Min temp	Max temp	Days in use	Max rate deg/hr	Range degrees	Heat Advisor	Temp	Convec tors	Pre heat	Prog Therm	Bigger pump
30	Brick		m	y	y								y					3.5	2.2	6.5					y	
31	Stone		l	y	y								y					1	1.2	8	y	y	y			
32	Stone		l	y	y				y					y		11		2	0.5	5						
33	Stone		m	y	?								y					5	1	6		y				
34	Stone/brick		y	m					y	y				y	y		11		5	1.4		7				
35	Stone		l	y	y								y					2	2	6.5	y					
36	Stone		m	y		y					y		y	y		13.5		1	0.2	1						
37	Stone		s	y	y								y	y		17		1	4	23						
38	Stone		s	y	y								y	y		14		7	1.3	7						
39	Stone		m	y	y								y					2.5	0.7	3				y	y	
40	Stone	y	m	y	y		y			y					y			3	3	8						
41	Stone		m															2	3	3.5						
42	Stone		m						y			y						1	10	30						
43	Stone		s	y	y								y	y		15		6	1	5					y	
44	Stone		l	y	y								y					4	1.3	5.5						
45	Stone	y	l	y	y								y					2.5	0.6	5						
46	Brick		m	y	y								y					5	1.3	6.5	y					
47	Stone		m	y	y								y	y			18	4	2	10		y				
48	Stone			y	y										y		20	6	7	20						
49	Brick	y	s	y	y								y	y			20	5	1.2	8		y	y			
50	Stone		m	y	y								y					4	2.4	4					y	
51	Stone		m	y	y								y					3	0.9	8					y	
52	Brick	y	m	y			y						y					5	1.4	8					y	
53	Stone		l	y	y								y	y			17.5	7	1.9	8						
54	Stone		m	y	y								y					5	0.8	6					y	
55	Stone	y	s						y				y					1	5	9	y					
56	Stone	y	l	y	y										y	8.5	20	2	0.7	6	y	y				
57	Stone		l	y	y		y						y					3	2.4	7	y	y				
58	Brick	y	m	y	y								y					7	2.4	7					y	
59	Stone	y	m	y						y			y	y		15		1.5	0.35	7	y					
60	Stone		m	y	y								y					5	0.6	5					y	
61	Stone		l	y	y								y					2	0.4	5	y					
62	Stone		m	y	y								y					1	2.7	8		y	y			
63	Stone	y	m						y					y		10		5	2	6						
64	Brick	y	s					y	y			y						1	1							

The histograms below summarise the results for the variation in initial rate of heating and the number of degrees increase in temperature as a result of the heating being on.