Review of BAT for New Waste Incineration Issues

Part 2 Validation of Combustion Conditions

Technical Report
P4-100/TR

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R&D Technical Report P4-100/TR
Part 2 Validation of Combustion Conditions

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Statement of Use
This study reviews and discusses the various techniques and methodologies that are available for monitoring and validating incinerator furnace operating conditions, with respect to minimum gas temperature and gas residence time. The study assesses the technical and financial implications of their application to UK waste incinerators. Recommendations are produced for guidance on best available techniques (BAT) for monitoring and validating the above furnace conditions which are suitable for inclusion in a new technical guidance note. The information in this document is for use by Agency staff and others involved in the regulation of industrial emissions.

Keywords
Residence time, residence temperature.

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EXECUTIVE SUMMARY

The EC Waste Incinerator Directives lay down minimum conditions for furnace residence time, temperature and furnace gas oxygen content. They also require that plant are subject to appropriate verification at least once to show that the minimum requirements are satisfied, even under the most unfavourable operating conditions. This report considers and assesses the available literature concerning possible monitoring methods and makes recommendations for guidance on BAT.

Design and measurement approaches are considered and the report recommends that verification should be based on measurement. The role of modelling is also considered and it is recommended that the use of techniques, such as computational fluid dynamics, should be encouraged to promote good design.

The study found that there are no standard methods covering this area and therefore the reviewed methods are described in some detail.

The report recommends that the minimum temperature requirements should be verified using a suction pyrometer system. Other approaches are also recommended, including shielded thermocouples, infra-red pyrometers and acoustic pyrometers, but these will need to be calibrated against a suction pyrometer and corrections applied.

Two residence time measurement approaches are recommended. The first is based on an assumption of "plug flow" and measures the residence time by monitoring the mean gas flow rate leaving the system. As plug flow is assumed then the mean and minimum gas residence times are considered to be identical. A suggested procedure is described which measures the mean gas flow in the stack or boiler outlet, and through subsidiary measurements this can be related to the mean furnace residence time at mean furnace gas conditions.

The second approach assumes that some stirring occurs within the furnace chamber and uses a time of flight determination. Two measurement methods are recommended and described. The first uses an inert gas pulse injection, with mass spectrometer detection of the response signal, which is compared to a reference pulse. The second uses a pseudo random binary pulse perturbation, in which propane is injected and the response signal detected by a fast carbon dioxide cross duct detector. Cross correlation techniques are used to compare the input and response signals. Such methods can measure residence time distribution, including minimum mean and peak values.

The report explains that a major obstacle concerned with validating residence times in incinerators is the lack of a comprehensive definition for this parameter. The report finds that clarification of the definition to be employed is essential to allow any verification procedures to proceed, and suggests several possible ways forward. When the plug flow approach is used the problem is avoided, because by convention minimum and mean residence time are taken as being the same. However, if the partially stirred reactor time of flight approach is followed then a distribution is produced. Consequently, minimum, mean and peak residence time values can all be obtained and interpretation of the data can become complex. Moreover, the minimum residence time obtained using this approach has little meaning and it is recommended that time of flight approaches should therefore take the mean or the peak value as the residence time parameter to be determined. An alternative approach is also put forward based on the system residence time of the partially stirred reactor. This occurs when

67% of the tracer has left the combustion zone. In practice, there is little difference between the mean, the peak and the system residence times.

For plant where combustion optimisation measures are not in place the time of flight and gas flow methods both tend to give results for residence time that are around two thirds of the design value. This should be taken into account when the design conditions for new plant are being agreed.

The use of the time of flight methodologies and the partially stirred reactor model represents the best approach, as it more closely reflects the real situation. It is recommended that these methods should be used for determining residence times in new plant.

Time of flight methods could be used at some existing plant but its use could become more difficult. This arises because of the need to provide additional access points in furnace chambers and could prove difficult and costly for existing installations. Consequently, it is recommended that existing plant be allowed to use the "plug flow " approach based on the mean gas flow measurement procedure.. When the gas flow measurement approach is employed, it is recommended that the residence time results are reported at actual mean furnace gas conditions and are not corrected to standard temperature, pressure and oxygen conditions.

Recommendations are given concerning the conditions to be tested, the minimum number of tests at each condition and minimum sampling times.

Recommendations are also made for defining the datum for the qualifying combustion zone. The technical difficulties likely to be encountered are considered for various type of plant, including existing and new plant. Recommendations are made on where latitude should be allowed.

It is recommended that because of inherent technical difficulties, bubbling fluidised bed combustors burning non-hazardous waste should have the temperature minimum relaxed to 800^{o}C. To compensate, it is recommended that the minimum residence time requirement be increased to 2.2 seconds.

The capital costs associated with the purchase of monitoring equipment are reviewed. The costs and implications for operators in providing access, space and services are considered. For existing water-wall furnaces it is concluded that making access holes in furnace (to provide the ideal monitoring positions) is likely to be impracticable and cost prohibitive. Consequently, compromises will need to be considered for much existing plant, and Regulators should accept that this would introduce additional uncertainty into any monitoring programme. It is recommended that new plant should meet the ideal monitoring port requirements laid out in the report.

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INTRODUCTION

1.1 Overall Project Aims

Technical guidance for waste incineration processes regulated under the integrated process control (IPC) regime was issued by the Environment Agency in 1996 (Environment Agency 1996). This guidance now requires revision to address developments in technology and new considerations brought about by new legislation, notably the change from the IPC regime to the Pollution Prevention and Control (PPC) and the recent EC Directive on the incineration of waste (EC 2000). This study was commissioned to supplement and update current information on best available techniques (BAT) contained within existing guidance in order to assist with the development of future guidance.

The study is presented in three parts:

Part 1 Waste pyrolysis and gasification
Part 2 Techniques for the monitoring and validation of furnace conditions
Part 3 New PPC considerations

This report presents the findings of the Part 2 study. Parts 1 and 3 are reported separately.

1.2 Part 2 study aims

The new EC Waste Incinerator Directive (EC 2000) lays down conditions for temperature and gas residence time within incineration combustion chambers in order to ensure efficient destruction of volatile organic compounds and any products of incomplete combustion present in the gas phase. The aim is to eliminate or minimise the release of such species from the combustion chamber. The current IPC technical guidance note, S2 5.01, (Environment Agency 1996) gives very few details of the precise methodology for meeting or demonstrating these conditions. This study was commissioned by the Environment Agency intends to provide updated information on standards and performance in the sector.

The main objectives of the study are to:

(a) Identify the best available techniques and methodologies for monitoring and validating furnace operating conditions.
(b) Assess the technical and financial implications of their application to UK incinerators.
(c) Produce recommendations for guidance on BAT for monitoring and validating furnace conditions, which are suitable for inclusion in a new Technical Guidance Note.

1.3 Method

The range of available techniques has been identified through a literature search, whilst the practical and resource implications has been assessed by drawing on our experience in this field and by talking with other researchers, equipment manufacturers and plant operators. The practical recommendations for guidance on BAT monitoring /validating has been produced after considering all the issues identified within the review and taking into account their applicability to new and existing incinerators of various types.

2. BACKGROUND

2.1 EC Directive requirements

The 1989 EC Directive on New Municipal Waste Incinerators (EC 1989 a) contained minimum requirements regarding furnace gas conditions. New plant were required to sustain a furnace temperature of at least 850^{o}C for at least two seconds. Existing plant were covered at the same time by a separate Directive (EC 1989 b) and those that had major technical difficulties in meeting the new requirements were required to satisfy them when the furnaces were replaced.

An EC Directive on the incineration of hazardous waste (EC 1994) was transposed into UK law in 1997 and also contains minimum furnace conditions. However, a new Directive on the incineration of waste (EC 2000) is replacing the earlier Directives and will apply to both the incineration of hazardous and non-hazardous waste, (with exemptions for vegetable waste, radioactive waste and animal carcasses). The new Directive contains minimum furnace condition requirements similar to those given in the earlier Directives, although a range of temperature criteria is specified that depend on the nature of the waste stream.

Unfortunately, the wording of the various directives in respect of the furnace gas condition criteria (see Boxes A and B) is ambiguous and this has led to problems when trying to demonstrate compliance.

BOX A: Article 4 of both 1989 Directives specifies that "the gases resulting from the combustion of waste must be raised, after the last injection of combustion air, in a controlled and homogenous fashion and even under the most unfavourable conditions, to a temperature of at least 850^{o}C, for at least two seconds, in the presence of at least 6% oxygen".

BOX B: Article 6 of the Directive on incineration of hazardous waste reads, "incineration plant shall be designed, equipped and operated in such a way that the gas resulting from the incineration of hazardous waste is raised, after the last injection of combustion air, in a controlled and homogenous fashion and even under the most unfavourable conditions anticipated, to a temperature of at least 850^{o}C**, as achieved at or near the inner wall of the combustion chamber**, for at least 2 seconds in the presence of at least 6% oxygen; if hazardous wastes with a content of more than 1% of halogenated organic substances, expressed as chlorine, are incinerated, the temperature has to be raised to at least 1100^{o}C".

Article 6 of the new Directive on the incineration of waste has similar wording to the Directive on the incineration of hazardous waste in respect of furnace conditions, but it allows the competent authority to authorise the use of an alternative "representative" measurement point for the monitoring of the minimum temperature.

2.2 Temperature issues

The 1989 Directives are not specific as to where furnace temperature is to be verified. However, the other two Directives at least give some indication on where verification should be carried out; for example, they mention the temperature minimum **"as achieved at or near the inner wall of the combustion chamber".** The 2000 Directive also gives Regulators some latitude and allows the competent authority to authorise the use of an alternative "representative" measurement point for the monitoring of minimum the temperature.

The Environment Agency has tried to give clearer guidance in guidance note S2 5.01, both on the temperature minima to be achieved by certain incineration processes and on the location of the measurement point. For example, it says that gas temperature at the point of exit from the secondary combustion chamber should be continuously measured and recorded.

The Directives (and guidance note S2 5.01) are quite clear that furnace exit temperatures are to be measured, but the issues to be resolved are "**where, when and how**" these measurements should be made.

2.2.1 Where to take minimum gas temperature measurements ?

The location of the minimum temperature measurement plane will need to be chosen carefully, taking into account furnace design gas residence time data. The exact location of a single measurement point is important, as there will be a temperature gradient across the chosen plane. Gas temperature is likely to increase as locations are selected further into the furnace chamber. As the minimum temperature is to be proved, then the verifying measurement point should be made where the temperature is likely to be lowest. The latest two Directives specify the temperature criteria as that "**achieved at or near the inner wall of the combustion chamber".** This location is sensible, as gas temperatures will be lowest near the wall.

However, the measurement should not be in the wall itself, as this would result in an atypically low reading as discussed in Section 3. It would be better to be more specific about the point of measurement and specify its location on the plane in terms of the furnace diameters. For example, measurements could be taken at a distance of no closer than 0.05 D from a wall, (D = furnace internal diameter), or no further than 0.5 meters from the wall in case of small plant. It would be even better to require four measurements points to be employed, each the same distance from the wall. This is because temperatures are likely to be different near certain walls depending on the geometry of the furnace, the attitude of the secondary air injections and the location of any support burners.

It should be borne in mind that whilst it may be possible to select the ideal position for the one-off proving of minimum furnace temperature, it may be much more difficult to use this same point for continuous temperature monitoring. It would be more practicable to undertake this activity at the outlet from the furnace, through the use of roof temperature sensor probes.

If gas residence time is to be determined assuming "plug flow" and by measuring or estimating the mean gas flow rates (see 2.3.1 below), then it will also be necessary to have some estimate of "bulk mean gas temperature" in the middle of the furnace chamber.

2.2.2 When to take minimum gas temperature measurements ?

The Directives are all clear that the gas minimum temperature is to be verified **at least once**, even under the most unfavourable conditions. Consequently, a range of firing conditions may need to be considered. Continuous furnace temperature monitoring requirements are also specified. However, these refer to the furnace exit gas temperature, and at that location the temperature is likely to be somewhat lower than at the position used to demonstrate temperature compliance for meeting the 2 second gas residence time criteria.

2.2.3 How to measure minimum gas temperatures ?

The Directives do not prescribe any techniques for verifying minimum gas temperatures, although it is clear that they are to be measured rather than estimated or calculated. Mean gas bulk temperatures are not mentioned, but if they were required for the chosen residence time validation approach, presumably estimation would be acceptable.

The description and assessment of available temperature techniques are two of the main objectives of this review, and recommendations will be made on those considered to be BAT.

2.3 Residence time issues

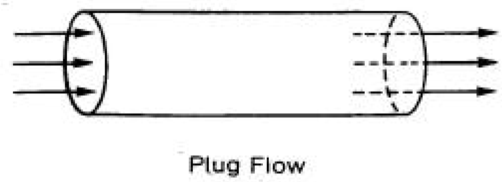
For demonstrating compliance with the residence time criteria, the word "verification" is used in the Directives. However, it is unclear whether verification can be based on design calculations and estimates, or whether only calculations based on actual measured data are acceptable. It is also unclear whether a minimum or an average residence time is being referred to. Consequently, a major obstacle for determining the residence time of an incinerator is the lack of a comprehensive definition of this parameter. Clarification of the definition to be employed is therefore essential to allow any verification procedures to proceed. If an incinerator furnace combustion chamber is considered as a reaction system (or vessel), then at least three situations can apply concerning residence time:

2.3.1 Plug flow

This is a simple hypothetical case in which there is no mixing and the gas velocity is uniform throughout the reactor vessel (see Figure 1a). If a short discrete pulse of tracer gas were injected into the reactor, it would emerge from the high temperature zone still as a discrete pulse but after a short delay. The duration of the delay is the minimum gas residence time (also called the plug flow time). Under this model, the minimum gas residence time and the average residence time are the same. Verification by this method is relatively straight-forward. The single gas residence time (RT) can be found by dividing the qualifying volume of the high temperature secondary combustion zone (V_{QSCZ}) by the average gas volume flow-rate (Qc) through the secondary combustion chamber.

Therefore, RT (in seconds) = V_{QSCZ} * 3600/Qc

Where V_{QSCZ} is in m^3 and Qc is in $m^3\ h^{-1}$)



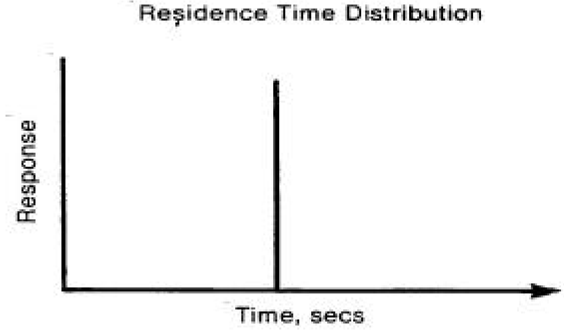


Figure 1a - No Mixing (Plug Flow Model)

2.3.2 Stirred reactor flow

The other extreme is also possible, i.e. a stirred reactor in which theoretical and instantaneous perfect gas mixing occurs. In this case, if a short pulse of tracer gas were injected into entered the reactor then some would immediately emerge from the high temperature zone. The remaining tracer would only emerge slowly and would exhibit an exponential concentration decay / time characteristic (see Figure 1b). This is because a small and ever decreasing concentration of tracer remains in the combustion chamber but this is being progressively diluted by incoming clean gas which contains no tracer. In this case, the minimum gas residence time would appear to be zero and verification would be irrelevant.

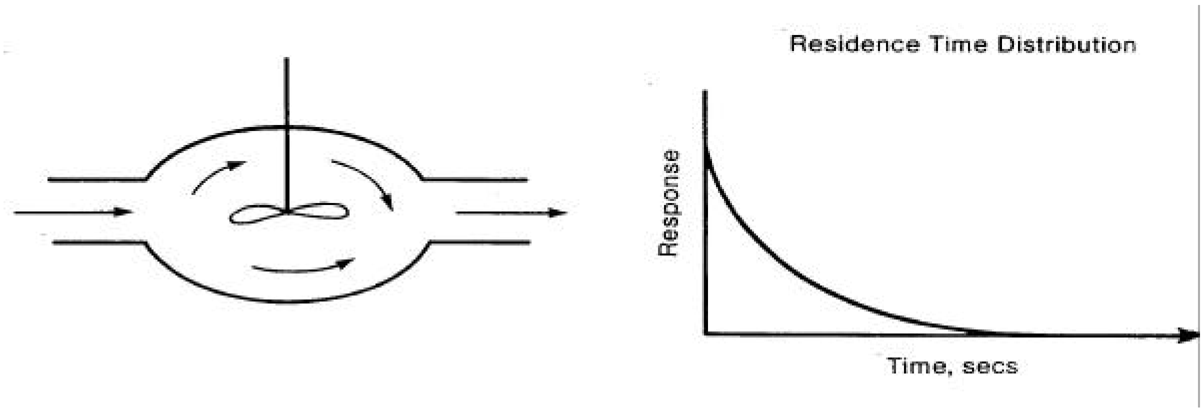


Figure 1b - Perfect Mixing

2.3.3 Real flow situation

In the real situation there is partial mixing, and both plug and stirred reactor flow characteristics will be present (see Figure 1c). If a short pulse of tracer gas were injected into the vessel, the resulting concentration curve would be somewhere between the above two extremes. After a short delay a small amount of tracer would emerge from the high temperature zone. A short time thereafter, the concentration would rise to a maximum (this approximates to the average residence time) before the concentration slowly decays away. Consequently, a distribution of residence times is now present which contain the characteristic components of both plug and stirred flow. More correctly the system has a plug flow time and a stirred reactor time constant.

The distribution may be bell shaped or, more likely, it will be skewed. The shape of the distribution will be influenced by several factors, including the existence of dead spaces, recirculation zones and high velocity channels. As a consequence, the interpretation of such a concentration / time response curve is difficult. Different approaches are possible.

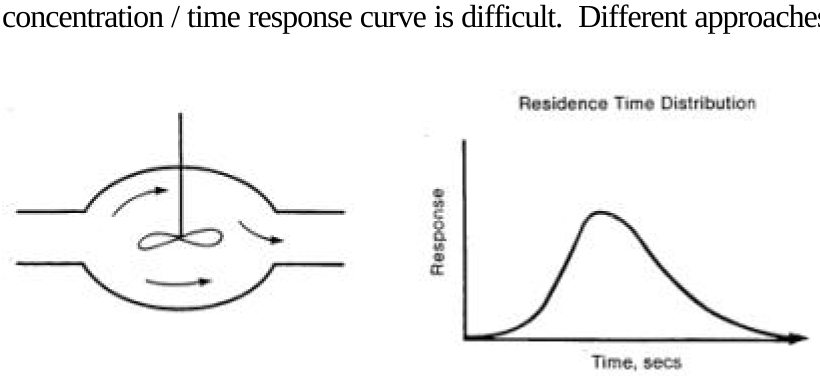


Figure 1c - Real Situation (Partially Stirred Reactor)

2.3.4 Implication of different approaches

If the plug flow model is to be taken as an acceptable approach to verification then compliance demonstration of residence time will remain relatively simple, as the minimum and mean residence time will be taken to be equal by convention. The simple equation given in Section 2.3.1 can then be used to find the residence time, with this parameter depending on the volume of the reactor and an estimate (or a measurement) of the gas volume flow rate.

If the real flow situation, using the partially stirred reactor model is to be verified, demonstration of compliance will inevitably become complex. For example, a time domain method will have to be employed and therefore a distribution of residence times will be obtained, as per Figure 1C. This presents a number of possibilities. For example, if the minimum gas residence time is required, should this be taken as the time when the tracer just becomes detectable? Uncertainty will be at a maximum at this point because any measured parameter will be close to the limit of detection. Alternatively, should the minimum gas residence time be taken as the time when 5% or 10% of the gas exits the high temperature zone. Either of these approaches will be very difficult to justify.

Verification could be made somewhat easier if the mean or peak residence time were accepted as the parameter to be determined. Nevertheless, a range of relatively difficult time domain measurement-based approaches (e.g. step-response and pulse response) would be required. A mathematical model (for example, based on computational fluid dynamics, CFD) alone would be unacceptable as, at best, this could only deliver results which are as good as the input information supplied to the model. Consequently, this would need a substantial measurement programme to deliver a reliable result.

An alternative approach has been put forward by Swithenbank (Swithenbank 2000), which may represent a useful way forward, especially where a distribution of times is concerned. Under this approach, the residence time is defined in terms of the system residence time, which will take into account both plug flow and stirred reactor characteristics.

For the partially stirred reactor the system residence time becomes $1-1/\log_e 10$. This means that the residence time of the system would be taken as the time when 63% of the tracer gas has left the system. This point in time can be found after integrating the time / concentration response curve. In this context, it should be noted that the problem of defining residence times has already been addressed for nuclear power plants (International Atomic Energy Agency 1996). In these cases, a centroid method has been employed, defining residence time in terms of 50% of tracer escaping the system.

3. REVIEW OF AVAILABLE TECHNIQUES

A search of available literature showed that a range of techniques could be used for verifying furnace temperatures and furnace gas residence times. The number of relevant published papers was quite small; for example, there were no measurement-based standards found. This may reflect the fact that this area has not attracted as much attention in recent years compared to that of demonstrating compliance with regulatory emission limits.

There was a wide range of practicability for the techniques and a summary is given below.

3.1. Furnace gas temperature techniques

3.1.1 Acoustic systems

Acoustic pyrometers have been commercially available for determining gas temperatures in very hot and dirty environments since the late eighties (Coe 1987) . They are non-invasive devices and have been used widely to provide a means of carrying out short or long term furnace gas temperature measurements in hot dirty flue gas environments such as cement kilns, coal fired boilers and waste incinerators. Their main advantage is that they are not susceptible to the physical degradation experienced by contact systems because they are not exposed to the very aggressive gas conditions present in furnace chambers. In addition, they are not labour intensive and can supply large amounts of data very quickly and accurately. They have a wide band of applications and have been used successfully from 30^{o}C to over 1700^{o}C.

Box C - Theory of Acoustic Pyrometers

The velocity of sound in the combustion gas mixture depends on three parameters, two of which depend on gas composition:

- The average specific heat ratio of the furnace gases, ϒ
- The average molecular weight of the gases, Mw
- The absolute temperature of the gases, T

These parameters are related to the velocity, V of the gas as follows:

$$V = [(R_0 * \Upsilon * T/ Mw)]^{0.5}$$

Where, R_0 is the universal gas constant.

If the distance travelled by the sound wave is known and the time for the sound to complete the trip is measured then the temperature is easily calculated, as long as the gas mixture remains approximately constant.

The equations governing an acoustic pyrometer are given in Box C, but simply the system operates on the principal that the velocity of sound passing through a gas is dependent on the gas temperature. A complex sound wave is emitted from a high power source (see Figure 2a), such as a compression driver, and is transmitted to a receiver (microphone) on the opposite or adjacent furnace walls. The source and receiver are located in recessed air-cooled guide pipes and are therefore not directly exposed to the full furnace temperature.

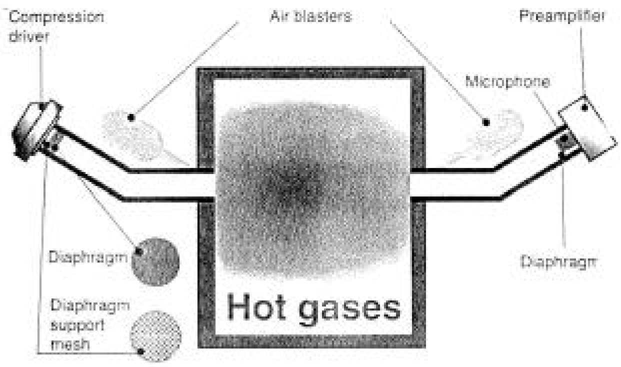


Fig 2a - Schematic Illustration of a Acoustic Pyrometer System

The emitter and receiver are controlled by a microprocessor. This scans the frequency range to select the optimal operating frequency, then sends a coded signal from the emitter and records the signal at the receiver. It uses cross correlation algorithms to check the validity of the readings. The received waveform is moved in time until it correlates with the emitted waveform (Figure 2b) and the time delay is the time of flight. Once the unit has verified that the received signal matches the emitted signal, it calculates the time of flight and derives the average temperature along the line of flight.

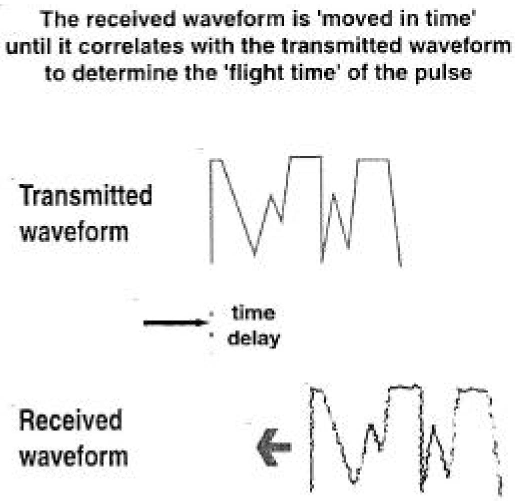


Fig 2b - Cross Correlation Technique

The technique is very useful for determining bulk mean gas temperatures, but would not normally be used to determine the temperature at a single point. However, if several devices are used, sophisticated furnace temperature profiling can be undertaken and point temperatures can be computed. A typical acoustic temperature profile across the top of the radiant shaft of an UK domestic waste incinerator can be seen in Figure 3. For this research programme (Scott and Loader 1989) two transmitters /receiver pairs were positioned in the front wall and each of the two adjacent walls. Although the temperature at the back wall was slightly over estimated (because there were no sensors in that wall), it is clear that the gas temperature falls off coming down the adjacent walls towards the front wall corners. In this experiment the balance of front and rear secondary air was carefully arranged to produce a short flame that was positioned in the centre of the shaft.

The main sources of error **(Kepple 1991)** are due to:

(i) Uncertainties in the estimates of furnace gas molecular weight, but for furnace gas of known composition this error reduces to less than 1%.

(ii) The error due to flight time through the wave-guides mounted on each side of the furnace. The relevant corrections require knowledge of the temperature of the wave-guides and the expected gradients. Extreme care must be taken to obtain a proper "end effect correction" and if carried out properly errors from this source can be contained to under ± 0.5%.

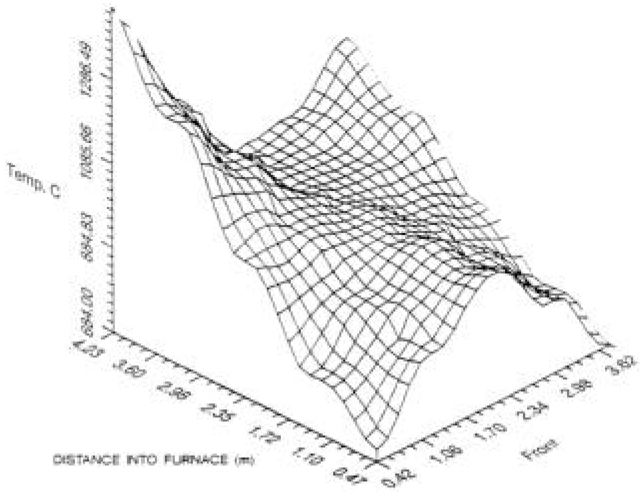


Fig 3 - Plot of Temperature Across Top of Radiant Shaft

Trials have been carried out comparing performance with suction pyrometers at waste incineration plant. These acoustic systems performed very favourably being generally within ± 1.5% of the suction pyrometer reading at temperatures around 900^{o}C (Scavuzzo 1990, Scott and Loader 1989 and Best Practice Programme Future Practice Profile). Some difficulties were found with early systems, as they were unable to provide a consistent signal over a prolonged period. These versions used spark discharge emitter units but these have now been superseded by the more reliable compression driver-types. In addition, the latest versions generate complex waveforms rather than just the simple "click" generated by the older spark discharge equipment. Early background noise problems (rumble from the burning zone) have also been overcome by use of the complex waveform and the cross correlation analysis technique (Fukayama 1996).

The equipment is relatively expensive compared to other systems and would not normally be used just for confirming minimum gas temperatures or bulk mean temperatures. Their main application is in large boiler plant where accurate high speed temperature data is required to ensure superheater tube protection from "over temperature" events.

3.1.2 Infrared pyrometers

Various types of infrared pyrometers are commercially available which have been demonstrated to be applicable for measuring gas temperatures within incinerator furnace chambers. Some are mainly used for examining temperatures close to the furnace wall, whilst others are available which can measure several meters into the furnace chamber. Some types have been widely used to provide a means of carrying out short and long term furnace gas temperature measurements in hot dirty flue gas environments.

They are non-invasive passive devices, which are not susceptible to the physical degradation experienced by contact systems. They are not labour intensive and can supply large amounts of data very accurately and quickly. For example, their time response ranges from between 1 and 10 seconds. Whilst their temperature application band ranges from 400°C to 1800°C, they perform best at gas temperatures above 800°C. Consequently, they are well suited to the range of temperatures expected in waste incineration furnaces.

Most infrared pyrometers designed for measuring gas temperatures operate on the principal of examining the infrared emission spectra of carbon dioxide (CO_2). Some use wide wave-band filters, i.e. where a range of infrared frequencies passes to the detector. Others have been developed which employ narrow wave band filters (Figure 4); these can look at a discrete CO_2 emission frequency and thereby reduce interference from other radiation sources. The pyrometers are fitted in an air or water-cooled mounting/ protection jacket fixed to the side of the furnace and view radiation from the furnace through a sighting tube located in the furnace wall.

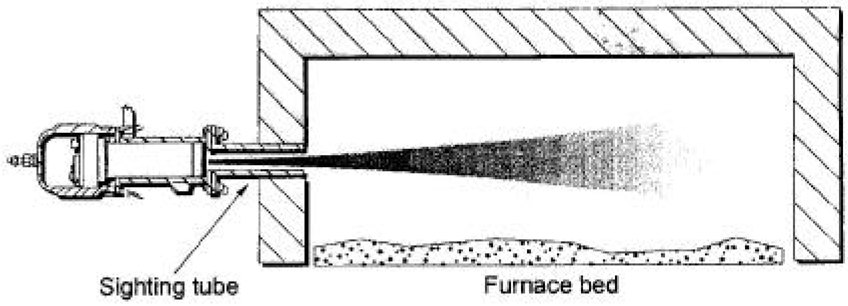


Fig 4 - Infrared Pyrometer

The average gas temperature along the line of sight is determined. If there is insufficient carbon dioxide present, or the atmosphere too cold, the sight path becomes extended and the instruments will see the "back-wall" to some degree. Consequently, there will be an under reading error (negative bias) of gas temperature. Errors are greatest for the wide wave band filters systems, and their application is therefore limited to measuring gas temperatures close to the furnace front wall.

Narrow band filter systems are less affected as they can receive radiation from at least two meters into the furnace chamber, depending on local carbon dioxide and temperature conditions. For cold, non-reflective back-walls, and CO_2 concentrations around 4%, the narrow-band systems read around 10°C low at around 1200°C for a 2 meter path length (Private Communication 2001a) . This bias increases with decreasing carbon dioxide concentration and decreasing gas temperature, so that at 900°C the bias is about -90 °C. The effect is substantially reduced at higher CO_2 concentrations. Therefore, for a more normal case of 6% CO_2 and back-wall reflectivity of 40% at 900°C, the bias is around -25°C for a 2 meter path. This increases to around -40°C for a 1 meter path.

Additional errors will arise when particles are present that have temperatures significantly different from the gas furnace temperature. If the temperature difference is less than ± 150°C, the additional error is likely to be less than 5°C at gas temperatures around 1200°C.

3.1.3 Infrared fibre optic pyrometers

Infrared pyrometers are also commercially available which utilise flexible fibre optic cables. In these systems, radiation from the furnace is collected by a fibre optic cable light guide which has the leading end of the optic bundle sited within a protection tube located in the wall of the furnace chamber. The radiation is transported along the cable to the detector, which contains a suitable wave band filter. The advantage is that the pyrometer detector and electronics can be located in a less hostile environment and access to difficult targets is made much easier.

The range of application is similar to normal infrared pyrometers, ranging from 600°C to 1600°C. Certain fibre optic pyrometers are most suitable for use in very hot dusty environments, such as incinerator furnace chambers. As with normal infrared pyrometers, response times are short. The normal commercial systems are non-invasive but their main drawback is that they do not measure gas temperature, rather they gather energy radiating from a target surface surface. In this application they would measure the temperature of the radiating particles entrained in the furnace gases and are likely to over-estimate the gas temperature

Special research fibre optic probes have also been developed which can be located within water cooled probes. These can be linked by fibre optic cable to Fourier transforming infrared spectrometers, rather than to simple band-pass filter detector systems. They are invasive devices and their applications are limited to high temperature furnace research applications. They are able to measure local flame temperatures by traversing the probe tip across the furnace shaft. The systems are not sufficiently robust for routine work, and as they are not available commercially they cannot be considered for BAT.

The accuracy for the non-invasive systems is not known, but the traversing optical fibre system has been assessed against suction pyrometers around 1100°C and found to show a slight positive bias of about 20°C (Clausen 1996).

3.1.4 Shielded thermocouples

Shielded thermocouples are commercially available and have been used for many years to measure gas temperatures within furnace chambers, including incinerator combustion chambers. They comprise two insulated metal wires with different metallic compositions held together in a flexible tube (probe). The wires are joined at the "hot" junction (the sensor) and generate a voltage proportional to the temperature of the furnace gas. Thermocouples have a wide range of temperature application, with K types spanning the 0°C to 1100 °C range and N types spanning from 200°C to 1700°C.

Their main advantages are that they are reliable, simple to use and relatively inexpensive; although those for special high temperature applications can be expensive due to the materials of construction. Thermocouples suffer from a number of serious disadvantages. Firstly, they are invasive, as the sensor must be placed within the furnace in order to measure the gas temperature. This means that the sensor would be fully exposed to the hostile environment encountered within the furnace chamber. If protective measures were not taken the probe would soon become damaged. For example, it may lose mechanical strength and droop or the electrical continuity of the circuit may be lost. Consequently, furnace thermocouple probes are normally protected by a stout ceramic (or high temperature resistant metal) shield. The use of the shield can cause a significant delay before the thermocouple can fully respond to a step change in temperature. Also, some thermocouple types can suffer from memory effects if their temperature maximum is momentarily exceeded. For example, if K types exceed 1100^{o}C they tend to over-read thereafter.

The main drawback to employing thermocouples is their characteristic temperature underestimation due to the "radiant" heat loss effect, which can become serious at furnace temperatures (see Box D). For example, in waste incinerator combustion chambers with temperatures around 850^{o}C, the bias has been shown to be about -150^{o}C compared to suction pyrometer and acoustic pyrometer systems (Scott and Loader 1989). The thermocouple actually indicates the temperature of the sensor itself, not the actual gas temperature. In attempting to measure the temperature of the gas it is necessary to give careful consideration to all the factors that may cause the indicated thermocouple temperature to differ from the actual gas temperature. Details on how to correct for the bias are given in Box D.

Workers commonly use suction pyrometers to evaluate the corrections (see below).

Box D - Correction for Bias in Thermocouples

For a steady-state energy balance on the thermocouple:

Qconv + Qrad + Qcond = 0 ------------Eq 1

Where,

- Qconv is the convective heat transfer from the gas to the thermocouple
- Qrad is the radiative heat transfer to the thermocouple (if the gas is transparent, Qrad represents the radiative energy exchange between the thermocouple and solid surfaces)
- Qcond represents the heat transfer to the hot junction by axial heat conduction along the thermocouple.

If the immersion depth of the hot junction is sufficiently large compared to the diameter, then Qcond can be neglected and Eq 1 simplifies to:

Qconv + Q rad = 0 -------------------------Eq 2

Many furnace situations involve extremely hot gases but the furnace walls are often water-cooled and are therefore much cooler than the gas. Therefore, Qrad will be negative, meaning that the thermocouple is losing energy by radiation to the cooler walls. The steady state energy balance then requires Qconv to be positive to balance this radiative heat loss. For Qconv to be positive, the thermocouple must be cooler than the surrounding gases and thus the thermocouple will indicate a temperature which is lower than the true gas temperature. Qrad and Qconv can be evaluated (**Zikratov 1999**) using the Equations 3 and 4 and corrections applied to yield the true gas temperature:

$$Qrad = \sigma A Э (T_w^4 - T_t^4) \text{ ---------------- Eq 3}$$

$$Qconv = hA(T_g - T_t) \text{ ------------------- Eq 4}$$

Where,

σ is the Stefan-Boltzmann constant; A is the surface area of the thermocouple

э is the effective graybody emissivity of the thermocouple

T_t is the actual temperature of the thermocouple

T_g is the measured gas temperature

h is the convective heat transfer coefficient

Thermocouples can also be affected if the sensor "sees" radiation from the flame. This would lead to a positive bias. It is normally overcome by shielding and positioning the thermocouple well away from the flame. In the case of proving furnace gas temperatures at the end of the combustion zone, the magnitude of this item is likely to be small in comparison to the radiant heat loss affect.

Although they can only measure the temperature at the point where the sensor is located, it is a simple matter to obtain traverse information by moving the probe slowly across the furnace. Information using one probe can only be obtained sequentially but as the system is inexpensive it is common practice to locate several thermocouples within a furnace chamber. If these are located at various positions through the furnace then at least an estimate of both the "bulk mean" gas temperature and the minimum furnace temperature can be obtained.

3.1.5 Suction pyrometers

Suction pyrometers (or high velocity thermocouples) are commercially available and have long been used to yield accurate gas temperatures within furnace chambers (including incinerators). They are often employed to calibrate or validate other types of temperature measurement systems. The pyrometer contains small diameter thermocouple wires linked to an electronic thermometer (Figure 5). The thermocouple is surrounded by a protective metal probe tube and the hot junction (sensor) is placed at the location where the measurements are to be taken.

Suction pyrometers can completely overcome the temperature under-reading difficulties associated with normal thermocouples. This is achieved by first surrounding the sensor with a series of ceramic shields, which isolates the thermocouple from the surrounding radiation. A known volume flow rate of flue gas is drawn into the probe and pulled over the shields containing the thermocouple. By maintaining a high rate of flow over the shields, the transfer of heat to the sensor due to convection increases while the losses due to radiation are minimised. Small diameter thermocouple wires (approximately 0.25mm) are needed to negate conductive heat losses. Therefore, the temperature of the thermocouple "hot" junction may be brought into equilibrium with the local true flue gas temperature.

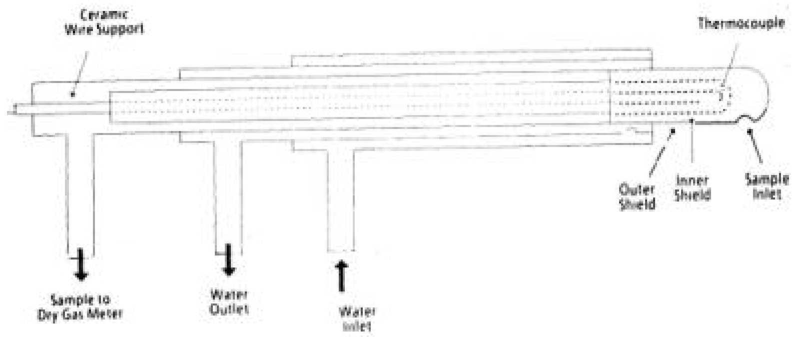


Fig 5 A Suction Pyrometer

The temperature reading of a suction pyrometer system increases with increasing gas mass velocity flowing between the inner and outer shields. It is important when using these pyrometers to ensure that an adequate mass velocity is maintained. It is therefore necessary to develop an "efficiency" curve similar to that shown in Figure 6 for each individual suction pyrometer design. This is accomplished by sampling at a low mass flow (approximately 10% of the pyrometers capacity) and recording the corresponding temperature. The gas mass velocity is then increased and a new temperature is recorded. Eventually, the temperature will reach a plateau (equilibrium). This temperature is the true temperature of the sampled gas stream and the mass velocity measured at this point is the minimum flow rate that must be pulled for that pyrometer design to measure the true gas temperature.

It is recommended that the gas mass velocity between the shields is not less than 1.2 kg. m^{-2} s^{-1} **(Private Communication 2001b and Rakes 1985).**

The suction pyrometer has a wide field of temperature application (0^oC to 1700^oC) depending on the choice of thermocouple and probe materials employed. For higher temperature work, it is normal to cool the probe by water cooling to maintain the mechanical strength of the probe material. Air-cooling is also possible.

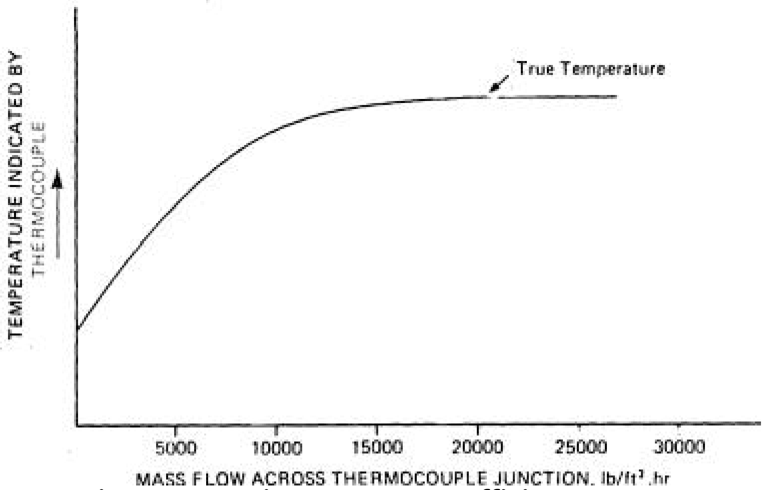


Figure 6 Suction Pyrometer Efficiency Curve

The main advantage of the system is its high accuracy and reliability. It also responds much faster than the normal shielded thermocouple system.

The system has several disadvantages. Firstly, it is an invasive technique, as the sensor must be placed within the furnace in order to measure the gas temperature. Secondly, it requires manual attendance and, in addition, the commercial systems are heavy and cumbersome. This is mainly due to the presence of the water-cooling jacket and because probes tend to be purchased in lengths long enough to cover various furnace chamber dimensions. The large mass is a major drawback when the system needs to be moved from one line to another, especially if work at different heights is involved. Another disadvantage is that the probe can quickly become clogged in the dust-laden environment found within incinerator furnace chambers and consequently sampling times in an incinerator combustion chamber would need to be limited to 15 minute increments.

Although the commercial systems are cumbersome, the technology involved is not sophisticated and therefore many workers tend to construct their own lighter probes.

Although suction pyrometers can only measure the temperature at the point where the sensor is located, it is a simple matter to obtain traverse information by moving the probe slowly across the furnace. Multi-point data from one probe can only be obtained sequentially, but if simultaneous information is required at several points the suction pyrometer could be used to calibrate several shielded thermocouples at various positions. In this way, "bulk mean" gas temperature, minimum furnace temperature and even profiles can be obtained.

3.1.6 Heat balance methods

It is possible to calculate combustion chamber gas temperatures by performing a mass and energy balance around the combustion chamber and by employing fundamental combustion calculations. Unfortunately, the detailed physical, chemical and thermodynamic data needed for each of the feed streams, effluents and combustion gases are often not readily available. Furthermore, a rigorous mass and energy balance calculation can be time-consuming unless a computerised routine is available. Consequently, a compromise approach is normally employed which uses a combination of known and "best estimate" information.

An iterative computer programme is normally used and estimates or actual data for input parameters are required. The calculation splits down into the following input components:

- Feed Chemical Compositional Data, i.e. Support Fuel and Waste Feed (approximate analysis for hydrogen, carbon, nitrogen, oxygen and sulphur contents)

- Support Fuel and Waste Feed Net Calorific Values

- Flue Gas Data (excess air, and flue gas composition worked from feed compositional data for O_2, CO_2, N_2, SO_2 and H_2O)

- Fuel / Waste Heat Release Rate

- Details of the Radiant Section Heat Transfer Data are required along with the target outlet temperature.

As all the heat from the fuel is released into the incinerator furnace chamber then the enthalpy of the resulting combustion gases can be computed. The adiabatic flame temperature can now be calculated along with the radiant temperature. The full adiabatic flame temperature is unlikely to be developed, especially if furnace chamber heat recovery is employed (e.g. water walls). The radiant temperature is considerably lower temperature and gives a reasonable estimate of the bulk mean gas temperature. However, experienced measurement teams can often produce just as good an estimate based on previous experience of similar combustion processes.

The approach has the advantage that it is comparatively cheap compared to other methods, especially if the inputs are based on estimates. Although it is good enough for providing reasonable estimates for furnace gas mean bulk gas temperature, it is not sufficiently accurate for predicting minimum gas temperatures at the end of the 2 second zone.

3.1.7 Comparison of Furnace Gas Measurement Techniques

A comparison of the above furnace gas measurement techniques is given in Table 1 with summary comments on key aspects of their performance characteristics.

Table 1 Comparison of Gas Temperature Measurement Systems

Methods	Measures	Response Time	Equipment	Suitable for Measuring: Point	Suitable for Measuring: Bulk Mean	Comments
Acoustic Pyrometry	Average over path	Instantaneous, continuous	Non-intrusive, permanent	Yes[1]	Yes	Good accuracy
Optical and Radiation Pyrometry	Average over path	Instantaneous, continuous	Viewing point	Yes[2]	Yes	Can suffer from "cold wall" and particle effects
Shielded Thermocouples	Gas temperature at point	Delayed response but can operate continuously	Permanent	Yes	Yes[3]	Considerable negative bias. Can droop if orientated horizontally
Suction Pyrometers	Gas temperature at point	Instantaneous, periodically	Special probe for periodic working only	Yes	Yes[3]	Very accurate but needs manual attendance. Can be cumbersome
Heat Balance	Estimate of bulk mean gas temperature	Requires computations	Off-line, based on knowledge of operating parameters	No	Yes	Estimate only, but acceptable for bulk mean temperature estimation.

Notes:
1. Can only deliver point data if several arrays are installed.
2. Only some systems can be focused.
3. Can deliver profile information only if several probes are used or traversing is undertaken.

3.2. Furnace as residence time assessment

3.2.1 Mean gas flow rate methods (assuming plug flow)

Furnace gas residence times have traditionally been assessed in incinerators using design or measured data that assume no mixing (i.e. plug flow). The main advantage is that these methods are relatively simple to use, and since plug flow is assumed, the mean and minimum gas residence times can be taken as being identical. The residence time is simply the quotient of the total available **qualifying** geometric volume, Vqscz (m^3) within the qualifying secondary combustion zone and the average gas flow rate, Q (in m^3/s) through the zone at the **actual** mean gas temperature conditions pertaining in the zone.

i.e., Gas residence time = Vqscz/ Q (seconds)

An explanation as to what volume of the combustion chamber should be counted as qualifying for the residence time calculation, and where datums should start and end, is discussed in Section 4.2.2.

3.2.1.1 Calculating residence time using design data

(i) A simple design approach - BS 3316

The simplest design based calculation is that given in **BS 3316:Part 2 (BS 3316:1987) .** This allows manufacturer's stated design data (for mean gas flow rate, temperature and geometric chamber volume) to be used, and no measurements are required. This information is secured from elementary combustion and heat transfer calculations. Although, the method is simple it contains several assumptions, which can lead to serious over-estimation of the gas residence time.

For example, any local variations in gas velocity caused by recirculation (Figure 7), dead space or high velocity (channelling) areas are not taken into account. Also, there is no consideration given to variations of gas flow with time due to changing combustion rates or excess air levels. Operators merely assume that the stated design gas flow rate gives a true estimate of the mean gas flow rate and therefore the mean gas residence time. Consequently, minimum gas residence time will be over-estimated if high velocities are present in some portions of the combustion chamber, or if gas flow increases as combustion progresses, or if excess air levels rise.

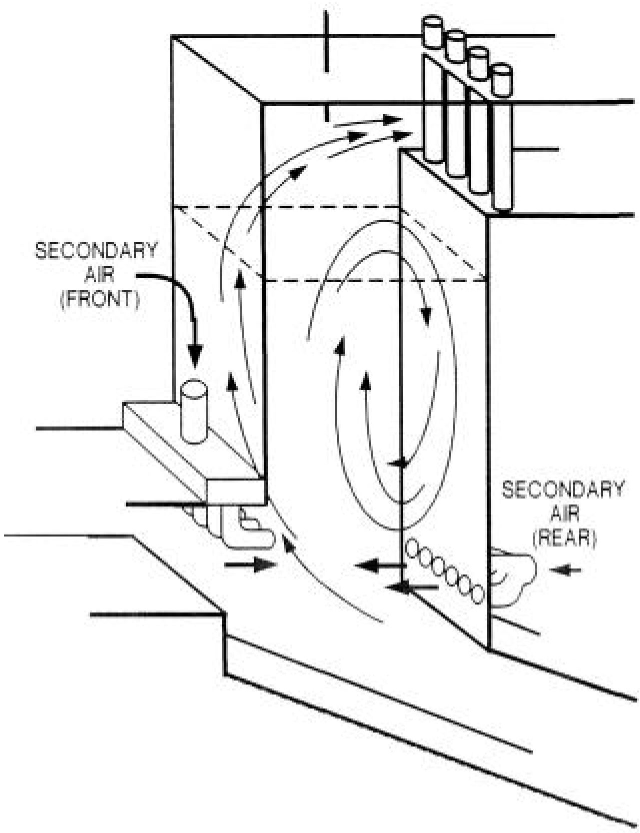


Fig 7 - Likely Flow Pattern Showing Channelling and Re-Circulation

BS 3316 residence time calculation starts with the stated design gas flow rate at the design outlet gas temperature but the procedure allows normalisation to the specified minimum temperature requirement, (for example, 800°C, 850°C or 1100°C etc). If the outlet gas temperature exceeds the specified minimum, normalisation will reduce the computed mean gas flow rate and thereby artificially raise the calculated minimum residence time above the actual value. The use of the outlet design temperature, rather than the bulk mean design temperature, will help to compensate for this factor.

This simplistic design approach can easily result in the computed minimum residence time being over-stated by up to 50% with respect to the measured value. The effect is most noticeable for batch feeding of heterogeneous solid waste materials. For example, Figure 8 shows measured gas residence time profiles (measurements based monitoring gas flow and assuming plug flow) for two identical batch incinerators. These both had design residence times of 3.0 seconds. The measured hourly means are both around 2.5 seconds, whilst the lowest 1 minute values are close to 2.0 seconds. Consequently, if the designs were based on 2 seconds the measured residence times would be below the design value for considerable periods during the firing cycle. Clearly, if this plug flow design approach were to be allowed then some considerable allowance for headroom would be required when setting minimum gas residence time criteria.

The errors with this simple design approach could be reduced in several ways. Firstly, design gas flow-rates and temperatures could be replaced by continuously measured data. This could be gathered over a 1 hour period and computed to show 1 minute residence time information. Secondly, the measurements could be made throughout a series of different burn cycles to give worst case. In addition, no gas volume flow rate correction should be applied for gas temperatures above the set minima, as this will artificially inflate the computed residence time.

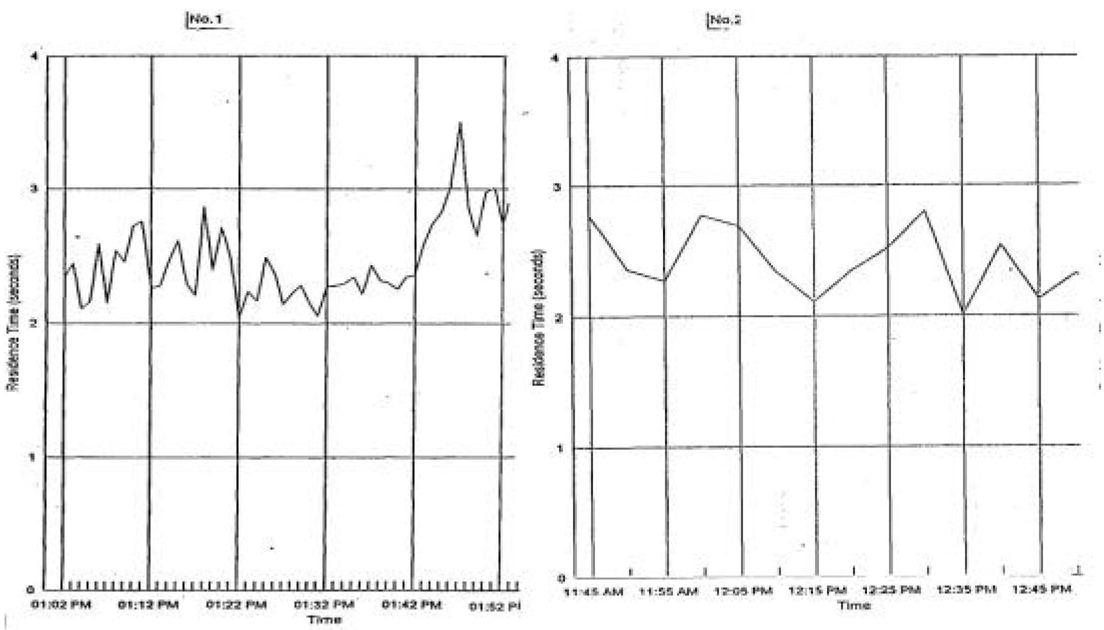


Fig 8 - Gas Flow Rate Flow Measured Residence Times in Two Batch Incinerators

(ii) More comprehensive and complex design approach

More comprehensive design procedures are available which can be used to generate theoretical residence time / temperature curves **(Scavuzzo 1990)** throughout the various zones (Figure 9) of a combustion chamber. This can provide the design engineer with a method for evaluating the gas phase combustion performance of a particular design throughout the whole furnace, and can look at the effect of intended waste throughput rates. The simultaneous liberation of heat from combustion and the absorption of heat by the furnace walls can be taken into account. The effects of conduction, convection and radiation heat transfer to bare furnace refractory or water walls, together with the energy associated with combustion gas mass flow, can be used to predict the temperature and location of a furnace gas control volume at any given time.

A computer model is used to calculate the temperature, quantity and composition of gas entering or leaving each zone, for a given waste analysis and set excess air value. Plug flow is assumed to simplify the model, therefore gas temperature and flow are taken as being evenly distributed at each zone boundary. The theoretical volumetric gas flow rate for each zone is determined from gas mass flow and density at the average temperature. Finally, the zone residence time is calculated by dividing the zone volume by the volumetric gas flow rate. If several zones are being examined, the cumulative residence time is the sum of the residence times for the preceding zones.

The results of such design approaches have been compared with measurement studies for several large waste to energy plant **(Scavuzzo 1990)** and reasonable agreement was found over most operating ranges.

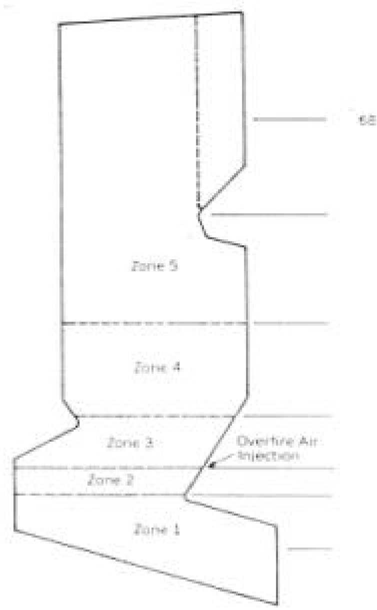


Fig 9 - Typical Zones of a Combustion Chamber (Energy from Waste Incinerator)

3.2.1.2 Simple measurement of gas residence time

The literature search did not reveal any standard methods for measuring gas residence times in waste incinerators, but there are at least three simple approaches that measure mean gas flow rate and assume plug flow. The first, see (i) below, uses a mixture of design (or estimated) furnace data and measured stack parameters. The other two are variations of this method, but utilise increasing amounts of measured data. As plug flow is assumed, the mean and minimum gas residence times are again taken as being identical. It is recommended that the approaches (outlined in (ii) and (iii) below) should be used as the basis for proving gas residence time in existing UK plant.

(i) Residence time based on design furnace data and measured stack data

The first approach described by **Eicher (Eicher 2000)** involves a mixture of calculations employing both design and measured data. The combustion gas flow rate through the qualifying zone (and the gas phase residence time) can be calculated. Standard thermodynamic reference tables and combustion chamber drawings are required, together with measured stack gas and combustion chamber bulk mean temperatures data. The technique is applicable to systems that incorporate adiabatic saturation cooling of the flue gas using direct water evaporation in a quench chamber or similar device. It can be extended to systems where adiabatic saturation cooling is not achieved (i.e. partial quenching) or where systems incorporate external heat removal (i.e. boilers, indirect scrubber water cooling, etc.).

The method relies on the assumption that the mass flow rate of dry stack gas is equal to the mass flow rate of dry combustion gas passing through the secondary combustion zone. It also assumes that the total combustion gas mass flow rate is equal to the sum of the dry gas mass flow rate plus the mass flow rate of water vapour in the combustion gas. It does not assume that the water vapour content of the combustion gas and the stack gas are the same.

The average dry stack gas volume flow rate is measured, along with the average stack gas temperature, moisture content, composition and dry molecular weight. The standard methods employed for these tasks are US EPA Methods 2, 3 and 4, but the relevant ISO, CEN or BSI methods could also be utilised. The mean bulk combustion gas temperature is also measured over the same period (e.g. by using a suction pyrometer).

The dry stack gas mass flow rate is calculated from the measured stack gas volume flow rate, at standard conditions. The total (wet) and dry stack gas enthalpies are determined from the measured mass flow, composition data and heat capacities (taken from the tables). Since the mass of dry stack gas is equal to the mass of dry combustion gas, the enthalpy of the dry combustion gas can be determined from the flow rate of dry stack gas and the measured temperature differences of bulk mean combustion chamber gas and stack gas.

Since the total enthalpy of the combustion gas is equal to the total enthalpy of the stack gas, then the difference between the calculated dry combustion gas enthalpy and the calculated total stack gas enthalpy must be attributed to water vapour in the combustion chamber gas. Thus, the amount of water vapour in the combustion gas can be found, see Box E

BOX E: Combustion Chamber Water Vapour Calculation

$m_w = H_w/h_{wc}$

Where:

m_w = Mass flow of water vapour in combustion gas

h_{wc} = Unit enthalpy of water vapour (superheated steam) at bulk combustion gas temperature

H_w = Enthalpy of water vapour in combustion gas

and, $H_w = H_{st} - H_{cd}$

Where:

H_{st} = Enthalpy of wet stack gas

H_{cd} = Enthalpy of dry combustion stack gas

The total (wet) volumetric flow rate of the combustion gas at normal conditions can now be determined from the measured dry stack gas flow at normal conditions, after applying a correction for the computed moisture content of the combustion gas. The total volumetric flow rate of combustion gas at combustion chamber conditions is calculated by correcting for the measured combustion chamber and stack gas temperature and pressure etc.

Finally, the combustion chamber gas residence time (RT) can be determined as follows:

RT= Vqscz*3600/Q

Where:

Vqscz = Available and qualifying geometric volume of the combustion zone, in m^3, taken from drawings. This is explained later in Section 4.2.2.

Q = Total combustion gas volumetric flow rate at combustion chamber conditions (m^3/h).

This method contains several errors that could lead to an underestimation of residence time. For example, only one feed condition is examined, whereas several should be looked at. Also, only the average stack velocity is measured. In addition, the method assumes there is no significant ingress of air between the furnace chamber and the stack. Whilst this is correct for many installations it is not true for others and serious error can result.

Also, there is also an assumption that any gaseous component removal between the furnace and the stack is not significant. Whilst this may be true in most cases, if hazardous waste is being burned, the hydrogen chloride level in the furnace gases may be very different from that in the stack due to the acid gas scrubber. Therefore, if the unabated hydrogen chloride level is likely to be greater than 5000 ppm, then its concentration in the furnace exit gases should be measured (or estimated) to enable a correction to be applied.

Only the bulk mean combustion gas temperature has been measured and the assumption is that this is the same as the gas temperature at the end of the two second residence time zone. This may not be correct and additional temperature measurement at this location will be required to confirm the actual end of zone temperature.

(ii) Residence Time Based on Measured Combustion Air Flow Rates and Furnace Temperatures

This measurement based approach has been commonly used in the U.K. on large mass burn waste to energy facilities **(Private Communication 1996a)**. Again, it assumes plug flow. The additional measurement features are included to try and reduce the error associated with the approach mentioned in (i) above.

The temperatures, pressures and flow rates of all the various combustion air supplies to the combustion chamber are continuously measured under a range of firing conditions. This data is used to deduce Q, (the total combustion gas volumetric flow rate at combustion chamber conditions. The installed plant flow meters and thermocouples are sometimes employed when the are linked to a data collection system (DCS). Alternatively, contractors tend to use pitot tubes and portable thermometers linked to a data logger. In this way, the dry gas flow rate of the combustion gases can be measured directly, without any need to carry out stack measurements. However, the moisture content of the combustion gases needs to be measured at the outlet from the secondary combustion zone and a correction factor applied.

The temperature and pressure of the combustion gas is measured and logged over a range of firing conditions. The bulk mean temperature is determined by monitoring furnace gas temperatures in the middle of the secondary combustion zone. Additional temperature measurements are also taken at the end of the secondary combustion zone, at a location that is at least 25% beyond the two second residence position (based on design calculations). If practicable, additional gas temperature measurements are taken about 0.5 to 1 meter beyond the last injection of secondary air so as to improve the estimate of the bulk mean gas temperature. The best estimate of the bulk mean gas temperature is used with furnace pressure data to calculate the total combustion gas volumetric flow rate at combustion chamber conditions.

Again plant drawings are employed to determine the available geometric volume of the qualifying combustion zone (Vqscz), in m^3. As before, the gas residence time, RT= Vqscz*3600/Q seconds.

The approach has a number of advantages. Firstly, the use of continuous measurement and logging of air flows means that 1 minute gas residence time data can be obtained over any chosen firing cycle. Therefore, a better estimate of the worst case can be obtained. However, as the plug flow model is used it is merely assumes that the measured 1 minutes are identical to the real situation minimum gas residence time. This is not correct because in the real situation (a partially stirred reactor) the true minimum could be considerably shorter.

The approach is very useful for municipal solid waste, where tests (**Private Communication 1996b**) have shown close agreement (± 10%) between combustion air deduced flow rates and those deduced from measured stack or boiler outlet gas flows. However, it is not suitable for all wastes. In addition, considerable error can be introduced under high draught conditions if any unmetered air enters the combustion chamber.

(iii) Residence Time Based on Measured Furnace Chamber Data and Measured Stack or Boiler Outlet Data

The third approach has been used on a wider range of incinerator facilities in the UK **(Private Communications 1996a and 1996b)**. Continuous measurements are taken of stack flue gas temperature, pressure, flow-rate, oxygen and / or carbon dioxide contents during a test firing (Figure 10). The same parameters can instead be measured in the boiler outlet duct (if a boiler is fitted) and if the velocity profile across the duct is acceptable. Stack or boiler outlet flue gas moisture content is also periodically determined by manual methods to yield gas composition and density data. As before, periodic measurements are made of the furnace gas moisture content at the outlet from the secondary combustion zone.

If gas flow rate monitoring takes place in the stack (i.e. after the air pollution control equipment), then simultaneous measurements of the carbon dioxide and / or oxygen contents of the secondary combustion zone outlet gases are also required to correct for any air ingress.

As before, furnace pressure and bulk mean furnace gas temperature are determined and logged. Temperature measurement data are also logged at the end of the secondary combustion zone at a location that is at least 25% beyond the design two second residence position.

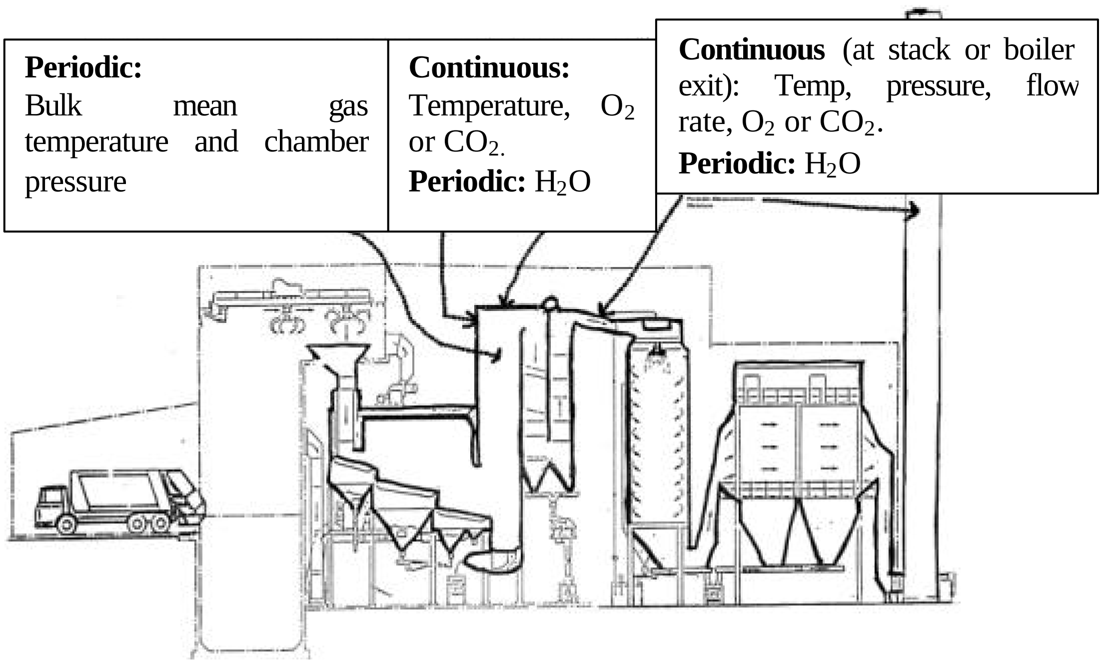


Figure 10 - Measuring Points (Based on Stack Flow Rate Methods)

Again, a range of firing conditions is examined and the measured data used to deduce the total combustion gas flow, Q, at furnace conditions. If installed, plant sensors (venturis and thermocouples) can be used to measure duct gas flow and temperature.

Again plant drawings are employed to determine the available geometric volume of the combustion zone and the gas residence time is computed as described previously.

This method retains many of the advantages of the second approach, including securing a better estimate of the worst case scenario due to the on-line profiling of residence time over any chosen firing cycle. It works well for any waste stream and is not affected by air ingress effects as these are taken into account by the continuous oxygen and /or carbon dioxide monitoring at the two locations.

There is still an assumption that any gaseous component removal between the furnace chamber and the stack is not significant. Consequently, if hazardous waste incineration is being examined (where chlorine levels normally exceed 1% by mass), then corrections may need to be applied for the differing hydrogen chloride concentrations pre and post abatement. Therefore, if the unabated hydrogen chloride level is likely to be greater than 5000 ppm, its concentration in the furnace exit gases should be measured (or estimated) to enable a correction to be applied.

3.2.2 Time Domain Methods (Assuming Partially Stirred Reactor Models)

Techniques also exist whereby the partially stirred (or real flow) reactor model can be used to predict or measure furnace gas residence times in waste incinerators. They are more complex and more difficult to use than those based on plug flow. The determinations of residence times in these cases are based on time domain methods, which can be predictive methods (using models), or they can be measurement based. The mean and minimum gas residence times are now different, but as the time domain methods are designed to provide the gas residence time distribution, both the minimum and mean can be obtained. Again no standard methods exist. The design and measurement methods are based on predicting or measuring the distribution of the times of flight of injected impulses (real or virtual) between two points (or planes). Therefore, the predicted or real mean bulk gas temperature is not required but the temperature at the end of the qualifying zone still needs to be demonstrated.

3.2.2.1 Prediction of Gas Residence Time Using Time Domain Models

Computational fluid dynamic (CFD) packages are now available which can be used to mathematically model and predict gas residence time distributions within almost any incinerator combustion chamber. Simultaneous studies were carried out a large mass burn waste to energy facility in the UK using a CFDCFD model and an injected impulse time of flight measurement technique (**Nasserzadeth 1995 and Loader 1993**). These showed good agreement; for example, the CFD predicted minimum residence time of 0.9 seconds and the peak of 1.1 seconds (Figure 11) were in good agreement with the measured time of flight data (0.8 and 1.3 seconds respectively).

It is now suggested (Swithenbank 2000) that it is more correct to interpret the data presented in Figure 11 in terms of the system residence time rather than minimums, means and peaks etc. If the curve is integrated and normalised the system residence time can be found. This takes both plug and stirred characteristics into account, and as explained in Section 2.3.4 this point occurs when 67% of the tracer has left the system. In this case, the CFD model predicted a system residence time of 1.2 seconds whilst the measured time of flight experiment gave 1.3 seconds, (ie 60% and 65% respectively of the designed 2.0 seconds residence time based on the BS 3316 approach).

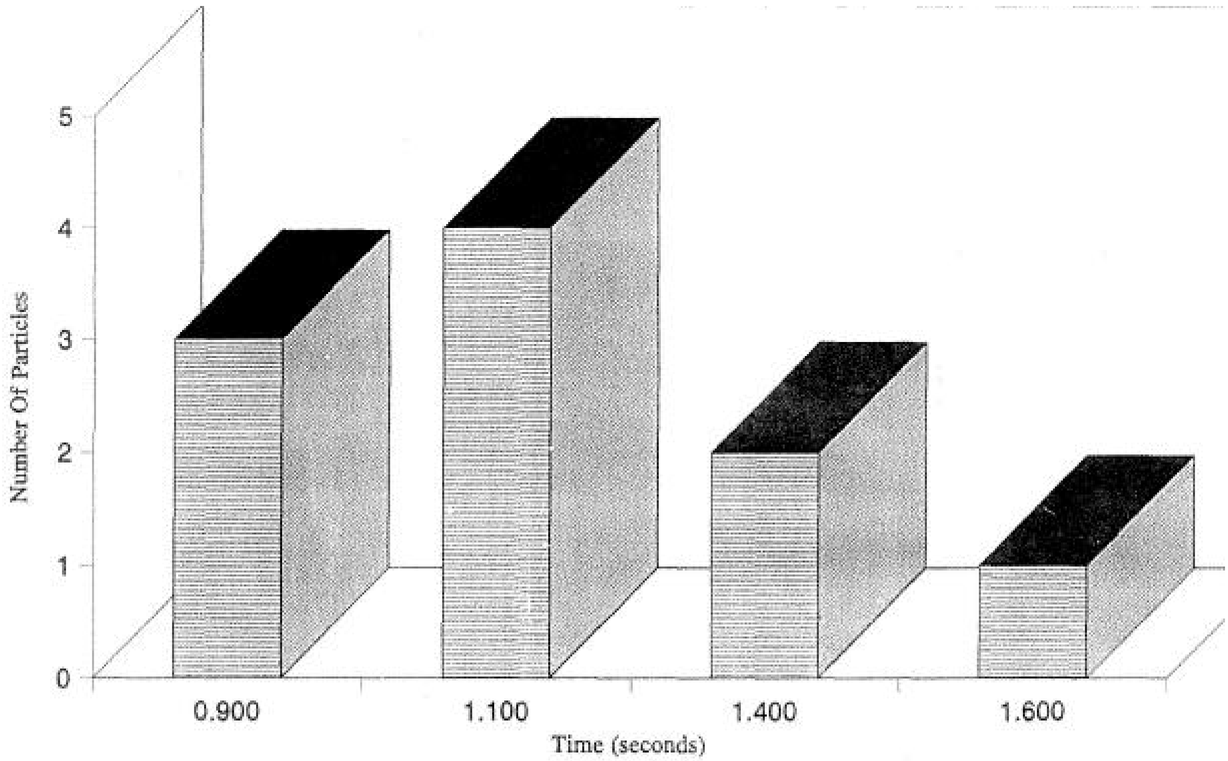


Fig 11- Histogram of Gas Residence Times Injection Point: Front Secondary Air

It should be realised that the good agreement between the two techniques was only achieved by **substantial** preliminary measurement support being provided to ensure that the CFD inputs were realistic. Consequently, CFD models should not in themselves be taken as confirmation of residence times. Although in agreement, these data are considerably shorter than the theoretical value of 2 seconds calculated for this facility on the basis of measured furnace volume, design gas flow rate and temperature data and assuming plug flow.

Provided the correct input information is supplied the CFD technique offers a very powerful design tool. For example, given the appropriate modelling, along with suitable boundary conditions, CFD codes can provide numerical results for gas velocity, temperature, and species concentration within the furnace chamber. The chosen key furnace parameters are modelled in slices. The gas flow, temperature, and gas composition distributions obtained can provide important information that can be used qualitatively to assess and improve the design and performance of the incinerator such that Good Combustion Practice (GCP) is satisfied. For example, local areas with almost no flow, (dead zones), recirculation zones, or channels of accelerated flow, can all be revealed and steps taken to optimise furnace flow profile.

Through extensive evaluations of computed flow performance of incinerators it has been concluded that the flow pattern is strongly affected by two major parameters: geometric shape and operational modes. CFD enables designers to deduce optimal shape for new installations and the operational strategies (combustion air injection patterns) required to optimise furnace gas flow and temperature profiles for new and existing plant (**Swithenbank, 1995 and Donghoon S. 1998**).

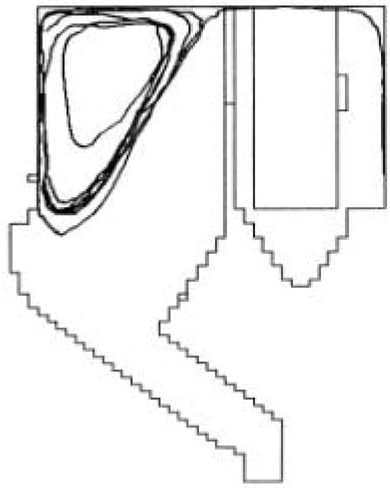


Figure 12 - Predicted CFD Particle Trajectories Injection in Front Secondary Air Tubes

The predicted residence time distribution in any zone can be obtained by injecting a large series of virtual particles into the mathematical model. In the case of the UK plant simultaneously studied by Nasserzadeth and Loader particles were introduced into the model just after the last injection of secondary air and their paths and flight times traced until they reach the end of the zone (Figure 12). The model can also incorporate a facility for predicting gas temperatures throughout the combustion chamber and therefore the predicted gas residence time distribution at temperature can be produced. For the large mass burn vertical shaft plant examined by Donghoon (Donghoon 1998) it is interesting to note that the design mean gas residence time criteria of 2.7 seconds was not satisfied, even after optimisation of the secondary air injection (Figure 13). For Case 1, before optimisation, 60% of the gas flow escapes the secondary combustion zone before 2 seconds. After optimisation, (Case 2), only 23% escapes after 2 seconds and 60% remains for at least 2.7 seconds.

Although the second case shows a clear improvement, it appears that for both cases a significant portion of the furnace gases will have a minimum gas residence well below 2 seconds. Consequently, it would suggest that if incinerators were to be tested on the basis of minimum gas residence time then most upgraded and, many new plant, w would fail. If, on the other hand, residence time were to be viewed in terms of the system, ie when 67% of the tracer has left the secondary combustion zone, the outlook is much more encouraging. For the optimised Case 2 the system residence time is about 2.9 seconds, whilst for Case 1 it is about 2.1 seconds.

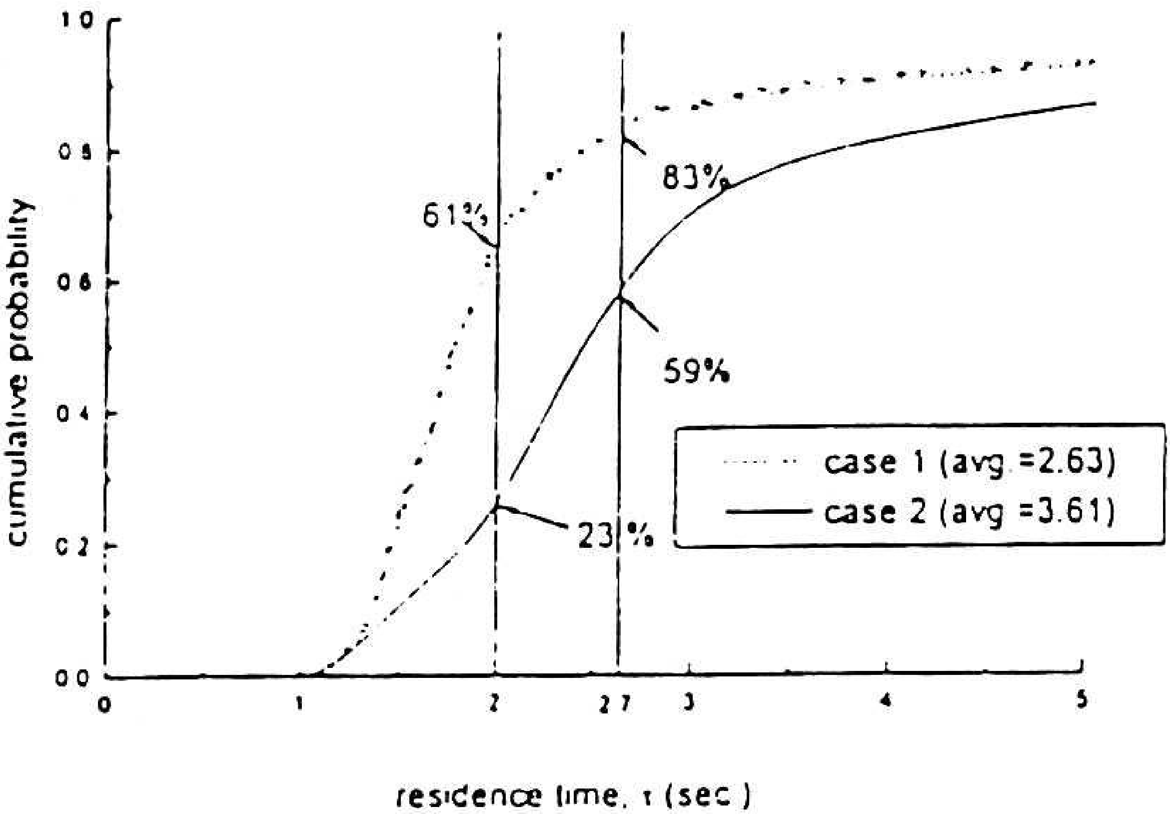


Fig 13 - Cumulative Probability Distribution Of The Residence Time At The Chamber Exit

3.2.2.2 Measurement of Gas Residence Time Using Time Domain Methods (Injected Pulses or Steps)

Time domain methods involve the injection of a tracer gas pulse or step. Radioactive argon, sulphur compounds, mercury vapour or helium tracers have all been used in incinerator residence time measurement studies with the injections into the combustion chambers being made as close as practicably possible to the last injection of secondary air. The time of flight through the secondary combustion zone is measured by analysing the concentration of the gas at the exit as a function of time. Several of the methods have been employed at waste incinerators but with varying success. Both step-response and pulse response approaches have been used.

The injection system requires a microprocessor control to mark the injection datum time on the concentration / time output response of the detection system. The use of both cross-stack and extractive detection systems has been investigated.

There are several common drawbacks associated with these methods. In the presence of signal noise either the input disturbance signal must be so large that the normal operation of the incinerator is affected, or the measurement time must be so long that process changes have a significant effect on the measured concentration.

Some methods have been more successful than others and a summary of their performance characteristics is given below:

(i) Radioactive Argon Gas Pulse Injection

This was developed by Kolar (**REF 25 1987**) and involved the introduced a short pulse of Argon[41] radioactive tracer gas into one of the secondary air injection tubes of a fluidised bubbling bed combustor.

The method gave good reproducibility for the mean residence time but a poor performance for measuring the residence time distribution. The main drawback for using this method is the associated health and safety issues as well as the emotive environmental questions surrounding the release of radioactive materials to the environment.

(ii) Injections of Gaseous Sulphur Compounds

Injections of either sulphur hexafluoride (SF_6) or sulphur dioxide (SO_2) have been employed for the measurement of incinerator gas residence times. Residence time measurements were made by Warren Spring Laboratory at a large UK mass burn facility using SF_6 (Loader 1991). Injection of SF_6 was achieved through one of the side walls of the vertical radiant shaft at the same elevation as the front secondary air nozzles. An alternative injection point was into one of the secondary air delivery tubes, ie.by passing the injector probe through the secondary air manifold duct. The gas delivery system was made from a pressurised cannon discharger of the type used in industry to clear blockages in storage hoppers. Detection was for the SF_6 oxidation derivative SO_2; this was accomplished using a fast response infrared cross-duct detector placed at the furnace outlet.

A number of problems resulted in poor response for the residence time distribution. Firstly, as the detected response was for SO_2 a relatively large pulse (20 litres at 5 bar) had to be injected to overcome the significant and varying background SO_2 concentration naturally occurring in the incinerator flue gases. Secondly, the pulse had to be delivered in a very short time (less than 0.1 seconds). In addition, there was substantial signal noise when the detector was placed immediately following the outlet from the radiant furnace shaft. This was probably due to interfering radiation emitted from high temperature particles in the flue gases.

Secondly, the need to deliver a relatively high gas volume in such a short time resulted in a disturbance of the furnace conditions (over-pressurisation). Consequently, some of the injected sample must have been forced downwards, towards the primary combustion section. In the case of injection into a secondary air delivery tube, a significant portion of the charge "spilled-back" into the secondary air combined manifold system and eventually found its way into the secondary combustion chamber sometime later.

All these effects meant that the residence time distribution became spread much wider than expected and probably did not reflect the true situation.

Modifications were introduced in an attempt to improve response. The temperature of the infra-red source was raised and the detector modified so that the absorption signal could be compared with a reference wavelength further away from the detection wavelength. The detector was also moved behind the first bank of super heater tubes to reduce noise due to the radiating particles. Although there was a marked improvement in signal the moving of the detector meant that the minimum and mean gas residence time could not now be detected directly from the detector response. Corrections had to be applied taking into account the displacement of the detector and these were greatly affected by the gas flow profile through the tube package. Consequently, the uncertainties in deducing the residence times became very large.

Although this technique is simple to use and shows promise, it clearly requires considerable development work before it can be considered as an available and reliable technique.

(iii) Helium Injections

Warren Spring Laboratory also carried out a gas residence time measurement programme on the same mass burn facility using a helium tracer gas injection technique (Loader 1993). The technique was a modification of that developed by Jager (Jager 1987).

The injection was delivered into one of the front secondary air tubes (Figure 14) using a 0.1 second pulse, and this was repeated 20 times for each test condition. Background helium levels were less than 10ppm and consequently a low injection flow rate (about 20 litres per second) was employed to give a resulting average helium concentration of around 1000ppm. The low flow delivery rate meant that a thin flexible helium delivery tube could be inserted deep inside the secondary air tube, almost all the way to the nozzle. Consequently, problems with "spill-back" into the air manifold chamber were avoided. Calculations were made of the affects of molecular diffusion and low gas density and were found not to be important.

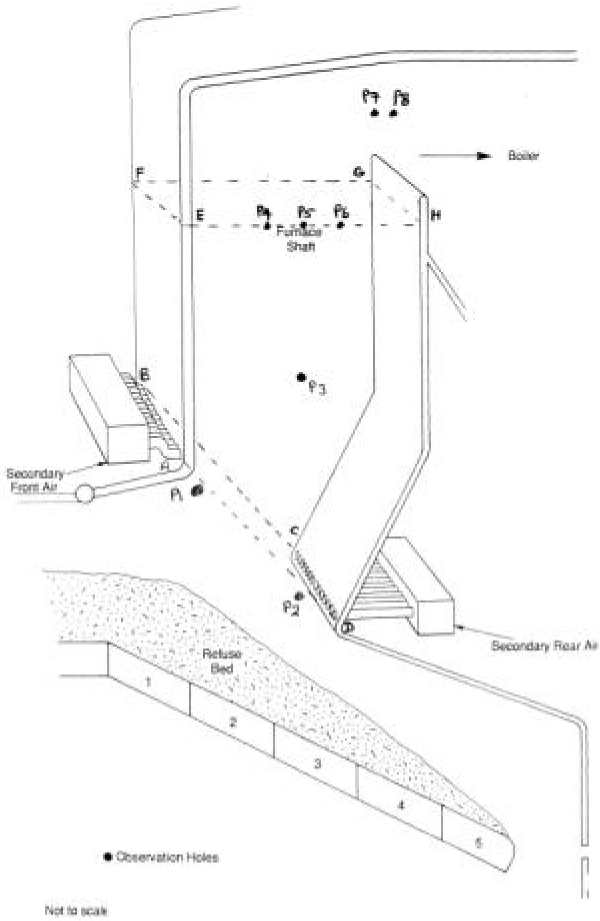


Figure 14- Incinerator Furnace, Showing Secondary Air and Helium Injection Points

The combustion gases from the furnace were continuously extracted from behind the first water-tube curtain section and a sub-sample transferred via a 100 meter heated line to an on-line, semi-portable mass spectrometer, where the helium concentration was monitored. The gas injection and detection systems were electronically linked so that triggering the gas injection automatically started the mass spectrometer recording the concentration of the sampled gas.

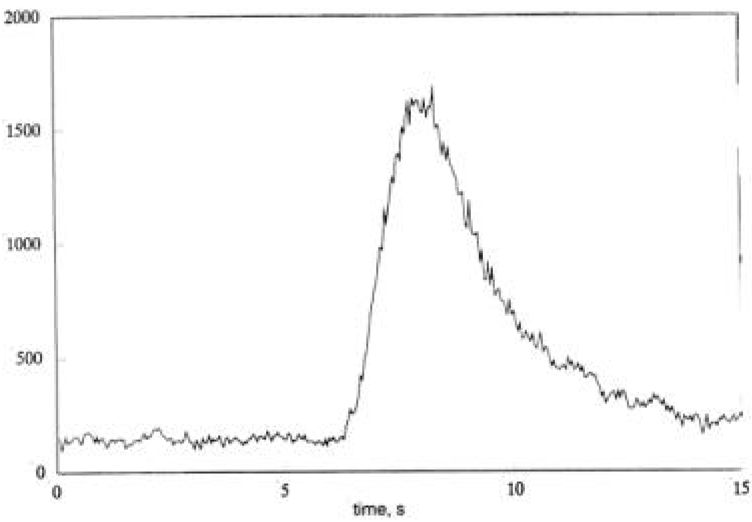


Figure 15 - Residence Time Distribution of 0.1s Pulse of He Injected Into Secondary Front Air

The technique was easy to use and gave good results for the peak residence time (Figure 15). There were some draw-backs that were mainly attributable to the logistics of the incinerator installation and the restrictions caused by the available equipment. However, the method is flexible enough to allow an improved approach to be developed. The draw-backs and possible solutions are outlined below:

(i) Helium was only injected into one of the fourteen front secondary air injection tubes but the tests could have been repeated using some of the other front and rear tubes. Alternatively, side-wall injection could have been used if ports had been available, and such approaches would have improved the accuracy of the derived residence time distribution.

(ii) The response signal was extracted from a single point in the entry to the boiler section and this incorrectly assumes that the tracer was equally dispersed across the exit duct. A simple improvement would have been to take individual samples from several locations across the duct and thereby produce a profile.

(iii) Insufficient access points were available at the end of the qualifying temperature zone (ie. anywhere on plane EFGH in Figure 14), near the top of the vertical radiant shaft. Therefore the sample was extracted after the first water tube curtain (P8 in Figure 14). Consequently, the measured residence times were significantly longer than those that would have prevailed at the end of the qualifying temperature zone. This meant that corrections had to be made to take the displacement into account and this introduces additional error. However, the sample could have been taken at the end of the qualifying secondary combustion zone if sample ports had been available and this would have obviated the need for the correction.

(iv) The use of the long extractive sampling line was necessary, as across-duct detection system for helium was not available and the semi-portable mass spectrometer had to be situated some distance away in a mobile laboratory. This introduced some additional uncertainty in residence time measurement as the sample transport system had plug and stirred reactor characteristics in the same way as the furnace chamber. This was compensated for in the case of the peak residence time by injecting a second pulse of helium at the furnace exit at the entrance to the sample extraction tube (P7 in Figure 14). It is now possible to improve this compensation technique by employing the new generation of truly portable mass spectrometers, as these can be positioned much closer to the extraction position.

(v) In the reported study the main and compensation (reference) pulses were separated by several seconds to avoid overlapping of the signal. Unfortunately the reference pulse approach did not allow full compensation to be made for the minimum gas residence time because some spreading occurred, especially for the main pulse. There was therefore a small overlap between the peak of the reference pulse and the initial rise of the signal pulse. This seemed to suggest that some helium was being detected as soon as it entered the furnace. This was thought to be due to a number of effects; (a) limit of detection problems; (b) mixing characteristics in the sample line being slightly different for main and reference pulses and; (c) the reference pulse time being 60% longer than the signal pulse (due to a slower solenoid valve response).

These effects all combined to prevent an accurate determination the minimum gas residence time and this is a feature of such methods. Several improvements could be applied. Firstly, the detection could be improved if neon is employed. Although it is more expensive, it has a higher atomic weight that would lead to improved detection and its background level is also low (less than 20 ppm). Secondly, the sample should be extracted from a position close to the end of the qualifying zone. Thirdly a short sample transport line should be used in conjunction with a modern portable mass spectrometer.

If the minimum gas residence is taken as the time when the concentration is 10% of the peak response (after making appropriate correction for the reference pulse), then the result is about 0.7 seconds. This is close to the minimum predicted by the CFD study (0.9 seconds) carried out at the facility at the same time **(Nasserzadeth 1995)**.

Alternatively, the residence time could be based on the time displacement of the peaks for the reference and main tracer responses. Using this approach the corrected peak of the residence time distribution was established at 1.3 seconds (Figure 16) and this was in good agreement with the 1.1 second value predicted by the simultaneous CFD study. Another alternative is to use the approach recommended by Swithenbank (Swithenbank 2000), ie computing the system residence time when 67% of the tracer has left. In this case, after making correction for the reference pulse, the residence time is again 1.3 seconds compared to the value of 1.2 seconds predicted by the CFD study. The residence time calculated from design data, and assuming the plug flow model, was 2.0 seconds.

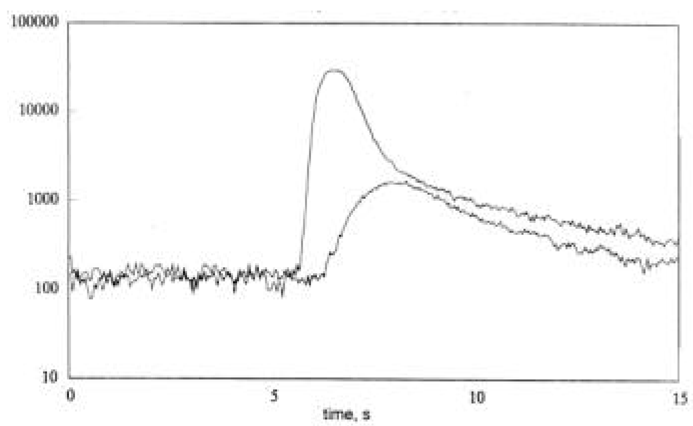


Fig 16 - 0.1s Pulse Of He Injected Into Secondary Front Air Inlet and Reference Pulse (Mean of 20 Runs, Logarithmic Scale).

The technique is simple to use and although it needs little further development it is flexible enough to benefit from the suggested improvements mentioned above. Consequently, it is recommended that this technique could be employed to establish the mean, the peak or the system residence time for new UK plant.

The estimated capital costs that contractors would incur in obtaining gas cylinders, a suitable injection probe, a computer programmed gas delivery system, a sample extract system and a portable mass spectrometer with dataloggers etc would be around £30,000. This would not include the costs of carrying out the study or the additional costs incurred by the Operator for providing the necessary services and access holes etc.

3.2.2.3 Measurement Using Pseudo-Random Binary Signal Tracer Techniques

These techniques share some common features with the time domain injection methods in that they can be used to measure gas residence times in incinerator furnace chambers and produce residence time distributions. They can use a tracer gas such as methane or carbon monoxide but could also rely on making rapid small changes to secondary air injection flows. In essence, they rely on producing disturbances of the steady state conditions within the furnace chamber that can be detected and the input and output responses compared by cross correlation analysis.

The method was successfully researched on a medium sized UK mass burn waste to energy facility (**Nasserzadeh 1995**). The furnace arrangement was very similar to that used in Figure 14 above for the helium injection method. The steady state furnace conditions were disturbed by the superimposition of small fluctuations (perturbations) in the form of a pseudo-random binary sequence of methane pulses and the response of the incinerator was detected by continuously measuring the carbon dioxide concentrations at the entry to the boiler section using a high frequency cross duct optical gas analyser detector. The output response was cross correlated with the perturbation signal to give the impulse response of the incinerator.

The pseudo random binary sequence (PRBS) technique has several advantages over those employing step and pulse injections. For example:

(i) The PRBS is on average a steady-state function and therefore the incinerator can be operated at close to steady-state conditions.

(ii) Unlike the pulse or step approach, the size of the fluctuation does not need to be large. Consequently, overloading (e.g. over-pressurisation) of the furnace chamber can be avoided.
(iii) For a given signal to noise ratio the sampling time is relatively modest.
(iv) Many disturbance frequencies can be generated for one easily generated code.

Preliminary experiments are necessary to aid the design of the final measurement programme. For example, it is advisable to establish the following before the main measurements begin:

(i) Major time constants
(ii) Permitted input amplitude
(iii) Presence of non-linearities and time variation of the process
(iv) Noise levels.

Sampling rates should be fast enough to extract all the available information in the input signal. Generally two to four output data samples per PRBS bit is adequate.

For the plant examined, the flow rates per injection ranged between 6 and 12 litres per second. This is similar to the rate required for the helium tracer injector technique but considerably smaller than the 1000 litres per second required for the SF_6 injection approach.

In the tests carried out by **Nasserzadeh**, methane from a cylinder was introduced via a water-cooled probe through a hole in one of the side-walls, just above the drying zone of the moving grate (P1 in Figure 14). A solenoid valve was fitted to the supply line and programmed with a pseudo-random signal to disturb the process. The location of the injection probe was below the secondary air injection level, therefore computed residence time distributions would be considerably extended beyond those commencing from the secondary air injection datum. However, the method is sufficiently flexible to allow injections to be made at more suitable positions, as long as access ports are provided.

The output response was detected on the cross-duct fast response CO_2 analyser positioned at the entry to the boiler section. This was cross-correlated with the perturbation signal to give the process impulse response of the process. The results indicate that the impulse response can be extracted from the noise by increasing the number of cycles over which the signal is integrated. The cross correlation function for a typical (impulse response) for the plant is shown in Figure 17 and shows a marked peak 1.5 seconds. Figure 18 shows the log plot of the integrated response versus time for this signal and the derived response indicates that most of the time delay is due to plug flow, with the remainder being due to well-stirred flow conditions. The derived system residence time for the incinerator is also 1.5 seconds and this is in good agreement with CFD studies at the same plant.

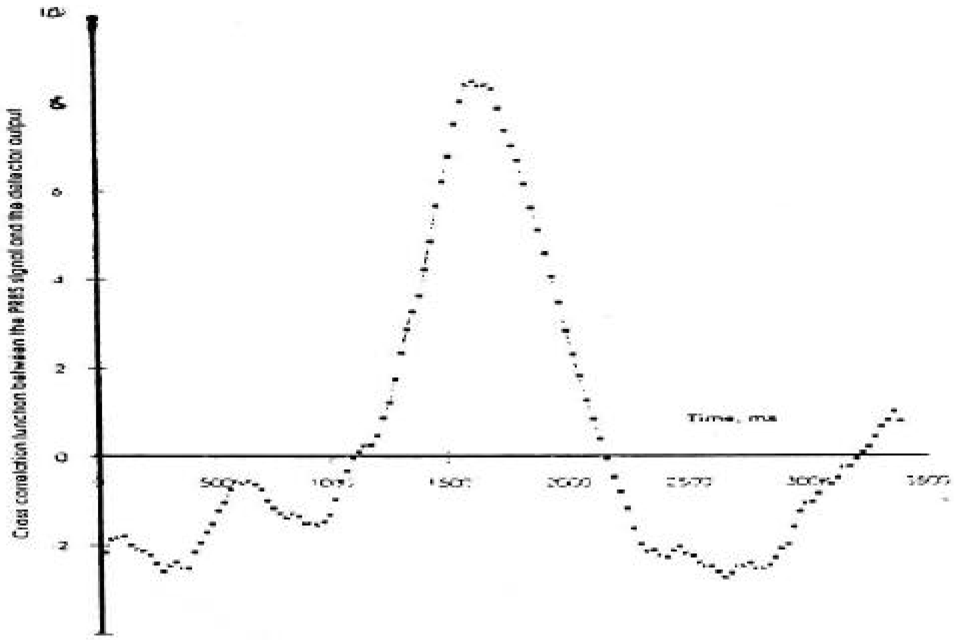


Fig 17- Cross Correlation Function (Impulse Recorded) for PRBS on Combustion Chamber

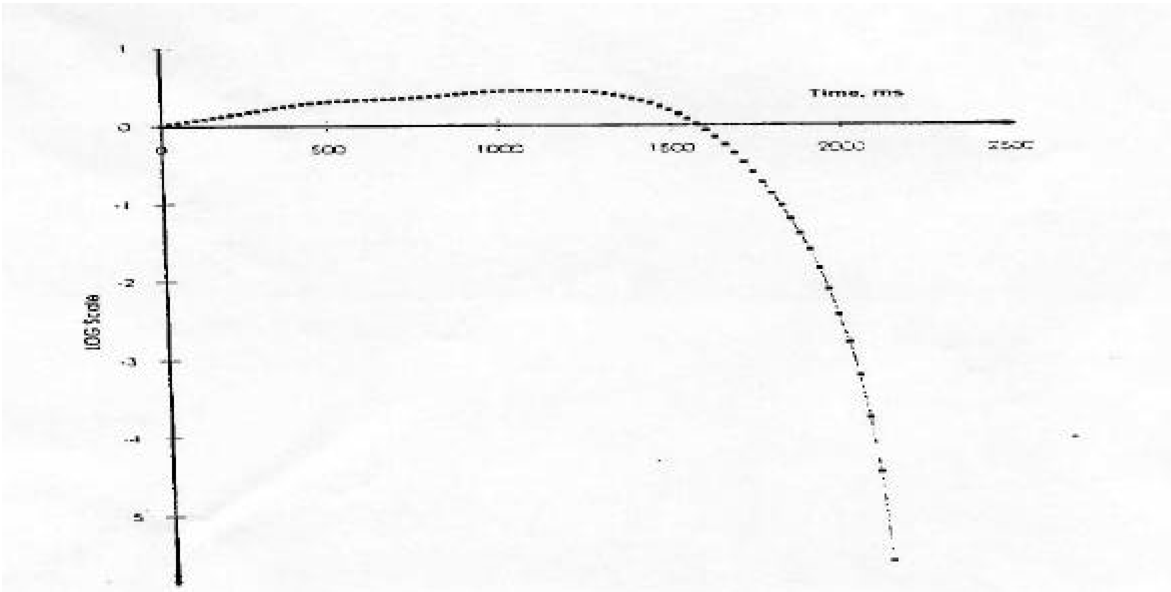


Fig 18 - Log Plot Of Integrated Response vs Time For The Incinerator Test

As the cross-duct detector was positioned at the entry to the boiler section the temperature there was less than the allowable minimum. Consequently, the residence time at the location where the temperature falls below the minimum allowable (i.e. 850^{o}C) would be significantly shorter. It is known that corrections were used to take account of this factor but it is unclear how they were applied. There were no reasons given for displacing the position of the detector but it is likely that it necessary to overcome possible interference effects with the IR source and detector. For example, high temperature particles could give rise to radiation interference and widow deposition problems.

The estimated capital costs that contractors would incur in obtaining gas cylinders, a suitable water cooled probe, a computer programmed gas delivery system, a suitable cross-duct fast detection system and dataloggers etc. would be around £30,000. This would not include the costs of carrying out the study or the additional costs incurred by the Operator for providing the necessary services and access holes etc.

Although this technique shows great promise, clearly some further development work is required to make it an available and reliable technique.

4. TECHNICAL IMPLICATIONS

4.1 Existing plant/new plant issues

There are some important factors that should be taken into account when considering existing plant versus new plant. The implication is that existing installations may need to be handled differently in a number of areas.

New plant operators should be able to meet the ideal requirements for providing the monitoring ports, access, and space, essential for carrying out the time of flight residence time determinations (ie they could be examined as for partially stirred reactors). However, there will be some practical difficulties for existing plant, which means it would be better to allow them to use the gas flow measurement techniques for residence time determination, (ie, assumption of plug flow). The ideal requirements are outlined in Section 4.2.3 (Table 2), but a summary of how allowance should be made for existing plant is as follows:

(i) Furnace access holes

The provision of new monitoring access holes in existing incinerator combustion chambers will be problematic, as cutting through bare refractory or modifying existing water-tube sections to provide appropriate apertures will raise practical difficulties and will be costly. Consequently, compromises may be necessary for existing plant.

For example, existing holes (e.g. viewing ports) may have to be employed even if the location is not ideal. Even where new ports can be provided, these still may not be in ideal locations.

(ii) Boiler exit or stack access holes

There may also be a need to allow some latitude in the provision of access holes in the boiler exit. However, the full provision for access ports should be met concerning the stack monitoring positions.

(iii) Space requirements

Meeting the full space requirements outlined below may be difficult around the furnace chamber for existing plant, as installed equipment and walls etc may interfere. Similar problems may arise at the boiler exits but the full space requirements should be met at the stack monitoring position.

4.2 General issues

4.2.1 Introduction

Several general questions need to be considered and settled before any recommendations can be made on guidance for BAT. These cover items such as describing clearly what should be considered as a qualifying combustion zone. In addition, the basic requirements for monitoring ports should be settled along with general equipment and personnel access questions. Finally, the test conditions need to be established under which residence time at temperature is to be measured.

In discussing these questions it should be noted that plug flow measurement methods (ie based on gas flow rate determinations) will be acceptable for some plant, whilst for others the stirred / real reactor flow measurement approaches (based on time-domain methods) should be used. Wherever possible, guidance should be clear cut and apply across the board, but compromises will be needed because of specific problems arising with particular types of plant.

4.2.2 Qualifying zones and datums

Establishing exactly where the qualifying zone for the gas residence time starts and finishes is presently unclear. It is important to settle this question, if possible with clear-cut guidance, otherwise the determination of residence time could be in continuous dispute. At the same time, it should be recognised that flexibility will be required for certain types of plant exist because of their design or operating considerations.

The various Directives state that the qualifying geometric volume will commence after the last injection of combustion air and end when the gas temperature falls below the allowable minimum. Moreover, the minimum temperature is to be measured at or near the inner wall. Such descriptions can cause confusion because it is not clear what is meant by combustion air. For example, are the Directives referring to primary, secondary, or tertiary air as combustion air, or are they referring to all of them. Also, what is the position regarding recirculated flue gases as these will contain some excess air that could be used in the combustion process? Where primary / secondary / tertiary air injections are present within the same vessel, it is unclear how Regulators and Operators should decide where the qualifying zone should commence. Also, the position of combustion air supplied to a support burner is confusing. For example, support burners positioned within the qualifying zone will be supplied with excess air (or cooling air) and it is unclear if the qualifying zone datum is to be reset because this air will contribute towards the gas phase combustion activity within the furnace chamber.

To avoid confusion it is recommended that the qualifying zone should be a **clearly identifiable discrete zone.** Primary combustion should not take place there, gas phase combustion should be completed there and gas temperature and oxygen concentrations should not fall below the allowable minima in this zone. It is therefore recommended that the zone be taken as commencing after the last injection of secondary air (or over-fire air). In some designs it is common to employ an array of secondary air nozzles and these are often staged, or they are situated on opposing (e.g.front and rear) furnace walls. In such cases, the start datum for the zone should be defined as the plane across the secondary combustion zone which links the last array of secondary air injections on one wall to the last secondary air injection array on another (usually the opposing) wall. For plug flow residence time determinations the datum should be taken as starting at the centre of this plane, and if the plant in Figure 14 is used as an example the datum plane of interest is ABCD. The zone of interest should be referred to as the qualifying secondary combustion zone (**QSCZ**) and in Figure 14 this is the geometric volume contained between planes ABCD and EFGH.

If a support burner is installed in this zone, the datum should not be reset unless the temperature falls below the allowable minimum.

Where tertiary air injections are present within the zone they are often installed for cooling purposes to protect refractory and prevent it from being taken above its design temperature maximum. If these injections follow the secondary air injections then the datum should normally be reset immediately behind them because; (i) these injections could contribute to the completion of gas phase combustion; and (ii) they could reduce gas temperature below the allowable minimum.

Where recirculated flue gases are being introduced into the zone these should be treated in the same way as tertiary and secondary air. Consequently, if their injection is after the secondary or tertiary injections then the datum should be reset to take account of this.

Specific examples of various incinerator designs are given in the next section to provide guidance on how to determine these issues. Some examples are also given where latitude should be allowed because of design and operating constraints.

4.2.3 Provision of monitoring ports

Plant operators will need to make provision for installing monitoring ports and providing necessary access and services so that monitoring can be undertaken. The specific requirements will depend on several factors, such as:

- The temperature and residence time measurement methods to be employed
- Plant factors (existing or planned facility, bare refractory furnace or water walls etc)

The specific factors that need to be taken into account for particular designs are discussed later but the ideal requirements are discussed here and are summarised in Table 2.

(i) For monitoring gas temperatures

Gas temperature monitoring could be required at at least three different locations, depending on the measurement method chosen for demonstrating gas residence time. A summary of the number of locations and required access port requirements is as follows:

- **At the end of the QSCZ -** All plant will need to have access provisions to allow for gas temperature to be monitored at the end of the qualifying secondary combustion zone (QSCZ) whilst the once-off gas residence time tests are being undertaken. Operators will also need to make some provision for permanently installed sensors for the continuous monitoring of temperature at or near this location. The directives require the measurements to be made at a single point, at or near the wall. It is recommended that at least two access ports be fitted side by side. In this way thermocouples could be used for the continuous measurements, but a suction pyrometer could be introduced periodically to calibrate the thermocouple or to prove the temperature during the residence time tests. Each port should therefore be large enough to accommodate a suction pyrometer. The internal diameter of the ports will depend on the type of suction pyrometer employed, but most systems could be accommodated using 3-inch BSP ports.

- **In the middle of the QSCZ-** Plant using the plug flow residence time measurement approach will need to determine temperatures in the middle of the qualifying secondary combustion zone, so that the bulk mean gas temperature can be established. Two 3-inch BSP access ports are recommended (fitted side by side). Although both ports could again be used for thermocouple sensors (or an infra-red pyrometer), both need to be able to take a suction pyrometer.

- **At the boiler outlet or the stack -** Plant using the plug flow measurement approach will also need to measure gas temperatures at either the boiler exit or the stack. At least two

4-inch BSP sampling ports will be required at these locations to accept the monitoring sensor. Other measurements such as gas flow and composition are also required at the same location, see (ii) below.

(ii) Flue gas velocity and gas composition monitoring

Plant measuring residence time by the plug flow approach will need to monitor flue gas velocity and composition, either at the boiler exit or in the stack. 4-inch BSP sample ports should be provided. The position and number of ports will need to be chosen such that representative velocity / temperature and gas composition profiles can be obtained. The selection procedure given in BS 3405:1983 would be acceptable. Therefore, **at least two** ports will be required, but it would be prudent to fit a third so that gas composition determinations do not interfere with the other measurements.

Plant using the plug flow residence time measurement approach also need to provide an additional 2-inch sampling port at the end of the end of the QSCZ, so that gas composition can be measured at that location. The port should be on the same plane as the two temperature measurement ports mentioned above.

(iii) Tracer pulse injection and response extraction ports

Plants using time of flight measurement techniques will need to provide ports for accepting the tracer injection probes. Provision of two 3-inch ports on the furnace wall, at the same elevation as the secondary air injections would be satisfactory.

Alternatively, if a secondary air injection array was installed, a series of quarter inch glands could be fitted in every second or third air delivery pipe. This would allow a flexible pulse injection tube to be inserted deep inside the chosen pipes, thereby avoiding "spill-back". In some plant it may be more convenient to install the series of 1/4 inch glands in the rear of secondary air manifold chambers, such that access into the air pipes can be obtained through the side of the manifold.

Extractive response detection systems (e.g. mass spectrometer) will also require a 2-inch access port to be supplied at the end of the QSCZ. This is needed to accommodate the extraction probe taking the response concentration parameter to the detector. Another 2-inch port will be needed just below the first to accommodate the reference injection probe.

If a cross-duct response detection system is to be employed then two 4-inch access ports would be needed at end of the QSCZ on diametrically opposed walls.

Table 2 - Summary of Ideal Access Ports For Monitoring

Residence Time Measurement Method	Parameter (and Location)	Size of Ports	No of Ports
Gas Volume Flow	Temperature (mid QSCZ)	3 inch	2 (side by side)
	Temperature (end of QSCZ)	3 inch	At least 2, (side by side)
	Temperature and Gas Velocity (boiler exit or stack)	4 inch BSP	At least 2
	Gas Composition (end of QSCZ)	2 inch	1
	Gas Composition (boiler exit or stack)	4 inch BSP	1
Time of Flight	Temperature (end of QSCZ)	3 inch	At least 2, (side by side)
	Injection of Pulse (wall)	3 inch	2
	Injection of Pulse (secondary air)	1/4 inch	Every 2nd or 3rd pipe
	Injection of Reference Pulse	2 inch	1
	Extracted Response Detection	2 inch	1
	Cross- Duct Detection	4 inch	2 (diametrically opposed)

4.2.4 Space, access and service provisions

Plant operators will also need to make the necessary space, access and service provisions to allow monitoring to be undertaken.

(iv) Space requirements

There needs to be sufficient space available at the monitoring positions so that injection /detection equipment, temperature probes and sample extraction systems can be mounted in position. At some furnace chamber locations the probes will be quite long, as they need to be traversed to the centre of the chamber. Therefore, sufficient clearance will be required to allow the probes to be removed without interference from walls or rails.

The temperature, velocity and gas composition monitoring at the boiler exit or stack will also involve traversing. In this case, the probes will need to reach across the whole duct and sufficient clearance will be required to allow the probes to be manoeuvred and removed.

(v) Access

Some of the monitoring ports may be located at height. In such cases, at least temporary access platforms and ladders will need to be provided. The size of the platforms will depend on the size of the equipment employed. In most cases the length of the sensor probes will be the determining factor, as platforms have to be large enough to allow the hot probes to be removed and handled safely.

(vi) Services

Operators will need to provide the essential services to enable any monitoring programme to proceed. Provision of adequate electrical supplies will be essential. In addition, some types of suction pyrometers and sample probes will require a cold water supply, whilst others will need compressed air (100psi).

4.2.5 Test conditions

All incinerator plant will have been provided with a manufacturer's firing diagram at the time of installation. The diagram will describe the acceptable firing envelope for the facility. Therefore, in addition to testing normal operating conditions, it is important that residence time at temperature is verified at the limits of this envelope (to represent worst case). Operators should therefore make arrangements for three conditions to be tested. These will be defined in the firing diagram in terms of a percentage of the Maximum Continuous Rating (MCR) and should be as follows:

- Normal operating conditions – This would be expected to fall in the range from 90 to 100 % MCR, unless the facility had been down-rated.
- The maximum-turn down condition – This will be very different for different type of plant, e.g. for mass burn waste to energy plant maximum turn down is around 70% MCR.
- Over-load condition – The firing diagram will probably have defined an over-load condition, where the plant will be allowed to operate for a few hours. This is normally set around 110% MCR.

4.3 Specific issues for different types of plant

4.3.1 Bare refractory systems

Existing incinerators with bare wall refractory furnace chambers should be able to provide the necessary access holes without too much difficulty. However, it should be recognised that installing access holes is a specialist activity and could only be undertaken when the plant is on a planned "shut-down". Some latitude will need to be allowed concerning the proximity of co-located sample ports. Access holes will have to be far enough apart such that there is no risk of structural damage to the refractory wall and operators will need to take professional advice on this matter.

Some furnace access holes will progressively become blocked due to clinker formation and operators will need to take steps to ensure that the holes remain free during any monitoring programme.

The costs of providing access holes in refractory walls are dealt with in Section 5. Costs will depend on several factors, such as wall thickness to be penetrated and whether staging will be required to reach the position. The costs will be most reasonable when the work is co-ordinated with other maintenance activities, i.e. annual "shut-downs".

4.3.2 Water wall systems

Existing incinerators with water tube wall furnace chambers will find provision of the ideal access holes recommended in Table 2 much more difficult. As well as having the same problems mentioned above for the bare refractory systems there is the added difficulty that for many water walls the clearance between the water tubes will be insufficient to allow access holes of the desired size to be cut.

Consequently, compromises will have to be considered which may affect the accuracy of determinations. In most cases, access will be possible using the existing furnace viewing ports. Although these holes may not be ideally located, reasonable corrections could often be applied. Each case will have to be considered on its merits.

Occasionally water wall furnaces need to be re-tubed. When this occurs, Inspectors should take the opportunity to consider requiring the ideal port requirements to be satisfied. As before, latitude will need to be allowed concerning the proximity of co-located sample ports.

4.3.3 Mass burn vertical radiant shaft systems

Many of the UK mass burn incinerators which burn solid waste are fitted with vertical radiant shafts constructed from refractory coated water tube walls. Consequently, many of the existing plant will need to consider compromises mentioned in the matter of providing access holes.

However, it is useful to consider a typical plant where furnace condition monitoring has already been carried out and note the location of the qualifying secondary combustion zone (QSCZ) datums and monitoring points. Referring to **Fig 14**, there is a clearly identifiable secondary combustion zone. For plug flow, the start datum for the QSCZ is the centre of plane ABCD that connects the front and rear secondary combustion air arrays. The end of the zone is plane EFGH, and its displacement from the start datum was based on plant design information and was set at the predicted height for 1.25 x the required 2 seconds residence time. Port P3 was for bulk mean gas temperature determination, whilst ports P5, P6 and P7 were for temperature and gas composition monitoring.

The same datums were used for time of flight (time-domain) monitoring using the partially stirred reactor model. However, in this case the front and rear secondary air injections would normally be utilised for tracer injection. Existing viewing Ports P1 and P2 could also have been employed for this task. Port P7 was used for the reference gas injection whilst Port P8 was employed for the probe extracting the system response to the on-line concentration monitoring device (mass spectrometer). Ports P5, P6 or P7 would have been better for this task but would have needed some modification.

4.3.4 Box furnace mass burn systems

Some UK incinerators for burning solid waste are fitted box shaped furnace chambers and most of these have bare refractory walls, ie no water wall cooling. These plant tend to be of older design and the operators may wish to count some of the box furnace as qualifying secondary combustion zone for gas residence time purposes. Such an approach is very difficult to justify and is not recommended.

The difficulty arises because there are several different types of air injections within the box and it is not possible to be sure where qualifying gas phase combustion starts and ends. For example, primary air is supplied through the solid waste from the wind-box, whilst secondary air is normally supplied through a roof array. It is therefore unclear where the distinct QSCZ datum should be taken.

Two other air injections arrays can often complicate matters further. The first is the emergency cooling air injections, normally situated on the front wall of the box furnace. These injections are needed to protect the furnace chamber refractory from high temperature excursions because there are normally no water tube walls associated with this type of furnace. The second is situated in the cross-over duct between the furnace and the first heat recovery section (if one is fitted). Both injections can promote or hinder the maintenance of good gas phase combustion.

It is recommended that none of the box furnace volume should be considered as QSCZ, therefore such designs will need a quite separate secondary combustion chamber.

4.3.5 Rotary kilns

Several incinerators designs employ rotary kiln furnace chambers. Most have bare refractory walls and only a few have heat recovery incorporated into the kiln. As before, a clear division between primary and over-fire air functions is difficult to establish. Again, it is recommended that none of the rotary kiln furnace volume should be considered as QSCZ and again such designs will need a quite separate secondary combustion chamber.

4.3.6 Fluidised bed systems

Fluidised bed incinerators may have to be considered as a special case. There are difficulties both with identifying the start of the QSCZ and there can be problems meeting the minimum temperature criteria.

Two designs are in common use, both employ vertically orientated furnace chambers. The first is the bubbling bed, which is suitable for homogeneous materials and is widely used for incinerating sewage sludge. The other is the circulating fluidised bed (CFB) combustor, which is popular for burning mixed shredded solid waste. Both designs employ sand or aluminium silicate combustion beds, which are suspended by the passage of heated primary (plenum chamber) air through them. The beds have a dense section where most of the primary combustion occurs. Above this, in the bubbling system, the bed has a clear area known as the "free-board". The circulating bed has no true free-board area, as the upper zone is merely less dense (the fast fluidising zone). Therefore, a significant fraction of the bed material is carried out of the furnace chamber by the flue gases before being trapped by a hot cyclone and returned to the bed.

Both designs have secondary air injections positioned above the dense zone. As can be seen from Figure 19, those for the CFB combustor are in the fast fluidising zone and some primary combustion is still occurring. Consequently, there is difficulty in establishing exactly where the QSCZ start datum should be taken. It is recommended that none of the volume in the vertical section of CFB furnace chamber should be considered as QSCZ and that such designs should have a quite separate secondary combustion chamber.

For the bubbling bed it is recommended that the datum should be set at the start of the free-board. However, it should be recognised that this level will move with changing air- flow and feed rate conditions. The level should be verified by use of inspection ports and the highest free-board level should be taken as the start datum.

Fluidised bed combustors will also have difficulty in consistently satisfying the minimum gas temperature requirements laid out in the various directives. This is especially the case for bubbling bed designs at start-up and at maximum turndown. The problem occurs at start up because the support burners must raise the bed and gas temperatures to at least 850°C before waste can be fed. However, as waste is fed temperatures can rapidly elevate above the ash slagging temperature, which can cause the bed to slump. Consequently, start up of the bubbling bed under such demanding conditions can cause a series of start-up / shut -down failure, with attendant gas phase combustion problems. It is therefore recommended that the gas temperature minimum requirements for bubbling beds burning non-hazardous waste be relaxed to 800°C. It is also recommended that the minimum gas residence requirements be raised accordingly to 2.2 seconds.

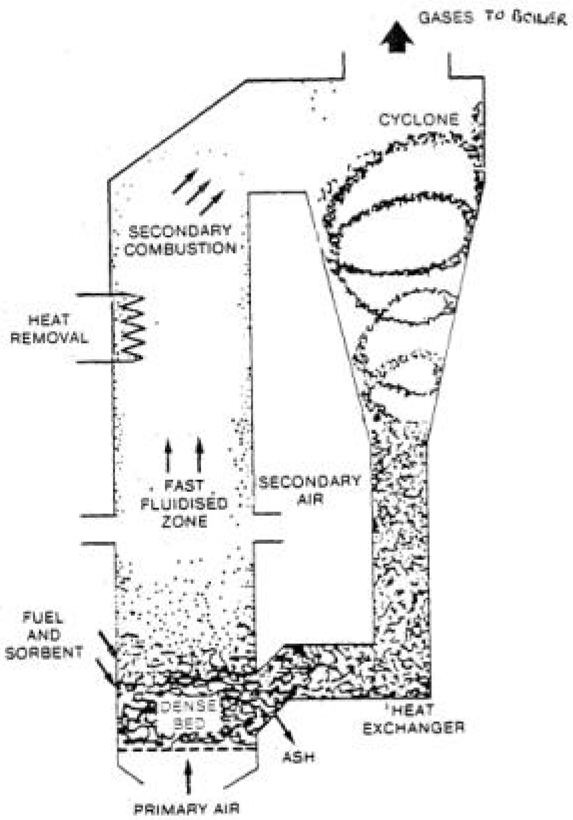


Fig 19- The Fast or Circulating Fluidised Bed Combustion System

4.3.7 Modular designs

Many modular designs exist, some based on box type furnace sections and some based on cylindrical combustion chambers. Many introduce secondary air into the primary combustion chamber and again some operators may wish to count parts of this furnace volume towards the gas residence. Again it is recommended that this should not be allowed because it is not possible to establish exactly where primary combustion finishes and gas phase combustion commences.

5. FINANCIAL IMPLICATIONS

5.1 General

The financial implications will be affected by several factors; (i) the measurement approach to be applied by the operators' monitoring contractors; and (ii) whether a new or an existing plant is involved. Some costs borne directly by operators, whilst others will be passed on by their monitoring contractors.

The costs to be borne directly by operators include:

- Provision of monitoring ports
- Providing the necessary space, access and services to allow monitoring to proceed
- Undertaking continuous monitoring of the temperature at the end of the qualifying secondary combustion zone (QSCZ).

Contractors will charge their full staff, fixed and consumable costs to operators, but it is not possible to state these. Contractors will also have to invest in new monitoring equipment, and a portion of these costs will be passed on to the operator when residence time confirmation work is commissioned. It is not possible to state what proportion of capital costs will be charged to an individual operator, as this will be a function of the expected instrument utilisation over its lifetime (normally 5 years). This will also depend on the number of plant that are likely to need this type of service.

5.2 Capital costs of monitoring equipment

The capital costs of the necessary temperature sensors will depend on the temperature monitoring method employed and the residence time approach to be followed. Table 3 summarises the various options. Choices can be made both by operators and contractors regarding the sophistication (and cost) of equipment. The table lists all the systems that could usefully be employed. For monitoring contractors, the use of at least one suction pyrometer should be obligatory, whilst the base temperature sensor could be the shielded thermocouple. For operators, their minimum requirement would be for the continuous measurement of QSCZ exit temperatures and the base item for this would be the shielded thermocouple. All systems would need some method of reading and logging the measured data.

Table 3- Capital Cost of Temperature Monitoring Equipment

Suitable Methods	Cost per Unit (£)
Accoustic Pyrometers	10,000 - 15,000[1]
Radiation Pyrometers(narrow band)	2000 - 3000[2]
Radiation Pyrometers(wide band)	1500 - 2500[2]
Shielded Thermocouples	200 - 1500[3]
Suction Pyrometers	5000 -10000
Logger	1000 - 2000
Reader / Computer	500 - 2000

Note 1: Price includes signal processor and purge system, additional paths are about £6000
Note 2: Price includes purge and cooling system
Note 3. Price affected by quality of the alloy and the length

5.2.1 Gas flow residence time measurement methods

The capital cost estimates for the monitoring equipment required for measuring residence time based on gas flow (assuming plug flow model) are given in Table 4. This assumes that the measurements will be based on monitoring certain parameters within the furnace chamber and at the stack, or at the boiler exit, as described in Section 3.2.1.29(iii). The capital costs for the necessary gas temperature measurement equipment is not included as that has already been given in Table 3.

Table 4 - Capital Cost of Gas Flow Residence Time Measuring Equipment

Monitoring Equipment*	Numbers of Units Required	Cost per Unit (£)
CO_2 Monitor	2	2,000 - 4,000
O_2 Monitor	2	1000 - 2000
Gas Velocity Meter / Sensor	1	1000 - 2000
Pressure Sensor	2	~ 500
Sample Pumps /Transfer Lines	2	500 - 1000
Loggers	2	1000 - 2000
Total Costs	-	11,000- 21,000

5.2.2 Time of flight residence time measurement methods

(i) low flow gas pulse injection

The capital cost estimates for the monitoring equipment required for measuring residence time based on the helium injection pulse time of flight approach is given in Table 5. This assumes that the measurements will be based on monitoring certain parameters within the furnace chamber, as described in Section 3.2.2.2(iii). Again, the capital costs for temperature measurement is not included as that has already been given in Table 3.

Item 1 in Table 5 has included for the purchase of a helium gas cylinder, but not rental charges. This would easily be sufficient to test at least 10 incinerator facilities. Neon gas could also be used but it is considerably more expensive (about £1000 for a No 1 sized cylinder).

Table 5 - Capital Cost of Helium Pulse Residence Time Equipment

Monitoring Equipment	Numbers of Units Required	Cost per Unit (£)
1.Tracer Helium Pulse Injection System and Electronic Trigger	1	2,000
2.Helium Reference Injection System and Electronic Trigger	1	1,000
3.Sample Extraction / Handling and Transfer System	1	2,000
4.Portable Mass Spectrometer, with data logger	1	20,000
Total	1	25,000

(ii) Pseudo random pulse

The capital cost estimates for the monitoring equipment required for measuring residence time based on pseudo random pulses of propane are given in **Table 6.** This assumes that the measurements will be based on monitoring certain parameters within the furnace chamber (as described in Section 3.2.2.3). Again, the capital costs for temperature measurement is not included as that has already been given in **Table 3.**

Table 6 - Capital Cost of Propane Pseudo Random Pulse Residence Time Equipment

Monitoring Equipment	Numbers of Units Required	Cost per Unit (£)
1.Propane Injection System and Randomiser	1	2,000
2. Fast Response Cross Duct CO_2 Monitoring System	1	10,000
3. Logger	1	2,000
4. Computer	1	1,000
Total	1	15,000

5.3 New Plant

The additional direct costs to be borne by the operators of new plant should not be great. For example, the full provision of monitoring ports laid out in Section 4.2.3 should easily be able to be accommodated within the price at the contract / design stage. The same would apply to ensuring that the plant design provided sufficient space, access and services to allow monitoring to proceed.

The undertaking of continuous monitoring of the temperature at the end of the QSCZ should also not entail additional cost, as it is already a requirement that furnace outlet temperatures are to be continuously monitored. The only issue is that the monitoring positions offered in most designs are at the furnace outlet, which may be significantly displaced from the end of the

QSCZ. If the minimum temperature requirements were guaranteed at the outlet, additional monitoring and additional access ports would not be required. However, it would be prudent for operators to specify additional ports closer to the end of the QSCZ (as determined from design calculations and models). Again the costs of these additional ports and the monitoring equipment should be able to be absorbed within the price at the contract design stage.

5.4 Existing plant

If the Agency were to decide that existing plant should fully meet the requirements given in Section 4.2.3 and Table 2, the additional costs could be substantial.

5.4.1 Costs of providing additional access ports

The costs of meeting the ideal access ports requirements shown in Table 2 could be the most expensive item for existing plant and are summarised in Table 7.

Modifications to existing plant with water-wall furnace chambers are likely to be most expensive and most technically difficult. Information was gathered by Warren Spring Laboratory during their 1989 furnace temperature / residence time profiling research programme (**Scott and Loader 1989**). For this programme, additional access apertures were necessary in three of the four furnace water walls of a large waste to energy plant. The programme was delayed to coincide with a major tube replacement activity and the modification costs were thereby reduced to about £1000 per aperture.

Major tube replacement programmes are infrequent events; consequently, if the ideal access port requirements were demanded for existing plant then stand-alone modifications would be required. The major cost of a stand-alone modification, would be the lost production, which for a 10 tonne per hour waste to energy plant will certainly be in excess of £5,000 per day of lost production. The modifications would probably take between 3 and 5 days and the engineering costs of providing a single aperture would be at least £2000. Therefore, such a modification would be prohibitively expensive as well as being practically difficult. If modifications could be co-ordinated with an annual shut down, the cost per aperture could be cut to around £1000 and there would be no lost production.

Modifications to bare wall refractory systems are less expensive but are still technically difficult and require to be carried out by experts. The cost of providing a single 3 or 4 inch access port depends both on the thickness of the refractory, the thickness of the metal casing and the access to the desired location. Cutting would need to be undertaken during a major shut-down and would cost between £800 and £1600 per port. As cutting may need to be undertaken on both the inner and outer surfaces there may also be a need to provide temporary access platforms, which would cost around £500.

The additional costs of providing two access ports on boiler exit ducts is not great at around £400, whilst there should be no additional costs of providing access ports on the stack as they should already have been provided as part of the normal emission monitoring requirements.

Table 7 - Cost of Providing Access Ports on Existing Plant

Item	Cost per Unit (£)
Loss of Production	5,000*
3 or 4 inch port in water wall (stand alone)	2,000-2500
3 or 4 inch port in bare refractory (stand alone)	800-1600
Internal scaffolding in chamber (for stand alone alterations)	500
4 inch port in boiler outlet duct	200
3 or 4 inch port in water wall (co-ordinate with annual shut-down)	1,000-1500
3 or 4 inch port in bare refractory (co-ordinate with shut down)	200-400
1/4 inch ports in air tubes	minimal

Note: based on daily loss of gate fee and electricity for a 10 te/ hr MSW incinerator.

5.4.2 Costs of providing space, access and services

5.4.2.1 Space

The space and access requirements to enable probes to be mounted in furnace, boiler or stack walls, (see Table 2), will be determined by the size of the ducting. In the furnace section, probes will need to reach at least to the centre of the duct, whilst at the boiler outlet or stack the probes must be able to traverse the whole duct. Consequently, there must also be enough clearance to allow probes to be safely removed, without interference from structures.

The cost of modifying hand rails etc is minimal, but moving permanent structures, such as plant machinery or walls would normally be prohibitive and impracticable.

5.4.2.2 Access

Temporary platforms may be needed at some plant to reach furnace and boiler outlet monitoring positions. The exact cost will depend on the height, size and duration of hire, but typical costs for a 3 x 3 meter 6 meter high platform, 1 week hire, are around £500.

There should be no additional costs involved in providing access to stack monitoring positions as this should already have been provided as part of the normal emission monitoring requirements.

5.4.2.3 Services

The cost of providing essential service to support a monitoring programme should be minimal as most plant will already have all the required services. In some case there may be a need to provide compressed air and some plant may not have this. Consequently, this item may have to be hired in. The typical costs for a 1 week compressor hire is around £100.

6. RECOMMENDATIONS ON GUIDANCE FOR BAT

There are a number of recommendations on guidance for BAT. These take into account both the technical assessments, as well as the technical and financial implications mentioned earlier. The recommendations fall into three main groupings:

- Those of a general nature for all plant, although some latitude should be allowed in certain specified cases.
- Those which should be applied to new plant.
- Those which should be required for existing plant

6.1 General recommendations

6.1.1 Definition of the qualifying secondary combustion zone

It is recommended that the interpretation of the qualifying zone within the furnace section for the purposes of proving the residence time requirements at temperature should be based on the recommendation given in Section 4.2.2. These are summarised in Box F below:

BOX F: Recommendations on Definition of Qualifying Zone

1. It is recommended that the qualifying zone should be a **clearly identifiable discrete zone.** Primary combustion should not take place there, gas phase combustion should be completed there and gas temperature and oxygen concentrations should not fall below the allowable minima in this zone.

2. The zone should be taken as commencing after the last injection of secondary air (or over-fire air). Where arrays of secondary air nozzles are situated on opposing furnace walls, the start datum should be defined as the plane across the furnace which links the last and penultimate secondary air array. For plug flow residence time determinations the datum should be taken as starting at the centre of this plane.

3. The zone should be referred to as the qualifying secondary combustion zone (**QSCZ**). . If a support burner is installed in the zone, the datum should not be reset unless the temperature falls below the allowable minimum.

5. Where tertiary air (or recirculating flue gas) injections are present within the zone, and are behind the secondary air injections, the datum should **normally** be reset because; (i) these injections could contribute to the completion of gas phase combustion; and (ii) they could reduce gas temperature below the allowable minimum.

6. For box and rotary kiln furnace designs (and for circulating fluidised bed combustors), it is recommended that none of the box , kiln or vertical suspension chamber should be considered as qualifying zone and such designs should require a quite separate secondary combustion chamber.

7 For bubbling fluidised bed combustors it is recommended that the datum should be set at the start of the free-board. It should be noted that this level will move with changing air flow and feed rate conditions. Therefore the level should be verified by use of inspection ports and the highest free-board level should be taken as the start datum. .

8 Bubbling fluidised bed combustors have insurmountable technical difficulty satisfying the minimum temperature requirements at start up and at maximum turn down. It is therefore recommended that when such units are used to burn non-hazardous waste, the gas temperature minimum requirement be reduced to 800^{o}C. It is also recommended that their minimum gas residence time requirements be raised to 2.2 seconds.

6.1.2 Design and validation

The general recommendations on this point are given in Box G below:

Box G - Recommendations on Design and Validation.

1. Whilst design data can be accepted as a starting point, it is recommended that minimum gas residence time and minimum temperature requirements be demonstrated periodically (at least once) under a number of specified conditions by carrying out a programme of measurements

2. It is recommended that modelling studies, such as computational fluid dynamics, should be encouraged to help identify operational and minor engineering strategies for optimising performance within QSCZ in existing plant.

3. It is recommended that such modelling studies be mandatory for new plant

6.1.3 Test conditions for the measurement programme

The general recommendations on test conditions are given in Box H below:

Box H – Recommendations on Test Conditions.

1. Gas residence time at temperature should be demonstrated by a measurement programme under the following three conditions; (i) close to maximum turn-down; (ii) normal operating conditions, i.e. between 90% and 100% of the maximum continuous rating; and (iii) over-load conditions, i.e. close to 110% of the maximum continuous rating.

2. Each condition is to be tested at least twice during the programme.

3. The monitoring within each test period should cover at least a one hour.

6.1.4 Monitoring times for the measurement programme

The general recommendations on test monitoring times and test numbers are given in Box I below:

Box I - Recommendations on Minimum Monitoring Times and Test Numbers

1. Furnace temperatures should be monitored and recorded continuously over the minimum 1 hour test period mentioned above and reported as 1 minute means.

2. When using suction pyrometers, then sub-tests of at least 10 minutes duration should be required and the number of such sub-tests should be sufficient to give at least 1 hour of valid data.

3. If time of flight residence time measurement methods are to be employed then at least 20 injections and response measurements are to be undertaken during each test period.

4. If mean gas flow rate measurement methods (plug flow) are to be used for determining residence time, then the required measurements of gas flow, oxygen / and or carbon dioxide etc should be continuously recorded over each test period. Flow and residence times should be plotted as 1 minute means. Flue gas moisture content should be determined at least once during each test period.

6.2 Recommendations for new plant

6.2.1 Residence time proving for new plant

The main recommendations are given in Box J below:

Box J Main Recommendations on Proving Residence Time

1. New plant should be required to measure residence time during proving tests using a time of flight (a time domain) method.

2. Either of two measurement methods is recommended:

- The procedure based on that described in Section 3.2.2.2 (iii), involving the injection of helium (or neon) and employing mass spectrometer response detection should be acceptable.
- The procedure based on that described in Section 3.2.2.3, involving the pseudo random binary signal tracer gas pulse with propane should be acceptable.

5. The injection rate should not exceed 1% of the nominal furnace gas flowrate and the pulse should not exceed 100 m seconds in duration.

6. Where an array of secondary air nozzles are installed, tracer injection should be carried out sequentially in a representative number of air delivery tubes and where the QSCZ is symmetrical it should be acceptable to use a sample of tubes on one side of the centre line.

7. Side wall probe injection should only be carried out if there is no suitable alternative.

8. The parameter to be determined should be either the peak or system residence time.

9. To be accepted, it is recommended that none of the computed peak or system residence time data should be below 2.0 seconds.

Additional recommendations for the helium or neon pulse / mass spectrometer method are given in Box K.

Box K - Additional Recommendations for Helium / Neon Pulse Method

1. The response signal should be extracted sequentially from a number of points across the outlet from the QSCZ. Where the QSCZ is symmetrical it should be acceptable to use tubes on one side of the centre line.

2. A reference compensation pulse should be employed.

3. The extraction sampling line should be as short as practicable.

4. The residence time should be taken as the time displacement between the peak responses of the main injection and reference pulses.

5. Alternatively, the system residence time can be taken, after correction for the reference pulse

5 For each test condition the residence time data should be averaged for each injection and extract point and a profile produced

Additional recommendations for the pseudo random pulse method are given in Box L.

Box L - Subsidiary Recommendations for Pseudo Random Pulse Method

1. A cross duct fast response detector should be used and this should be free of interference from radiating particles.

2 Cross correlation techniques should be used to compare the perturbation and process impulse response signal

3. The sampling rate should be fast enough to extract all the available information in the input signal and two to four output data samples per pseudo random binary sequence bit should be acceptable.

4. For each test condition the peak or system residence time data should be averaged for each injection point and a profile produced.

6.2.2 Temperature proving for new plant

As residence time for new plants is to be measured by time of flight, it is therefore only necessary to measure the temperature at the outlet from QSCZ. The recommendations for temperature proving are given in Box M.

Box M - Recommendations for Temperature Proving (New Plant)

1.Gas temperature traverse measurements should be required at (or shortly after) the end of the QSCZ for each condition so that the lowest temperature location can be identified.

2. Where furnace sections are asymmetrical it should be acceptable to traverse only half way across the furnace.

3. Gas temperatures should be monitored and recorded continuously at the lowest temperature location over each test period (at least 1 hour) and reported as 1 minute means.

4. The use of suction pyrometers should accepted as the reference technique for proving furnace gas temperatures. Therefore, data collection should be allowable in 10 minute sub-tests as per Box I.

5. Other systems such as acoustic pyrometers, and shielded thermocouples should be allowed but only if they are calibrated against a suction pyrometer and the appropriate corrections applied.

6. For an acceptable test it is recommended that at least 95% of the corrected 1 minute means should be meet the stated minimum temperature requirement.

6.2.3 Monitoring positions for new plant

It is recommended that new plant meet the full requirements for providing ideal monitoring port access, as given in Section 4.2.3, Table 2 (for time of flight residence time measurement method).

6.3 Recommendations for existing plant

Some existing plant may be able to meet the full recommendations for monitoring as per new plant. However, the engineering modifications required to be able to follow the same monitoring approach is likely to be impracticable due to technical difficulties or prohibitive cost. Consequently, an alternative approach is recommended for existing installations.

6.3.1 Residence time proving for existing plant

The main recommendations are given in Box N below:

Box N Main Recommendations on Proving Residence Time
1. Existing plant should be required to measure **mean** gas residence times during proving tests by monitoring the mean gas flow rate through the QSCZ, and assume plug flow.
2. The measurement procedure outlined in Section 3.2.1.2 (iii) is recommended. It will require the continuous measurement of both bulk mean furnace chamber gas temperatures and the QSCZ outlet temperature, together with the periodic determination of moisture and oxygen content of the furnace chamber gases.
3. Stack (or boiler outlet) gas flow should also be simultaneously and continuously measured at a single point over the same 1 hour test period. The location chosen should be shown to be representative by undertaking a preliminary traverse as per BS 3405.
4 Simultaneous continuous measurements should also be made in the stack (or boiler outlet) for temperature, pressure and oxygen / and or carbon dioxide. Only periodic determination of stack (or boiler outlet) moisture content is necessary.
5. The measured mean gas flow rates should be averaged over 1 minute intervals and mean gas residence time at furnace conditions computed. The resulting 1 minute means should be plotted over at least a 1 hour test period.
6 Residence time performance should be accepted if at least 95% of the 1 minute mean data meet the 2 second requirement and the temperature minimum is satisfied.

6.3.2 Temperature proving for existing plant

The recommendations for temperature monitoring at existing plant should take into account the need to measure temperatures at following three locations:

(i) in the centre of the QSCZ to provide an estimate of the bulk mean temperature;
(ii) at the outlet from the QSCZ to prove the minimum temperature requirement is satisfied; and
(iii) in the stack or boiler outlet to allow accurate calculation of gas velocity.

Our recommendations for temperature proving are given in Box P.

Box P - Recommendations for Temperature Proving (Existing Plant)

a. Bulk Mean Gas Temperature (BMGT)

1. Continuous temperature measurements should be required near the centre of the QSCZ during the proving tests to provide the bulk mean gas temperature (BMGT).
2 The exact location of the measurement position should not be considered critical as only an estimate is needed of the BMGT.
3. Measurement by suction pyrometer, shielded thermocouple, infra-red pyrometer, acoustic pyrometer should all be acceptable, but corrections should be applied where appropriate.
4. If measurement of BMGT is not practicable then estimation by other means it should be allowed

b. QSCZ Outlet Temperatures

5.Gas temperature traverse measurements should be required at (or shortly after) the end of the QSCZ for each condition so that the lowest temperature location can be identified for the tests.
6 Where access to the ideal location is not practicable then a compromise location should be considered and corrections applied. .
7 Where furnace sections are asymmetrical it should be acceptable to traverse only half way across the furnace.
8. Gas temperatures should be monitored and recorded continuously at the lowest temperature location over each test period (at least 1 hour) and reported as 1 minute means.
9. The use of suction pyrometers should accepted as the reference technique for proving furnace gas temperatures. Therefore, data collection should be allowable in 10 minute sub-tests as per Box I.
10. Other systems such as acoustic pyrometers, and shielded thermocouples should be allowed but only if they are calibrated against a suction pyrometer and the appropriate corrections applied.
11. For an acceptable test it is recommended that at least 95% of the corrected 1 minute means should be meet the stated minimum temperature requirement.

c. Stack or Boiler Outlet Temperatures

12. Stack or boiler outlet temperatures should be monitored continuously at a single representative point over the same period.
13. The point should be chosen after traversing in line with BS 3405. Use of an appropriate a thermocouple should be acceptable.

6.3.3 Monitoring Positions for Existing Plant

It is unlikely that existing plants will be able to meet the full ideal monitoring access requirements, as given in Section 4.2.3, Table 2 (for gas volume flow methods). It is recommended that Regulators apply some latitude, but should recognise that even after applying corrections the uncertainty in the final results may be considerable.

7 REFERENCES

Environment Agency 1996	IPC Guidance Note S2 5.01, Processes subject to integrated pollution control- waste incineration, Environment Agency, 1996, HMSO.
EC 2000	New WID Incinerator Directive
EC 1989 a	Directive on the prevention of air pollution from new municipal waste incinerators, (89/369/EEC), (OJL 163, 14/6/89, p32)
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