DEVELOPMENT OF A SMALL-SCALE, SIMPLE AND ROBUST MEDICAL WASTE INCINERATION SYSTEM

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ABSTRACT

Incineration is conceptually sound and offers advantages as a waste treatment technology. There is, however, concern over its air emission resulting from improper design and operation. This paper describes the development of a small-scale (50 kg/h) medical waste incineration system to meet a specific set of air emission limits and design criteria of simplicity and robustness.

The rationales for the selection of the combustion chamber design and operation, and the scrubber are described, as well as the results of the commissioning and performance testing. These include the operating protocol to eliminate the "black-smoke" problem, the selection of wet venturi as the scrubber and the elimination of carry-over liquid droplets from the scrubber.

The system met not only the target performance criteria, but also guidelines that were developed for large incinerators operating in a developed country. Highlights included concentrations of particulate matter of < 20 mg/m^3, hydrochloric acid of < 3 mg/m^3 and carbon monoxide of < 5 ppm, with the latter corresponding to combustion efficiencies of > 99.99%.

INTRODUCTION

Incineration of medical and other combustible wastes reduces the volume and mass for final disposal. Furthermore, it "destroys" toxic organic compounds and pathogens in the waste and it also offers the potential for recovery of energy and materials. In some jurisdictions, incineration has been designated as one of the preferred waste management technologies. There is, however, a well-recognized and well-founded concern over its air emission that results from improper design and operation. The pollutants of concern include particulate matter, acid gases and products of incomplete combustion, such as chlorinated dioxins and furans.

Recognizing both the above factors, we postulate that successful applications of incineration, especially in the developing countries, require *simplicity* and *robustness* as criteria for design, operation and performance. Simplicity refers to ease of manufacture, operation and maintenance, which manifest in low capital and operating costs. Robustness refers to capability of meeting regulatory standards under a wide variety of operating conditions. Also, we contend that the development of such an *appropriate technology* for waste incineration is still needed.

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This paper describes the design considerations, the commissioning and the performance testing of a *small-scale* medical waste incineration system to meet a set of operating and air emission requirements. For various commercialization reasons, the regulations in India were used. Comparison with other jurisdictions is also made to show the scope of the resulting system.

PERFORMANCE CRITERIA

Table 1 is a summary of the performance criteria. These were taken from the previous version of the Indian regulations.[1] Notice therefore the relaxation in requirements for some of the parameters, most notably in combustion efficiency.

Table 1. Design, Operating and Air Emission Requirements

ITEM	SPECIFICATION
Design configuration	
Combustion chambers	Dual chamber
Operating conditions	
Combustion Efficiency (CE) ▪ CE = %CO_2 / (%CO_2 + %CO)	> 99.99% (99%)(a)
Primary chamber temperature, °C	800 ± 50
Secondary chamber ▪ Gas residence time, sec ▪ Temperature, °C ▪ Oxygen in stack gas, % vol.	 > 1 1050 ± 50 > 3
Pollutants in flue gas (b)	
Particulate Matter (PM)	< 100 (150) (a)
Nitrogen Oxides (NO_x)	< 550
Hydrochloric Acid (HCl)	< 50
Sulphur Dioxide (SO_2)	< 150 (not specified) (a)

(a) Values in brackets are in the current Indian regulations; (b) mg / Nm^3 corrected to 12 % CO_2 (dry)

Two other criteria were also set: (i) a target capacity of 50 kg/h for medical waste over an 8-h operation, (ii) transportability to allow the dismantled components to be placed in a 2.4 m × 2.4 m × 6.1 m container.

OVERVIEW OF DESIGN AND OPERATION

Table 2 is a summary of the main considerations in the design and operation of the system. An elaboration on the major items is given in the following.

Table 2. Main Design and Operating Considerations

ITEM	CONSIDERATION	RESULT
1. System configuration	Need for a scrubber?	▪ Yes ▪ ID Fan, Dump Valve
2. Waste charging and ash removal	Simplicity	Manual, intermittent
3. Configuration and operation of combustion chambers	▪ Complete combustion ▪ Low PM emission(a)	▪ ARC design in geometry and combustion air entries ▪ Starved-air
4. Primary chamber size/geometry	▪ Heat release ~ 450-670 MJ/h/m^3; ash retention for 8-h operation ▪ Area ~ 60-80 kg/h/m^2	▪ Volume: 1.5 m^3 ▪ H/D = 1.36
5. Secondary chamber size/geometry	▪ Gas residence time of 1 second ▪ L/D "rule of thumb"	▪ Volume: 0.7 m^3 ▪ L/D ~ 3/1
6. Scrubbing system	▪ Removal efficiency ~ 90% ▪ Cost, ease of operation; number of components; clogging and erosion ▪ Ease of pH control	▪ Venturi wet scrubber, with lime as scrubbing chemical
7. Miscellaneous		
▪ Auxiliary fuel	▪ Local requirement	▪ Diesel
▪ Stack	▪ Min. gas velocity (~ 7m/s) & L/D (~ 10/1) for compliance testing	▪ 25 cm dia ×3 m high
▪ Refractory and Insulation	▪ Heat losses (fuel consumption), safety and weight	▪ 11.4 cm and 7.6 cm thick
▪ Safety interlocks, control panel, burners, blowers, pump and fan specifications	▪ Common engineering practice	▪ (Various)

(a) PM: Particulate Matter

System Configuration

A scrubber is needed to meet the target levels of particulate matter (PM) and hydrochloric acid (HCl). In turn, this requires an induced draft (ID) fan to transport the flue gas through the scrubber and the stack. For safety, a "dump valve", located upstream of the scrubber, is also needed to discharge the flue gas in case of scrubber or fan malfunction.

The system, incorporating the above considerations and the requirement for dual chamber configuration (Table 1), is shown schematically in Figure 1, and its photograph in Figure 2. The waste is charged into the primary chamber, into which under-fire air is also introduced to support partial combustion.[*] Combustible gases (and in many cases, also soot) are generated in the primary chamber which are combusted in the secondary chamber. To support this combustion, flame-port air is introduced in the transfer duct.

The resulting flue gas is withdrawn by an ID fan through a scrubber, where PM and acid gases are removed, and discharged to the atmosphere via a stack. In case of scrubber or fan failure, the dump valve automatically opens to allow emergency venting of the flue gas.

During start-up and in cases where the waste has insufficient calorific values, auxiliary burners are used to maintain temperatures in the primary and secondary chambers within the target values.

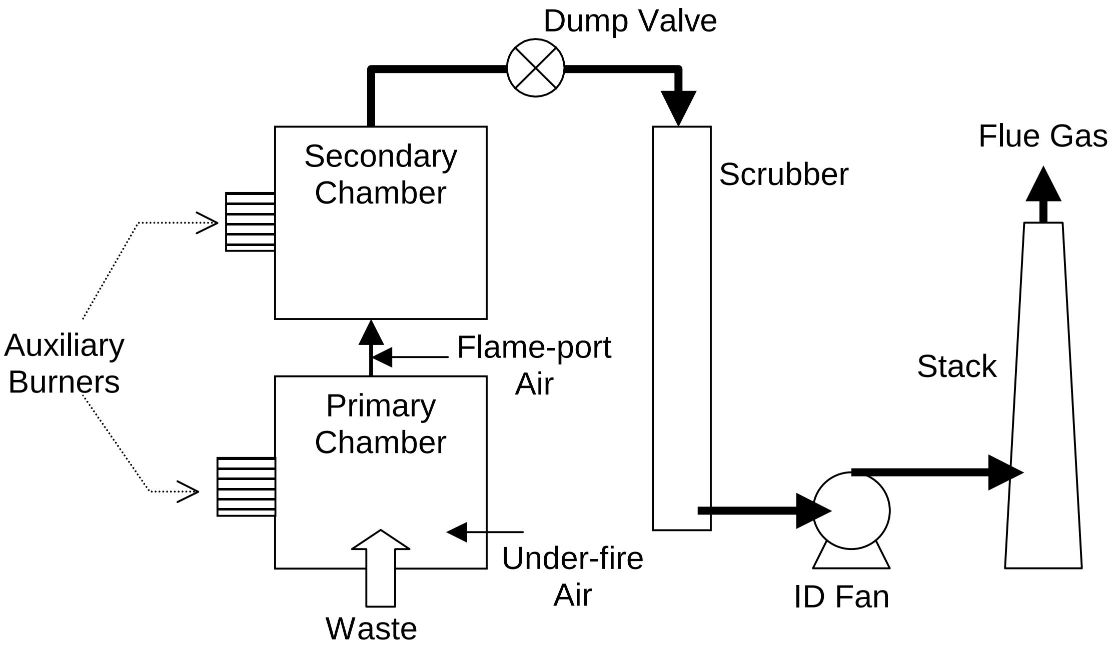

Figure 1. Major Components in the Incineration System

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[*] Terms shown in Figure 1 are underlined when they first appear in the text.

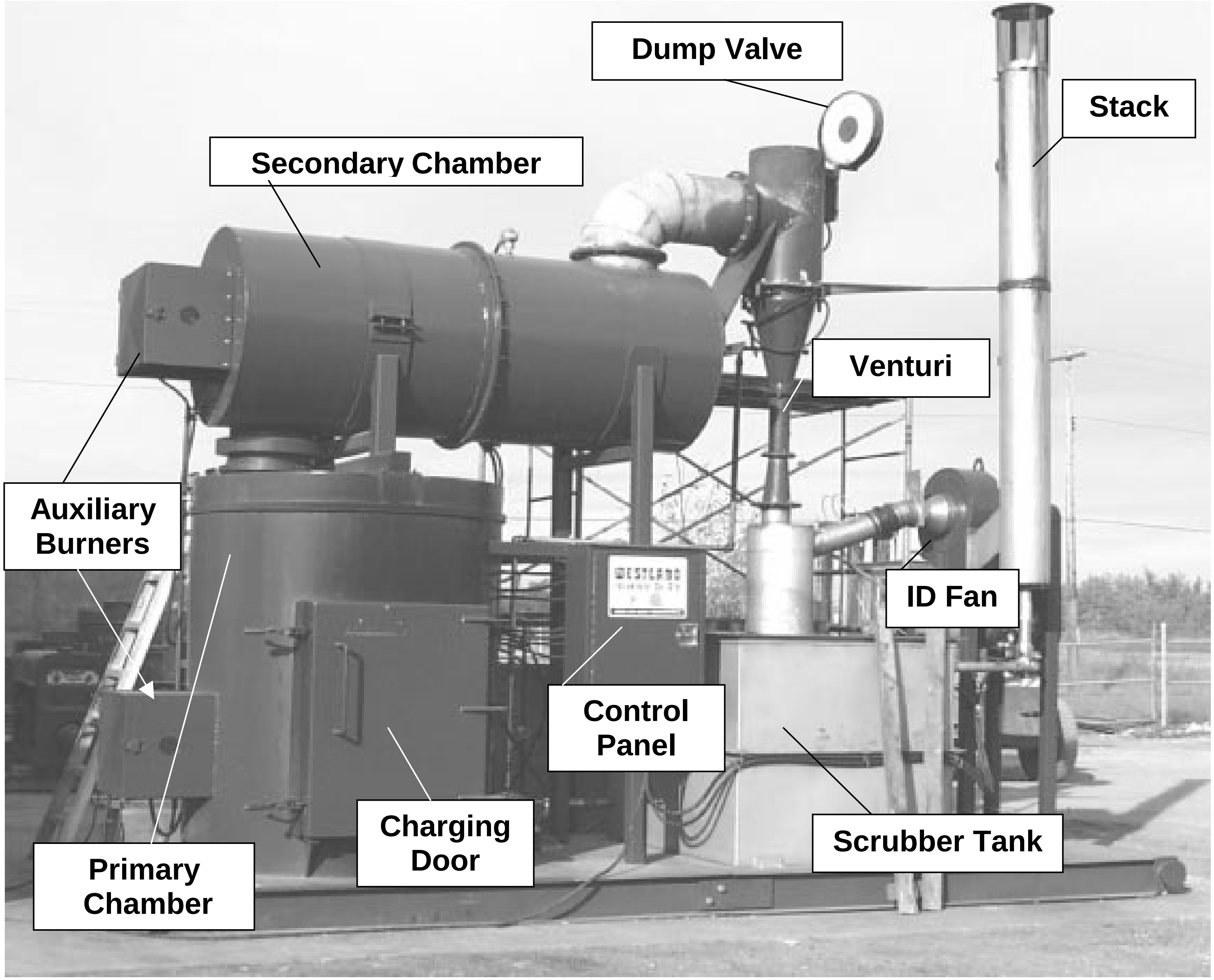

Figure 2. Photograph of Incineration System

Waste Charging and Ash Removal

The target capacity is too small to warrant automated waste feeding and ash removal. Thus manual, intermittent method was selected. The waste charging frequency will be discussed later, and ash removal is conducted on the following day after the end of the 8-h operation

Configuration and Operation of Combustion Chambers

Considerable experience was gained in the operation of the ARC's pilot incineration system. Of particular note was the high levels of combustion and destruction efficiencies that were achieved despite the short residence time (~ 0.2 s) in its secondary chamber. Various halogenated compounds were destroyed with > 99.9999% efficiencies, and concentrations of chlorinated dioxins and furans of < 0.1 ng (TEQ)/m^3 were achieved.[2, 3] This was attributed to the excellent turbulence and mixing of the combustible gases produced in the primary chamber and the flame port air.

The key design features adopted were the geometric configuration, with an upright primary chamber and a horizontal secondary chamber, and the entries of the under-fire and flame-port air.

The starved-air operation, where only about 30% of the air needed for complete combustion is supplied in the primary chamber, was adopted for the following reasons:

- low gas flow in the primary chamber minimizes PM entrainment, and hence PM emission;
- evolution of combustible gases and soot can be controlled by regulating the under-fire air;
- combustion in the secondary chamber can be enhanced by proper design of the flame-port air entry to promote mixing and turbulence.

The latter two features are critical in eliminating the "black smoke" problem that often plagues this type of incinerator. This will be discussed later.

Combustion Chambers

Well-established design criteria in terms of volume and area (aspect ratio) for the primary chamber are available, cited for example in Reference 4.[4] The secondary chamber volume was computed on the basis of design capacity, temperature and excess air (oxygen in flue gas) requirements to meet the target gas residence time of 1 second.

Scrubbing System

Preliminary tests and literature information indicated the need for PM removal efficiency of about 90%. The following options were evaluated and rejected. A bag-house or an electrostatic precipitator was considered too costly and too complicated to operate. Cyclonic separators, while simple and inexpensive, would not likely meet the required performance. Reported maximum removal efficiencies for cyclones are 77% and 42% for 2 μm and 1 μm particles, respectively.[5]

The remaining option of wet scrubbing and the use of a venturi seemed to be suitable on the basis of simplicity and flexibility. With respect of the latter, the removal efficiency can be increased by reducing the venturi “throat” diameter (thereby increasing pressure drop) to about 97% for 1 μm particle.[5] Furthermore, a venturi acts very effectively as a quencher, thereby eliminating the need for a spray nozzle, which is prone to clogging and erosion. Reference 6 was used as basis for the design of the venturi geometry.[6]

Lime was selected as the scrubbing medium on the basis of cost and convenience. It is readily available, inexpensive and can be added intermittently to eliminate the need for a sophisticated pH control system. The absence of the potential for clogging in the scrubbing system was also an important consideration in the selection.

COMMISSIONING

Elimination of “Black Smoke” and Other Operating Strategies

Small-scale, intermittently charged incinerators are prone to the “black smoke” problem, which is the presence of unburned soot in the flue gas. Typically, this occurs when the evolution of combustible gases and soot in the primary chamber is so rapid that there is insufficient oxygen in the secondary chamber for complete combustion.

The occurrence of the “black smoke” problem and its solution can be better understood by observing the temperature “profiles” (change with time after waste charging) in the primary and secondary chambers, as shown in Figure 3.

The profiles can be divided into three distinct stages, as shown in Figure 3 and described in Table 3. The actual profiles will vary depending on waste composition and other operating conditions, but the pattern is qualitatively universal for dual-chamber, starved-air and intermittently charged incinerators.

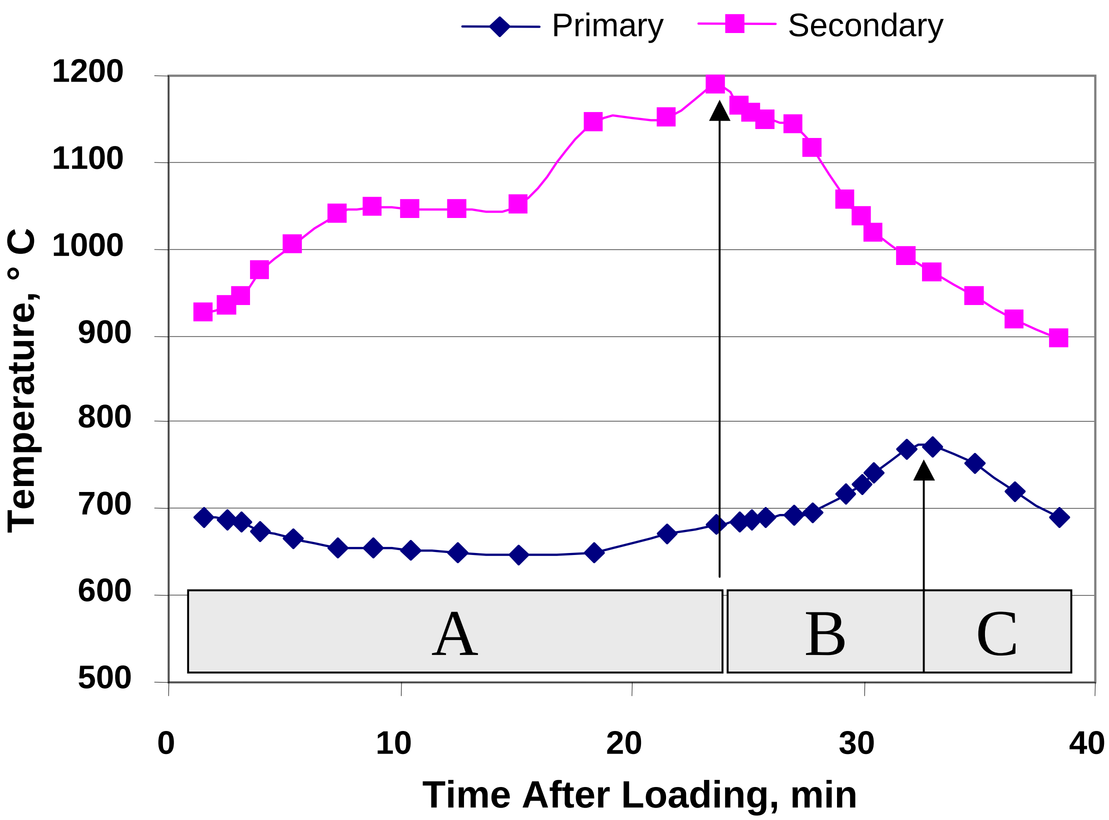

Figure 3. Temperature Profiles After Waste Charging
(25 kg charge of biomedical waste)

Table 3. Combustion Characteristics

Stage	Phenomenon	Pattern*		Remarks
		PC Temperature	SC Temperature	
A	Evolution of combustible gases and soot (cg&s) in PC with subequent combustion in SC, and also, evaporation of water in PC	Varies and may temporarily drop due to door opening, and after the door is closed, evaporation of water in the waste	May temporarily drop due to door opening, then rises very rapidly due to cg&s combustion	▪ Insufficient flame-port air in SC causes “black smoke” ▪ Evolution of cg&s is slowed down by minimizing under-fire air ▪ Very wet load may require auxiliary burner operation
B	End of cg&s evolution, start of combustion of carbonaceous matter in PC	Rises due to combustion of carbonaceous matter	Drops (no more cg&s combustion)	▪ More under-fire air to increase combustion in PC ▪ Less flame-port air to reduce SC cooling
C	End of combustion (practically, there may be carbonaceous matter not readily accessible by oxygen)	Drops (no more combustion)	Drops (no more combustion)	▪ Less unde-fire and flame-port air to reduce cooling ▪ Signal for preparation for the next load

PC: primary chamber; SC: secondary chamber

Also included in Table 3, under “Remarks”, are the operating strategies that can be used not only to eliminate “black smoke”, but also to conserve auxiliary fuel and to increase capacity. These include the following:

- Stage A. Regulating the under-fire air to ensure that the maximum flame-port air is sufficient for the combustible gasses and soot generated in the primary chamber. This would eliminate the black smoke problem.
- Stage B. Increasing the under-fire air for combustion of carbonaceous matter in the primary chamber, and decreasing the flame port air. This would increase the combustion rate in the primary chamber (hence the incinerator capacity) and conserve auxiliary fuel use in the secondary chamber by reducing the cooling effect of the flame-port air.
- Stage C. Decreasing both the under-fire and flame-port air. This would conserve auxiliary fuel and could be used to initiate timely waste charging, thereby also increasing capacity.

An operating protocol was developed and in the process of being automated on the basis of the understanding of the above phenomena.

Scrubber Operation

Quenching. The hot gas exiting the secondary chamber, at up to 1200°C, was consistently cooled to < 80°C, corresponding to its adiabatic saturation temperature. This eliminates the need for a spray nozzle, which is prone to plugging and erosion. In turn, this allows the use of lime as scrubbing chemical. The selection of a venturi thus fulfills the design criteria of simplicity.

Droplet carry-over. Removals of PM and acid gases are attributed to the generation of fine liquid droplets in the venturi throat through which the flue gas flows at a high gas velocity (~ 200 km/h). These liquid droplets, unless separated and removed from the flue gas, would be carried over though the ID fan and the stack, causing these two undesirable consequences: (i) the dissolved solids in these droplets would contribute to PM emission, and (ii) an increased load to the ID fan, adversely affecting its operation and lifetime.

In the initial design, where no droplet removal unit was present, excessive droplet carry-over occurred. This was indicated by the “laboured” operation of the ID fan and the large rate of condensate return flowing from the stack to the scrubber tank.

An often-used device to remove these droplets is a “mist eliminator” or “demister”, which consists of “packing” where the droplets coalesce by impingement and are then separated from the flue gas. But such a device is prone to clogging, and furthermore, re-entrainment occurs, rendering it ineffective.

The above option was rejected in favour of a method based on *inertial* and *gravitational separation*. In essence, it is based on forcing the flue gas to undergo abrupt changes in direction, and on reducing the gas velocity prior its entry to the ID fan to ~ 15 km/h. This method proved to be very successful in effectiveness and simplicity. The ID operation became noticeably "smooth", the condensate return flow from the stack was minimal, and as shown later, the PM emission met regulatory compliance. And, the unit can be readily manufactured and requires no maintenance to prevent plugging or clogging.

Heat recovery potential. The quenching of the hot flue gas was achieved by evaporation, thus converting the sensible heat of the flue gas to the latent heat of the moisture in it. This "low level" heat could be recovered in the form of hot water in a condensing heat exchanger. The potential for heat recovery was about 525 MJ/h (500,000 Btu/h) based on the measured evaporation loss of about 4 L/min.

PERFORMACE TESTING

Capacity for an 8-h operation

Waste batches. During commissioning it was suspected that the composition of biomedical waste, obtained from a local waste collector, varied a great deal amongst different batches. This was deduced by the large variation in how the incinerator was operated to prevent the occurrence of "black smoke". Of particular importance were the contents of the waste components that produced combustible gases and soot, such as plastics and rubber.

Pre-sorting to produce "representative" biomedical waste in each batch was not possible. Therefore, there was the risk of testing with non-representative batches, thereby producing misleading results. The approach taken was to use domestic waste and "spike" it with plastics and rubber to produce a composite with *at least* the average contents of plastics and rubber in biomedical waste. The rationale was (i) to ensure minimum contents of plastics and rubber in all the batches tested, and (ii) to avoid exceedingly high contents of plastics and rubber in any of the batch tested. (It was suspected that some of batches used during commissioning contained practically only plastics and rubber.)

Capacity definition. The capacity is expressed as "running average", as defined below:

$$W_n = \sum_{i=1}^{n} L_i \,/\, (t_{n+1} - t_1)$$

where W, L and t denote capacity (kg/h), load size (kg) and time of charging (h), respectively, and subscript i denotes the i^{th} charge, ranging in values from i = 1 (the first charge), through n (the variable charge) to N (the last charge). The time t_{N+1} corresponds to a "hypothetical" time, when the incinerator would be ready for the next charge if there were one.

Results. The conditions for the tests and the results are summarized in Table 4 and Figure 4. The 8-h capacity results for the two tests were 52.0 and 55.4 kg/h (400 kg/7.6h and 400 kg/7.2h), thus exceeding the target capacity of 50 kg/h. The results also indicate the robustness of the system in handling variations in batch size, charge frequency and contents of plastics and rubber. Notice also that a short period of testing could produce misleading results. For example, as shown in Figure 4, a 1-h test in the beginning would produce a capacity of about 65 kg/h.

Therefore, it is important that a capacity value be qualified with parameters such as averaging time, duration of the operation and some description of the waste composition.

Table 4a. Conditions for 8-h Capacity Testing

Test	Waste Composite Composition (wt%)			Estimated Contents (wt%)		Nominal Charge Rate
	Domestic	Plastics	Rubber	Plastics	Rubber	
A	81.6	16.9	1.5	23.3	1.5	25-30 kg/(30 min)
B	88.5	10.5	1.0	17.9	1.0	17-20 kg/ (20 min)

(a) 7.4% plastics and 0% rubber in domestic waste; biomedical waste in the U.S. contains 14.2% plastics and 0.7% rubber.[7]

Table 4b. Results of 8-h Capacity Testing

Test	Ash (wt%)	8-h Capacity (kg/h)
A	7.0	52.0
B	8.3	55.4

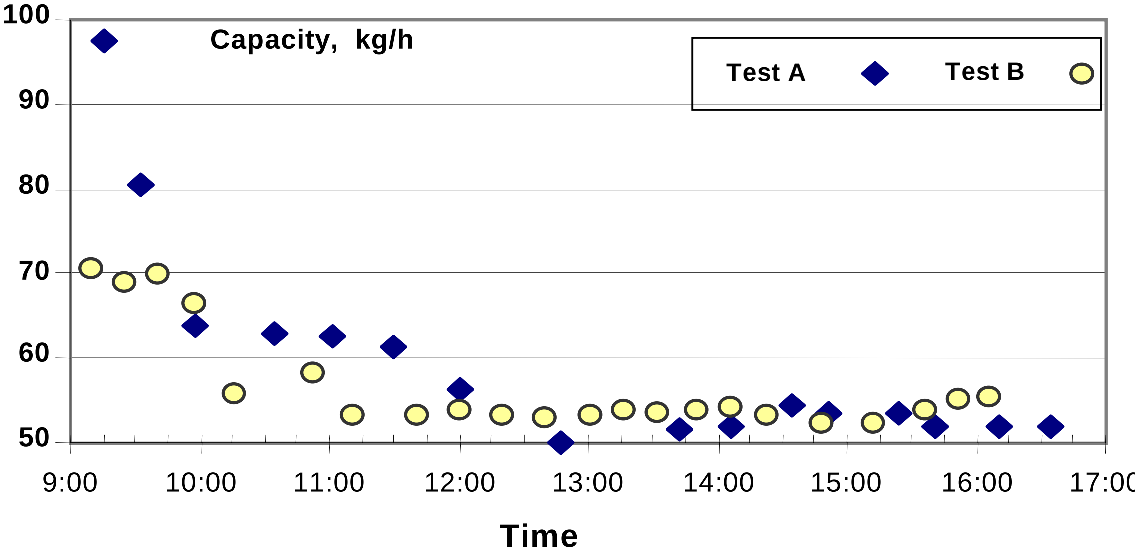

Figure 4. Running Average Capacity during an 8-h Operation

Regulatory Compliance

Test Description. The following combustion and emission parameters were measured: O_2, CO_2, CO, H_2O, particulate matter (PM), HCl, Cl_2, SO_2, and NO_x. Flue gas temperature, pressure and flow rate were also measured for computations of concentrations and emission rates. All the sampling and analysis were conducted in accordance with the Alberta Stack Sampling Code[8] by an independent and consultant that has been certified by the Canadian Association of Environmental Analytical Laboratories.

Two tests, each consisting of triplicate measurements, were conducted. In the first (Test C), all the above-mentioned parameters were measured. As will be shown later, very good results were obtained for HCl, SO_2 and NO_x (Cl_2 not regulated) and hence these were not repeated. In the second (Test D), the PM removal in the venturi was improved by reducing its throat diameter from 10.2 to 7.6 cm.

“Simulated” biomedical waste was used for the same reason as that given for the 8-h capacity tests, with composition and batches similar to those in the Test B (Table 4a).

Meeting target performance. Table 5 is a summary of the test results and comparison of with the target performance criteria shown in Table 1.

Table 5. Compliance Test Results vs. Performace Criteria

Item	Results		Target
	Test C	Test D	
Combustion Efficiency, %	99.994	99.995	> 99.99
Primary Chamber Temperature, °C	800-900	690-800	800±50
Gas Residence Time in Secondary Chamber, second	0.9	1.1	> 1
Secondary Chamber Temperature, °C	1000-1100	1050-1200	1050±50
Oxygen in Flue gas, %vol (dry)	11.6	11.8	> 3
Particulate Matter (PM), mg/m^3	146	20	100
Hydrochloric Acid (HCl), mg/m^3	6.0	n/m	< 50
Sulphur Dioxide (SO_2), mg/m^3	22.3	n/m	150
Nitrogen Oxides (NO_x), mg/m^3	287.1	n/m	550

n/m not measured; all pollutant concentrations on a dry, standard basis, corrected to 12%CO_2; CO_2 in flue gas = 5.7-7.3 % vol.

Notice that in Test C, *only* the PM concentration at 146 mg/m^3 did not meet the target performance criterion of 100 mg/m^3. But this could be readily corrected by simply reducing the throat diameter of the venturi, as shown in the results of Test D, where a PM concentration of 20 mg/m^3 was obtained. The flexibility of the scrubbing system has thus been demonstrated.

Another highlight of the results was the high combustion efficiencies (> 99.99%) that were achieved, which corresponded to concentrations of CO of < 5 ppm vol (dry). It has been suggested that low CO concentrations are one of the indicators for low concentrations of chlorinated dioxins and furans. The results of tests conducted at the ARC's pilot plant, on which the current system's design was based, seem to support that contention, as shown in Table 6.

Table 6. Emissions of CO and PCDDs and PCDFs in ARC's Pilot Plant [2, 3, 9]

Waste Incinerated	Carbon monoxide ppm vol (dry)	PCDDs/PCDFs ng (TEQ)/m^3	Ref.
MSW (processed as RDF)	5	< 0.1	2
1,2,4 trichlorobenzene and tetrachloroethylene (10% wt Cl)	6	< 0.1	2
Freon 12 (4% wt F)	2	< 0.5	3
Salted wood waste (bark)	22	3.2	9
Wood waste (bark)	11	0.02	9

It is significant to note, therefore, that high combustion efficiencies could be achieved at relative low gas residence times in the secondary chamber, about 0.2 second in the ARC's pilot plant and 1 second in this system.

Comparison with other regulations and guidelines. To offer a perspective of the performance of the system, a comparison is made with the current Indian[1] regulations and the Canadian[10] and Albertan[6] guidelines. The Canadian (CCME) guidelines were developed for large municipal incinerators, hence they are quite strict. On the other hand, the Albertan (AEUB) guidelines target small incinerators operating in oil fields, hence they are less strict.

A convenient graphical representation of the comparison is to use the ratio of the actual pollutant concentration to its respective limit in each jurisdiction. This eliminates the confusing factor of different bases used for expressing flue gas volume in different jurisdictions, such as correction to x% CO_2 or y% O_2. The results are shown in Figure 5

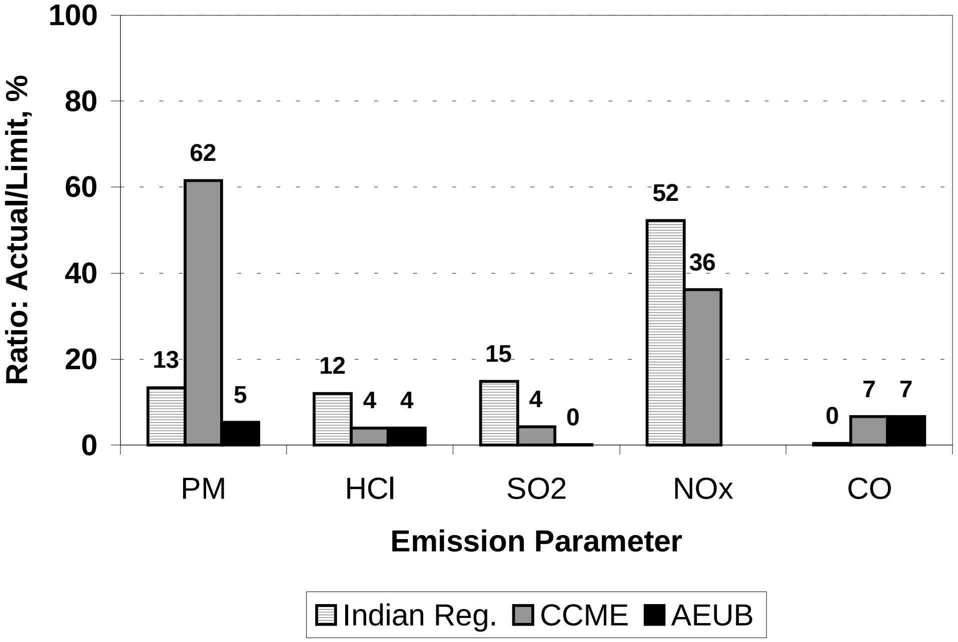

Figure 5. Comparison Between Actual Concentrations and Regulatory Limits and Guidelines (PM: particulate matter; HCl: hydrochloric acid; SO2: sulphur dioxide; NOx: nitrogen oxides; CO: carbon monoxide; CO limit for Indian Regulation computed at the specified limit of 99% combustion efficiency; no NOx limit in AEUB.

In the interpretation of the results, note that:

- a ratio of < 100% indicates compliance, and conversely > 100% non-compliance;
- a lower ratio indicates better performance;
- for each pollutant, the relative strictness of different jurisdictions can be readily seen: since the same pollutant concentration is used, a larger ratio indicates stricter (lower) limit.

Notice, therefore, that this small-scale and simple system could meet guidelines that were set for large incinerators operating in a developed country.

CONCLUDING REMARKS

The objective of developing an appropriate incineration system which is simple and robust has been met. The system met, not only the target performance criteria, but also guidelines that were developed for large incinerators operating in a developed country. Another highlight was the achievement of high combustion efficiencies of > 99.99%.

These performance criteria were achieved under a wide range of operating conditions using simple components capable of:

- eliminating the “black smoke” problem by controlling the release of combustible gases and soot in the primary chamber, and effectively mixing them with flame-port air for “complete” combustion;
- quenching hot flue gas and removing particulate matter and acid gases in one unit;
- eliminating liquid droplet carry-over without plugging or clogging problems;
- scrubber operation without a sophisticated pH control system.

The present system is limited in that it is small-scale, and uses manual intermittent waste charging. However, the knowledge gained in achieving high combustion and scrubbing efficiencies can be readily transferred to larger systems employing different waste feeding methods.

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