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The National Incinerator Testing and Evaluation Program: Two-stage Combustion (Prince Edward Island)

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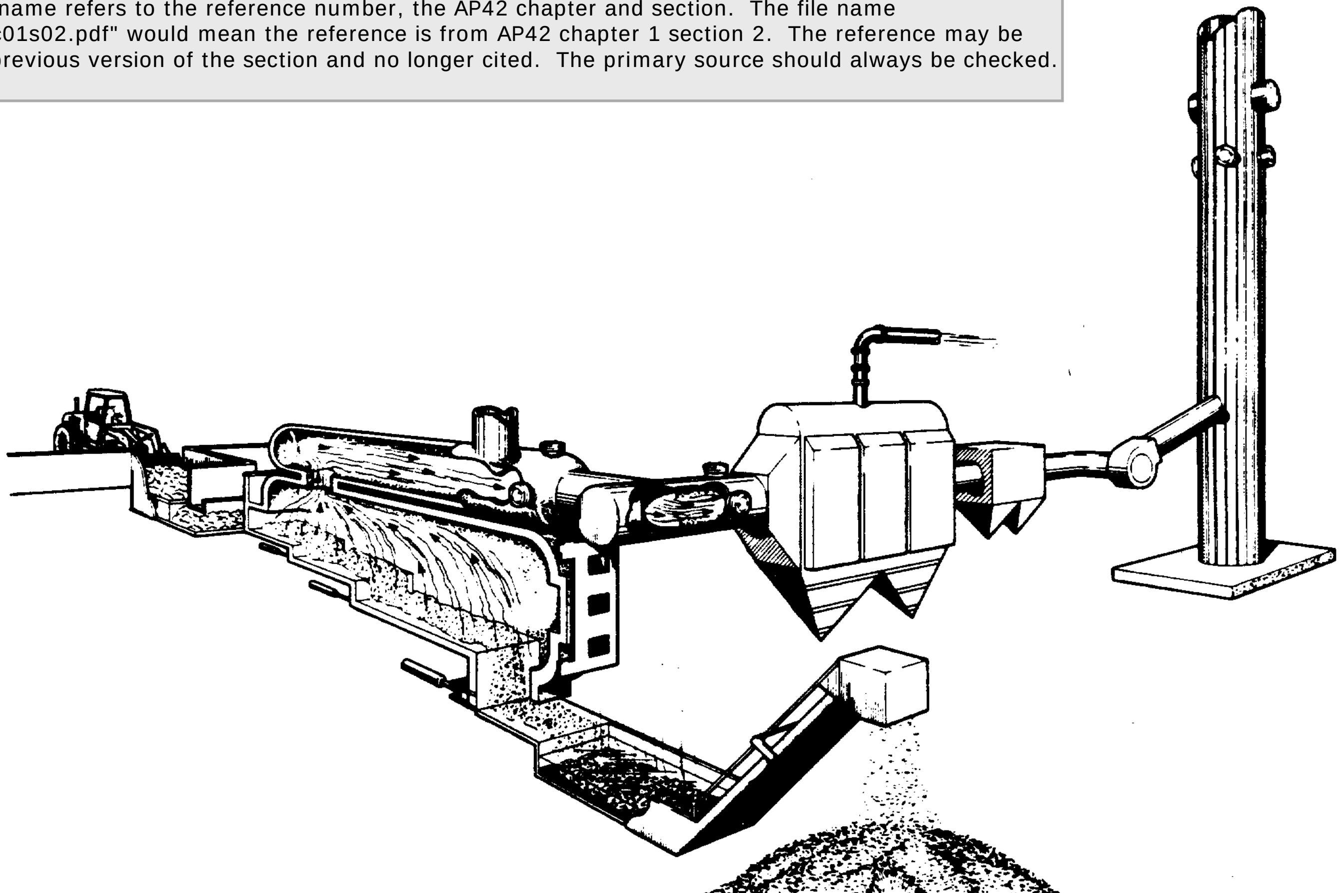
Report EPS 3/UP/1
September 1985



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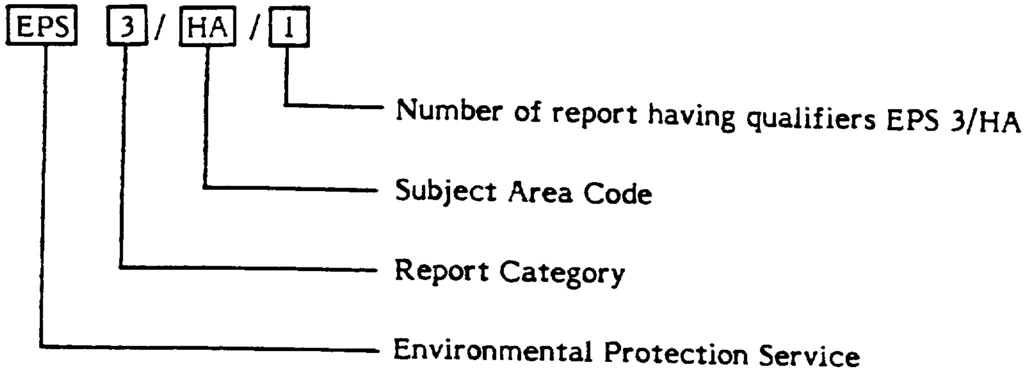

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THE NATIONAL INCINERATOR TESTING AND EVALUATION PROGRAM:

TWO-STAGE COMBUSTION (PRINCE EDWARD ISLAND)

Summary Report

Urban Activities Division
Environmental Protection Service
Environment Canada

Report EPS 3/UP/1
September 1985

COMMENTS

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ABSTRACT

The results of an emissions testing program conducted at the municipal solid waste incinerator in Parkdale, Prince Edward Island, are summarized in this report. These tests were the first in a series being carried out under the National Incinerator Testing and Evaluation Program (NITEP).

The Parkdale energy-from-waste (EFW) plant consists of three two-stage controlled air combustion incinerators with flue gas heat recovery. The field tests were divided into two parts: characterization, to develop an understanding of the incinerator operation, and performance, to examine the effects of various operating conditions on emissions from the incinerator. Parameters examined during characterization testing were primary and secondary chamber temperatures, ram cycles, and refuse loading rate and frequency. The main process variable adjusted during the performance tests was secondary chamber temperature. Emissions of concern were organics, including dioxins/furans; acid gases; particulates; and metals.

Secondary chamber temperature appeared to affect a number of the organic and metal emissions. At high temperatures, organic emissions were lowest; however, the highest metals emissions occurred at these temperatures. Emissions of dioxins/furans were within the lower range of previously published values. Hydrogen chloride emissions were typical of those found at other EFW facilities. Particulate emissions were low in comparison to uncontrolled emissions from conventional (mass burning) incinerators. In general, it was concluded that good design and proper operation can minimize emissions of concern from two-stage combustion systems.

No attempt has been made in this report to assess either the health or environmental impacts of the findings. These will be ongoing program activities at Environment Canada. This report is primarily intended to define the technological capability of two-stage combustion processes for municipal solid waste destruction and energy recovery, and the emission levels resulting from such operations.

RÉSUMÉ

Dans le présent rapport, sont résumés les résultats d'un programme d'essais (les premiers du Programme national d'essai et d'évaluation des incinérateurs) des émissions de l'incinérateur de déchets urbains solides de Parkdale, Île du Prince Edouard.

L'installation intégrée de Parkdale comprend trois incinérateurs à deux étages, à air contrôlé et à récupération de la chaleur des gaz de combustion. Les essais sur place étaient divisés en deux parties: les essais de caractérisation visant à comprendre le fonctionnement de l'incinérateur; les essais de performance visant à étudier l'effet des variables opératoires sur les émissions. Dans le premier cas, les paramètres étudiés ont été la température des chambres de combustion primaire et secondaire, le volume enfourné et la fréquence d'enfournement; dans le second cas, la principale variable a été la température de la chambre secondaire. Les émissions examinées ont été les matières organiques, y compris les dioxinnes et les furannes; les gaz acides; les particules; et les métaux.

La température de la chambre de combustion secondaire a semblé influer sur l'émission d'un certain nombre de matières organiques et de métaux. Quand elle a été élevée, les émissions organiques ont été minimales, les métalliques maximales. Les émissions de dioxinnes et de furannes se sont maintenues dans la plage inférieure des valeurs antérieurement publiées. Celles de chlorure d'hydrogène ont été caractéristiques des dégagements d'autres incinérateurs intégrés. Les émissions de particules ont été faibles, comparativement à celles, non épurées, des incinérateurs ordinaires (de déchets non conditionnés). En général, il été conclu qu'une bonne conception et un bon fonctionnement permettent de réduire les émissions préoccupantes des incinérateurs à deux étages.

Le rapport ne porte pas sur les prolongements des conclusions sur la santé et l'environnement. Les effets seront évalués en continu par Environnement Canada. Le rapport se limitant aux qualités techniques des incinérateurs à deux étages pour ce qui est de la destruction des déchets solides urbains, de la récupération de l'énergie et des émissions résultantes.

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ACKNOWLEDGEMENTS

We would like to thank everyone involved in carrying out the first phase of the National Incinerator Testing and Evaluation Program (NITEP) at the Prince Edward Island (PEI) energy-from-waste facility. In particular, we are grateful to Mr. Arthur Hiscock, General Manager, and the Board of Directors of the PEI Energy Corporation; Mr. Nigel G.H. Guilford, Director, Resource Recovery Programs; and Mr. George Reddom, Plant Manager of Tricil Limited, for their cooperation in the successful completion of the test program. Many people and organizations were involved in the NITEP - PEI tests, without whose dedication and efforts this test program would not have been a success. It would be impossible to acknowledge everyone involved, but some key individuals were:

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1 INTRODUCTION

Landfill, recycle, and incineration are three viable methods of municipal solid waste disposal. Effective long-term waste management programs must fully explore each of these options, and health and environmental issues are often in the forefront of the evaluation process.

The benefits of reducing the number and size of landfills and the potential for energy recovery associated with municipal refuse incineration have focused attention on energy-from-waste (EFW) technologies. Unfortunately, reports on emissions from energy-from-waste facilities have been highly variable and have lead to some confusion about health and environmental effects. Nevertheless, through an Expert Advisory Committee on Dioxins, the Ministers of Health and Welfare Canada and Environment Canada recognized that refuse incineration represents the most significant controllable input of dioxins into the atmosphere. The committee recommended that the best available incineration technologies in Canada be identified and ranked through an environmental monitoring program. In addition, it recommended that further efforts be made to define the optimal design and operating conditions for municipal and industrial incinerators to reduce or eliminate emissions of concern.

In response to the committee's report, the National Incinerator Testing and Evaluation Program (NITEP) was established by Environment Canada to examine not only its recommendations but also the potential impact of energy-from-waste facilities on health and the environment. This will be accomplished through an extensive three-year program which will touch upon all aspects of incineration. Attempts will be made to correlate various combustion conditions with trace organic and inorganic emissions such as dioxins, furans, and heavy metals. Efforts will be made to define the best "operating window", which will provide both existing and future EFW facilities the incentive to incinerate refuse in an environmentally safe manner, while maintaining optimal combustion efficiency.

The NITEP program addresses five key areas (see Figure 1):

- Environmental/Health Impacts
- Sampling and Analytical Methods
- The Link Between Combustion Conditions and Emissions
- Incineration and Pollution Control Technology Assessment
- Regulatory Controls

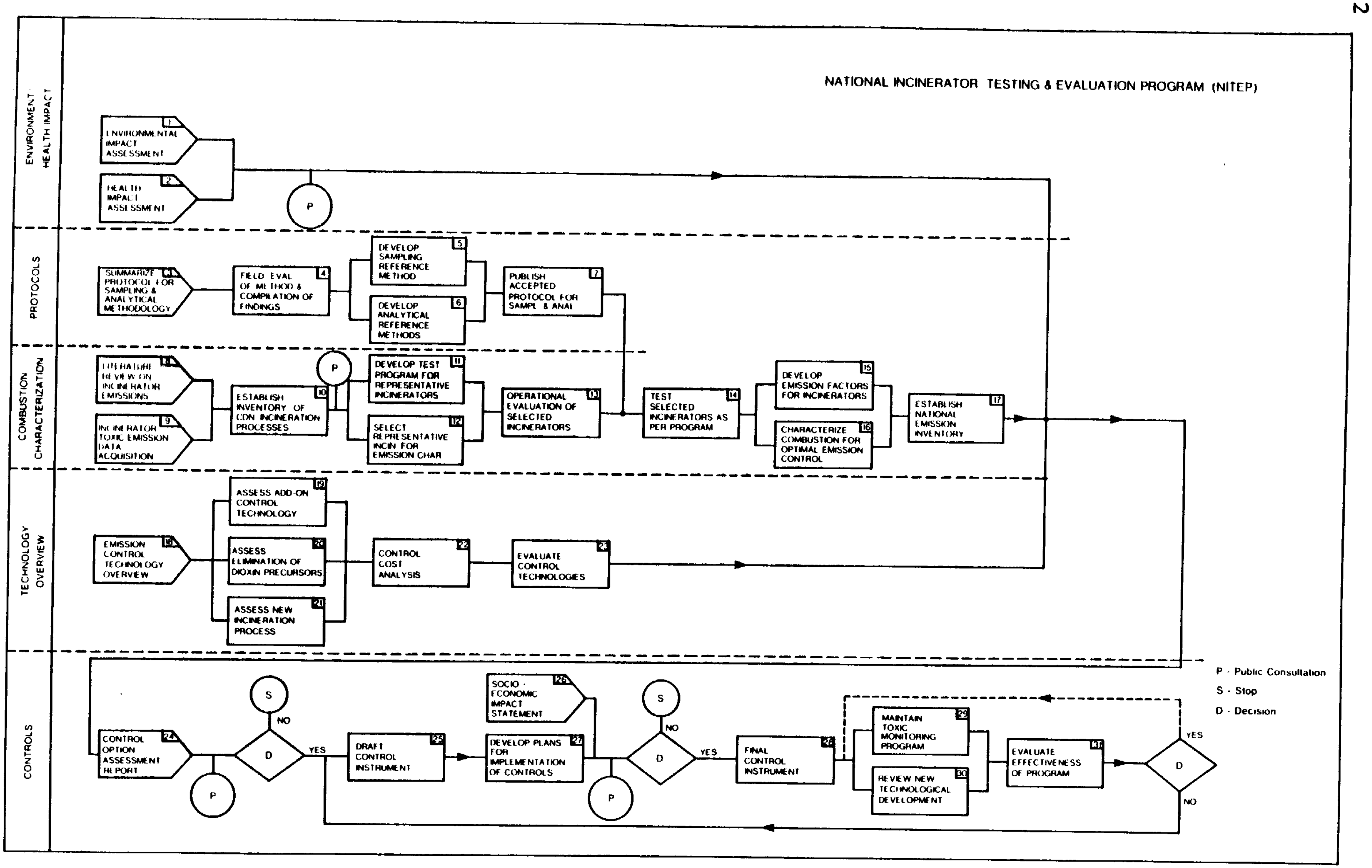


FIGURE 1 KEY COMPONENTS OF THE NATIONAL INCINERATOR TESTING AND EVALUATION PROGRAM

Environmental/Health Impacts

NITEP will assess, if at all possible, the level of risk to urban populations from EFW facility emissions. Also, efforts will be made to put into perspective the contribution that pollutants from EFW incinerators may make to the total load of pollutants to which urban populations are currently exposed.

Sampling and Analytical Methods

Incinerator sampling and analytical procedures are not uniform, making it difficult to compare various published data. Under NITEP, Environment Canada intends to make a significant contribution internationally to the development of a uniform means of data collection and evaluation.

The Link Between Combustion Conditions and Emissions

The program will study the relationship between combustion conditions and emissions. The classical "add-on" control technology may not always be the best strategy to control emissions of concern.

Incinerator and Pollution Control Technology Assessment

Several conventional incineration systems, as well as add-on control technologies, will be tested and evaluated. These data will assist municipalities in selecting the most appropriate equipment designs to meet their specific needs.

Regulatory Controls

The main thrust of the program is to define the effectiveness of operational and abatement controls for EFW facilities. The degree of regulatory involvement will be determined by the above four program components.

In summary, the main objective of NITEP will be to refine incinerator technology so that EFW incinerators will:

- function so that they do not pollute the environment or pose a health hazard;
- be a viable and sensible complement to landfill sites as a method of municipal solid waste disposal;
- make a significant contribution to the energy needs of communities, thereby reducing energy costs; and
- operate economically on a stand-alone basis.

Milestones

In Phase I of NITEP, criteria for the selection of municipal solid waste incinerators for testing and evaluating were established. Based on the established criteria, three candidate incinerators were selected. The generic incinerator designs chosen were a two-stage combustion system, mass burning, and prepared burning, because these designs exemplified projected future trends in incinerator technology. The first candidate selected was the two-stage combustion facility in Parkdale, Prince Edward Island, a suburb of Charlottetown, owned by the PEI Energy Corporation and operated by Tricil Limited of Mississauga, Ontario.

In Phase II of NITEP, a program was developed to field-test and evaluate the PEI incinerator. This established the necessary groundwork required to facilitate the field test. In addition, test matrix format, operating conditions, a schedule, sampling procedures, analytical protocols, documentation, and coordination with the owner/operator were established to ensure the integrity and timeliness of the test program.

This report summarizes the results of the actual field test program. Due to the considerable amount of data gathered during the test program, the complete results were compiled in four volumes, whose contents are described in Appendix B. These more comprehensive volumes are available separately from the Urban Activities Division at the address provided at the beginning of this report.

2 PLANT DESCRIPTION

The Prince Edward Island energy-from-waste plant is based on two-stage controlled air combustion with flue gas heat recovery (Figure 2). The plant is owned by the Prince Edward Island Energy Corporation, and is located in Parkdale (Charlottetown), PEI. It receives municipal solid waste from Charlottetown and vicinity and delivers steam to the Queen Elizabeth Hospital (and subsequently to the Riverside Memorial Hospital). The plant was designed, built, and is being operated by Tricil Limited. Plant operation began in 1983.

The plant consists of:

- a receiving floor/loading bay;
- three two-stage Consumat CS 1600 incinerators each rated at 33 tonnes per day;
- a common exhaust manifold leading to a waste heat recovery boiler and economizer; an exhaust fan; and a stack.

Related equipment includes:

- primary and secondary combustion air systems;
- hydraulically operated rams to move the waste through the primary chamber;
- a cooling water system to protect the rams, primary air headers and primary chamber refractory;
- a wet ash removal system;
- instrumentation and controls; and
- a by-pass stack on each incinerator secondary chamber.

The incinerators are housed in a steel frame building with an inside waste receiving area. Municipal refuse is delivered to the plant in vehicles ranging from packer trucks to family automobiles. The plant attempts to restrict the waste to material that will readily burn and discourages the dumping of rubble, automobile parts or large items of furniture. Any of these materials that do arrive are segregated: metal to a scrap metal bin, and other material to a bin used to haul material to the dump. The waste is discharged onto the concrete receiving floor inside the plant building. A front end loader operator stacks the refuse into the storage pile.

The waste is mixed with the front-end loader to provide a feed of relatively uniform properties to the incinerator and to enable the operator to find any material not segregated during stacking. Batch loads are fed into the primary chamber from the

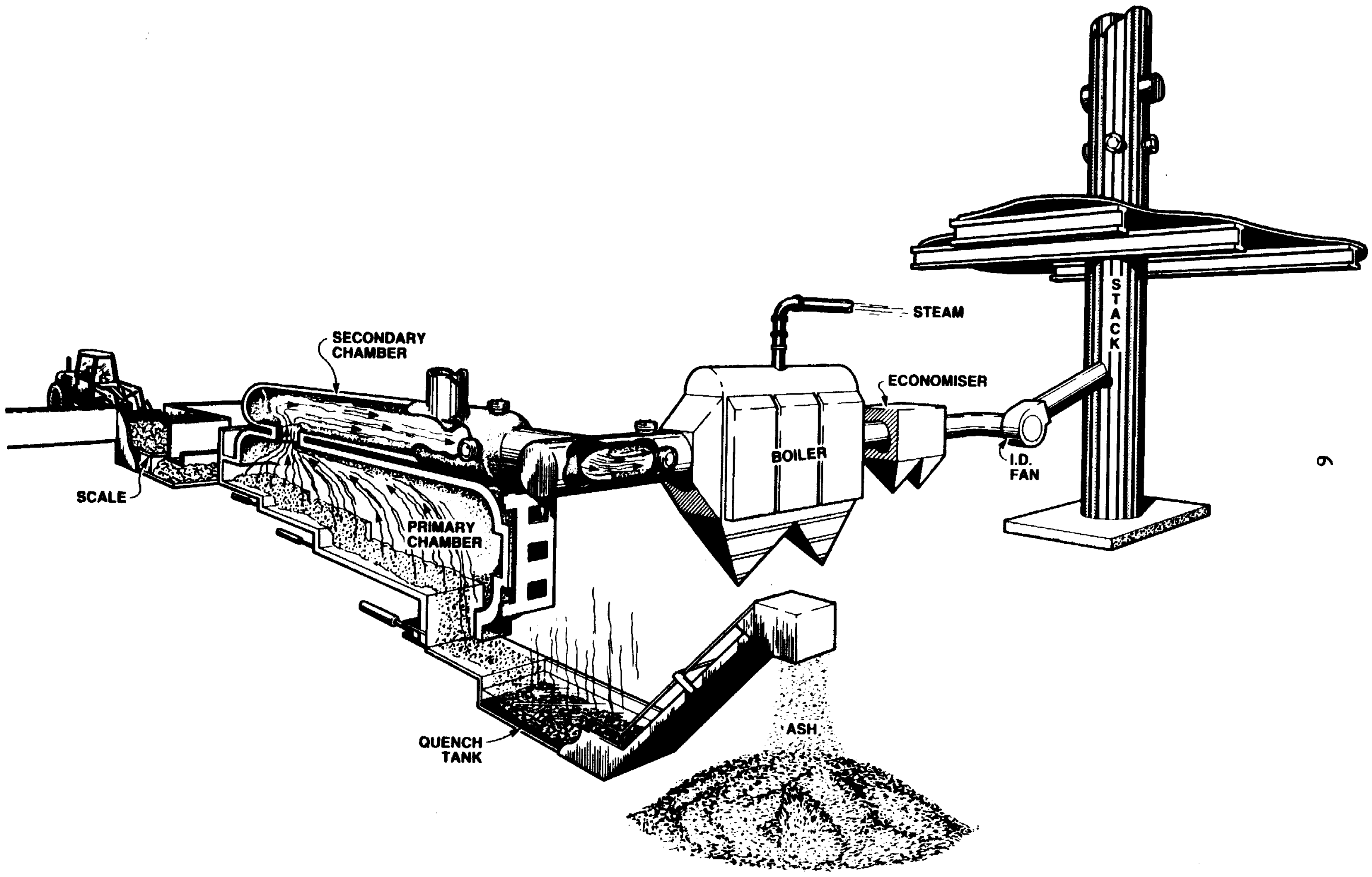


FIGURE 2 PROCESS SCHEMATIC OF P.E.I. TWO-STAGE COMBUSTION SYSTEM

loading hopper. The chamber is sealed from the hopper by a hydraulically operated loading door. The charge is pushed into the chamber by a water-cooled hydraulic ram. Material fed into the primary chamber is moved through the primary chamber along the stepped bottom by water-cooled transfer rams. At the far end of the chamber is the ash sump, where the residue is discharged into the ash quench tank.

Primary air is provided at low velocity into the lower portion of the fuel bed. This represents only a portion of the total air required for complete combustion. Primary chamber temperature is sensed by a thermocouple on the roof of the chamber. Every effort is made to maintain the primary chamber temperature in the range of 620-730°C. Light loads burn more rapidly and increase the primary chamber temperature. When the temperature is above the desired range the controller signals for a heavy load. Heavy loads burn more slowly and reduce the primary chamber temperature. The loader operator receives directions on the size of load required to be charged via a dedicated set of indicator lights mounted above the charge chute of each incinerator.

Combustible gases and any entrained particulate matter leave the primary chamber through a short circular refractory-lined vertical interconnection at the front end of the secondary chamber. In the secondary chamber the combustible gases are mixed with preheated secondary air to complete the combustion of the unburned gases. Air flow to the secondary chamber is modulated to maintain the temperature at approximately 1000°C. As the temperature increases, the flow of air is increased. If the temperature drops below the control point, the damper of the secondary air fan begins to close to decrease the air flow. The damper continues to close until the desired temperature is re-established or the damper is fully shut.

When operated in a heat recovery mode, the products of combustion from the secondary chamber are drawn from each incinerator into a refractory-lined horizontal manifold leading to the boiler. The connection between the secondary chamber and the manifold is refractory-lined, and is fitted with an isolation damper to allow the boiler to be isolated from the incinerator, if required.

When operating in the incineration mode, the isolation damper in the flue to the common manifold is closed and the combustion gases are discharged vertically upwards through a steel bypass stack mounted in a rectangular section of the secondary chamber. The common manifold connects the waste heat recovery boiler and economizer to the inlet of an induced draft (ID) fan.

The waste heat recovery boiler is a two-drum type with a close-spaced full water-tube boiler bank. Gas flow through the units is of the single-pass configuration parallel to the axis of the boiler drums. Low pressure steam (1965 kPa) from the boiler is furnished to a nearby hospital in accordance with its requirements. If more steam is being generated than is required by the hospital, the excess is vented. If insufficient steam is being generated, a conventional oil-fired boiler, maintained on hot stand-by in the steam plant at the hospital, is brought on line to make up any deficiency.

The economizer, located at the outlet of the waste heat boiler, has two gas passes over horizontal bare tubes. Feedwater to the economizer is returned from the hospital as a mixture of condensate and softened water make-up. From the economizer, the flue gases are drawn through the ID fan into a stack. The overall stack height is approximately 21 m, of which approximately 17 m is above the stack breeching and 11 m is above the roof level.

Ash from the primary chamber ash sump of each incinerator is discharged into a common water-filled quench tank. A submerged hood extending out from the incinerator into the quench tank eliminates the intake of air. While the ash transfer ram is operating, water sprays deluge the ash before it drops into the quench tank. This eliminates violent reactions when the hot ash drops into the quench tank and minimizes the amount of ash floating on the surface of the quench tank. Ash in the quench tank is removed by a drag chain conveyor and taken up an incline; most of the free water drains back to the tank. The conveyor discharges ash to a 40-yard (30.6 m^3) transportable container. The filled container is taken by truck to a landfill.

A control panel located on the operating floor adjacent to the secondary chamber of each incinerator monitors and displays the incinerator operation through a series of lights, instruments and audible alarms. All set points for primary and secondary air flow, temperature alarms and operating conditions are provided on this panel.

The load and transfer cycles of each incinerator and the ash conveyor are controlled by a computerized process controller. The computer times the waiting period between the completion of the loader ram cycle and the start of the next cycle. Normal operation provides 390 seconds for this time out. After the time out, one of the following transfer rams is activated: ash, lower, or upper. The sequence then progresses up the unit to the loading ram.

A control panel for the boiler and auxiliaries is located on the operating floor adjacent to the boiler. This panel monitors and displays the status of boiler operation by a series of lights, instrument and audible alarms.

3 TEST PROGRAM APPROACH AND PLANT MODIFICATIONS

3.1 Approach

Most of the test program strategy was based upon the results of an initial planning contract completed prior to the test program. To assist the contractor, Environment Canada negotiated all the major arrangements with the owner and the operator of the facility.

The initial planning contract established not only operating parameters but also general sampling locations. This information was used as the basis for the original project definition, but was further developed once the field test program began. The planning contract also recommended two levels of testing: characterization, for developing an understanding of system response; and performance, a series of detailed tests to monitor the effects of operating parameters on emissions. Further refinements to the field test program strategy were based on the following:

- the planning document,
- a site visit,
- new initiatives, and
- meetings between Environment Canada personnel, the plant operator and contractors.

The most appropriate unit to test and the final sampling locations were selected based primarily on site constraints. Unit no. 1 was selected for testing because it was the furthest from the boiler inlet, providing the most uniform flow into the boiler inlet, which was important for sampling. In addition, incinerator no. 1 and its control panel were closest to the process recorder, enabling the combustion engineer to easily monitor all operations from one location, and was closest to the manifold viewport, for visual observation of the combustion process.

The sampling locations and the level of information to be monitored were determined by program cost constraints and field data limitations. The following sampling locations were selected.

i) **Stack** - Since emissions to the environment pass through the stack, it was selected as the most obvious location for the gaseous, particulate and organic sampling work.

ii) **Economizer Outlet** - Temperature data from the gas stream immediately at the economizer outlet and before the ID fan were required to calculate system thermal efficiencies.

iii) **Boiler Inlet** - It is of scientific interest to determine if organic concentrations change across the boiler.

iv) **Secondary Chamber Outlet** - To develop an understanding of the temperature profiles within the secondary chamber, temperature measurements were made across the chamber cross section.

v) **Connection Between Primary Chamber and Secondary Chamber** - To observe the characteristics of the gases leaving the primary chamber, provisions were made to monitor gases and temperature in the neck between the primary and secondary chamber.

vi) **Primary Chamber** - To monitor the primary chamber temperature, plant instrumentation was used as no other provisions were possible.

vii) **Ash Discharge** - To determine both the quality of ash going to landfills and the completeness of combustion, ash was sampled using specially designed devices at the primary chamber discharge, boiler and economizer hopper outlets.

viii) **Garbage** - A special scale was developed to weigh the amount of garbage being fed to the incinerator to determine both the charge rate and the variation in charge size. Composite samples were collected, shredded and segregated for each test run.

ix) **Operator Panel** - All plant instrumentation was monitored continuously throughout the tests, which provided an indication of both the function of the instrumentation control devices and the variability in their operation.

3.2 Plant Modification

The installation of test equipment to measure various parameters in the plant required some modifications to the test incinerator and ancillary equipment. After reviewing plant operation and discussing the required changes with the owner and operator, local contractors were hired to make the following modifications.

i) **Refuse Charging Rate** - Energy production and primary chamber temperature in the PEI facility are both linked to feed rates. To ensure these conditions could be thoroughly investigated, it was necessary to measure the flow of refuse into the unit. This was accomplished by constructing a weigh scale inside the feed chute of the test incinerator. Load cells installed between the scale and the chute registered the weight of each load placed on the scale. The front-end loader operator was thus able to prepare the charge in his usual fashion, without any undue intervention. The weight of each load was recorded from a digital panel meter installed near the incinerator instrument panel.

ii) **Ash Sampling** - Ash was sampled from three locations in the system: the incinerator bottom, the outlet of the boiler hoppers, and the outlet of the economizer hoppers. Modifications were required at two locations to facilitate sampling and prevent system disruption. A special port with cap was installed on the quench tank hood for access and to prevent air infiltration. To minimize the infiltration of air into the boiler while collecting ash samples, the boiler outlet hoppers were modified. The existing hopper slide plate closures were removed and replaced with a special extension to facilitate the installation of a gasketed glass jar over the hopper opening. Since bottom ash is discharged from all three incinerators into a common trough, it was not possible to measure the individual incinerator ash discharge rates without incurring an unjustified expense.

iii) **Observation Ports** - To observe the bed depth and combustion conditions in the primary chamber, the plant operators usually opened the rear door of the primary chamber, causing noticable disturbances. The existing door was replaced and a tempered glass view port was installed to permit observation of the combustion conditions without disturbing the process. The old door was moved to the end of the gas manifold to provide a means of observing any combustion in the manifold.

iv) **Sampling Ports** - Six flue gas sampling locations were identified during the original field visit. These locations were associated with various critical locations in the process as previously outlined.

v) **System Sealing** - The incinerator isolation dampers fitted between the secondary chamber and the common manifold to the boiler were not leak tight. To prevent contamination by the gases from the two other incinerators, and to prevent air leakage into the system from an idle incinerator, a refractory wall was constructed to isolate units no. 2 and no. 3 from the manifold and the boiler.

The incinerator dump stack damper was found to be perforated. To ensure proper operation and prevent leakage, the plate was replaced by the operators.

vi) **Site Facilities** - Over 30 engineers and technicians were involved in the performance testing phase of this project. Seven manual stack sampling trains, nine continuous gas monitors and over thirty individual thermocouples were used during performance testing. In addition, power for the instrumentation, laboratory work space for sample recovery, and shelter for samplers and personnel presented a problem due to the limited site facilities. To accommodate these requirements, four trailers were installed.

- A 9-m office trailer was raised to the roof to serve as shelter for the sampling crews and laboratory, for train preparation, and sample recovery.
- A 12-m semi-trailer, converted to a mobile laboratory, housed the continuous analysers and distributed power to the other trailers.
- An 18-m trailer was used as a washroom, storage area and laboratory.
- A 12-m trailer served as a field office and lunch room.

4 SAMPLING AND ANALYTICAL PROTOCOLS

Details of the sampling and analytical protocols employed during the test program are presented in Volume III of the study report (see Appendix B). Some of the procedures followed are reviewed here.

4.1 Sampling

Continuous Emission Monitoring - Continuous real-time instrumentation, calibrated at least twice during each test, was used to measure the concentrations of carbon monoxide, carbon dioxide, oxygen, sulphur dioxide, nitrogen oxides and total hydrocarbons at the stack. Simultaneous measurements of CO, CO_2 and O_2 were made at the exit of the secondary chamber. Using a heated pump, samples were withdrawn through a specially constructed manifold (Figure 3), then transported through a heated sample line and a coarse filter to a sample conditioning system. In the conditioning system the gas was filtered a second time, then dried before being delivered to the analyzers. The analyzer outputs were fed to a strip chart recorder to produce a continuous trace of the data, and to a data logger to record measurements. Data were also routed to a field computer for storage on magnetic disk.

Temperature Data - Temperatures in the gas streams at the secondary outlet, the boiler inlet and the stack were measured by a series of calibrated thermocouples. At each location the thermocouples were arranged in a grid pattern so that between 6 and 12 individual gas temperature readings were recorded. Outputs from the thermocouples were fed directly to the data logger and the field computer.

Plant Operating Data - All plant operating data were recorded every 15 minutes. Information on temperatures, steam flow, operating pressures and feed rates were collected under the direction of the combustion specialist. The specialist also observed the operation of the unit, in particular the appearance of the flame in the various chambers so that any differences that could have indicated unusual operation were noted.

Manual Stack Gas Sampling - During performance tests, manual sampling for various solid and gaseous compounds in the gas stream was accomplished using seven separate sampling systems, six at the stack location and one at the boiler inlet. A dedicated sampling train was used for each of the following: dioxins/furans; polycyclic aromatic hydrocarbons; polychlorinated biphenyls, chlorobenzenes, and chlorophenols; particulate matter and heavy metals; acid gases; particle size; and residual combustibles.

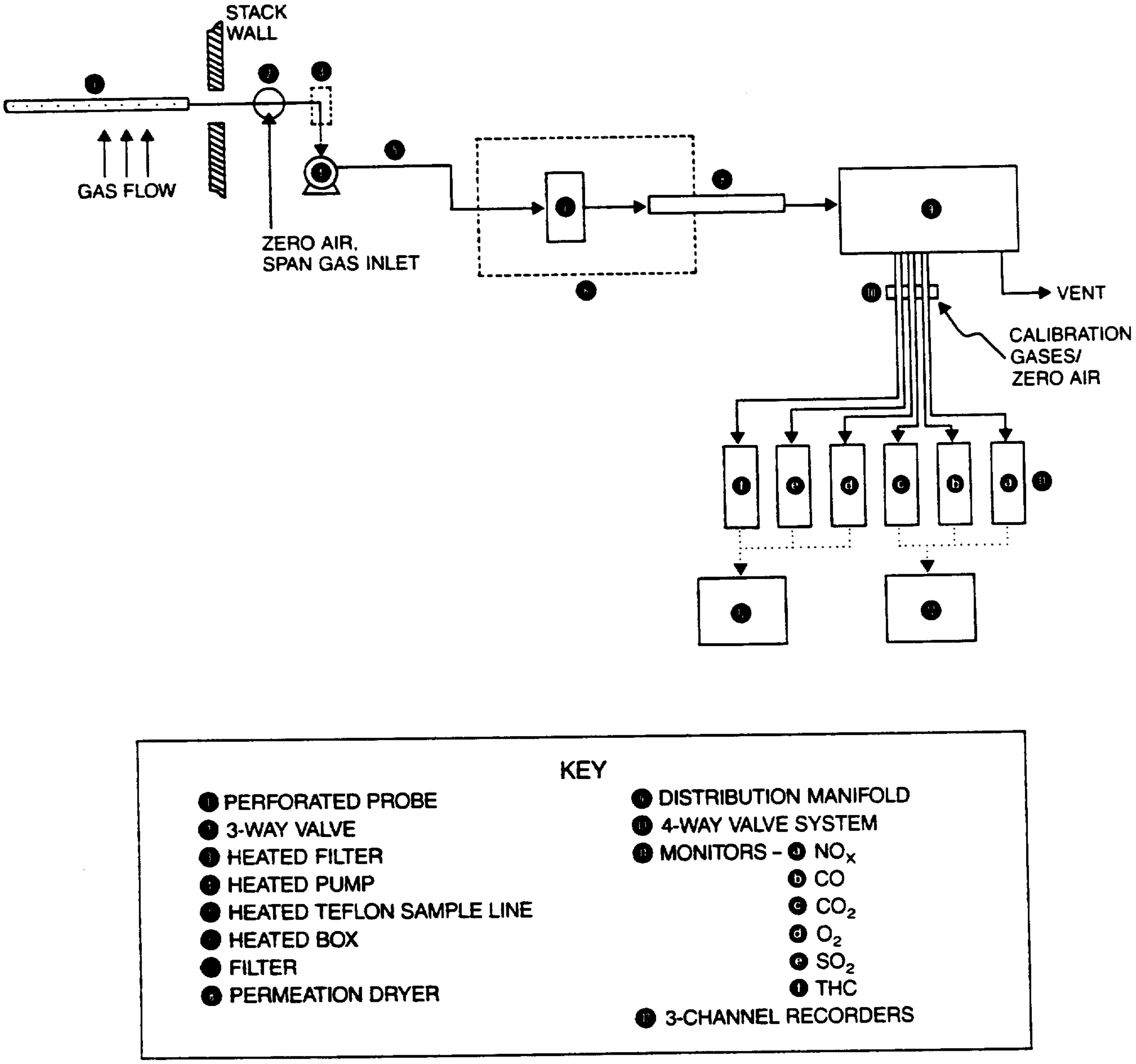


FIGURE 3 CONTINUOUS EMISSION MONITORING SYSTEM

In general, the manual sampling systems (trains) consisted of the following components:

- a specially sized goose-neck nozzle,
- a heated probe,
- a heated filter assembly,
- a series of impingers with various reagents, contained in an ice bath, and
- a sample case containing controls and the sampling pump.

Manual sampling was accomplished isokinetically (i.e., by withdrawing the gas sample from the stack at a rate equal to the stack gas velocity at that point). During sampling, the equilibrium (isokinetic variation) of the nozzle sampling velocity and the stack gas velocity was maintained within a range of ± 10 percent. Particulate matter was separated from the sample stream on a heated filter. Subsequent to the filter, the gas temperature was reduced and condensibles were collected. Various sample constituents were then recovered from the train for laboratory analysis.

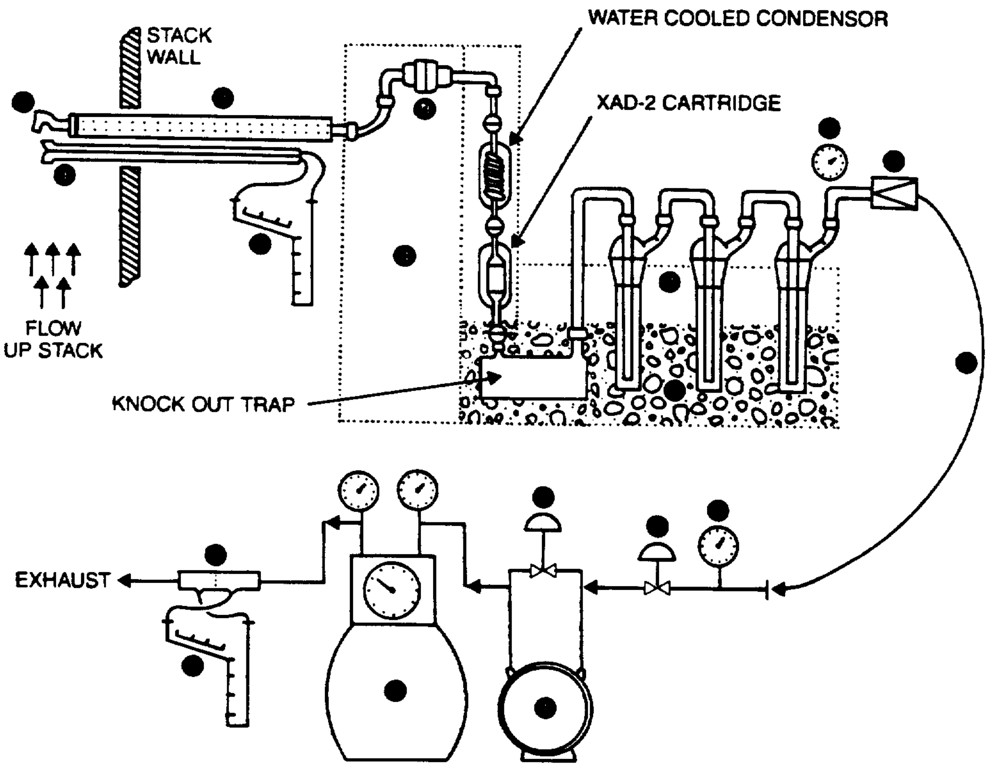
Leaks in the sampling train were a serious concern since these could be a potential source of sampling error. The acceptable leakage rate was set at 0.02 ft^3/minute at 15 psi vacuum (9.4 cm^3/s at 103 kN/m^2).

Sampling trains for organics were modified according to the ASME protocol by adding a condensor and resin trap after the filter. The resin trap collects the gaseous organic constituents which are then extracted during analysis in the laboratory (Figure 4). Special cooling features were provided for the high temperature train at the boiler inlet to ensure adequate cooling of the gas for collection of all trace organics.

Sampling for total particulates and metals followed Environment Canada procedures (Figure 5). Impingers containing aqua regia and permanganate were used to collect volatile metals, whereas particulate matter was collected on a glass fibre filter.

Acid gas emissions were measured by using a glass-lined probe and a series of impingers containing caustic solutions. Particulate matter was separated from the gaseous fraction by a glass wool plug located in the probe inlet. Samples were collected from a single point at a rate proportional to the stack gas velocity at that point. Impinger solutions were analyzed by ion chromatography.

Particle sizing was accomplished using a commercially available (Gram Slam) in-stack multi-cyclone system (see Figure 6). This unit was operated isokinetically at a single point in the stack. Once established, this sampling rate was maintained constant for the duration of the test. Size fractions were determined gravimetrically.



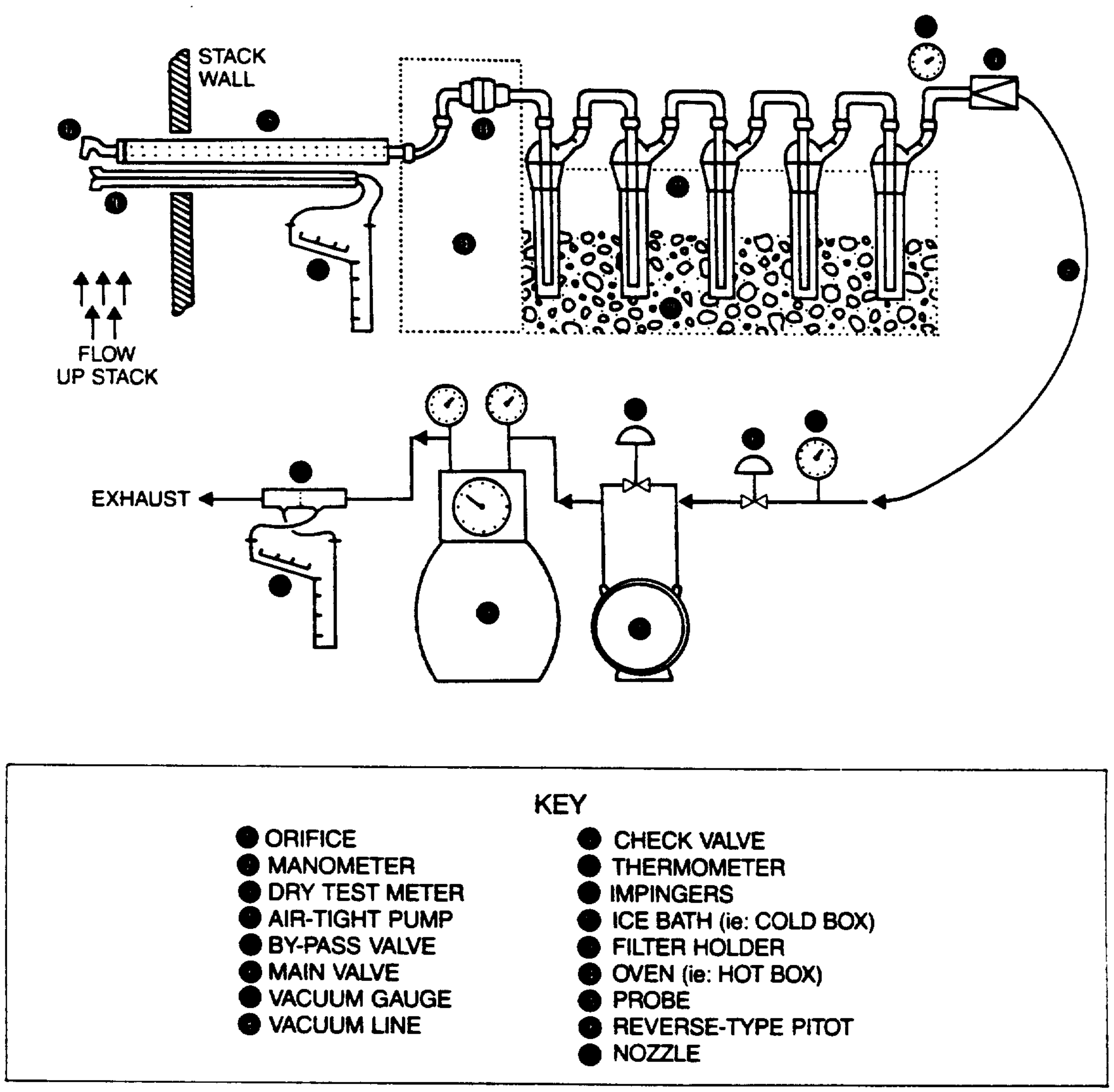
KEY

- ● ORIFICE
- ● MANOMETER
- ● DRY TEST METER
- ● AIR-TIGHT PUMP
- ● BY-PASS VALVE
- ● MAIN VALVE
- ● VACUUM GAUGE
- ● VACUUM LINE
- ● CHECK VALVE
- ● THERMOMETER
- ● IMPINGERS
- ● ICE BATH (ie: COLD BOX)
- ● FILTER HOLDER
- ● OVEN (ie: HOT BOX)
- ● PROBE
- ● REVERSE-TYPE PITOT
- ● NOZZLE

NOTE: IMPINGERS ARE MODIFIED GREENBERG – SMITH TYPE.

IMPINGER 1 – 100 mL ETHYLENE GLYCOL
2 – EMPTY
3 – 200 – 300 GRAMS SILICA GEL

FIGURE 4 SAMPLING TRAIN FOR ORGANICS (Modified U.S. Environmental Protection Agency Method 5)



NOTE: METALS/PARTICULATE TRAIN

5 IMPINGERS USED:
1 AND 2– 100 mL 5 % AQUA REGIA
3– 200 mL 2 % $KMnO_4$ IN 10 % H_2SO_4
4– EMPTY
5– 200–300 G SILICA GEL

FIGURE 5 SAMPLING TRAIN FOR METALS AND PARTICULATE

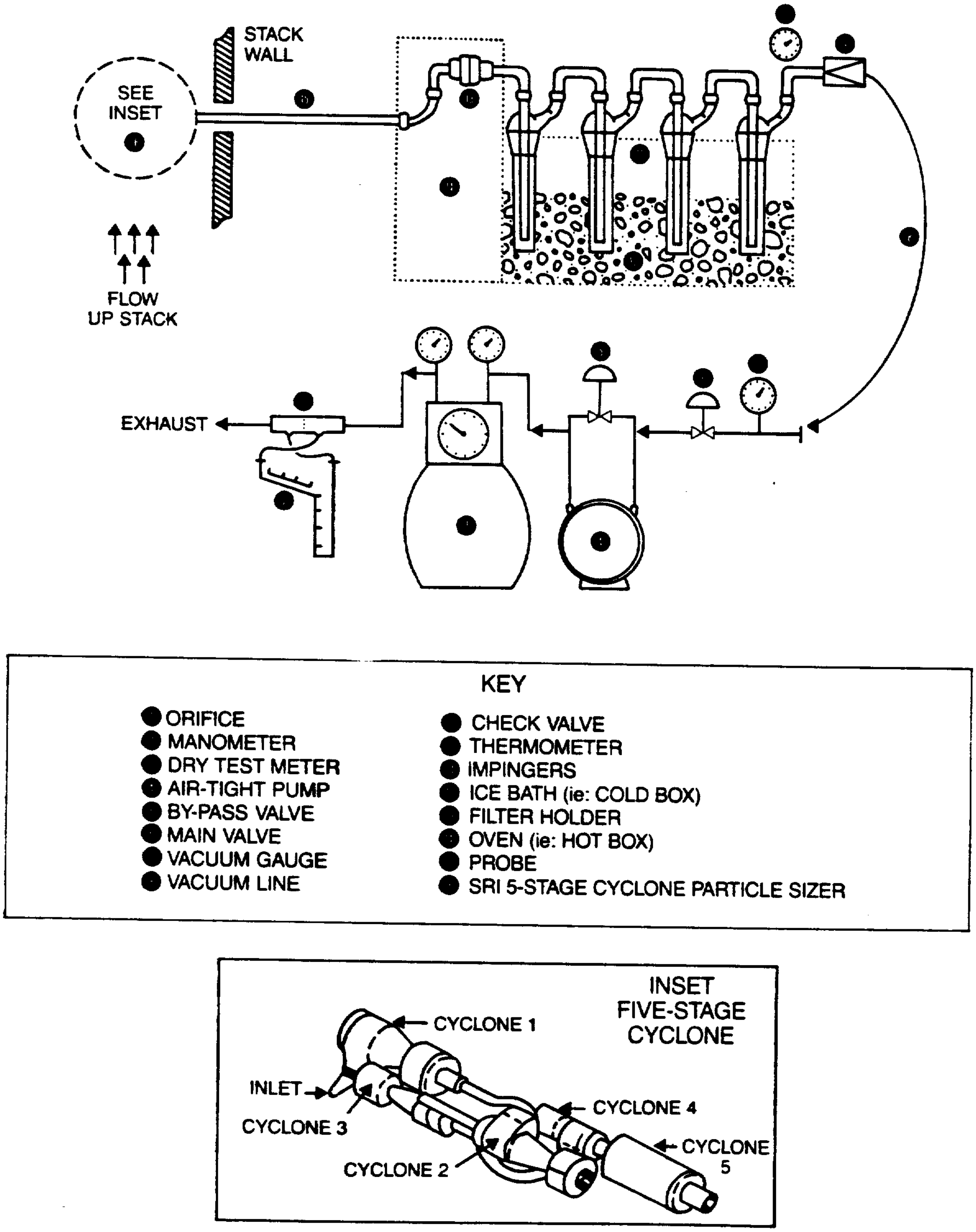


FIGURE 6 FLOW SENSOR PARTICULATE SIZE SAMPLING TRAIN

Samples for residual combustibles were collected on an in-stack filter (Balston). This was also a single-point sample collected isokinetically over the duration of the test.

Rigorous preparation and clean-up procedures were followed with all trains to ensure minimal contamination.

Process Stream Sampling - Garbage feed and all waste streams from the incinerator were sampled as shown in Figure 7. A representative sample of about 500-700 kg of refuse was collected for each run. This was subsampled into special containers for analysis and archiving.

Ash from the incinerator was sampled before each operation of the ash ram by inserting a 10-cm diameter tube into the ash bed. Samples removed were quenched prior to storage and analysis. Ash from the boiler and economizer were collected in special glass jars and stored for subsequent analysis.

4.2 Analysis

Organics - Organic analyses involved three steps:

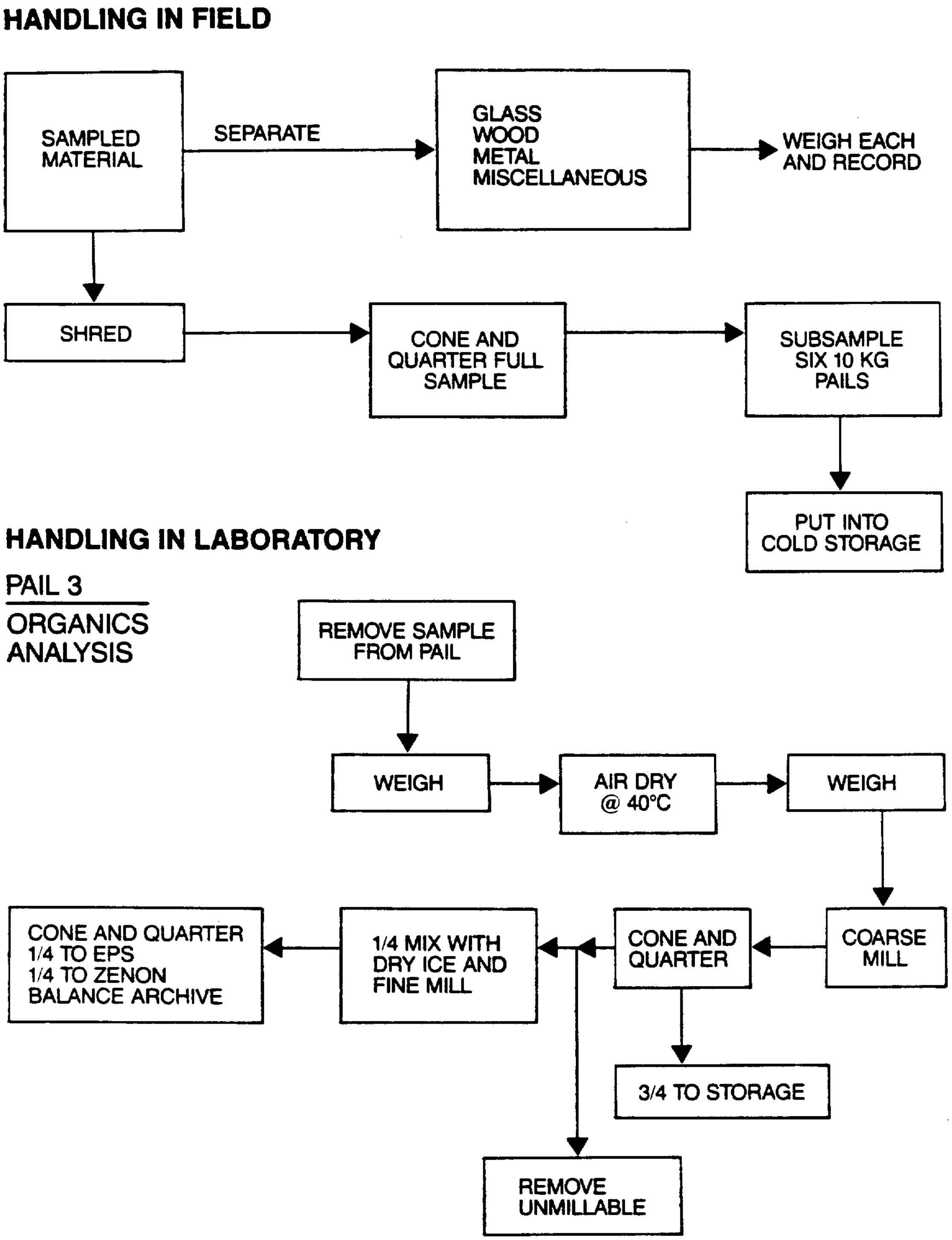
- extraction of organics from the recovered sample,
- clean-up of the extract to remove interfering compounds, and
- analysis by gas chromotography/mass spectroscopy/data system (GC/MS/DS).

Dioxin/furan analysis was carried out using the procedure outlined in Figure 8. The procedure was based on the ASME analytical draft protocol with changes implemented to improve the method.

Each sample was internally spiked with a standard mixture of isotopically-labelled dioxin/furan isomers prior to extraction. A dedicated sample was used for polychlorinated dibenzo-ρ-dioxin/polychlorinated dibenzofuran (PCDD/PCDF) analysis. For all other organic compounds of interest, analyses were performed using a sample dedicated for these compounds.

For dioxin/furan analysis, concentrated raw extracts were passed through a series of three clean-up columns which removed interfering organics that were co-extracted with PCDD/PCDF. Cleaned sample extracts were then concentrated to small, known volumes before analysis.

Qualitative and quantitative analysis of all samples was performed by GC/MS/DS. For each PCDD/PCDF congener group, two characteristic ions were selectively monitored. Identification was achieved when these target ions were detected



PAIL 4 – AS PER PAIL 3 EXCEPT OVEN DRY @ 105-110°C FOR ANALYSIS OF METALS AND ULTIMATE/PROXIMATE

PAIL 1 – OVEN DRY AND SHIP TO EPS FOR STORAGE.

FIGURE 7 GARBAGE SAMPLING AND ANALYSIS PROCEDURE

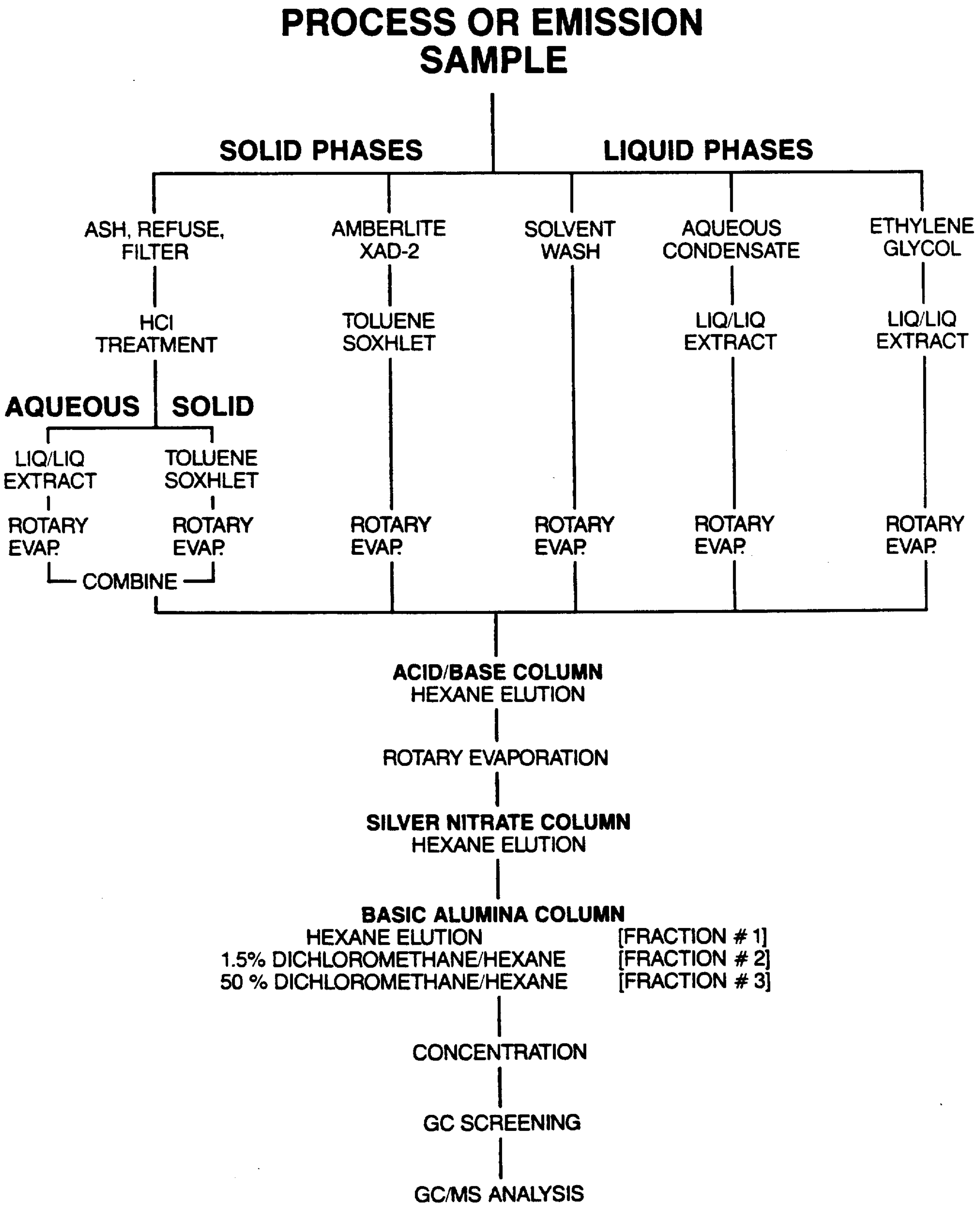


FIGURE 8 EXTRACTION AND CLEAN-UP PROCEDURES

in the correct abundance ratio within established retention time windows. Quantitation, including internal spike recovery determination, was based on the use of an external calibration standard mixture.

Metals - Train component samples for metals analysis were prepared in a manner compatible with the nature of the sample and the type of analysis required. The preparation of solid samples involved a digestion procedure using one or more of the following reagents: H_2SO_4, HCl, HNO_3 and aqua regia, followed by concentration and analysis.

The acetone probe wash was evaporated to dryness to measure total particulate and then redissolved with the acid probe rinse before digestion for heavy metal analysis. For mercury analysis, this digest was further digested with permanganate.

The filter sample was digested with aqua regia, as were the ash samples prior to metals analysis.

Impinger contents were analyzed as received.

Mercury analysis of ash was performed on an H_2SO_4, HNO_3, and HCl digest treated with potassium persulphate and potassium permanganate.

On the garbage samples, a H_2SO_4/HNO_3 digestion was used for mercury analysis; $HClO_4$ was added during the digestions for other metals. Trace metals were, for the most part, analyzed using a direct coupled plasma analyzer. Mercury analysis was carried out using atomic absorption because of the requirement for increased sensitivity. All analyses were carried out following standard laboratory quality control practices.

Other Analyses - Proximate, ultimate and higher heating value analyses were conducted on garbage samples. Ash samples were analysed for loss on ignition.

Proximate analysis is a relatively quick and inexpensive laboratory technique to analyze samples for percentage moisture, volatile matter, fixed carbon and ash. The analytical procedure involves sequential heating of the sample to high temperature and weighing the residue.

Ultimate analysis is a standard procedure used for the determination of the quantities of carbon, hydrogen, sulphur, oxygen, nitrogen and halogens present in a sample. It is required in order to determine the combustion air requirement and the nature of the off-gas or combustion products of a material. Ultimate analyses were performed using a gas chromatograph, infrared scanner and/or mass spectrometer developed specifically for elemental analyses.

High heating values were measured using an oxygen bomb calorimeter. Using this instrument, a measured sample was ignited by an electric wire in an atmosphere of pure oxygen. The sample heat of combustion heated a water bath surrounding the bomb. The temperature rise proportional to the heat of combustion was measured and used to calculate the high heating value.

Loss on ignition was measured by first taking a sample to dryness and then heating it in a open crucible in a muffle furnace to 750°C until it reached constant weight.

5 TEST PROGRAM DESCRIPTION

As previously discussed, the test program was divided into two parts: characterization, and performance series testing. The objective of characterization testing was to develop an understanding of incinerator operation and the factors affecting emissions so that final performance test conditions could be selected.

5.1 Characterization

The characterization program was divided into two parts, pre-tests and regular tests, which were conducted over 13 days. During the pre-test phase, six tests were conducted to familiarize the crew with the plant operation. These tests provided considerable knowledge about the following incinerator traits:

- normal operation,
- primary chamber variations,
- secondary chamber variations, and
- part-load operation.

Upon completion of the pre-tests, a series of 22 characterization tests were conducted. To ensure that an adequate assessment was being made, all major sampling locations were used to monitor incinerator performance, as outlined in chapter 3. All the data obtained were reduced to summary tables and graphs which were available to the field manager on the following day to assess test objectives. Tabular and graphical presentations of these results are presented in Volume II (see Appendix B).

Based on the field data, it became evident that the only major variables of unit operation were secondary chamber temperature, primary chamber air flow rate, and refuse loading rate. In addition, an interest was generated in possible ways of improving ash quality by varying the feed and ash ram cycles. A comprehensive review of how these variables affected system performance is also presented in Volume II.

The rationale for the final performance test conditions selected was based on a review by program field managers. Since only seven variables were observed, the characterization tests were grouped according to these variables. Table 1 provides a summary of the characterization tests (CTs) and a short list of the tests selected for further consideration.

TABLE 1 SUMMARY OF CHARACTERIZATION TESTS

Characterization Test Description	Characterization Test No.	Conditions Selected for Performance Testing
Normal Operation	1	
	14B	*
	15	
	18	
Variable Secondary Chamber Temperature	3	*
	4	*
	5	*
	19	* (Same as 4)
High Primary Chamber Temperature	6	
	7	
Starved Primary Chamber	8	*
	9	*
	16	* (Same as 8)
	17	*
Part Load Operation	10	
	11	
Modified Feed Cycle	12A	*
	12B	*
	13	
Modified Ash Cycle	14A	
	20	
	21	

Test Conditions Rejected for Performance Tests

High Primary Chamber Temperature (CT-6, CT-7). These test conditions were difficult to maintain because furnace water sprays were frequently triggered. Water sprays, used to prevent excessive temperatures in the primary chamber, increased the percent combustible in the ash.

Part-Load Operation (CT-10, CT-11). At part load, high primary chamber temperatures occurred. These were attributed to lighter loads, increased air leakage, and higher than normal primary combustion air. This condition once again activated the water sprays, deteriorating the ash quality. Difficulty was also experienced during this series of tests in raising the secondary chamber temperature above 800°C. It was speculated that most of the volatiles were being combusted in the primary chamber.

Modified Feed Cycle (CT-13). Adjustments to the ash ram cycles and primary chamber air distributions resulted in little or no perceivable difference from those experienced under normal test conditions.

Test Conditions Meriting Performance Testing

Normal Operation (CT-1, CT-14B, CT-15, CT-18). Normal operation was established at the outset of the test program as an essential performance test condition, both to provide a benchmark and to provide emission data pertinent to normal plant operation.

High and Low Secondary Chamber Temperatures (CT-3, CT-4, CT-5, CT-19). High secondary combustion chamber temperature was considered to be a prime candidate for performance testing because high temperature has been linked to the possible destruction of organic emissions such as dioxins. On the other hand, low secondary combustion chamber temperature was also considered important because of its potential for increased products of incomplete combustion as well as providing a third point by which to plot the impact of temperature on organic emissions.

Starved Primary Chamber (CT-8, CT-9, CT-16, CT-17). Starved air conditions were considered of interest due to lower NO_X and SO_2 levels than those measured during normal operation. In addition there was the potential for increased retention time in the primary chamber.

Modified Feed Cycle (CT-12A, CT-12B). Of particular interest to plant operations staff was a longer feed cycle to decrease the demands on the tractor operator. Certain parameters (CO, NO_x, ash analysis) indicated that performance was better than or equal to normal operations. Finally, it was believed that a longer feed cycle would present fewer disruptions to the combustion air by reducing bed agitation.

5.2 Performance

Upon completion of an extensive evaluation of the various characterization runs, four conditions were selected for detailed performance testing. A brief summary of the test condition settings and the rationales used in their selection is shown in Table 2.

For each of the performance test conditions selected, sampling and data collection were conducted in four key areas: process variables, refuse, ash and flue gases. Figure 9 illustrates the four key areas investigated and summarizes what was monitored

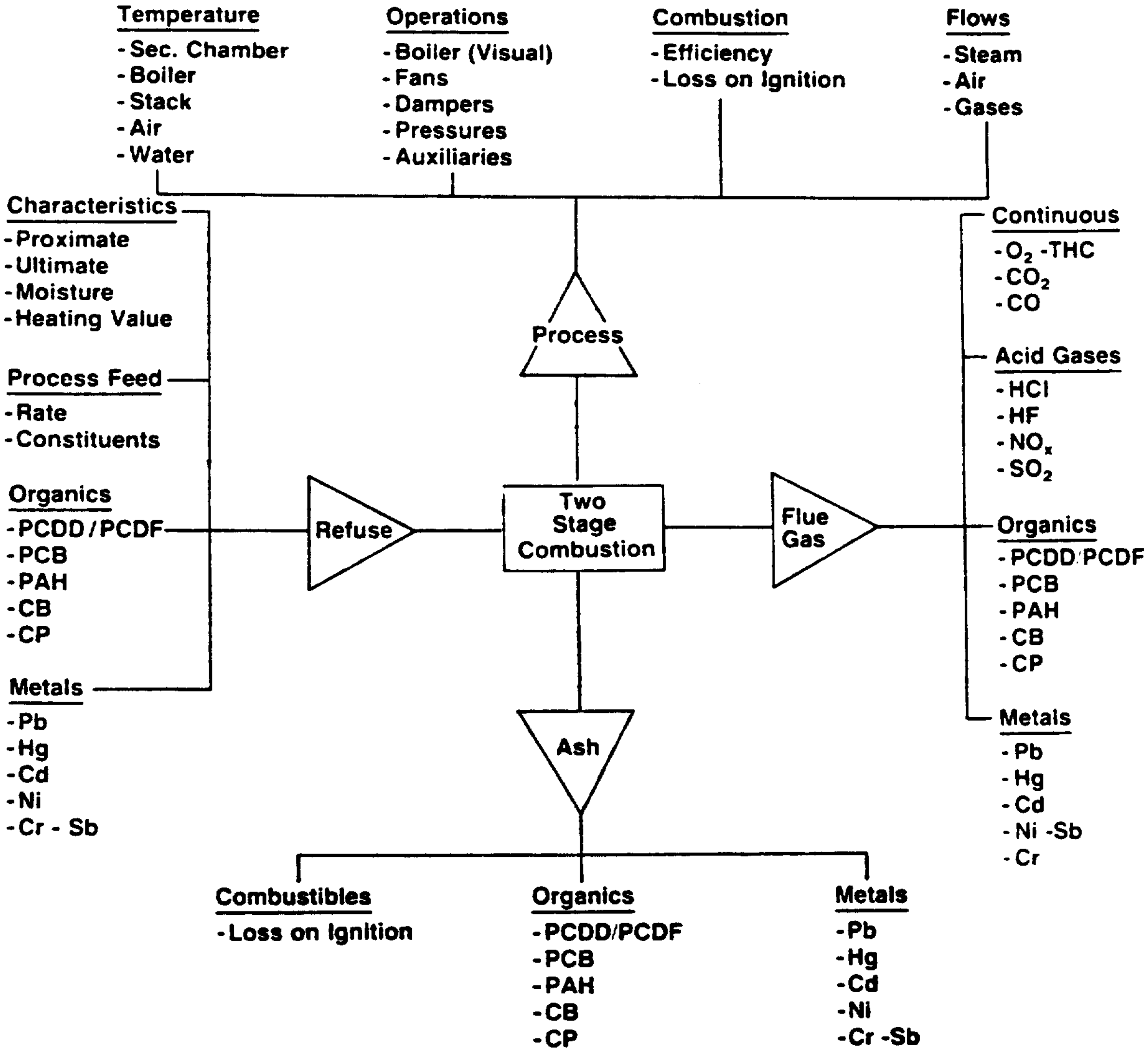


FIGURE 9 PERFORMANCE TESTING SUMMARY

TABLE 2 PERFORMANCE TEST CONDITION SELECTIONS AND SETTINGS

Condition	Settings			Rationale
	Primary Temp. °C	Secondary Temp. °C*	Feed Cycle Min.	
Normal Operation	700	1000	8.7	Benchmark for comparison with other tests
Long Feed Cycle	700	1000	12.5	Observed improvements in performance and reduced demands on plant loader operator
High Secondary Temperature	700	1135	8.7	To determine influence of high temperature on organic emissions such as dioxins and furans
Low Secondary Temperature	700	900	8.7	To investigate a condition which was thought to create higher organic emissions

* Control Panel Settings

or measured. All the information collected is provided in Volume IV of the study report (see Appendix B).

To accommodate the anticipated variability in feed quality, combustion air conditions and other process parameters, three tests were conducted under the same operating conditions. These tests were carried out on consecutive days and the results are summarized in Section 6.

A substantial portion of the performance data presented in this report has been greatly reduced to facilitate the review of possible areas of interest. For a more thorough insight into the effects of system performance on emissions from two-stage combustion facilities, the reader might wish to review Volume II.

6 PERFORMANCE TEST RESULTS

In this chapter the performance test results are briefly discussed and the key findings highlighted. As discussed previously, based on the characterization test results, four operating conditions were selected for detailed performance testing. The descriptions and run numbers for each of the test groups were as follows:

Group	Performance Test Operation Description	Test Numbers
1	Normal Condition	PT-2, 3 and 4
2	Long Feed Cycle	PT-5, 6 and 7
3	High Secondary Temperature	PT-8, 9 and 10
4	Low Secondary Temperature	PT-11, 12 and 13

6.1 Comparison of Test Data Within Groups

A detailed review of all data obtained for each of the three tests within a group was made. The objective of this review was to identify the similarities and differences that occurred among the tests in each group.

The operating parameters recorded or calculated, such as primary and secondary chamber temperatures, feed rate, heat input rate, steam production rate and visual appearance of flame conditions, were all reviewed. Similarly, continuous combustion gas data, e.g., for oxygen and carbon dioxide, were also closely examined.

Analysis of the above parameters provided sufficient evidence to conclude that the operating conditions for each test run, within any one group, were within an acceptable range. In addition, it was concluded that the group averages provided a good representation of the selected performance condition.

Emission data for the test runs within each group were also closely reviewed. Continuous data for gases, such as SO_2, CO, and THC, indicated that some variability existed. This variability was manifest in fluctuations during each test run and also became evident when comparing test averages. Stack sampling results for particulate matter and acid gases were very similar within each group. Organic emission results showed some similarities but at times significant differences occurred within a group. Upon examination of this data, it was concluded that, in general, the group averages provided a good indication of emission levels for a performance test group. However, organics data for some test runs were significantly different from the group average and this aspect must be considered when comparing group averages. Data for each test run can be found in Volumes II and IV.

Operating conditions and emissions were therefore compared on the basis of test group averages. The results and sampling locations are summarized in Figures 10, 11, 12 and 13, representing the normal condition, long cycle, high and low temperature runs, respectively.

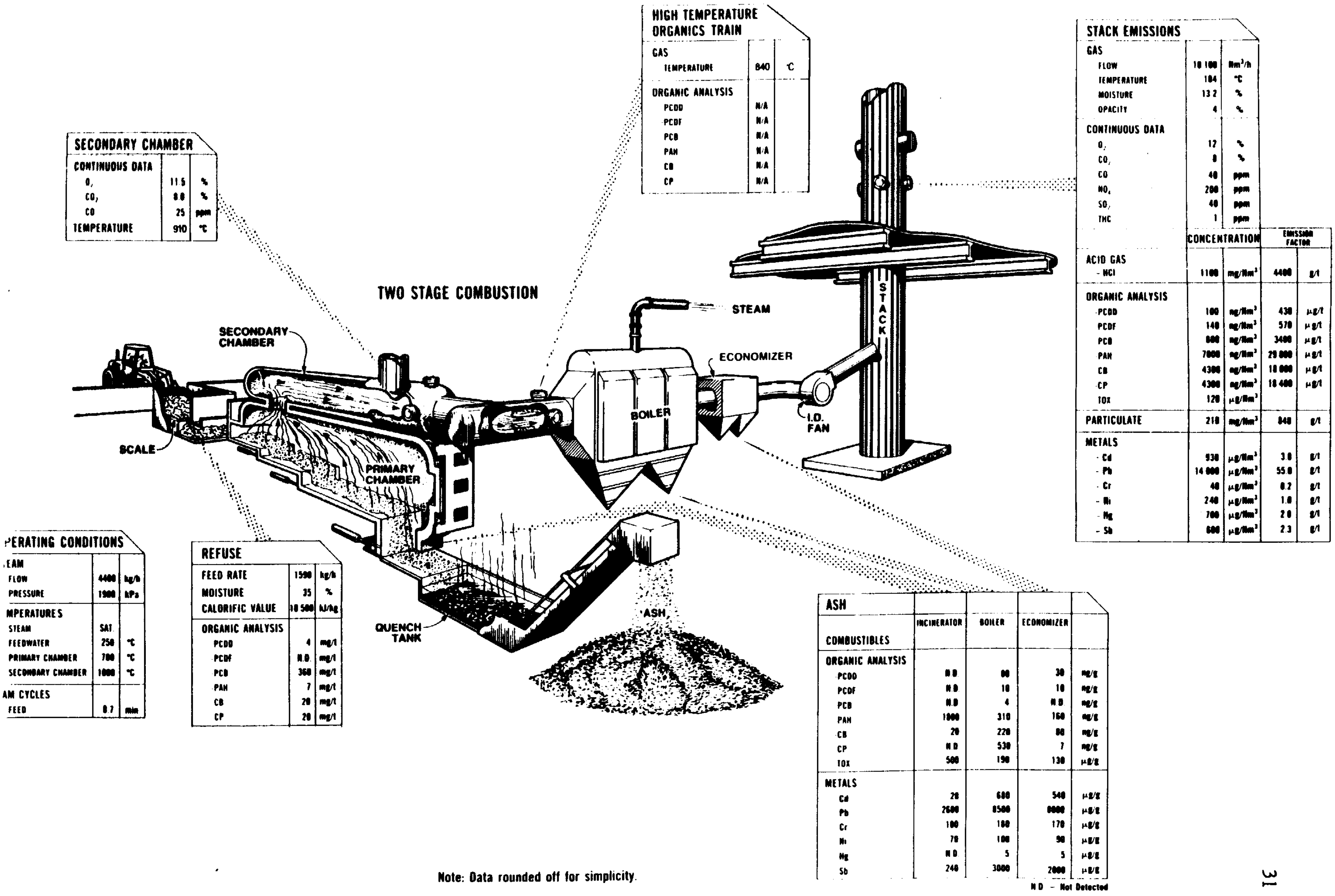
6.2 Group Averages

6.2.1 Operating Data. Key operating parameters are summarized in Table 3 for each of the four operating conditions.

TABLE 3 SUMMARY OF KEY OPERATING PARAMETERS

Operating Conditions	Normal Condition	Long Cycle	High Secondary Temperature	Low Secondary Temperature
Primary Temperature (°C)	695	690	703	676
Secondary Temperature (°C)	910	890	1080	780
Steam Rate (kg/h)	4360	4020	4470	3960
Refuse - Rate (kg/h wet)	1590	1600	1700	1520
- Calorific Value (kJ/kg as fired)	10 530	10 220	10 430	10 770
- Moisture (%)	35	35	32	35
- Non-combustibles (% wet basis)	14.0	13.9	15.0	13.0
Energy Input (kJ/h) x 10^6	16.8	16.2	17.6	16.0
Efficiency (%) - Input/Output	59.6	56.6	58.4	55.9
- Heat Loss	52.0	50.9	58.1	50.7

Primary and secondary chamber temperatures. The primary chamber temperature was maintained at a relatively constant 700°C for three of the four performance conditions and at 676°C for the low temperature test group. Primary chamber temperatures tended to follow the energy input to the system and could be controlled reasonably well within an operating band of ±40°C.



SECONDARY CHAMBER

CONTINUOUS DATA		
O_2	11.5	%
CO_2	8.0	%
CO	25	ppm
TEMPERATURE	910	°C

HIGH TEMPERATURE ORGANICS TRAIN

GAS		
TEMPERATURE	840	°C
ORGANIC ANALYSIS		
PCDD	N/A	
PCDF	N/A	
PCB	N/A	
PAN	N/A	
CB	N/A	
CP	N/A	

STACK EMISSIONS

GAS				
FLOW	10 100	Nm^3/h		
TEMPERATURE	104	°C		
MOISTURE	13.2	%		
OPACITY	4	%		
CONTINUOUS DATA				
O_2	12	%		
CO_2	8	%		
CO	40	ppm		
NO_x	200	ppm		
SO_2	40	ppm		
THC	1	ppm		
	CONCENTRATION		EMISSION FACTOR	
ACID GAS				
- HCl	1100	mg/Nm^3	4400	g/t
ORGANIC ANALYSIS				
PCDD	100	ng/Nm^3	430	µg/t
PCDF	140	ng/Nm^3	570	µg/t
PCB	800	ng/Nm^3	3400	µg/t
PAN	7000	ng/Nm^3	29 000	µg/t
CB	4300	ng/Nm^3	18 000	µg/t
CP	4300	ng/Nm^3	18 400	µg/t
TOX	120	$µg/Nm^3$		
PARTICULATE	210	mg/Nm^3	840	g/t
METALS				
- Cd	930	$µg/Nm^3$	3.8	g/t
- Pb	14 000	$µg/Nm^3$	55.0	g/t
- Cr	40	$µg/Nm^3$	0.2	g/t
- Ni	240	$µg/Nm^3$	1.0	g/t
- Hg	700	$µg/Nm^3$	2.0	g/t
- Sb	600	$µg/Nm^3$	2.3	g/t

PERATING CONDITIONS

EAM		
FLOW	4400	kg/h
PRESSURE	1900	kPa
MPERATURES		
STEAM	SAT.	
FEEDWATER	250	°C
PRIMARY CHAMBER	700	°C
SECONDARY CHAMBER	1000	°C
AM CYCLES		
FEED	0.7	min

REFUSE

FEED RATE	1590	kg/h
MOISTURE	35	%
CALORIFIC VALUE	10 500	kJ/kg
ORGANIC ANALYSIS		
PCDD	4	mg/t
PCDF	N.D.	mg/t
PCB	360	mg/t
PAN	7	mg/t
CB	20	mg/t
CP	20	mg/t

ASH

COMBUSTIBLES	INCINERATOR	BOILER	ECONOMIZER	
ORGANIC ANALYSIS				
PCDD	N.D.	80	30	ng/g
PCDF	N.D.	10	10	ng/g
PCB	N.D.	4	N.D.	ng/g
PAN	1000	310	160	ng/g
CB	20	220	80	ng/g
CP	N.D.	530	7	ng/g
TOX	500	190	130	µg/g
METALS				
Cd	20	600	540	µg/g
Pb	2600	8500	8000	µg/g
Cr	100	180	170	µg/g
Ni	70	100	90	µg/g
Hg	N.D.	5	5	µg/g
Sb	240	3000	2000	µg/g

N.D. - Not Detected

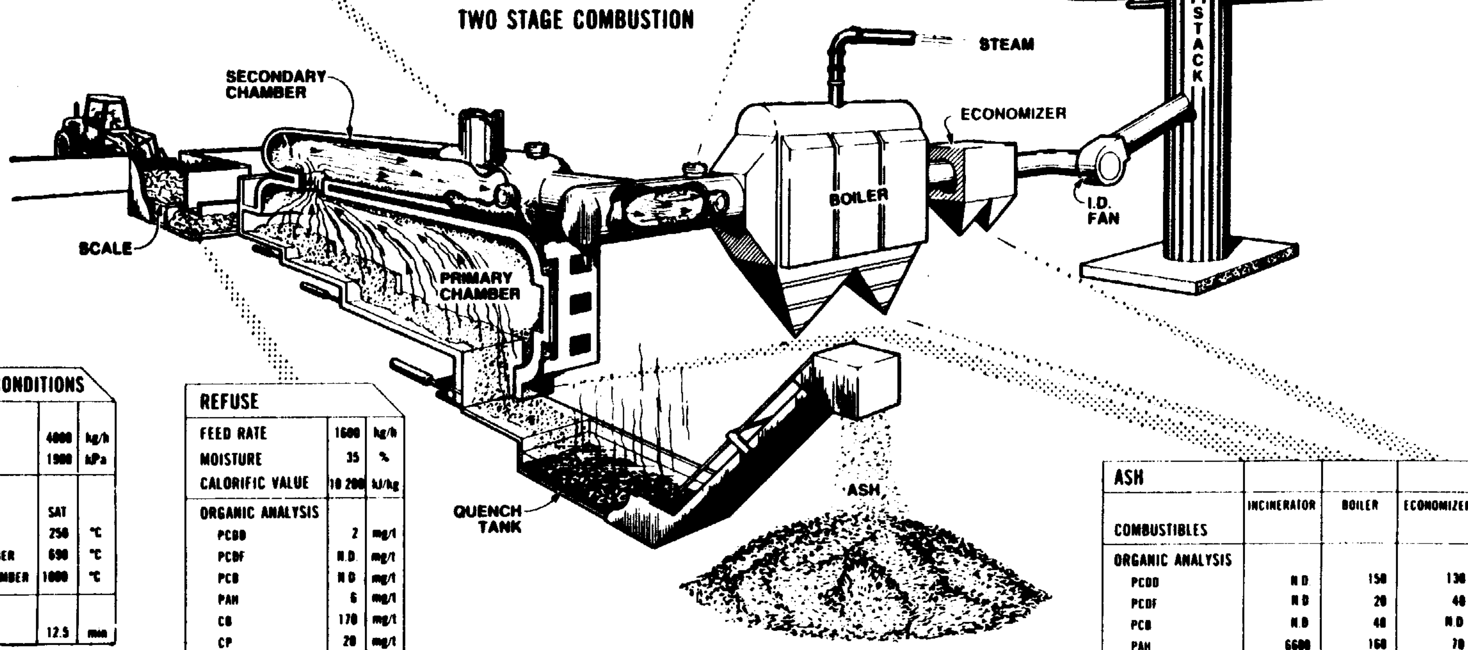
Note: Data rounded off for simplicity.

FIGURE 10 PERFORMANCE TEST SUMMARY - NORMAL CONDITIONS

SECONDARY CHAMBER		
CONTINUOUS DATA		
O_2	11.0	%
CO_2	6.0	%
CO	24	ppm
TEMPERATURE	890	°C

HIGH TEMPERATURE ORGANICS TRAIN		
GAS		
TEMPERATURE	840	°C
ORGANIC ANALYSIS		
PCDD	N D	ng/Nm³
PCDF	N D	ng/Nm³
PCB	11	ng/Nm³
PAH	10 000	ng/Nm³
CB	6600	ng/Nm³
CP	500	ng/Nm³

STACK EMISSIONS				
GAS				
FLOW	9700	Nm³/h		
TEMPERATURE	184	°C		
MOISTURE	14	%		
OPACITY	5.5	%		
CONTINUOUS DATA				
O_2	12	%		
CO_2	8	%		
CO	25	ppm		
NO_x	170	ppm		
SO_2	50	ppm		
THC	1	ppm		
	CONCENTRATION		EMISSION FACTOR	
ACID GAS				
- HCl	1070	mg/Nm³	4130	g/t
ORGANIC ANALYSIS				
PCDD	110	ng/Nm³	400	µg/t
PCDF	160	ng/Nm³	570	µg/t
PCB	60	ng/Nm³	250	µg/t
PAH	8000	ng/Nm³	33 000	µg/t
CB	3200	ng/Nm³	13 000	µg/t
CP	3800	ng/Nm³	15 000	µg/t
TOX	N/A			
PARTICULATE	230	mg/Nm³	870	g/t
METALS				
- Cd	790	µg/Nm³	3.0	g/t
- Pb	15 000	µg/Nm³	58.0	g/t
- Cr	30	µg/Nm³	0.1	g/t
- Ni	300	µg/Nm³	1.0	g/t
- Hg	500	µg/Nm³	2.0	g/t
- Sb	2600	µg/Nm³	0.6	g/t



OPERATING CONDITIONS		
STEAM		
FLOW	4000	kg/h
PRESSURE	1900	kPa
TEMPERATURES		
STEAM	SAT	
FEEDWATER	250	°C
PRIMARY CHAMBER	690	°C
SECONDARY CHAMBER	1000	°C
RAM CYCLES		
FEED	12.5	min

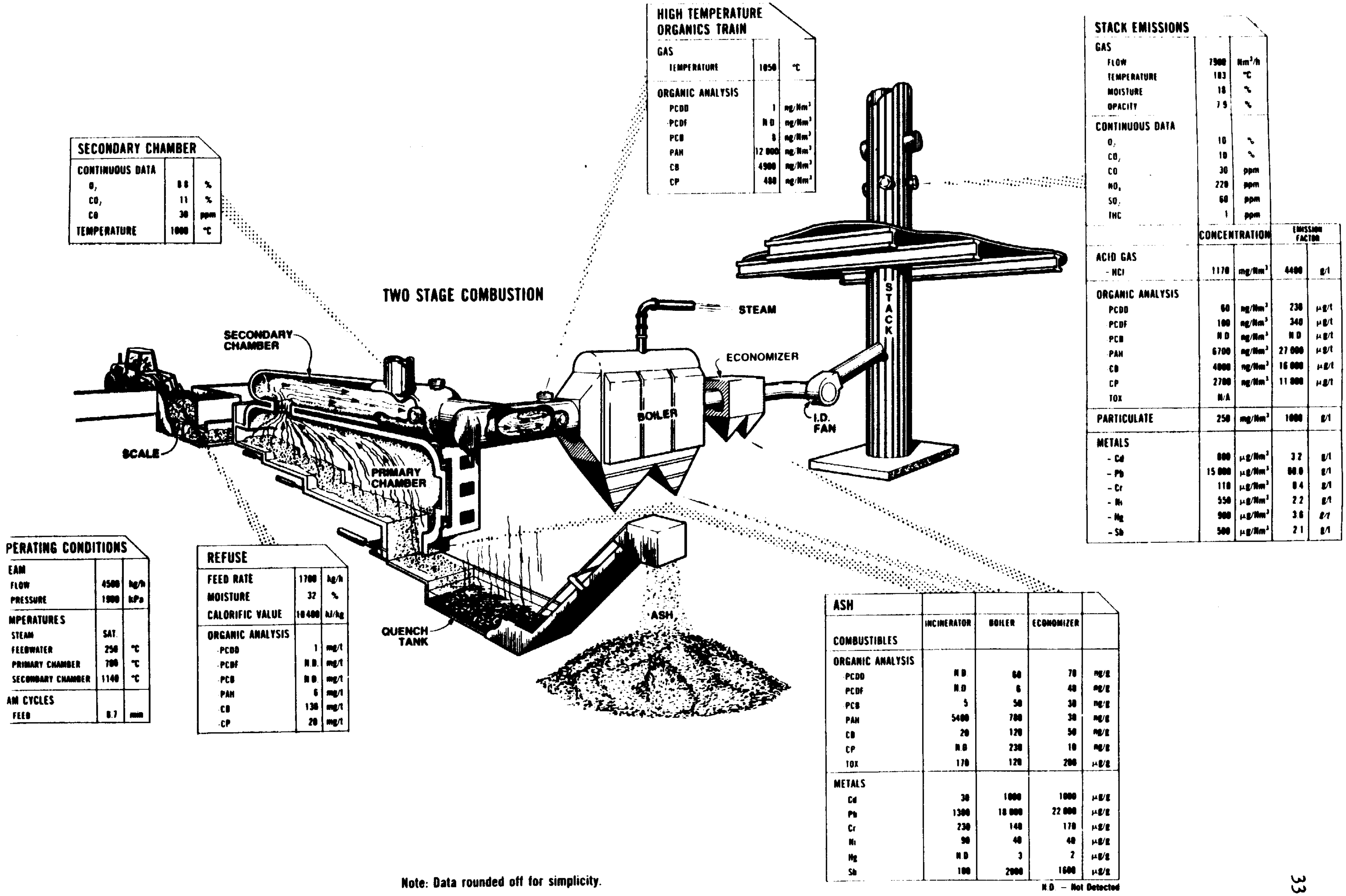
REFUSE		
FEED RATE	1600	kg/h
MOISTURE	35	%
CALORIFIC VALUE	10 200	kJ/kg
ORGANIC ANALYSIS		
PCDD	2	mg/t
PCDF	N.D.	mg/t
PCB	N D	mg/t
PAH	6	mg/t
CB	170	mg/t
CP	20	mg/t

ASH				
COMBUSTIBLES	INCINERATOR	BOILER	ECONOMIZER	
ORGANIC ANALYSIS				
PCDD	N D.	150	130	ng/g
PCDF	N D	20	40	ng/g
PCB	N.D	40	N.D	ng/g
PAH	6600	160	70	ng/g
CB	80	940	70	ng/g
CP	N D.	320	N.D.	ng/g
TOX	200	140	120	µg/g
METALS				
Cd	14	920	730	µg/g
Pb	1800	11 000	9000	µg/g
Cr	100	120	120	µg/g
Ni	50	40	40	µg/g
Hg	N D.	3	3	µg/g
Sb	210	2000	2200	µg/g

N.D. — Not Detected

Note: Data rounded off for simplicity.

FIGURE 11 PERFORMANCE TEST SUMMARY - LONG CYCLE



SECONDARY CHAMBER

CONTINUOUS DATA		
O_2	8.8	%
CO_2	11	%
CO	30	ppm
TEMPERATURE	1000	°C

HIGH TEMPERATURE ORGANICS TRAIN

GAS		
TEMPERATURE	1050	°C
ORGANIC ANALYSIS		
PCDD	1	ng/Nm³
PCDF	N.D.	ng/Nm³
PCB	8	ng/Nm³
PAH	12 000	ng/Nm³
CB	4900	ng/Nm³
CP	480	ng/Nm³

STACK EMISSIONS

GAS				
FLOW	7900	Nm³/h		
TEMPERATURE	103	°C		
MOISTURE	18	%		
OPACITY	7.9	%		
CONTINUOUS DATA				
O_2	10	%		
CO_2	10	%		
CO	30	ppm		
NO_x	220	ppm		
SO_2	60	ppm		
THC	1	ppm		
	CONCENTRATION		EMISSION FACTOR	
ACID GAS				
- HCl	1170	mg/Nm³	4400	g/t
ORGANIC ANALYSIS				
PCDD	60	ng/Nm³	230	µg/t
PCDF	100	ng/Nm³	340	µg/t
PCB	N.D.	ng/Nm³	N.D.	µg/t
PAH	6700	ng/Nm³	27 000	µg/t
CB	4000	ng/Nm³	16 000	µg/t
CP	2700	ng/Nm³	11 000	µg/t
TOX	N/A			
PARTICULATE	250	mg/Nm³	1000	g/t
METALS				
- Cd	800	µg/Nm³	3.2	g/t
- Pb	15 000	µg/Nm³	60.0	g/t
- Cr	110	µg/Nm³	0.4	g/t
- Ni	550	µg/Nm³	2.2	g/t
- Hg	900	µg/Nm³	3.6	g/t
- Sb	500	µg/Nm³	2.1	g/t

PERATING CONDITIONS

EAM		
FLOW	4500	kg/h
PRESSURE	1900	kPa
MPERATURES		
STEAM	SAT.	
FEEDWATER	250	°C
PRIMARY CHAMBER	700	°C
SECONDARY CHAMBER	1140	°C
AM CYCLES		
FEED	6.7	min

REFUSE

FEED RATE	1700	kg/h
MOISTURE	32	%
CALORIFIC VALUE	10 400	kJ/kg
ORGANIC ANALYSIS		
PCDD	1	mg/t
PCDF	N.D.	mg/t
PCB	N.D.	mg/t
PAH	6	mg/t
CB	130	mg/t
CP	20	mg/t

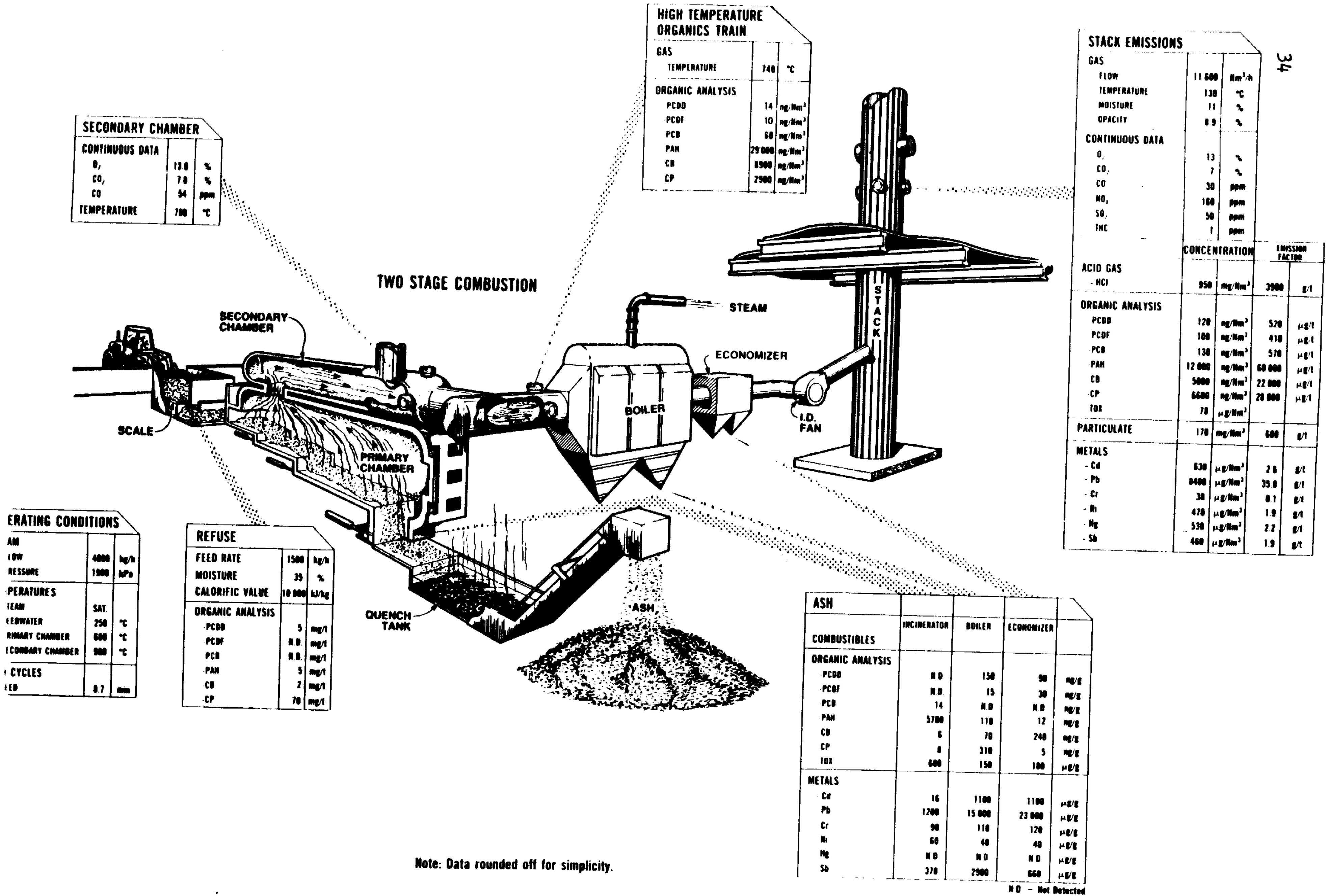
ASH

COMBUSTIBLES	INCINERATOR	BOILER	ECONOMIZER	
ORGANIC ANALYSIS				
PCDD	N.D.	60	70	ng/g
PCDF	N.D.	6	40	ng/g
PCB	5	50	30	ng/g
PAH	5400	700	30	ng/g
CB	20	120	50	ng/g
CP	N.D.	230	10	ng/g
TOX	170	120	200	µg/g
METALS				
Cd	30	1000	1000	µg/g
Pb	1300	18 000	22 000	µg/g
Cr	230	140	170	µg/g
Ni	90	40	40	µg/g
Hg	N.D.	3	2	µg/g
Sb	100	2000	1600	µg/g

N.D. – Not Detected

Note: Data rounded off for simplicity.

FIGURE 12 PERFORMANCE TEST SUMMARY - HIGH SECONDARY TEMPERATURE



SECONDARY CHAMBER

CONTINUOUS DATA		
O_2	13.0	%
CO_2	7.0	%
CO	54	ppm
TEMPERATURE	700	°C

HIGH TEMPERATURE ORGANICS TRAIN

GAS		
TEMPERATURE	740	°C
ORGANIC ANALYSIS		
PCDD	14	ng/Nm³
PCDF	10	ng/Nm³
PCB	60	ng/Nm³
PAH	29'000	ng/Nm³
CB	8900	ng/Nm³
CP	2900	ng/Nm³

STACK EMISSIONS

GAS				
FLOW	11 600	Nm³/h		
TEMPERATURE	130	°C		
MOISTURE	11	%		
OPACITY	8.9	%		
CONTINUOUS DATA				
O_2	13	%		
CO_2	7	%		
CO	30	ppm		
NO_x	160	ppm		
SO_2	50	ppm		
THC	1	ppm		
	CONCENTRATION		EMISSION FACTOR	
ACID GAS				
- HCl	950	mg/Nm³	3900	g/t
ORGANIC ANALYSIS				
PCDD	120	ng/Nm³	520	µg/t
PCDF	100	ng/Nm³	410	µg/t
PCB	130	ng/Nm³	570	µg/t
PAH	12 000	ng/Nm³	60 000	µg/t
CB	5000	ng/Nm³	22 000	µg/t
CP	6600	ng/Nm³	20 000	µg/t
TOX	70	µg/Nm³		
PARTICULATE	170	mg/Nm³	600	g/t
METALS				
- Cd	630	µg/Nm³	2.6	g/t
- Pb	8400	µg/Nm³	35.0	g/t
- Cr	30	µg/Nm³	0.1	g/t
- Ni	470	µg/Nm³	1.9	g/t
- Hg	530	µg/Nm³	2.2	g/t
- Sb	460	µg/Nm³	1.9	g/t

ERATING CONDITIONS

AM		
LOW	4000	kg/h
RESSURE	1900	kPa
PERATURES		
TEAM	SAT.	
EEDWATER	250	°C
RIMARY CHAMBER	600	°C
ECONDARY CHAMBER	900	°C
CYCLES		
EED	0.7	min

REFUSE

FEED RATE	1500	kg/h
MOISTURE	35	%
CALORIFIC VALUE	10 000	kJ/kg
ORGANIC ANALYSIS		
PCDD	5	mg/t
PCDF	N.D.	mg/t
PCB	N.D.	mg/t
PAH	5	mg/t
CB	2	mg/t
CP	70	mg/t

ASH

COMBUSTIBLES	INCINERATOR	BOILER	ECONOMIZER	
ORGANIC ANALYSIS				
PCDD	N.D.	150	90	ng/g
PCDF	N.D.	15	30	ng/g
PCB	14	N.D.	N.D.	ng/g
PAH	5700	110	12	ng/g
CB	6	70	240	ng/g
CP	8	310	5	ng/g
TOX	600	150	100	µg/g
METALS				
Cd	16	1100	1100	µg/g
Pb	1200	15 000	23 000	µg/g
Cr	90	110	120	µg/g
Ni	60	40	40	µg/g
Hg	N.D.	N.D.	N.D.	µg/g
Sb	370	2900	660	µg/g

N.D. – Not Detected

Note: Data rounded off for simplicity.

FIGURE 13 PERFORMANCE TEST SUMMARY - LOW SECONDARY TEMPERATURE

The secondary chamber exit temperature, a key operating condition, was examined at between 780°C and 1080°C. The temperature was maintained ±10°C by adjusting the amount of combustion air supplied to the secondary chamber.

Feed/energy input. The feed rate to the unit, for each of the four test groups, indicated that a relatively consistent feed rate of between 1500 and 1700 kg/h was maintained during all 12 tests. It should be noted that even at the lowest feed rate (1500 kg/h) the nominal design loading rate of the incinerators (1400 kg/h) was exceeded. The corresponding energy input rate was calculated at 16 to 17.6 x 10^6 kJ/h. Clearly the feed rate did not vary significantly between any of the four groups and made only a marginal impact on energy input.

Energy output/efficiency. Steam production averaged between 4400 and 4500 kg/h for the normal and high temperature group tests. The long cycle and low temperature groups each averaged approximately 4000 kg/h steam production. During the normal and high temperature operations, the calculated efficiencies using input/output were 59.6 and 58.4 percent, respectively. At the other two test conditions, long cycle and low temperature, efficiencies were slightly lower at 56.6 and 55.9 percent, respectively. An examination of steam production rates indicated a correspondence with the input/output efficiencies calculated for this system.

A different picture is presented when the heat loss efficiency calculation, which reflects changes in ignition losses of the ash, is employed. Two major factors influencing the variability in the heat loss calculation were dry air losses and the loss from the ash which are discussed in greater detail in Volume II.

Flame observations. The flame condition in the primary chamber was similar during all four groups of tests: a slow, lazy flame, when visible, with most of the chamber being black and hazy. The flame intensity in the secondary chamber increased with temperature, i.e., was brightest for the high temperature test group. Significantly more sparks were observed in the manifold to the boiler during the low temperature test runs.

Combustion gases. Since secondary chamber temperature levels were controlled by the flow of combustion air to the chamber there were significant differences in the measured oxygen and carbon dioxide concentrations and the calculated excess air levels. These results were as expected and are presented below:

Operation Description	% CO_2	% O_2	% Excess Air
Normal Condition	8	12	140
Long Cycle	8	12	145
High Secondary Temperature	10	10	85
Low Secondary Temperature	7	13	185

Continuous gas monitors. The emissions of carbon monoxide, sulphur dioxide, total hydrocarbons, and nitrogen oxides were continuously recorded and are presented below:

	Concentration (ppm dry corrected to 12% CO_2)			
Operation Description	CO	THC	SO_2	NO_x
Normal Condition	67	0.8	61	309
Long Cycle	40	0.8	83	271
High Secondary Temperature	33	0.9	75	258
Low Secondary Temperature	52	1.2	87	292

Carbon monoxide levels were much lower than have been published for tests on similar incinerators. The high secondary temperature data presented above suggest lower carbon monoxide levels with increased temperature; however, the statistical analysis completed using data from all 12 test runs showed only a weak correlation.

Total hydrocarbon data indicated almost zero levels of hydrocarbons in all cases. A minor increase in the total hydrocarbon concentrations occurred with the low temperature test data; however, only a weak relationship existed between temperature and THC levels.

Sulphur dioxide concentrations showed no particular trend, and on first glance neither did the nitrogen oxides. A further assessment of the nitrogen oxide data is made in the following chapter.

6.2.2 Stack Emissions. The stack emissions data are summarized in Table 4.

Flue gas flow rate. The flue gas flow rates for each of the groups tested were as follows:

Operation Description	Uncorrected Stack Flow (Nm^3/h)
Normal Condition	10 100
Long Cycle	9 700
High Secondary Temperature	7 900
Low Secondary Temperature	11 700

The stack flow rates were calculated by averaging data from all the isokinetic trains which were operated simultaneously during each test. Differences in flow rates between the different operating conditions were primarily the result of changing secondary air flow to maintain secondary temperature.

Total suspended particulate matter (TSP) emissions. The measured average particulate matter concentrations of 170 to 250 mg/Nm^3 at 12 percent CO_2 are relatively low in comparison with other facilities, considering the plant is not equipped with pollution control equipment. The data shown in Table 4 indicate that the low secondary temperature operating condition has the lowest rate of emission of particulate matter (TSP). This low emission rate appears to be an anomally considering that the highest concentration of sparklers in the manifold was observed during low temperature operation. Conversely, the high secondary temperature test group had few sparklers in the manifold and recorded the highest TSP emission rate. A possible explanation for this behaviour is the inertial properties of the particulates and their loss of momentum through rapid and frequent changes in direction. High velocities through the system would increase the inertial properties of the particulate matter. Conversely, with high secondary temperatures, lower velocities would decrease the inertial properties.

Particle size data shows that 40 percent to 80 percent of the particulates were less than 1 μm in size. Since the particulate size is so extremely fine, the selection of a particulate control device for two-stage combustion systems must be carefully considered.

Acid gases. Acid gas emissions, as HCl, were relatively similar for the four performance test conditions. Emissions averaged approximately 1 g/Nm^3 or 4.2 kg/tonne of refuse.

TABLE 4 COMPARISON OF EMISSIONS DATA

Contaminant	Normal	Long	High	Low
	Stack Concentration (at 12% CO_2) Dry			
TSP (mg/Nm^3)	208	230	247	167
HCl (mg/Nm^3)	1 085*	1 070	1 165	950
PCDD (ng/Nm^3)	107	107	62	123
PCDF (ng/Nm^3)	143	156	95	98
PCB (ng/Nm^3)	801	58	ND	126*
PAH (ng/Nm^3)	7 005	8 010	6 653	12 490*
Chlorophenol (ng/Nm^3)	4 346	3 773	2 706	6 591*
Chlorobenzene (ng/Nm^3)	4 321	3 161	3 968	4 884*
Cadmium (mg/Nm^3)	0.9	0.8	0.8	0.6
Lead (mg/Nm^3)	13.5	15.2	15.2	8.4
Chromium (mg/Nm^3)	0.04	0.03	0.1	0.03
Nickel (mg/Nm^3)	0.2	0.3	0.5	0.5
Mercury (mg/Nm^3)	0.7	0.5	0.9	0.5
Antimony (mg/Nm^3)	0.6	2.6	0.5	0.5
	Stack Emissions per tonne of Feed (as fired)			
TSP (g/tonne)	843	874	977	682
HCl (g/tonne)	4 400	4 130	4 480	3 930
PCDD (µg/tonne)	428	400	228	516
PCDF (µg/tonne)	570	574	340	411
PCB (µg/tonne)	3 413	245	ND	574*
PAH (µg/tonne)	29 305	33 201	26 956	54 514*
Chlorophenol (µg/tonne)	18 403	15 042	10 814	28 973*
Chlorobenzene (µg/tonne)	18 014	12 807	16 061	22 045*
Cadmium (g/tonne)	3.8	3.0	3.2	2.6
Lead (g/tonne)	54.8	57.8	60.0	34.2
Chromium (g/tonne)	0.2	0.1	0.4	0.1
Nickel (g/tonne)	1.0	1.0	2.2	1.9
Mercury (g/tonne)	2.8	2.0	3.6	2.2
Antimony (g/tonne)	2.3	9.6	2.1	1.9

* based on average of two tests only

ND - Not Detected

This level is typical of that reported for municipal refuse incinerators with no HCl removal equipment.

Dioxins (PCDD)/Furans (PCDF). The total dioxin emissions were in the range of 200 to 600 µg/tonne of refuse fired. This level is at the lower range of data published elsewhere from municipal solid waste incinerators. Higher temperatures in the secondary chamber appear to have reduced the quantity of dioxins leaving the stack but not significantly.

Total furan emissions were in the range of 250 to 1000 µg/tonne of refuse fired. Results show lower furan emissions at high secondary chamber temperature conditions, supporting the expected trend of lower emission at higher temperature. The emissions of furans were also lower at the low temperature operating condition than they were at normal operating conditions. There is no explanation for the latter result.

An important factor to consider is the distribution pattern of the various dioxins and furans homologues and how this distribution changes by test. Figure 14 presents the overall average distribution and indicates the following:

- the proportion of each dioxin homologue in the sample increases with its molecular weight so that octa dominates, and
- a predominance of hexa furan homologue exists with a bias towards the lower weight material in a bell-shaped distribution.

The influence of different test conditions on dioxin homologue distribution can be found in Figure 15. Dioxin homologue distributions show the following:

- low secondary temperature biases the distribution to the heavier compounds,
- normal and high secondary temperatures produce similar distributions, and
- long cycle operation biases the distribution to the lighter compounds.

In Figure 16, furan homologue distributions show the following:

- a very close agreement between the distribution pattern for normal and long cycle operation, and
- low temperature operation biases the distribution towards octa homologue.

The correlations between homologue distributions and test condition were not significant, however.

Other organics. Polychlorinated biphenyl (PCB), polyaromatic hydrocarbon (PAH), chlorophenol (CP) and chlorobenzene (CB) concentrations were also monitored in the stack. Results, shown in Table 4, indicate that the levels of these various compounds may be affected by temperature. The data have sufficient scatter to warrant further testing to

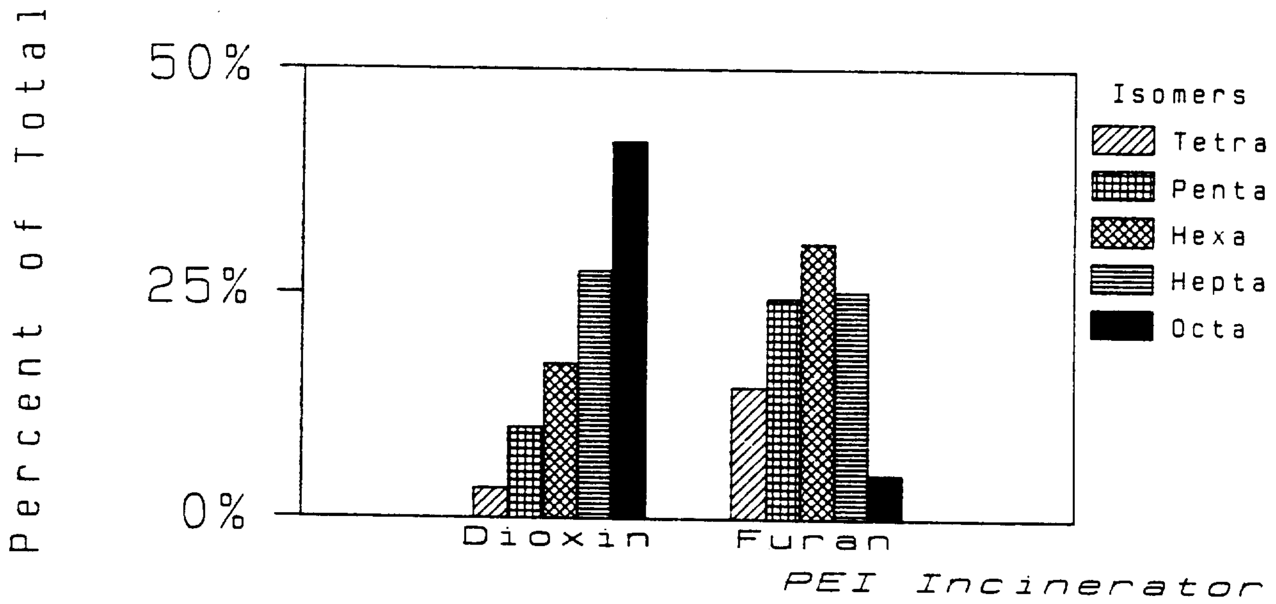


FIGURE 14 STACK DIOXIN AND FURAN HOMOLOGUE DISTRIBUTION

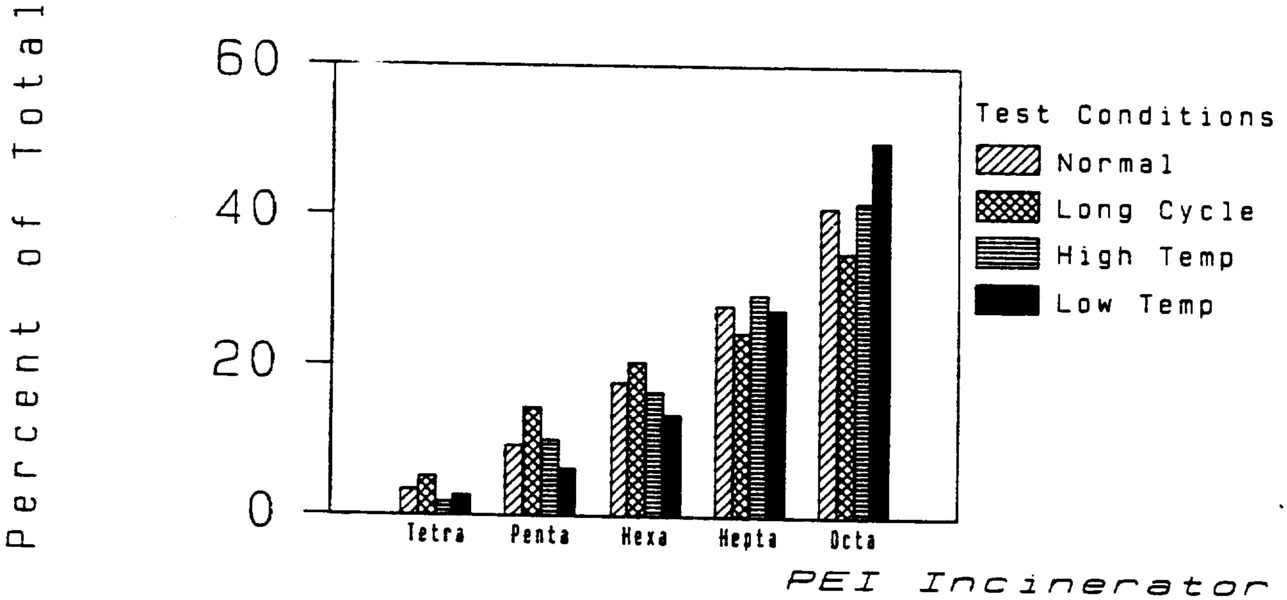


FIGURE 15 STACK DIOXIN HOMOLOGUE DISTRIBUTION BY TEST CONDITION

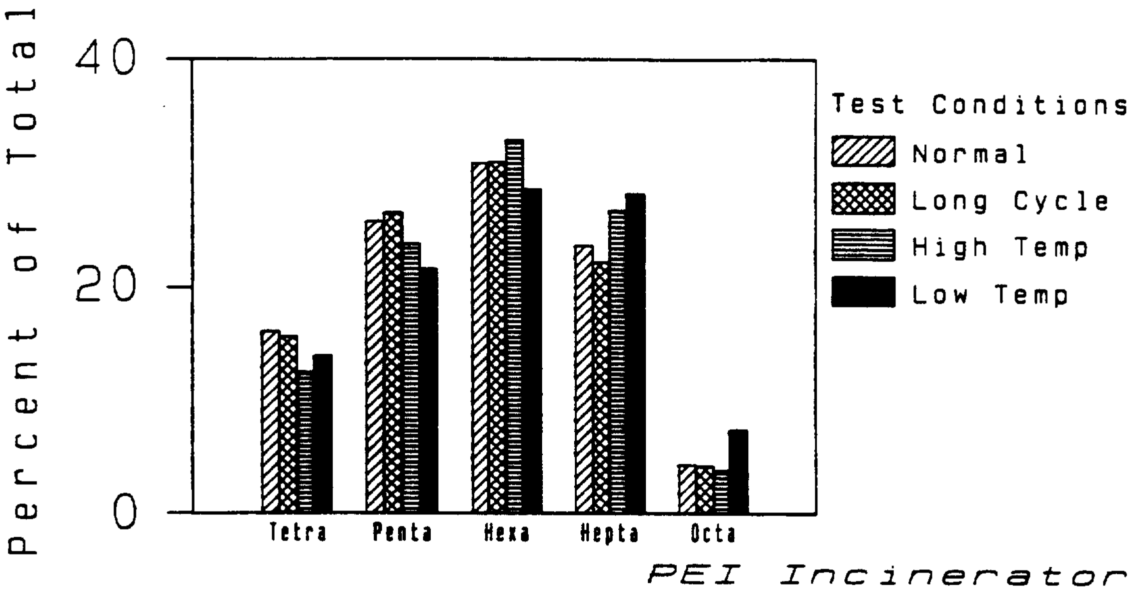


FIGURE 16 STACK FURAN HOMOLOGUE DISTRIBUTION BY TEST CONDITION

prove this hypothesis. It is interesting to note that the PCB levels in the stack were very low and that only under the low temperature secondary chamber condition were PCBs found for more than one test run.

Metals. While a complete scan for a full range of metals was made for all samples, only selected emission concentrations are shown in Table 4. It is interesting to note that there appears to be a trade-off between higher metal emissions and lower organic emissions. Chromium, lead and copper emissions vary directly with secondary chamber temperature. This is confirmed by the trend analysis in the following chapter.

Boiler inlet organics. For three of the test groups, various organic compounds were sampled at the inlet to the boiler. The concentrations of compounds found at this location during the various group tests compared to stack concentrations are shown in Table 5. Dioxin and furan concentrations at the boiler inlet were virtually undetected compared to stack emissions. PCB concentrations in the stack were higher than those at the boiler inlet for both the long cycle and the low temperature conditions. However, at high temperatures, no PCBs were emitted from the stack and PCB was measured at the boiler inlet for only one test run. Chlorophenols were higher at the stack than at the boiler inlet. PAH data shows that concentrations at the stack were lower than at the boiler inlet. Although the group averages for chlorobenzenes suggest that concentrations at the stack were lower than at the boiler inlet, several individual test runs showed the opposite.

TABLE 5 CONCENTRATIONS OF ORGANIC COMPOUNDS AT BOILER INLET IN COMPARISON TO STACK

	Concentration (ng/Nm^3 @ 12% CO_2)					
	Long Cycle		High Temperature		Low Temperature	
Compound	Boiler Inlet	Stack	Boiler Inlet	Stack	Boiler Inlet	Stack
PCDD	ND	107	1	62	14	123
PCDF	ND	156	ND	95	10	98
PCB	11*	58	8*	ND	61	126**
PAH	10 475	8 010	12 226	6 653	29 481	12 490**
Chlorophenol	486	3 773	479	2 706	2 941	6 591**
Chlorobenzene	6 595	3 161	4 895	3 968	8 906	4 884**

* only one non-zero value (two readings were below detection limit)
** based on average of 2 tests only.

In most cases the concentrations of these compounds varied inversely with temperature, resulting in the highest levels for the lowest secondary chamber temperatures. In view of the potential significance of the difference between stack and boiler inlet concentrations, further investigation of these differences is warranted.

6.3 Oxygen Cycle

During performance testing it was noted that the oxygen concentration at the stack varied in a cyclical manner. This was attributed to the operation of the various feed and ash rams in the incinerator. A typical oxygen cycle is shown in Figure 17.

Starting at the time when the charge ram begins to operate, a trend very quickly becomes apparent. The oxygen concentration drops during charging, since the primary chamber air supply is interrupted to prevent the flame from travelling into the charging hopper. Upon completion of the charging phase, the fire door closes, air is reintroduced into the primary chamber, and an increase in oxygen content is observed. A second depression in the oxygen concentration follows this peak. While insufficient data was collected to determine the cause of the secondary depression, it is likely the result of overshoot in the system controlling secondary air flow. The secondary depression is quickly followed by a relatively steady state condition for about five minutes, in the case of normal operation, or until the commencement of the succeeding charge cycle. When

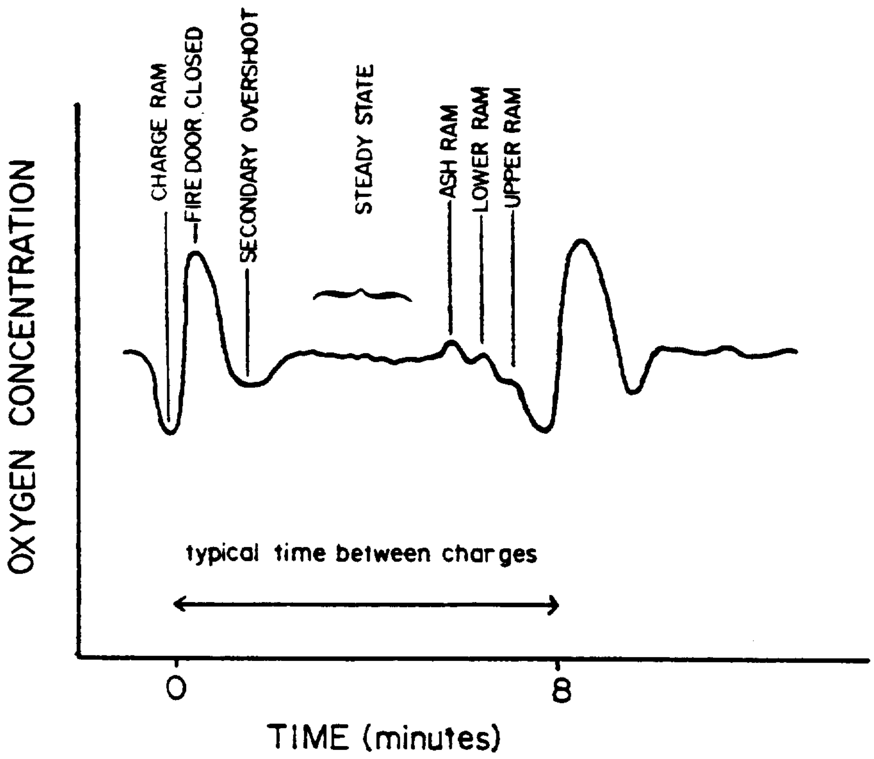


FIGURE 17 TYPICAL OXYGEN CURVE

internal rams are operated, changes occur in the oxygen content which are likely due to an air pressure change caused by ram action and the displacement and replacement of fuel on the various hearths.

For each of the four performance conditions, this cyclical pattern is repeated although the amplitude of the variations is different for each performance condition. Whereas amplitudes were less for the low temperature condition, due to a higher ratio of secondary air to primary air, the amplitudes were greater at the high temperature condition, since the ratio of secondary air to primary air is minimal under this condition. For a long feed cycle, the cyclical behaviour is similar to the low temperature condition, with the distance between the charge cycles spaced further apart.

6.4 Isotherms

Measurements of temperature at various locations across a cross-section of the secondary chamber exit were used to construct a pattern of equal temperature curves (isotherms). The example shown in Figure 18 is typical and represents the results for the group average for high temperature operating conditions. A high temperature zone

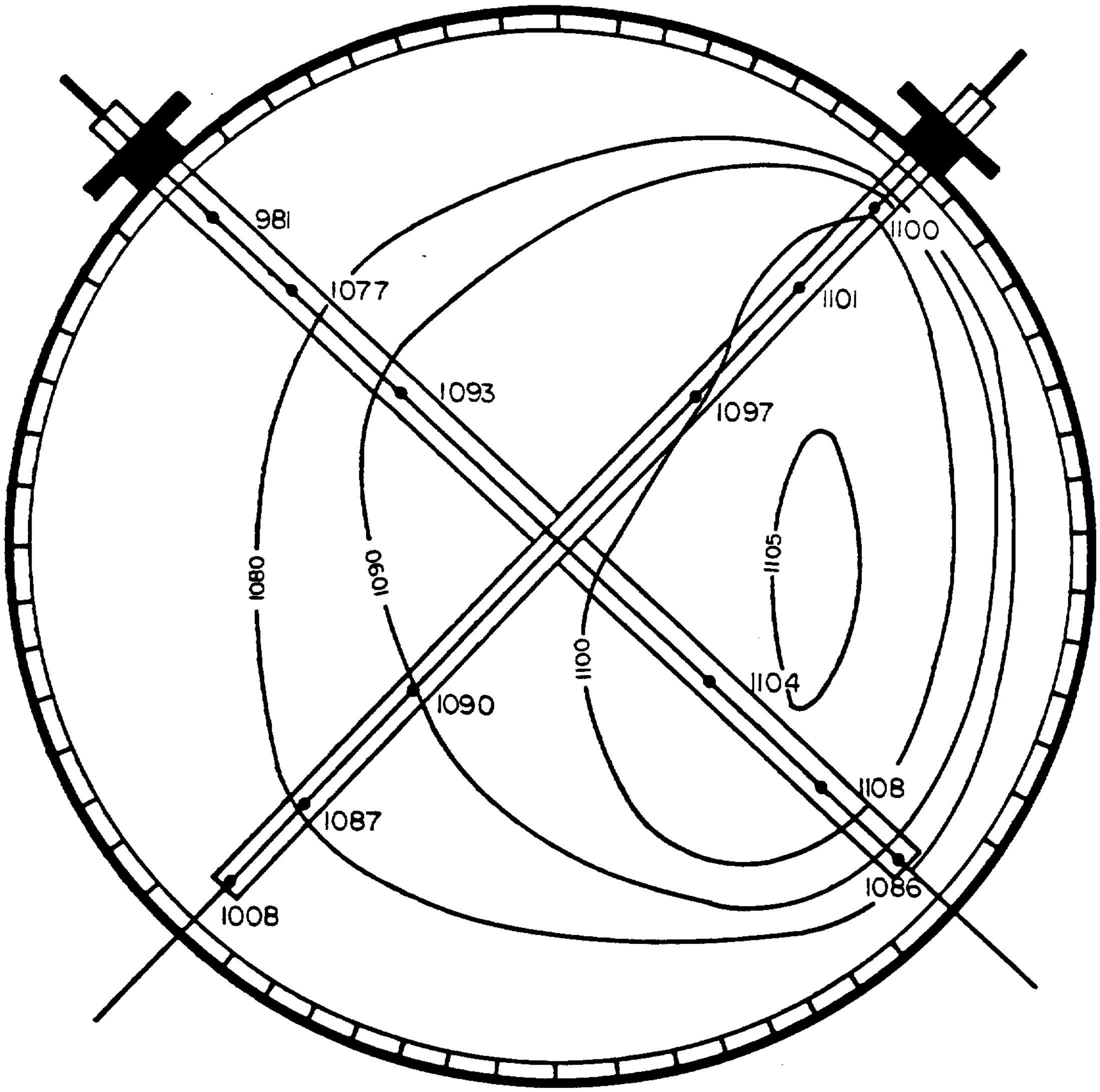


FIGURE 18 HIGH-TEMPERATURE TEST SECONDARY CHAMBER TEMPERATURE DISTRIBUTION

occurs, offset to the right of the figure. Similar occurrences were noted for the other test conditions.

A possible explanation for this offset in isotherm pattern may lie in the manner by which secondary air is introduced. Air flows from nozzles located in the chamber may not generate uniform pressure drops, thereby distorting the air penetration. Another possible explanation may be a flow field effect induced by the gases going through a change in direction into the manifold.

7 TREND ANALYSIS

This chapter assesses the emission changes induced by varying operating conditions. Volume II provides a more thorough discussion of trends observed; in the following discussion, only the more significant trends in emissions will be highlighted. The main process variable adjusted during the performance tests was secondary chamber temperature. Other parameters such as primary chamber temperature, refuse quality, feed rate and frequency, were also examined.

All the data from the tests were entered into a computer matrix and reviewed to assess the apparent significant trends between various operating parameters. An explanation of the statistical procedures employed is provided in Appendix C.

Many comparisons were undertaken for this study. Some are discussed in Volume II and later in this chapter; most of the results are presented in Volume IV.

7.1 Dioxins and Furans

Discussions in the previous chapter indicated that emissions of dioxins and furans correlate to some operating parameters. To illustrate some of the trends encountered, selected paired data were plotted as described below.

Figure 19 presents a plot of average dioxin and furan emissions (µg/h) by test group. The figure shows relatively consistent emissions for normal and long cycle operation, with lower dioxin and furan emissions for the high temperature run and higher dioxins for the low temperature condition. Since the major change in operation was secondary chamber temperature, these data suggest that an inverse relationship exists between dioxin emissions and temperature. To test this relationship, a correlation between the above variables was calculated. Figure 20 shows that the line fit through the data has an r^2 value of 0.40. By excluding PT-13, the r^2 improves to 0.62. The slope of the line in all cases indicates a decrease in dioxin emissions with higher temperature. It should also be noted that various other operating parameters at the incinerator such as flow rate, percent O_2, percent CO_2 and percent excess air correlated highly with secondary chamber temperature, and hence showed a relationship similar to dioxin and furan emissions (Table 6).

Furan emissions for the low temperature runs were lower than those recorded for normal operation. As shown from Figure 19, furans do not exhibit the same temperature/concentration relationship as dioxins; an r^2 value of 0.04 was determined for furan emission versus secondary temperature.

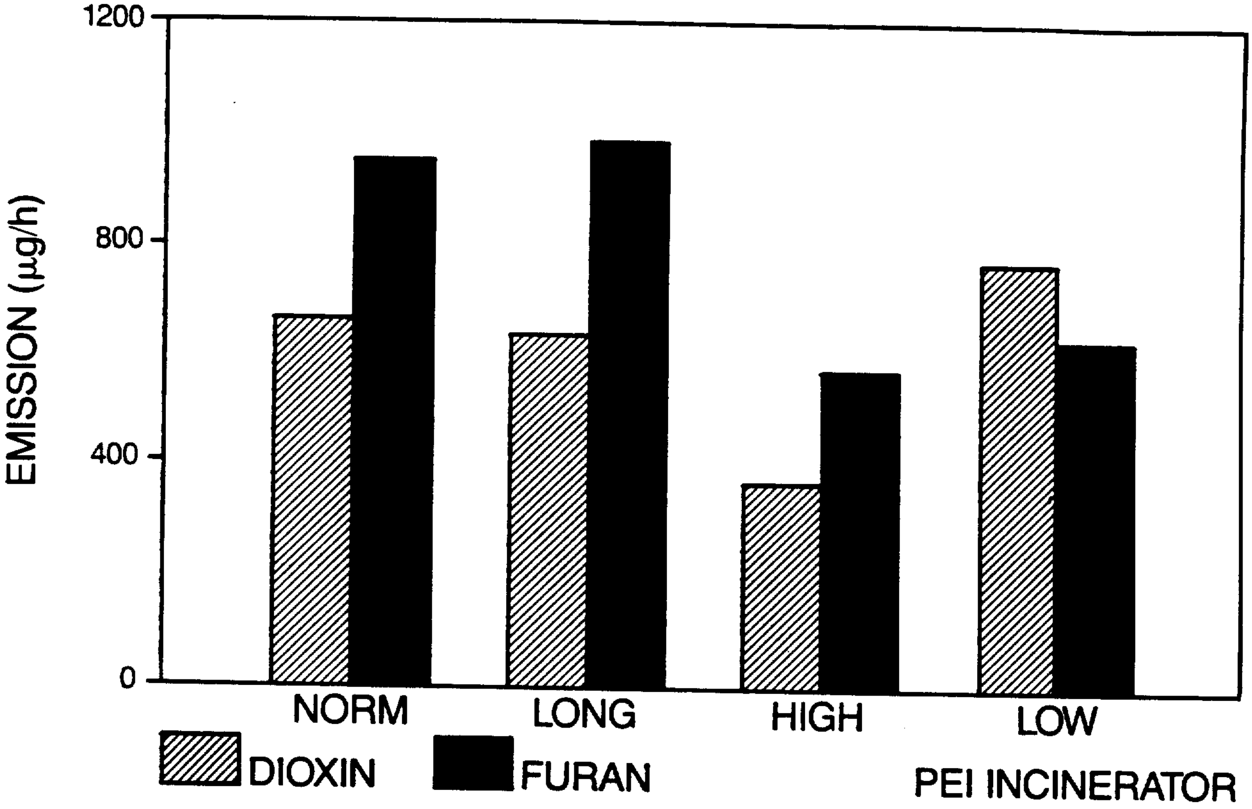


FIGURE 19 TOTAL DIOXIN/FURAN EMISSIONS BY GROUP MEAN

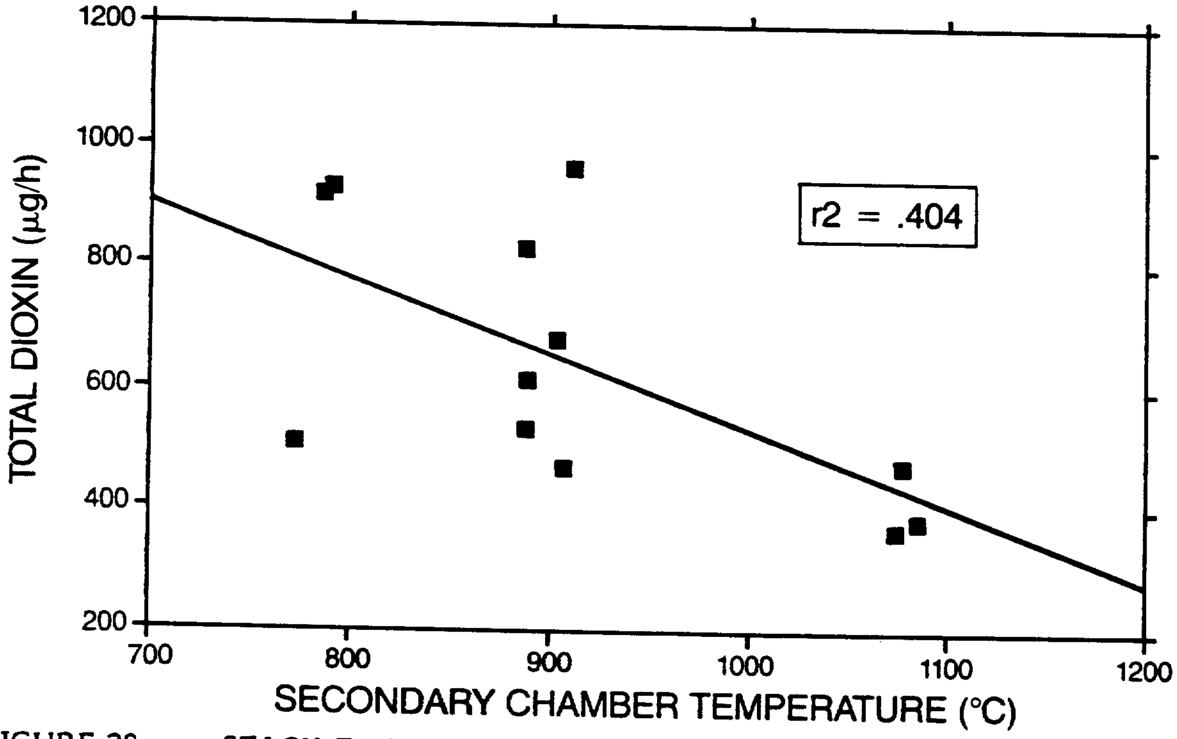


FIGURE 20 STACK TOTAL DIOXIN EMISSIONS vs. SECONDARY CHAMBER TEMPERATURE

TABLE 6 COORELATION COEFFICIENTS FOR PROCESS PARAMETERS vs. SECONDARY TEMPERATURE

Description	r	r^2
Primary Temperature	0.79	0.62
Flow Rate	-0.97	0.94
% Excess Air	-0.97	0.94
% Oxygen	-0.98	0.96
% Carbon Dioxide	0.99	0.98

Further examination of the dioxin data indicates that not all the variability is accounted for by secondary temperature variations. For instance, a review of dioxin emissions versus refuse moisture (Figure 21) shows an r^2 of 0.66. Furan emissions versus refuse moisture (Figure 22) provides a lower r^2 (0.55) but a much better correlation than that found for temperature.

Another important observation was the dioxin/furan distribution throughout the incinerator system (i.e., garbage, incinerator ash, boiler ash and economizer ash). In Figure 23 the concentrations of dioxins and furans found in the system are shown on a log scale graph to emphasize the large differences. Basically, this graph shows that neither dioxins nor furans were found in the incinerator bottom ash and virtually no furans were measured in the garbage. The graph does show concentrations of dioxins in the boiler and economizer ash to be significantly greater than those measured in the garbage. Although the concentrations are relatively high for these ashes the significance of this cannot be assessed because ash quantities could not be measured.

In Figure 24, the mass flow rate of dioxin entering with the garbage is compared to the mass flow rate of dioxin stack emissions. It can be seen that substantially more dioxins are input with the garbage than are emitted from the stack on an hourly basis. The picture is substantially different when looking at the furans, since virtually none was found in the garbage. In both cases, the dioxin and furan stack emissions on an hourly basis were about the same. The above observation points out the need for a closer examination of destruction/formation mechanisms occurring in the incinerator.

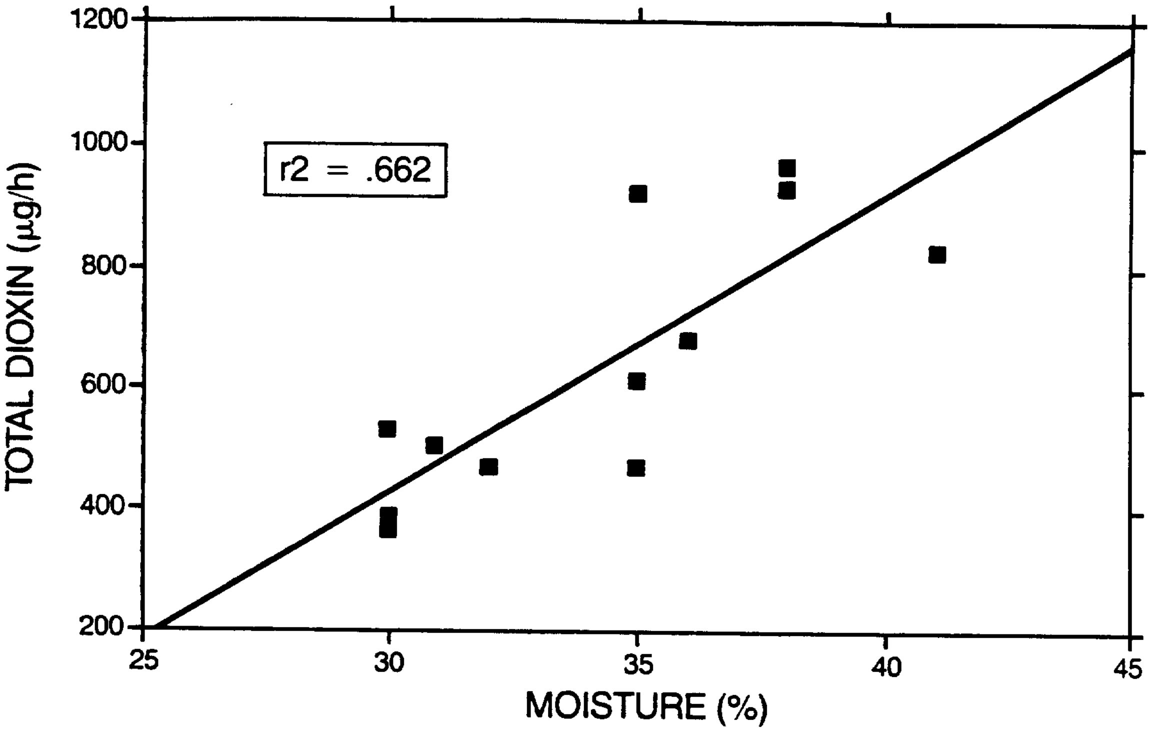


FIGURE 21 STACK TOTAL DIOXIN EMISSIONS vs. REFUSE MOISTURE

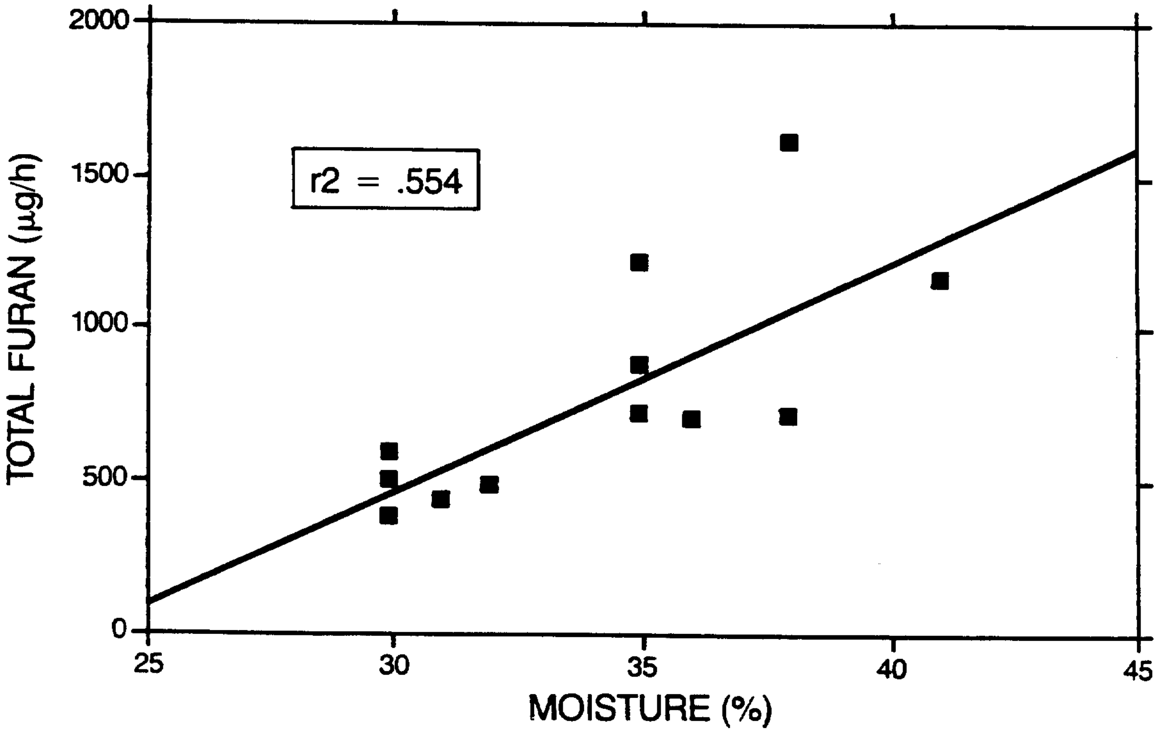


FIGURE 22 STACK TOTAL FURAN EMISSIONS vs. REFUSE MOISTURE

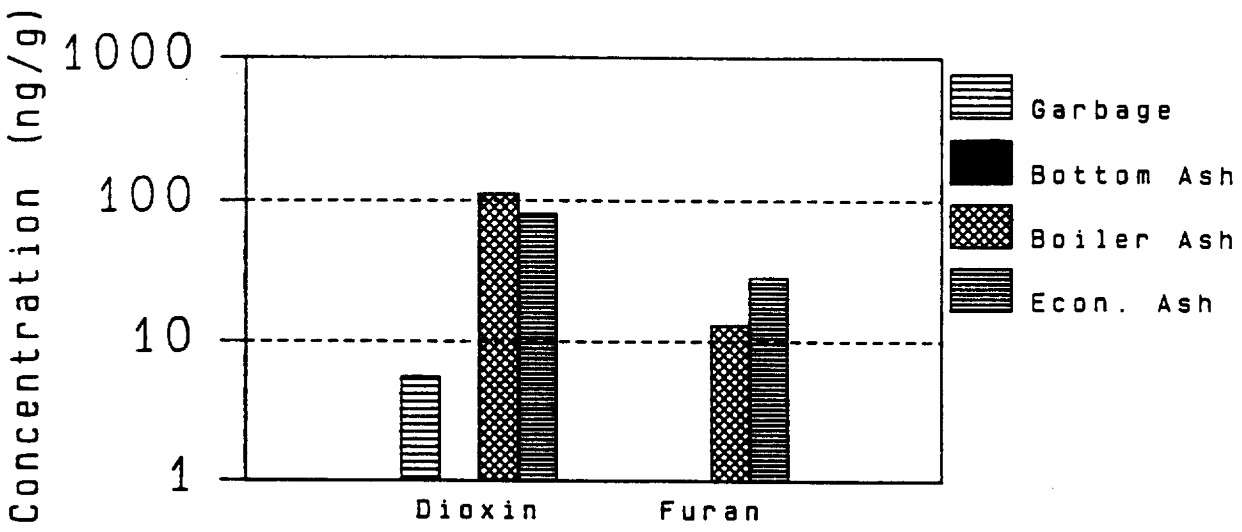


FIGURE 23 DISTRIBUTION OF DIOXINS/FURANS IN SOLIDS (as analysed)

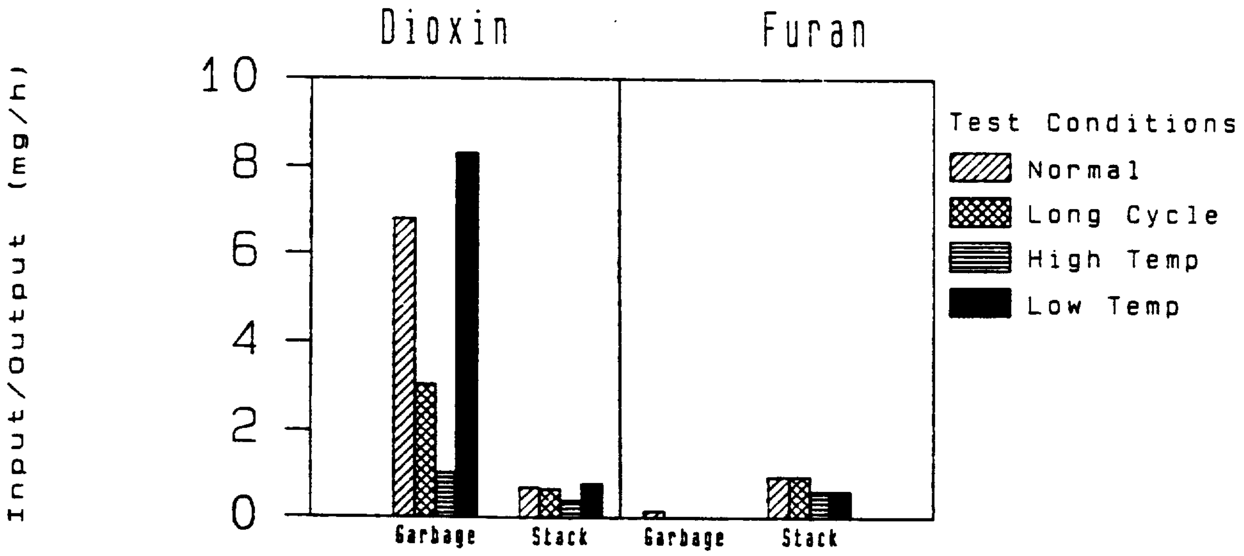


FIGURE 24 TOTAL DIOXIN/FURAN INPUT/OUTPUT

7.2 Other Organic Substances

Average emission factors for polycyclic aromatic hydrocarbon (PAH), polychlorinated biphenyl (PCB), chlorobenzene (CB) and chlorophenol (CP) compounds (on a mg/tonne of dry feed basis) are shown in Figure 25. The CP emission concentrations appear to be lower with higher secondary temperature as do the PAH and CB emissions.

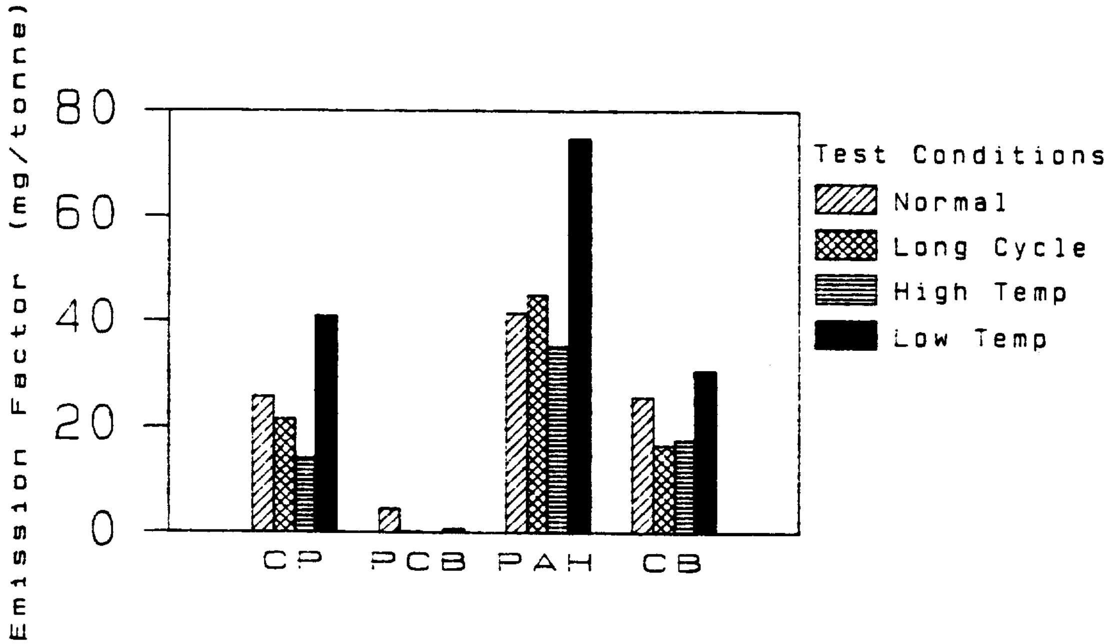


FIGURE 25 TOTAL ORGANIC EMISSION FACTORS (mg/tonne dry feed)

The PCB concentration to temperature relationship is not clear from Figure 25. PCB was found in only one test run of three for both normal and long cycle operations. Samples from two low temperature runs had PCBs; none was found in any of the high temperature run samples.

To assess the apparent relationship between organic emissions and secondary chamber temperature, correlation coefficients were calculated using individual run values. Since test results were not obtained for PT-13, r^2 values for the data were based on 11 runs. This resulted in the following correlation coefficients:

PCB r^2 = 0.01,
PAH r^2 = 0.27,
CP r^2 = 0.4, and
CB r^2 = 0.05.

This analysis indicates a large degree of run-to-run variability in the relationship between organic emissions and secondary chamber temperature. The use of group average data may not be appropriate to assess these interrelationships.

Although no dioxins or furans were found in the bottom ash, significant concentrations of other organics were found, in particular PAH. The average distributions of other organic compounds in the system are compared in Figure 26.

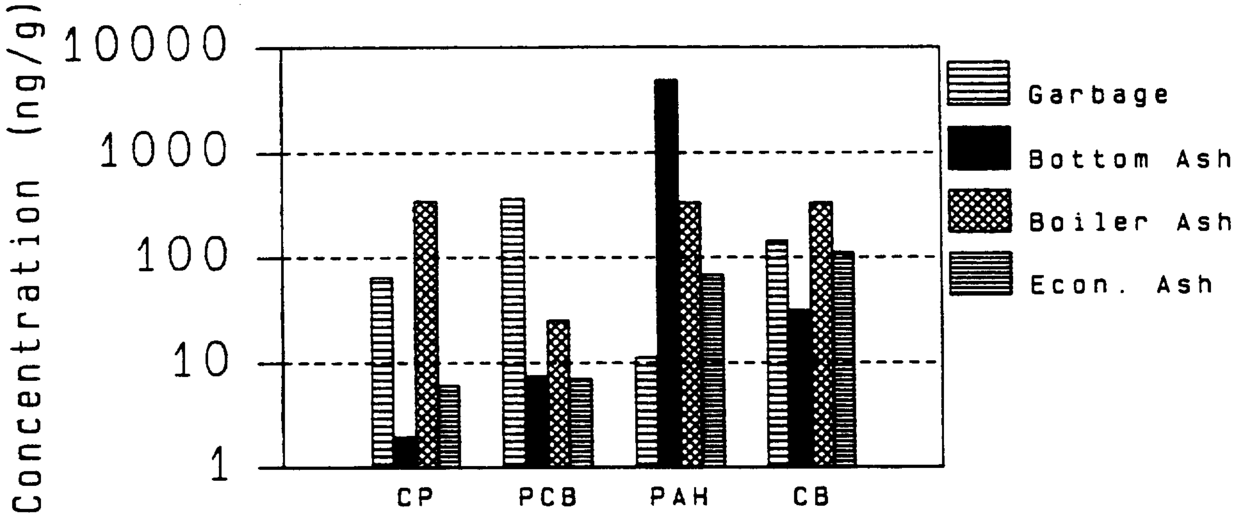


FIGURE 26 DISTRIBUTION OF ORGANICS IN SOLIDS (as analysed)

7.3 Gaseous Emissions

Stack NO_x concentration (not corrected for CO_2) versus secondary temperature gives an r^2 value of 0.75, suggesting a good fit using all run data. If NO_x concentration is corrected to 12% CO_2, the correlation is very poor ($r^2 = 0.29$). This can be attributed to the significant correlation between percent CO_2 and secondary temperature.

Coefficients for SO_2 to refuse sulphur content or temperature, HCl to refuse Cl concentration, and CO to THC, showed poor correlations.

7.4 Particulate Matter and Metals Emissions

A summary of selected metal emission factors (on a dry feed basis) is shown in Figure 27. It is evident from this figure that lead emissions are the highest of all metals emissions for all operating conditions.

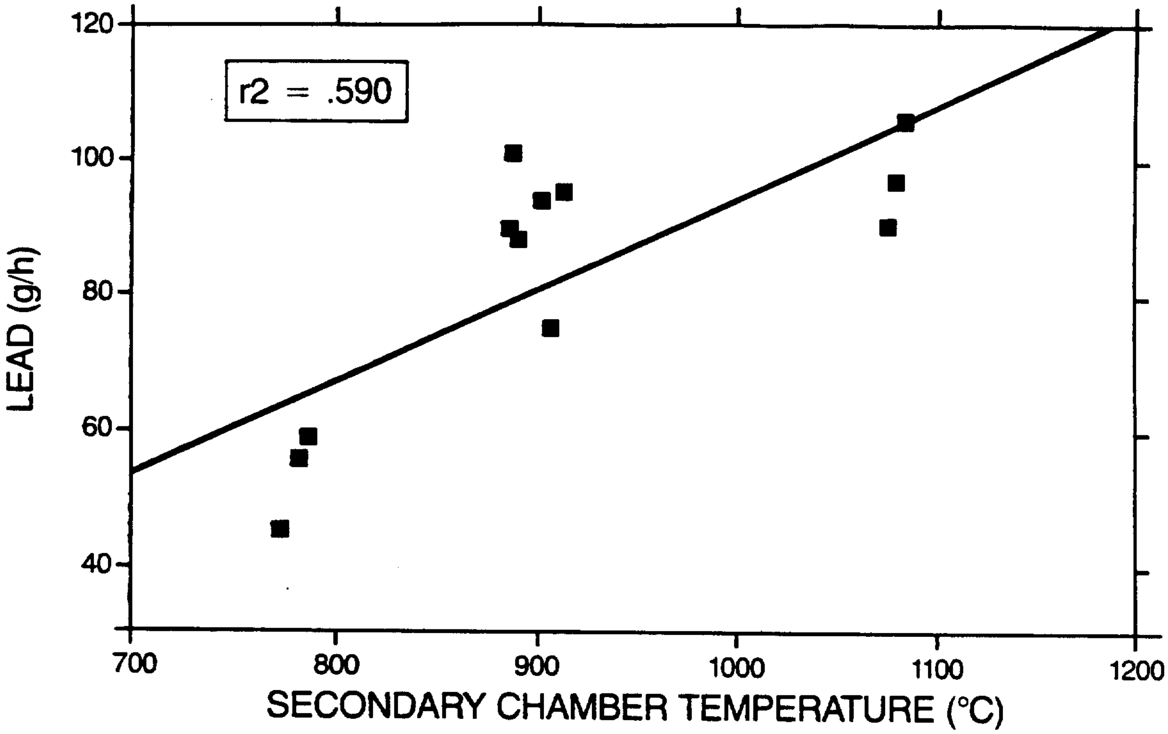


FIGURE 29 STACK LEAD EMISSIONS vs. SECONDARY CHAMBER TEMPERATURE

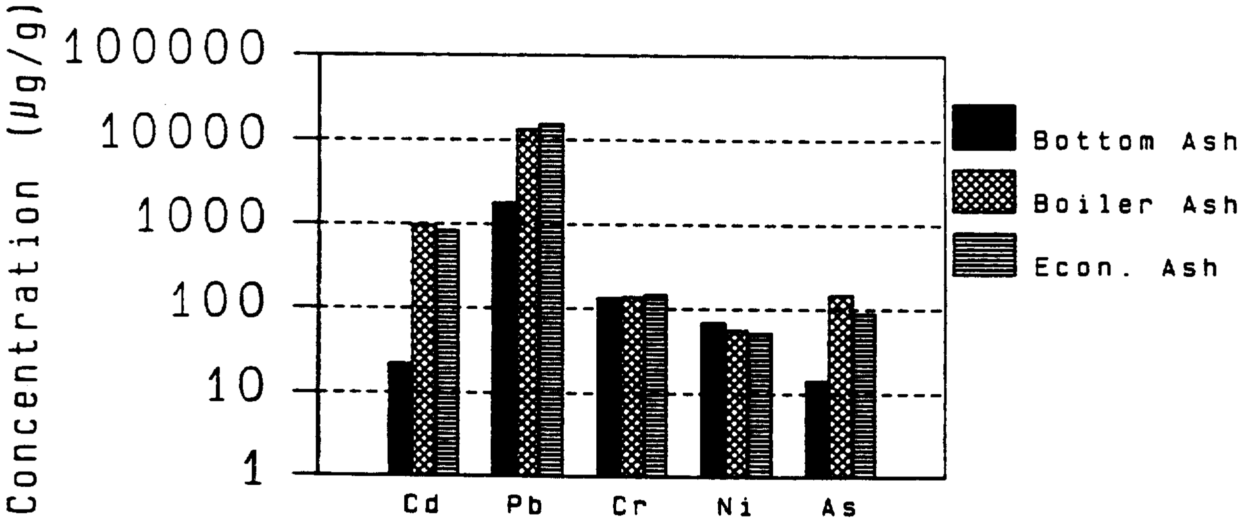


FIGURE 30 DISTRIBUTION OF SELECTED METALS

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Based on the test data, the following key conclusions were drawn:

1) Stack emissions factors for dioxins/furans were within the lower range of previously published values.
2) A relationship was found between dioxin emissions and secondary chamber temperature.
3) No evident precursor could be identified for dioxins/furans from such data as refuse chlorine content. However, these data were limited, since only one analysis of a composite refuse sample was completed per test run.
4) The range of low values recorded for carbon monoxide and total hydrocarbons (characteristic of good combustion) limited their use as surrogates for dioxins/furans. However, the low CO/THC values are associated with relatively low levels of dioxin/furan emissions. Therefore, it appears that low CO/THC levels could be indicators of low dioxin/furan emissions.
5) Because little published data on emissions of the other organic compounds from combustion sources were available, it is difficult to place these emissions into perspective.
6) Hydrogen chloride emissions were typical of uncontrolled emissions measured at other energy-from-waste facilities.
7) Particulate emissions were relatively low in comparison to uncontrolled emissions from conventional (mass burning) energy-from-waste incinerators.
8) A direct relationship was found between certain metals emitted from the stack and secondary chamber temperature. There also appears to be a potential trade-off between decreasing organic emissions and increasing metal emissions by varying combustion conditions.
9) Compared to stack emissions, the levels of dioxin and furan measured at the boiler inlet were significantly lower, virtually below the detection limit for some test runs. Conversely, the concentrations of polycyclic aromatic hydrocarbons were found to decrease across the boiler. This suggests possible chemical transformations occurring due to cooling.
10) The range of operating conditions under which the unit was tested represents the practical operating window for the two-stage system. No substantive differences in

emissions were found over this range. Therefore, it appears that good design and proper operation, as observed for the PEI energy-from-waste facility, can minimize emissions of concern.

8.2 Recommendations

Based on field observations and results obtained in the test program, some key areas for improvements in facility design, operation and testing procedures are presented.

8.2.1 Combustion and Operation.

1) The primary chamber temperature was observed to wander with refuse moisture and characteristics. Better primary temperature control can possibly be achieved through the use of a proportional load indicator.
2) Higher temperature limits in the primary chamber would reduce water spray operation and minimize poor burnout caused by wetting of the material on the hearth.
3) At times unburned material appeared in the bottom ash. Improved primary air distribution to the chamber may increase burnout.
4) In the design of future units, the location of the secondary chamber thermocouple may merit reconsideration. If secondary chamber temperature and residence time were specified in an operating permit, a representative temperature would be required. At present, the PEI system functions satisfactorily with the existing thermocouple as located.
5) The very high percentage of fines measured during the particle size determinations indicates that careful consideration should be given to the selection of add-on particulate control systems for two-stage combustion facilities.
6) The volume of the secondary chamber should be conservatively selected to ensure adequate residence time. During the PEI tests, combustion was noted to occasionally continue in the manifold. For systems with close-coupled boilers, this could lead to both operational and performance problems.
7) Careful attention should be given to the design of boilers operating on refuse incinerator systems to prevent excessive fouling. Considerable experience gained on conventional incinerator boilers would indicate that special attention should be given to:

   - tube spacing,
   - access for cleaning, and
   - clear fallout into the ash hoppers.

8.2.2 Future Sampling.

1) Only one organics train is adequate for polychlorinated dibenzo-p-dioxin/polychlorinated dibenzofuran, polycyclic aromatic hydrocarbon, polychlorinated biphenyl, chlorophenol and chlorobenzene sampling at each test location. No particular problems related to sample handling and extraction procedure were experienced during this project.
2) Analytical costs associated with the organics are significant. Serious consideration should be given to combining samples to minimize analytical costs.
3) A proofing procedure involving gas chromatography/mass spectroscopy should be adopted. At the levels being measured serious concerns can arise if gas chromatography/electron capture detection proofs are misinterpreted.
4) Continuous hydrogen chloride monitoring is desirable.
5) A broader band in primary chamber temperature during a test run should be considered acceptable on two-stage combustion systems.
6) A pre-test program should be adopted to determine the gaseous concentration expected from the combustion source being assessed. Calibration gases for the parts per million range should thus be within 100 percent of the anticipated level for each constituent selected. The linearity of response on all continuous gas instruments should be determined to ensure that they will adequately handle the anticipated range.
7) Boiler inlet testing should be considered, where possible, for future work to provide additional information on the levels and the distribution of organic contaminants in incinerator/boiler systems.
8) Environment Canada and Transport Canada should develop a suitable procedure for handling the shipment of sensitive environmental samples to laboratories to avoid shipping delays.

8.2.3 Further Work. Two types of investigation utilizing the PEI data are suggested:

1) Multivariate factor analysis of the data may provide an indication of the dependent versus independent parameters influencing emissions.
2) Further study of the organic data, particularly the results of the boiler inlet train may yield important understandings of the mechanisms involved in organic formation/destruction.

APPENDIX A
SYMBOLS AND ABBREVIATIONS

APPENDIX A

SYMBOLS AND ABBREVIATIONS

SI Prefixes

Prefix	Symbol	Multiplication Factor		Exponent
mega	M	1 000 000	=	10^6
kilo	k	1 000	=	10^3
hecto	h	100	=	10^2
deca	da	10	=	10^1
unit	-	1	=	10^0
deci	d	0.1	=	10^{-1}
centi	c	0.01	=	10^{-2}
milli	m	0.001	=	10^{-3}
micro	µ	0.000 001	=	10^{-6}
nano	n	0.000 000 001	=	10^{-9}
pico	p	0.000 000 000 001	=	10^{-12}

Units

Symbol	Unit	Comments
Mass/Weight		
g	gram	-
tonne	metric tonne	1 tonne = 1 Mg
lb	pound	1 pound = 453.592 g
Length		
m	metre	-
ft	foot	1 ft = 0.3048 m
Volume		
L	litre	-
m^3	cubic metre	1 m^3 = 1000 L
Nm^3	normal cubic metre	at standard conditions 25°C, 101.325 kPa
cm^3	cubic centimetre	
ft^3	cubic foot	1 ft^3 = 0.02832 m^3

SYMBOLS AND ABBREVIATIONS (Cont'd)

Symbol	Unit	Comments
Time		
s	second	-
m (min)	minute	1 min = 60 s
h (h)	hour	1 h = 3600 s
Temperature		
°C	degree Celsius	
Electricity		
V	volt	
Pressure		
bar	bar	-
Pa	Pascal	1 Pa = 10^{-5} bar
Energy		
J	Joule	
BTU	British Thermal Units	BTU ≃ 1055J
Acronyms		
ASTM	American Society for Testing and Materials	
P.E.I.	Prince Edward Island	
NITEP	National Incinerator Testing and Evaluation Program	
EPA	Environmental Protection Agency	United States of America
EPS	Environmental Protection Service	Environment Canada
ASME	American Society of Mechanical Engineers	
Sampling and Analytical Terminology		
OD	Dioxin Train	
OC	Organic Train	
MP	Metals and Particulate Train	
A	Acid Gas Train	
OZ	High-Temperature Train	

SYMBOLS AND ABBREVIATIONS (Cont'd)

OB	Blank Train for OC and OD	
OZB	Blank Train for OZ	
HVT	High Velocity Thermocouple	
ISOJET	Steam Driven Eductor	Sampling Probe
XAD-2	Resin Trap	
GC	Gas Chromatography	
MS	Mass Spectrometry	
EC	Electron Capture Detection	
MID	Multiple Ion Detection	
HV	High Volume	Air Sampling
PS	Particle Size	
CT	Characterization Test	
PT	Performance Test	
QA/QC	Quality Assurance/Quality Control	

Compounds

PCDD	Polychlorinated - dibenzo-p-dioxins	e.g., TCDD = Tetrachlorinated dibenzo-ρ-dioxin
PCDF	Polychlorinated dibenzofurans	e.g., TCDF = Tetrachlorinated dibenzofurans
PCB	Polychlorinated Biphenyls	
PAH	Polycyclic Aromatic Hydrocarbon	
THC	Total Hydrocarbons	
TOX	Total Organic Chlorides	
CP	Chlorophenol	
CB	Chlorobenzene	
CO	Carbon Monoxide	
CO_2	Carbon Dioxide	
O_2	Oxygen	
NO_x	Nitrogen Oxide	
SO_2	Sulphur Dioxide	
N_2	Nitrogen	

SYMBOLS AND ABBREVIATIONS (Cont'd)

HCl	Hydrogen Chloride
TSP	Total Suspended Particulate or Particulate Matter
HF	Hydrogen Fluoride
NaOH	Sodium Hydroxide
$KMnO_4$	Potassium Permanganate
H_2O	Water
H_2SO_4	Sulphuric Acid
HNO_3	Nitric Acid
Na_2SO_4	Sodium Sulphate
$HClO_4$	Perchloric Acid

Metals

Cd	Cadmium
Be	Beryllium
Mo	Molybdenum
Ca	Calcium
V	Vanadium
Al	Aluminum
Mg	Magnesium
Ba	Barium
K	Potassium
Na	Sodium
Zn	Zinc
Mn	Manganese
Co	Cobalt
Cu	Copper
Ag	Silver
Fe	Iron
Pb	Lead
Cr	Chromium
Ni	Nickel

SYMBOLS AND ABBREVIATIONS (Cont'd)

Si	Silicon
Ti	Titanium
B	Boron
P	Phosphorus
Hg	Mercury
As	Arsenic
Sb	Antimony
Bi	Bismuth
Se	Selenium
Te	Tellerium
Sn	Tin

Miscellaneous

psi	pound force per square inch	lbf/in^2
Hi	high	
Lo	low	
ppm	parts per million	
°	Degree	Angle or Temperature
±	plus or minus	
<	less than	
>	greater than	
=	equal	
x	Multiply	
HHV	Higher Heating Value	
ID	Induced Draft	Fan
BFW	Boiler Feed Water	
r	Correlation Coefficient	Statistic

APPENDIX B

INDEX TO VOLUMES II, III AND IV

APPENDIX B

INDEX TO VOLUMES II, III AND IV

The considerable amount of data gathered during the test program was compiled in four volumes. This summary report (Volume I) highlights various components of the program and summarizes the results, conclusions and recommendations. The other three volumes are:

Volume II - Main Report
Volume III - Methodology
Volume IV - Detailed Results

As a guide, the indexes for these volumes are included in this appendix. Volumes II, III or IV may be obtained by writing to the Urban Activities Division, Environmental Protection Service, Environment Canada, Ottawa, Ontario K1A 1C8.

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APPENDIX C
REGRESSION AND CORRELATION

APPENDIX C
REGRESSION AND CORRELATION

A major objective of many investigations is to establish relationships which make it possible to predict one or more variables in terms of others. For example, various researchers have shown that a positive linear relationship exists between NO_x emissions and combustion temperature. If one were to assess emission data to test for this relationship, a linear regression equation would be calculated using a least squares technique. It can then be determined how well this equation describes the linear relationship between variables by calculating the correlation coefficient 'r'. The r value allows one to assess the strength of the association between variables and also to compare this strength to that of another pair of variables. Values of r will vary between -1 and +1; the signs + - are used to indicate positive correlation or negative correlation respectively. Zero or near zero values for r indicate that 0 linear relationship does not exist between variables while a value near 1 or -1 indicates a perfect or near perfect fit to a linear equation. It should be noted that only linear relationship were investigated for the PEI data set; low r values do not rule out the possibility that a good non-linear relationship may exist between variables.

Researchers also use the value r^2 to describe the portion of the total variance in the data that is explained by the regression. Values of r^2 can be judged on a relative basis (comparing parameter to parameter) or on an absolute basis (defining a minimum value of r^2 for a correlation to be judged statistically significant). Increasing the number of data points used in a linear regression analyses generally reduces the minimum value of r^2 needed to define a significant fit. Based on the 11 or 12 data pairs available for most of the regressions calculated during this study, r^2 values of 0.36 ($r = 0.58$) or greater would be considered indicators of statistically significant relationships between variables (95% Confidence Level for $n = 12$).