Incineration of waste at Casey Station, Australian Antarctic Territory

Joanna S. O'Brien, John J. Todd and Lorne K. Kriwoken
Centre for Environmental Studies, University of Tasmania,
Private Bag 78, Hobart, Tasmania 7001, Australia

Received June 2003

ABSTRACT. The Australian Antarctic Division manages four permanent stations in the sub-Antarctic and Antarctic. At each station a municipal waste incinerator is used to dispose of putrescible waste, wood, paper, cardboard, and plastics. Incineration significantly reduces the volume of waste but this combustion also emits toxic compounds. This study examined the waste incineration stream at Casey Station, Australian Antarctic Territory. The waste stream was sorted, burnt, and the incinerator emissions monitored. Twelve chemical compounds in gaseous emissions and heavy metals in the ash were measured. Results indicate that emissions of carbon monoxide are higher than one might expect from a small incinerator, and hydrocarbon emissions from the incinerator exceed combined hydrocarbon emissions from other sources on station. Arsenic and copper concentrations in ash, which is returned to Australia for disposal, exceed limits for hazardous waste disposal and so treatment would be required. Recommendations are provided on controlling source material in order to reduce or eliminate toxic emissions and undertaking incinerator maintenance to optimise combustion.

Contents

Introduction

Under the 1991 Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol), Antarctica was declared a 'natural reserve, devoted to peace and science.' The Protocol sets out comprehensive regulations for waste management planning and waste disposal for all human use in Antarctica. During winter 2000, 18 nations operated 43 stations in the Antarctic and sub-Antarctic. The winter population of scientists and support personnel approached 1100 with at least twice as many during the summer (Headland 2000).

The Australian Antarctic Division (AAD), established in 1948, operates four permanent stations. Casey, Mawson, and Davis stations are located on the Antarctic continent, and Macquarie Station is on sub-Antarctic Macquarie Island. In the summer the AAD supports a number of scientific field camps. The total yearly population of Australian Antarctic personnel is in the order of 200. Municipal waste incinerators, first introduced at Casey Station in 1988, are used at each of the stations to reduce the volume of waste returned to Australia. The AAD must also manage waste returned to

Australia for disposal, and as such has responsibilities to meet Commonwealth of Australia and state waste management policies and strategies. Previously, no study had been undertaken to assess the extent and magnitude of impacts derived from incinerator emissions in Antarctica or emissions returned to Australia.

The objective of this paper is to determine if waste incineration, currently practiced at Casey Station, meets existing environmental best-practice guidelines. The paper commences with an overview of the institutional and legislative framework for Australian Antarctic waste management. This is followed by an outline of current Australian Antarctic waste management procedures and a brief overview of Casey Station. The methodology adopted to assess emissions at Casey Station is then explained with specific reference to waste sorting, loading of the incinerator, and measurement of the gas emissions. The next section discusses the results from 23 burns undertaken during the summer of 2000/2001. The discussion provides a comparison between the emissions measured from the incinerator at Casey Station with selected best-practice guidelines. Recommendations are made on controlling the type of source material incinerated.

Legislative framework for Australian Antarctic waste management

International obligations for the protection of Antarctica are found in the Madrid Protocol, which came into force 14 January 1998. The Waste Disposal and Waste Management Annex (Annex III) to the Protocol requires that 'the amount of wastes produced or disposed of in the Antarctic Treaty areas shall be reduced as far as practicable so as to minimise impact on the Antarctic environment and to minimise interference with the natural values of Antarctica' (Article 1(2)). Annex III also requires that 'waste storage, disposal and removal from the Antarctic Treaty area, as well as recycling and source

reduction, shall be essential considerations in planning and conduct of activities' (Article 1(3)). Article 3 makes specific reference to waste disposal by incineration. Combustible wastes can be burnt in incinerators that to the maximum extent practicable reduce harmful emissions. Solid residue of such incinerators shall be removed from the Antarctic Treaty area and open burning of waste was to be phased out by the end of the 1998/99 season.

Within Australia, the Madrid Protocol is given effect under the Antarctic Treaty (Environment Protection) Act 1980, and the Antarctic (Environment Protection) Legislation Amendment Act 1992. The Antarctic Treaty (Environment Protection) (Waste Management) Regulations 1994, part 2, division 4, regulation 13 'Disposal of waste by incineration,' provides the following guidelines to assist in the implementation of Article 3:

  (2) combustible waste . . . must burn in an incinerator that:
    (a) minimises harmful emissions; and
    (b) is designed and operated in a way that takes into account any emissions and equipment standards or guidelines . . . :
      (i) recommended by the Committee [for Environmental Protection] or the Scientific Committee on Antarctic Research (SCAR); or
      (ii) issued by the Commonwealth or the government of the Australian Capital Territory.

Neither the Committee for Environmental Protection nor SCAR has produced emission and equipment standards or guidelines for waste incineration. However, the Australian government has developed ambient air-quality limits for six priority pollutants (carbon monoxide, ozone, nitrogen dioxide, sulphur dioxide, lead, and particulates) (National Environment Protection Council 1998) and air toxics (National Environment Protection Council 2002). However, these goals are not directly transferable to the Antarctic environment, because different environmental conditions exist.

Australian Antarctic waste management and Casey Station

The Australian Antarctic Territory is managed by the Australian Antarctic Division for the Commonwealth Department of the Environment and Heritage. Australian waste management practices in the Antarctic have changed as regulations and legislation have developed. Australia used landfill rubbish tips in Antarctica until this practice ceased in the mid-1980s (AAD 2000). Other historic waste disposal methods included 'sea icing' (dumping waste onto sea ice that breaks away and drifts out to sea), dumping directly to sea, and open-pit burning. In 1985, Australia began a programme of installation of incinerators at the permanent Australian stations.

The aim of the Australian Antarctic Division's Waste Management Strategy (1994), similar to the Madrid Protocol mentioned above, is 'to minimise, as far as practicable, the environmental impacts caused by wastes generated from past, present, and future activities' (Arens 1994: 2). To this end, all waste, except sewage and solids for incineration, is returned to Australia for either recycling or disposal. Typical activities likely to generate waste products include: logistical operations; science programmes (including field programmes); normal station operations; rebuilding programme, construction or maintenance activity; and clean-up programmes. At the end of the 1999/2000 season, approximately 197 t gross weight of waste (158 t net) was returned to Australia, representing 25% of all cargo transported back to Australia (AAD 1999/2000). In comparison, approximately 53 t of waste was incinerated at Casey, Mawson, and Davis in 1999/2000 (AAD 1997–2000). Thus, about 25% of all waste generated at the stations is incinerated. Of the 53 t of waste incinerated at the three Australian Antarctic stations in one year, kitchen or putrescible waste accounted for 46%, wood product accounted for 19%, cardboard for 18%, paper for 5% and miscellaneous waste 10%.

The original incinerators are still in operation, in varying states of repair. Typically the station plumber controls incinerator operations, including variables such as the primary chamber temperature, burn time, and types of waste. The amount of waste to be burnt is usually at the discretion of the operator. Whilst an operations manual is used as a reference, the main source of operational information is transferred informally between plumbers at season hand-over. This exacerbates the variation between incineration practices at each station.

The monitoring reported here was carried out at Casey Station over a three-month period in the summer of 2000/01. Emissions from incineration have the potential to impact the fellfield communities of lichen and mosses found adjacent to Casey Station. Areas adjacent to Casey are representative of rich and diverse colonies of moss, lichen, and algae with small capacity to absorb change (Kriwoken 1991). Site of Special Scientific Interest (SSSI) 16 (now renamed to Antarctic Specially Protected Area (ASPA) 135) was declared adjacent to Casey Station to protect this unique and fragile terrestrial ecosystem (Fig. 1).

Overview of experimental design

The experimental methodology was designed to establish a link between incinerator operations and emissions. To achieve this the waste stream was manipulated and incinerator operations were monitored, whilst emissions were collected and measured under controlled conditions.

Twenty-three monitored burns were conducted at Casey Station between December 2000 and February 2001. A full set of gas and ash measurements was obtained for 16 of these burns. A fault in sampling equipment meant that the results from the first seven burns were unreliable. Table 1 details the operational parameters that were monitored or controlled throughout the experimentation.
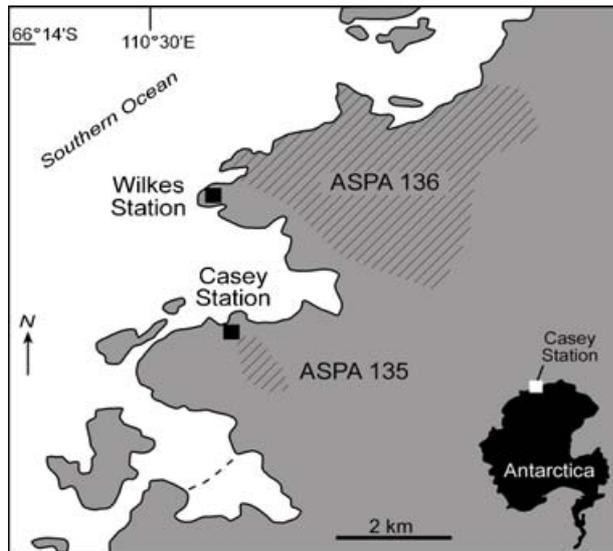
Fig. 1. Location of Casey Station, Antarctica.

Waste

Station garbage is sorted at each building into 'recyclables,' 'RTA' (return to Australia), and 'burnables,' the last being sent to the incinerator building. For this research, material from the 'burnables' waste stream was sorted as it arrived at the incinerator building. The garbage bags were opened and the contents emptied onto a clean stainless-steel sorting table. More than 2000 kg of waste was manually sorted into kitchen, plastic, and paper categories. Cardboard and wood were already largely segregated from the waste. Each waste category was weighed. In addition to the main categories of waste, any general RTA, foil, recyclable materials, and oil/clothing rags were taken out of the garbage. This waste was kept aside and burned separately. The sorted waste was then combined in fixed proportions for each burn to allow correlations between emissions and waste composition.

Loading the incinerator

When sufficient waste had been accumulated and sorted for a burn, the incinerator was loaded as follows:

- A quantity of timber was chopped and weighed. This timber formed a platform on the bottom of the incinerator and lifted the waste for better air circulation. It was also supposed that the wood promoted combustion by providing a proportion of dry waste. This replicated normal incinerator operator practice at the base.
- The bags of waste were weighed on spring scales, then packed into the incinerator primary chamber.

Table 1. Operational parameters monitored for each burn. [1] = BMCS monitors and controls the state of all station buildings, including internal temperatures and alarm conditions. [2] = 700°C was the recommended operational maximum temperature to avoid refractory damage; 600°C was the minimum temperature at which the waste would still burn adequately for a minimum burn time of three hours. [3] = This permitted an efficient sorting and packing procedure without measuring the actual moisture content of each load, which would have been logistically very difficult. The actual moisture content of samples of waste was measured using standard laboratory conditions.

| Parameter	Equipment	Method
Incinerator variables		
Flue temperature	Temperature sensor connected to the Building Maintenance Control System (BMCS)[1]	Sensor installed at same point that gases were drawn from the flue. BMCS recorded temperature data automatically (every 5 minutes) to a data file.
Primary chamber temperature	Internal incinerator thermostat	Manually set at 600°C or 700°C[2].
Length of burn	Internal incinerator control	Manually set at 20-minute warm-up and 3-hour burn.
Fuel volume	Dipstick in fuel tank	Manually dipped and read.
Waste variables		
Moisture content		
100% dry-waste burns to 20% dry-waste burns. A dry-waste burn refers to the type of waste in the burn as opposed to the actual measured moisture content of the waste. Kitchen waste was classified as wet. Plastic, paper, and wood waste were classified as dry. Combinations of these wastes constituted the percentage of dry waste for each burn[3].		
Weight		
50–200 kg. The weight was both selected by the researcher and a product of the amount of wet or dry waste in the burn, which tried to replicate normal practice. Paper and cardboard had a much higher volume to weight ratio than wet kitchen waste and therefore occupied more volume in the incinerator chamber, which resulted in a lighter weight burn.		
Composition		
A combination of kitchen, plastic, paper or cardboard, and wood waste. In addition, oil and clothing rags, unburned ash, and general waste were included in a selection of burns. This facilitated the monitoring of gases relative to specific waste inputs.		
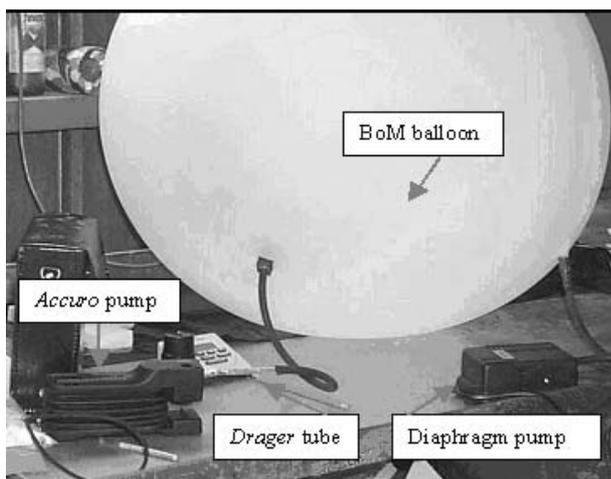
Fig. 2. Gas sampling system.

The wettest waste was placed directly in front of the flame to ensure the best possibility of destruction, which was also normal practice. Once the selected amount of waste was packed into the incinerator, the doors were sealed and the incinerator was started.

Gas emissions

To measure incinerator emissions a sample of flue gas was extracted from the flue. The short stretch of straight flue in the building meant that normal isokinetic sample location criteria (for example, Perry and Green 1984) could not be met, but since particulates were not sampled this was not a problem. The actual sampling site selected was 1062 mm from the first bend, which was as high up the flue as possible whilst staying inside the building to avoid the elements. The gas sample was drawn from the centre of the flue via a length of 6 mm-diameter stainless tubing. The stainless probe extended to floor level, where it was joined to a length of accuro extension hose — an inert black rubber tubing provided by Drager. This hose connected the flue to a simple diaphragm pump, which pumped the sample into a collection bag. The collection bag was a 100 g Bureau of Meteorology balloon. The balloon collected about 115 L of flue gas at a constant rate for the first 70 minutes of the incineration cycle in a three-hour burn (Fig. 2). Initial tests showed that the majority of the waste was consumed in the first 70 minutes. It was felt that sampling for the entire length of the burn would dilute the pollutants produced as a result of the incinerator waste with the pollutants produced from diesel combustion.

The chemical composition of the sample was analysed using Drager gas detection tubes for short-term measurement. The Drager tubes were selected as an appropriate gas measurement system because they were readily available, acceptably accurate (10–15% SD), small and light for easy transport down to Antarctica, as well as reasonably priced for this project. Each Drager tube was used in turn, with one end being inserted into the Drager accuro pump and the other end into the collection balloon. Results were recorded on a spreadsheet and later

corrected for atmospheric pressure in accordance with the Drager instructions. The disadvantage of the Drager tubes is the cross-sensitivity associated with various gases. For example, benzene measurements were made but high cross-sensitivity to carbon monoxide meant that the results were invalid. For full details refer to the Drager tube specifications, which can be obtained from Drager Sicherheitstechnik GmbH, Revalstraße 1, 23560 Lübeck, Germany.

Each gas detection tube is calibrated for a specific type of gas. The sealed glass tubes are filled with a solid carrier material containing reagents that discolour on contact with specific contaminants. The tubes are designed for use with a Drager pump, in this case the accuro pump. The gas is drawn through the opened tube with a specified number of pump strokes of the bellows and the measured concentration is then read directly from the calibrated scale on the side of the tube.

To determine which tubes to use, it was necessary to consider which gases were most likely to be present and estimate their concentrations. As a guideline, the United States Environment Protection Agency (USEPA) AP-42 emission factors were referenced (USEPA 1996a, 1996b). There were no tables available that were specific to small oil-fired incinerators, so the closest comparable tables were considered. 'Emission factors for modular starved-air combustors' had the closest matching incinerator conditions to Casey Station (except that the Casey incinerator was smaller than the smallest size mentioned in AP-42). Modular starved air combustors burn waste that has not been pre-processed. Also, air is provided in the primary chamber below the level required for perfect combustion. The incomplete combustion products (CO and organic compounds) pass into the secondary chamber where additional air is added and combustion is completed (USEPA 1996a, 1996b). Organic emissions from residential wood stoves were also considered in order to broaden the range of possible gaseous pollutants.

The following Drager tubes were taken: arsenic trioxide; carbon dioxide; carbon monoxide; hydrogen chloride; benzene; oxygen; sulphur dioxide; chlorobenzene; toluene; hydrogen fluoride; mercury; and nitrogen dioxide. Final selection was determined by likely presence of the compound, availability of the tubes, and cost.

Ash sampling

After each burn, a representative sample of ash was collected from the primary chamber of the incinerator. Ash was collected from different positions around the incinerator chamber, for example, along the back wall, in front of the fuel flame and at the door. Care was taken to not touch the side walls as this may have contaminated the sample. Beakers, pre-treated in nitric acid to remove metal contamination, were used to collect the ash. Between 100 g and 500 g of ash was taken for each sample, which represented 1–5% of the total residue in the incinerator. Once the ash had cooled, it was transferred into plastic bags, which were weighed and labelled for each burn.

Table 2. Composition of waste for each burn. Pap = paper/cardboard; Mag = magazine; Tet = tetra pak (drink containers); and Res = the weight of the residue (% of total weight). Temperatures in the incinerator/flue: Ch = set chamber temperature; Max = maximum flue temperature; Ave = average flue temperature.

| Burn | Weight of waste (kg) | | | | | | | | | | Temp deg C | | |
	Kitchen	Pap	Plastic	Wood	Mag	Rags	Ash	Tet	Total	Res	Ch	Max	Ave
9		52.5							52.5	8%	600	902	525
10		52.8							52.8	7%	700	955	565
11	52.5	12.9		19.6	20				105	10%	700	632	512
12	80.4			20.2					100.6	na	na	na	na
13	80.5			20.3					100.8	6%	600	458	392
14	135.6	23.5	22.6	19.5					201.2	5%	700	1013	832
15	133.4	19.5	21.1	22.2					196.2	8%	600	863	598
16	109.3	7		17.8		29.6	8.1		171.8	9%	700	892	647
17	81.5		6.8	14					102.3	3%	700	648	na
18	79.7		6.1	14					99.8	7%	700	788	na
19	84.1		5.6	14.6					104.3	6%	700	592	488
20	78.1	24.2	3.2	16					121.5	5%	700	890	599
21		35			15				50	12%	700	940	539
22	99.7	20.8	10.4	15.4					146.3	8%	700	785	582
23	96.7	12.3	15.7	17.3				9.4	151.4	9%	700	974	637

The bags were stored in the freezer and transported back to Australia for analysis. The remaining residue (ash plus unburned material) in the incinerator chamber was then cleaned out, collected, and weighed to calculate the percentage of residue from each burn. The ash samples returned to Australia were sub-sampled after careful mixing and any unburnt objects (such as nails) were removed. Heavy-metal analysis was carried out using the inductively coupled plasma (ICP) atomic emission spectroscopy method in a NATA accredited laboratory (Analytical Services Tasmania).

Chemical analysis

Sixteen complete sets of results were collected (burns 8–23). Eight operating parameters were recorded including waste characteristics, ash weight, and temperature. The moisture content was measured for 12 waste categories, of which nine were varieties of kitchen waste. The burn cycles were also monitored for gas and ash emissions. The ash from each burn was analysed for nine heavy metals by Analytical Services Tasmania. Mercury was also measured but as a composite sample because of the cost of this analysis.

General observations

Being on site in Antarctica provided the opportunity to observe operations particularly with regard to the state of the incinerator; visual emissions; sources of waste; and different types of wood burned.

Initially the door seal of the incinerator was not airtight and fumes were emitted into the incinerator building (as indicated by CO measurements made in the building). In addition, the incinerator had experienced recent mechanical failures, which resulted in either a shutdown or continual burning, where the burner did not shut down at the end of the set time. For some burns, carbon deposits were seen on the fuel inlet to the primary chamber, which indicated incomplete combustion. Further, the refractory lining on the inside of the primary chamber was cracked and broken, which reduces the insulating properties of the chamber.

The visual quality of emissions varied between burns. A plume of black smoke, accompanying a 2 m-high flame from the top of the flue, was observed for the first 10–20 minutes of burns 4, 5, 10, and 22. These burns were 100% dry-waste burns and the smoke indicated the presence of unburned carbon products resulting from insufficient oxygen in the burn. This was not observed for the other burns.

After two months of analysing waste, different sources became readily identifiable. It was apparent that incorrectly assigned 'burnables' resulted from certain activities. Typically, the waste from field trips, personal bathrooms, and Friday barbeques was not sorted and was all sent to the incinerator. A selection of RTA waste was also sent from the workshops. Finally, different types of wood were identified in the woodpile, which became critical in understanding the different levels of copper, chromium, and arsenic in the ash results.

Operational results

Operation records and waste characteristics are summarised in Tables 1 and 2. The minimum waste weights (50–53 kg) occurred in burns with a high proportion of dry material, where the large volume-to-weight ratio of cardboard meant that these low weights filled the combustion chamber. The mix of dry and wet waste was controlled to range from 20–100% dry-waste burn.

The maximum flue temperature was 1013°C for burn 14. This burn had a primary chamber temperature set at 700°C, a high waste weight (201 kg) and a medium dry-waste content (33%). The average flue temperatures were recorded for the sampling period and the entire burn (as shown in Table 2). Over the entire burn, the average flue temperatures were lower than for the sample period (except burn 13), indicating that the burn was

Table 3. Gas species measured in incinerator flue: carbon monoxide (CO), hydrochloric acid (HCl), benzene (C_6H_6), chlorobenzene (C_6H_5Cl), oxygen (O_2), carbon dioxide (CO_2), sulphur dioxide (SO_2), arsenic trioxide (AsO_3), toluene ($C_6H_5CH_3$), hydrogen fluoride (HF), mercury (Hg), and nitrogen dioxide (NO_2). n/a = not analysed.

Burn	CO ppm	HCl ppm	C_6H_6 ppm	C_6H_5Cl ppm	O_2 %	CO_2 %	SO_2 ppm	AsO_3 ppm	$C_6H_5CH_3$ ppm	HF ppm	Hg ppm	NO_2 ppm
8	1021.7	0.0	>61.3		15.8	3.1	9.7	0	122.6	0	0	0.4
9	2047.0	0.0	>61.4		16.5	2.7	5.1	0	>307.1	0	0	0.1
10	>3070.3	0.0	>61.4		14.2	4.6	10.2	0	>307.0	0	0	0.1
10 (2)	2354.0	n/a	>61.4		17.4	2.1	9.2	n/a	>307.0	n/a	n/a	0.0
11	1227.8	n/a	>61.4		12.5	5.2	17.1	n/a	127.9	n/a	n/a	1.0
12	1000.0	n/a	>60		15.4	4.3	6.7	n/a	275.0	n/a	n/a	0.5
13	826.8	n/a	n/a		17.3	1.6	5.2	n/a	n/a	n/a	n/a	0.3
14	>3068.8	6.8	n/a		9.9	8.2	13.6	n/a	n/a	0	n/a	4.1
15	1132.4	2.6	100.0		11.8	n/a	5.2	n/a	n/a	n/a	n/a	5.7
16	511.1	0.0	n/a		15.6	n/a	13.6	n/a	63.9	0	n/a	2.0
17	n/a	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
18	n/a	n/a	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
19	1032.2	2.1	n/a	4.1	15.5	n/a	13.8	n/a	103.2	n/a	n/a	0.5
20	411.5	3.7	n/a	4.1	15.4	n/a	5.1	n/a	57.6	n/a	n/a	2.1
21	1846.2	n/a	n/a	4.6	18.5	n/a	15.4	n/a	200.0	n/a	n/a	0.0
22	n/a	10.2	n/a	5.1	11.9	n/a	n/a	0	n/a	0	0	5.1
23	610.5	4.1	n/a	5.1	20.4	n/a	n/a	n/a	n/a	n/a	n/a	n/a

usually hottest during initial combustion and cooled as the burn progressed. The average flue temperature over the sampling period ranged from 392°C for burn 13 to 832°C for burn 14. The lower flue temperature occurred with a primary chamber temperature set at 600°C, a low waste weight (100 kg), and a low dry-waste content (20%).

The majority of waste for each burn was a combination of kitchen scraps, paper, plastic, and wood, which represents normal incinerator operation at the base. Of the 16 burns sampled, seven contained a combination of kitchen scraps, paper, and wood waste. Three burns were 100% dry waste, composed only of paper and cardboard. General plastic waste (present in eight burns) included soiled and unsoiled kitchen plastics, such as chicken wrappers and biscuit packets, and photographic negatives. The plastics in burn 20 were recyclables (PET and HDPE plastics) and non-recyclables that should have been in the selected RTA waste streams. The plastics in burn 22 included an assortment of any contaminants (waste that should not have been in 'burnables') collected during the two-month experiment time.

The moisture content from a selection of waste samples was measured in the laboratory. By summing the average of all kitchen and food categories, kitchen waste had the highest moisture content at 54% (wet weight basis). Paper (which included absorbent kitchen paper towels) had a moisture content of 29% and plastic 12%. The moisture content of air-dry wood was not measured but assumed to be approximately 12%.

Emission analysis

The gases were measured once for each burn (except burn 10 where two samples were collected). The gas results are recorded in Table 3. Twelve compounds were measured, of which three were undetected — arsenic trioxide, hydrogen fluoride, and mercury. Increasing the sample passing through the Drager tube above the recommended volume still did not detect these three compounds. Once it was determined that these compounds could not be detected with the equipment available, measuring ceased. Had arsenic pentoxide (a better arsenic indicator in high oxidising conditions) been measured, arsenic may have been detected. The Drager sample volume for some measurements of SO_2, NO_2, and HCl was increased, although this meant that the calculated absolute gas concentrations could not be verified by Drager. A concentration range is indicated instead. Toluene concentrations were too high for the tubes selected.

Chlorobenzene was only measured for the last five burns as these Drager tubes arrived on voyage 5 near the end of the sampling period. For burn 17 the pump was accidentally turned off, so no gas measurements were taken. For burn 18 the pump bag had leaked and emission testing did not proceed.

Three of the four highest CO and toluene readings occurred for 100% dry-waste burns. HCl was detected on six burns that all contained plastics. When plastic was not burnt, HCl was not detected. The highest SO_2 recordings were for burns that contained magazines (burns 11 and 21). The highest oxygen readings coincided largely with the highest maximum flue temperatures. During burn 10, the oxygen level was low in the first sample, which indicated that the rapid burn resulted in oxygen starvation. Once the burn had slowed, the oxygen level increased. This is indicated in the second sample from burn 10.

Ash results

The results of ash analysis are recorded in Table 4. Of the nine heavy metals tested for each burn, there were higher than average readings for six of the metals in burns 17, 18, and 22, and for seven of the metals in burn 23. Burns 17 and 18 had waste compositions of kitchen,

Table 4. Heavy metals sampled in the ash from burns 8–23. Measured in mg kg^{-1} DMB.

Burn	As	Cd	Co	Cr	Cu	Mn	Ni	Pb	Zn	Hg
8	810	3	3	257	337	193	43	39	1000	
9	24	1	9	69	306	235	21	24	293	
10	5	1	7	52	276	232	28	29	189	
11	249	13	8	74	327	150	22	34	1290	
12	206	2	4	218	205	316	22	30	455	
13	1090	5	1	488	649	339	39	68	658	
14	17	2	3	34	258	436	29	70	371	
15	10	18	6	94	437	265	47	232	2280	
16	1	1	5	678	334	141	29	25	1070	
17	1500	6	4	1100	1260	488	147	754	1900	
18	2050	7	7	745	1120	930	77	180	1470	
19	347	9	1	173	285	528	21	30	1110	
20	206	2	2	170	14600	77	12	55	5200	
21	13	1	6	94	316	132	50	58	1060	
22	288	62	8	180	2220	408	85	206	1570	
23	86	113	107	213	2460	358	181	207	1360	
Av	423	19	11	277	1506	320	52	123	1316	
Composite 8–23										<0.02

plastic, and wood. Burn 22 contained kitchen, plastic, wood, and paper, where the plastic comprised a variety of contaminants. Burn 23 was a kitchen, plastic, paper, wood, and tetra waste (drink containers) mix. Copper had a reading of 14,600 mg kg^{-1} in burn 20, which was more than five times higher than the next closest reading. There are two possible explanations for this anomaly; either the entire burn may have had a large copper content or the sub-sample was not representative.

Since ash is normally returned to Australia in a mixed drum, not as individual samples, the total average heavy metal content is of most interest. The highest readings of arsenic, chromium, and copper all occurred when wood was present. This suggests that wood treated with copper, chromium, and arsenic (CCA) was being burned. There were burns that contained wood that did not have high arsenic, chromium, and copper readings (burns 11, 12, 14, 15, and 19). A visual comparison indicated that the wood was from different sources. It would be reasonable to assume that some wood is CCA-treated wood whilst some was likely to be free from treatment.

There are no high metal readings for burns 9, 10, 11, 12, and 21. Of these burns, 9, 10, and 21 contained only cardboard and paper. Burn 11 contained kitchen, paper, wood, and magazines, and burn 12 contained only kitchen and wood waste. Burn 23 returned high readings of cobalt, nickel, and cadmium, and burn 22 returned a high cadmium result. These results show that CCA-treated wood and plastics produced ash that was higher in heavy metals than kitchen, paper, and untreated CCA wood.

Discussion

Correlations between operational parameters, atmospheric emissions, and ash were examined through scatter graphs comparing pairs of results, for example oxygen and carbon dioxide (Fig. 3). A least square line was fitted to the
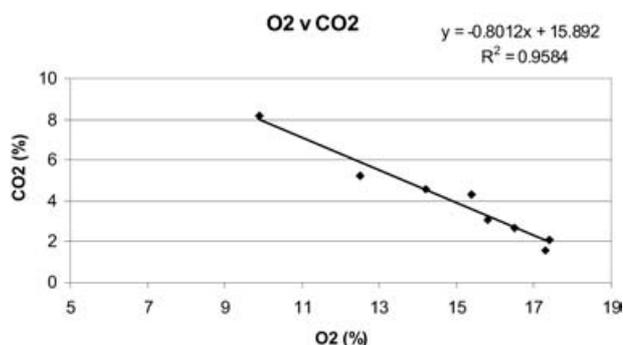

Fig. 3. Oxygen vs carbon dioxide.

data from which the strength of the correlation between the two result sets could be determined. This method had some limitations. Extreme results could influence the correlation.

Chlorobenzene was not graphed because there were not enough absolute results to provide adequate trends in the data. The gases HCl, NO_2, and SO_2 were graphed for the calculated absolute values as these represented the best available estimate of emission levels. Toluene was detected absolutely in seven burns and as a range in three burns.

Waste weight, flue temperature, moisture content, and ash

There was no apparent linear relationship between incinerator/flue temperatures, waste composition, or ash. Some unburned waste remained after two burns but this could not be correlated with low flue temperature or high moisture waste. It is likely that the loading geometry of the waste is a factor because most complete combustion takes place at the front of the incinerator chamber. In practice, the unburned waste is simply included in the next incinerator load.
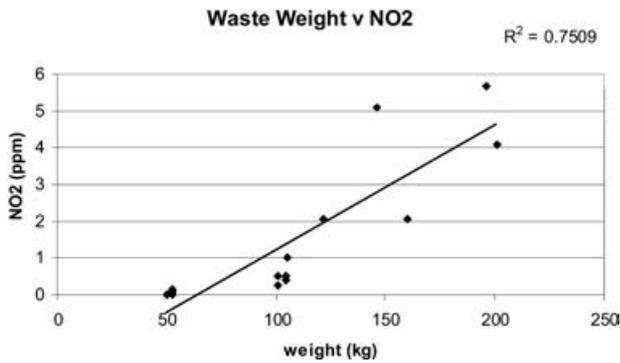
Fig. 4. Weight of waste burned vs NO$_2$.

Fig. 5. Waste weight vs toluene.

Fig. 6. NO$_2$ vs O$_2$, toluene, and HCl (y axis = 0–350 ppm for toluene, 0–35 ppm for HCl, and 0–35% for O$_2$).

Correlation between operations and emissions

Gas emissions were plotted against waste weight, moisture content, and average flue temperature over the sample period to ascertain any correlation between operations and emissions. A correlation was observed between waste weight and NO$_2$ (Fig. 4). Nitrogen oxides are formed during combustion by the oxidation of nitrogen in the waste and the fixation of atmospheric nitrogen. Conversion of nitrogen in the waste usually occurs at relatively low temperatures (<1090°C), whereas fixation of atmospheric nitrogen occurs at higher temperatures (USEPA 1996b). Since municipal waste incinerators operate at relatively low temperatures, 70–80% of the nitrogen oxides formed in these types of incinerator are associated with nitrogen in the waste (USEPA 1996b). This may explain the direct relationship between waste weight and nitrogen dioxide.

Another apparent correlation is the inverse relationship between waste weight and toluene (Fig. 5). Both CO and toluene emissions are high for 100% dry-waste burns (that is, low-weight burns) (see Tables 2 and 3). One explanation for this is that the rapid burning of dry waste at the start of the burn resulted in insufficient oxygen leading to greater quantities of unburned hydrocarbon emissions (USEPA 1996b).

Heavy metals in the ash were plotted against waste weight, moisture content, and average flue temperature during the sample period but no correlation was apparent.

Gas emission analysis

All possible pairs of gases were compared. Of the 35 possible combinations, there were seven that suggested some correlation existed. A correlation was observed between O$_2$, CO$_2$, and CO, as would be expected for most combustion processes. Further correlation was observed between:

- nitrogen dioxide and oxygen;
- nitrogen dioxide and toluene;
- nitrogen dioxide and hydrogen chloride; and
- toluene and carbon monoxide.

Oxygen, carbon dioxide, and carbon monoxide are all indicators of the efficiency of the combustion process. As waste burns with fuel, it releases CO, hydrogen (H),
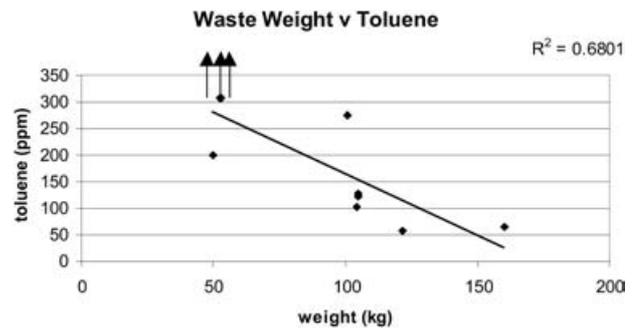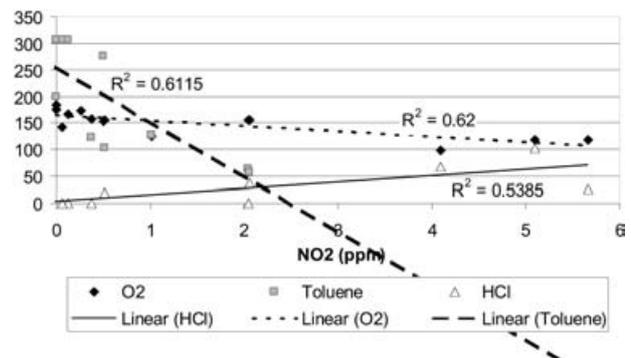
and unburned hydrocarbons. Additional air then reacts with the gases escaping from the fuel bed to convert CO to CO$_2$ and H to H$_2$O (USEPA 1996b). When there is more air than needed for complete combustion, the excess air is emitted with the combustion products. If a small amount of O$_2$ is emitted, then the rest has been converted to CO$_2$ and H$_2$O, resulting in a large CO$_2$ emission. This explains the inverse relationship between O$_2$ and CO$_2$ during combustion (Fig. 3). This relationship was used to estimate the CO$_2$ for burns 16–23 because, by burn 16, the Drager measuring tubes for CO$_2$ had all been used.

Carbon monoxide is a product of incomplete combustion resulting from either adding too little air or adding too much air to the combustion zone, which lowers the local gas temperature and slows the oxidation reactions (USEPA 1996b). There is an inverse relationship between CO and O$_2$, although the R^2 value suggests that there is weak correlation. One explanation for this is that CO was formed during brief periods of the 70-minute sample time, when O$_2$ levels were low. For example, during 100% dry-waste burns, the black plume that was observed during the first 10 minutes of the burn indicated a decreased O$_2$ level, and hence the likely formation of CO. This strong relationship is diluted over the course of the sample time and thus the overall correlation is weak.

Nitrogen dioxide has already been associated with the waste weight. Further analysis suggests an inverse relationship with O$_2$ and toluene and a direct relationship with HCl (Fig. 6). The formation of NO$_2$ is a function of the temperature of the incinerator as explained above.
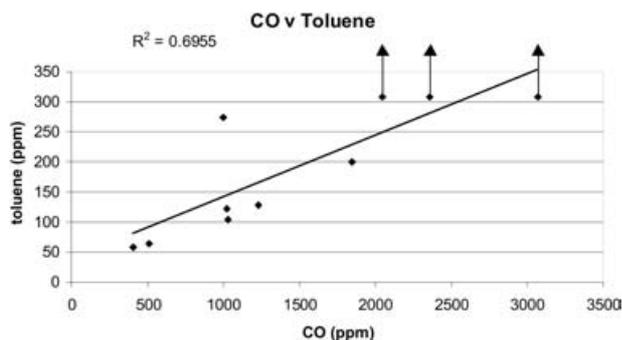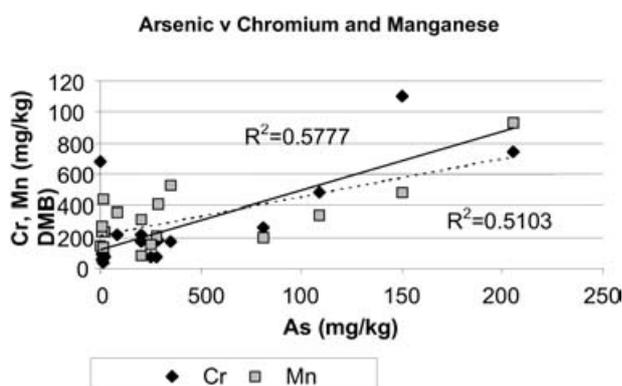
Fig. 7. CO vs toluene.

Fig. 8. Arsenic vs chromium and manganese.

High emissions of CO and toluene occurred in 100% dry-waste burns (burns 9, 10, 21). Since CO and toluene appeared to be produced under the same conditions, a direct relationship can be expected (Fig. 7).

Ash analysis
Of the 35 possible combinations of heavy metal concentrations in the ash, there were five combinations that suggested a correlation existed:
- arsenic and chromium;
- arsenic and manganese;
- amended copper and nickel;
- amended copper and cadmium; and
- nickel and lead.

Arsenic was plotted against each of the other heavy metals, correlating the strongest with chromium ($R^2 = 0.58$), and manganese ($R^2 = 0.51$) (Fig. 8). There appeared to be no correlation between arsenic and copper ($R^2 = 0.002$). The correlation between arsenic and chromium supports the idea that CCA-treated wood was being burned. An explanation for the lack of correlation between arsenic and copper is that copper may have existed in a number of different sources (for example, copper conduction wire) that confound the appearance of a direct relationship. Whilst arsenic and manganese showed some correlation, it was not possible to identify any common source.

Within the copper data set, one result (14,600 mg kg^{-1} DMB (dry mass basis) for burn 20) is more than five times

greater than the next closest result. From Table 4 the high copper result coincides with a high zinc result, which suggests that the copper and zinc likely originated from the same source in this burn.

Stoichiometric calculations
Concentrations of pollutants in the flue gas provide a useful guide for determining whether best-practice incineration is being achieved. However, they do not provide information on the total quantity of pollutants emitted each burn or over one year, nor do they allow a comparison of emission rates of pollutants from incineration to other combustion sources on the base. For these reasons, a rough estimate of total pollutant emissions from the incinerator has been attempted.

Flue gas velocity or mass emission rate were not measured during these experiments, so it was necessary to use an indirect method for calculating the total mass/volume of gas emitted through the flue. A common method for doing this is to use stoichiometric calculations (Metz 1976). If flue gas temperature and carbon dioxide (or oxygen) concentrations are measured (as they were here) and if the approximate chemical composition of the fuel is known (as estimated below), a straightforward formula allows estimation of the mass emission rate.

In view of the many approximations and assumptions in these estimates, average emission concentrations for all 16 monitored burn cycles were used in the calculations. The following assumptions were made:
- 75% of the waste was burnt in the first 70 minutes (gases were monitored for 70 minutes, and visual inspection and photographs suggested the 75% estimate is roughly correct);
- 75% of the carbon in the waste was released in the first 70 minutes;
- 75% of each pollutant was emitted in the first 70 minutes;
- 50% of the diesel fuel was consumed in the first 70 minutes; and
- the average weight of waste per burn was 116 kg consisting of 45% dry waste, and the average diesel fuel use per burn was 71 L.

The assumed weight of carbon, oxygen, and hydrogen in oven-dry, ash-free waste was 50%, 43.5%, and 6.5%, respectively (a typical figure for biomass (Todd and Sawyer 1984)). The diesel fuel was assumed to be 88% carbon, 12% hydrogen (Bush and others 1995). For stoichiometric combustion the CO_2 concentration was calculated as 19.6%, whereas measured CO_2 was 4.1% (average), indicating about 400% excess air. The calculated average flue gas emission over the 70-minute sample period was 2270 m^3 at standard temperature and pressure. On the basis of this estimate, the mass of each pollutant emitted per average burn is given in Table 5. The significance of these estimates is discussed in the following section.

Table 5. Pollutants emitted for an average incinerator burn. The range indicates uncertainties in assumptions about the proportion of waste consumed in the first 70 minutes and the proportion of each pollutant emitted in the first 70 minutes.

Gas	Measured ppm	Gas volume	Best estimate	Range
CO	1440	4400 L	5500 g	4200–10,700 g
HCl	4.9	15 L	24 g	18–47 g
Chl. Benz.	4.61	14 L	70 g	54–140 g
SO_2	10	30 L	87 g	67–170 g
Toluene	187	570 L	2300 g	1800–4500 g
NO_2	1.56	5 L	10 g	8–19 g

Best practice

The emissions measured from the Warren controlled-air incinerator at Casey Station were compared with selected environmental best-practice guidelines. This comparison seeks to establish the significance of the incinerator emission levels. The concentrations of the gases are compared with the USEPA guidelines for emissions from small municipal waste incinerators (USEPA 1995). The concentrations of heavy metals in the ash are compared with soil contamination information provided by the Department of Primary Industries, Water and the Environment (DPIWE 2002). In addition, a comparative study of the incinerator mass emissions with other major emission sources on Casey Station is provided. This comparison demonstrates the relative significance of incineration emissions to other Casey Station emissions. Finally, the results and analysis are discussed with a view to reducing emissions from incineration by controlling operations.

Limitations of the data

Before comparing the measured emissions with other data, it is necessary to acknowledge some limitations. Where the average incinerator emissions were calculated from absolute values measured under extended test conditions, Drager can only verify a concentration range rather than a precise figure. Further, the incinerator operations in the USEPA guidelines are not identical to the Australian Antarctic operations. The USEPA standards apply to small MWC units that have a capacity between 35 t and 250 t per day (USEPA 1995), whereas the Antarctic incinerator burns range from 100–200 kg and only three burns per week. In addition to the volume of waste combusted, the composition of waste is likely to be different. The waste at the Australian Antarctic stations is generally more refined than municipal waste in the United States, since the Antarctic waste is relatively well sorted and a large portion is sent back to Australia for disposal. The USEPA guidelines are created primarily for health and safety in an urban environment, whilst emission levels in Antarctica may need to address different criteria, since the environment is unique and the tolerable level of pollutants may be different. Finally, the emissions

Table 6. USEPA limits for emissions from small[1] municipal waste incinerators compared to measured emissions from the Casey Station, Antarctica, incinerator (adapted from USEPA 1995). [1] = Small refers to a capacity of >35 t per day and ≤ 250 t per day. [2] = MWC is municipal waste combustion. [3] = All concentrations are corrected to 7% oxygen. [4] = Total mass of tetra through octachlorinated dibenzo-p-dioxins and dibenzofurans; and ng dscm^{-1} is nanograms per dry standard cubic metre.

Pollutant[3]	USEPA limits for MWC[2]	Measured Casey emissions
Carbon monoxide (ppmv)	50	1440
Dioxins/furans (mg dscm^{-1})[4]	125	n/a
Cadmium (mg dscm^{-1})	0.1	n/a
Lead (mg dscm^{-1})	1.6	n/a
Mercury (mg dscm^{-1})	0.08 (or 85% reduction)	n/a
Particulate matter (mg dscm^{-1}).	70	n/a
Sulphur dioxide (ppmv)	80 (or 50% reduction)	10
Hydrogen chloride (ppmv)	250 (or 50% reduction)	4.9
Toluene (ppmv)	n/a	187
Chlorobenzene (ppmv)	n/a	4.61
Nitrogen dioxide (ppmv)	no limit	1.56

produced by other sources on station are estimated from generic emission data and were not measured individually.

Comparison of gas emissions with USEPA guidelines

Australia does not have any emission guidelines for municipal waste incinerators, so environmental best-practice guidelines had to be selected from overseas. The USEPA guidelines were selected for being both well-established and within stringent limits. The measured incinerator emissions from Casey Station were compared to the USEPA limits for small municipal waste incinerators. The comparison is detailed in Table 6. The USEPA has two regulations for small incinerators (40 CFR Part 60: subpart Cb 1995 and 40 CFR Part 60: New source performance standards for new small MWC units 2000) (USEPA 1995, 2000), although they both specify the same emission levels. Four of the seven pollutants measured (excluding O_2 and CO_2) were listed in the USEPA guidelines (CO, SO_2, NO_2, and HCl). Limits for hydrocarbons, chlorobenzene, and toluene were not listed.

The measured emission of CO exceeds the USEPA limits by a factor of 29. The measured emissions for SO_2, NO_2, and HCl are all well below the USEPA emission limits.

Table 7. Maximum concentrations of contaminants allowed in soil to be disposed of as fill material and hazardous waste material compared to measured heavy metals in the ash from Casey Station (adapted from DPIWE 2002).

Contaminant	Fill material max. conc. (total) mg kg^{-1} dry weight	Hazardous waste max. conc. (total) mg kg^{-1} dry weight	Measured average conc. for burns 8–23 mg kg^{-1} dry weight
Arsenic	20	300	423
Cadmium	3	50	19
Chromium	50	2500	277
Copper	60	1000	1506
Cobalt	50	500	11
Lead	300	3000	123
Mercury	1	20	< 0.02
Molybdenum	40	400	n/a
Nickel	60	1000	52
Tin	50	500	n/a
Selenium	–	100	n/a
Zinc	200	5000	1316
Manganese	n/a	n/a	320
Cyanide	50	500	n/a
Fluoride	400	4500	n/a
Phenols	1	10	n/a
Monocyclic aromatic hydrocarbons	1	70	n/a
Polycyclic aromatic hydrocarbons	5	200	n/a
Total petroleum hydrocarbons (C6–C9)	100	1000	n/a
Total petroleum hydrocarbon (> C9)	1000	10,000	n/a
Organochlorine compounds	–	10	n/a

Comparison of heavy-metal concentrations with soil guidelines in Tasmania

Incineration ash is returned to Australia for disposal in Tasmania. The most appropriate environmental best-practice guideline for the comparison of heavy-metal concentrations in ash is provided by the Tasmanian government in the 'Off-site disposal of contaminated soil in Tasmania' (DPIWE 2002). Tasmania has three classifications of contaminated soil: fill material, hazardous waste, and hazardous waste for remediation, determined by Table 7.

Fill material must exhibit contaminant levels below those specified in Table 7 'fill material maximum concentration.' The off-site disposal of fill material is not restricted, although the disposal must not result in any off-site impact. Fill material should (in most cases) be suitable for disposal within an urban environment or as cover material at a well-managed and appropriately sited refuse disposal site (DPIWE 2002).

Hazardous waste must exhibit contaminant levels below those specified in Table 7 'hazardous waste concentration.' Hazardous waste should (in most cases) be suitable for disposal in a secure section of a nominated regional landfill site (DPIWE 2002).

Hazardous waste for remediation must exhibit contaminant levels above those specified in column 3 of Table 7. This material requires remediation to reduce contaminant concentrations to levels acceptable for landfill disposal. Mixing or dilution is not considered to be an appropriate remediation method (DPIWE 2002).

From the sampled ash emissions, the average concentration of each heavy metal was calculated for all burns. The average concentrations were compared to the Tasmanian limits (Table 7). Measured arsenic and copper levels require the waste to be classified as hazardous waste for remediation; cadmium, chromium, and zinc levels require the waste to be classified as hazardous waste; and cobalt, nickel, lead, and mercury levels mean that the waste is classified as fill material. From this information, the reduction of arsenic and copper levels in the ash emissions should be a priority since remediation of heavy metals in ash is an expensive procedure.

Comparison of gas emission sources on station

The incinerator gas emissions (discharged at about 4 m above ground level) are compared here, with other emission sources on station to establish the relative significance of the incinerator emissions. Emission sources on station are the powerhouse generators, boilers, heaters, and vehicles. Results of emissions from a powerhouse generator, model 3306B DIT, were provided by the AAD. The other emission sources were assumed to produce the same emissions as the powerhouse generator (discharged at about 6 m above ground level). As such, a comparison between total yearly emissions from incineration and the other emission sources could be conducted. The results are shown in Table 8. The low discharge height of all emissions suggests that plume dispersal will be similar.

The powerhouse emissions were converted from (grams per hour) to (grams per litre) and multiplied by the fuel consumption in 2000 for Casey Station. The incinerator mass emissions were multiplied by 138 burns, the estimated total burns at Casey Station for 1999. These calculations created yearly estimates of emissions.

Table 8. A comparison of estimated emissions from different sources on Casey Station with measured incineration emissions. The hydrocarbon emissions from the powerhouse and vehicles are total hydrocarbons, whereas the incinerator figure is for toluene only; thus total hydrocarbons from the incinerator must be larger than the number stated. Measurements estimate g a^{-1} (2000).

Emissions	Powerhouse	Boiler/vehicle	Incinerator
CO	20,000,000	5,600,000	760,000
CO_2	1.3E+09	3.7E+08	21,000,000
Hydrocarbon[1]	130,000	38,000	>470,000
NO_x	16,000,000	4,600,000	1400
Particulates	3,000,000	750,000	n/a

According to the analysis, incinerator emissions for CO, CO_2, and NO_2 were significantly less than total emissions produced by other sources on station in 2000 (by a factor of 33, 80, and 150,000, respectively). However, hydrocarbon (toluene) emissions were more than 250% higher than total hydrocarbon emissions from other sources on station. The amount of fuel used for incineration in 2000 was 1% of the total fuel used for Casey Station. This suggests that the hydrocarbon emissions from incineration are significant compared to other sources. Of course, this does not necessarily mean these hydrocarbons are causing any ecological damage.

Links between operations and emissions

The aim of the AAD's waste management strategy is to minimise environmental impacts. The results suggest that correlations exist between operations and emissions. It is likely that by regulating the incinerator operations, emissions will be minimised. A consideration of the major pollutants prioritised the control of pollutants that exceeded the selected environmental best-practice guidelines. This included: CO, since it exceeded the USEPA limits (Table 6); hydrocarbons (toluene in particular), since they exceeded the emissions from other sources on station (Table 8); and the heavy metals arsenic and copper, since they are categorised as 'hazardous waste for remediation' by the Tasmanian government (Table 7). Control of the type of waste burned is likely to contribute to a reduction of HCl and SO_2 emissions as well.

Reducing copper, chromium, and arsenic emissions

The high levels of copper, chromium, and arsenic in the ash samples coincided with the incineration of selected wood waste. It is possible that by identifying CCA-treated wood and removing it from the waste to be incinerated, the concentration of these heavy metals will be reduced.

The weak link between copper and both arsenic and chromium suggests that copper is also present in other sources of waste. It may be possible to identify likely sources of copper that could be entering the 'burnables' waste stream and redirect these to the RTA waste stream.

Reducing carbon monoxide and toluene emissions

The results indicate that dry-waste burns result in high concentrations of CO and toluene. It is likely that rapid combustion, induced by the dry waste, starves the incineration process of excess oxygen required to convert CO and unburned hydrocarbons to non-pollutants. Adding a portion of wet waste to the burn slows the combustion process and allows a sufficient amount of oxygen for complete combustion. This may reduce the CO and toluene emissions.

The 100% dry-waste burns were removed from the calculations of the average gas concentration and mass emissions, and the results were noted. The average concentration of CO reduced 25% from 1440 ppm to 1080 ppm, which was still more than 20 times larger than the USEPA guidelines in Table 6. The concentration of toluene reduced 33% from 187 ppm to 125 ppm. This reduced the estimated total toluene incinerator emissions but it was still above contributions from other sources on the station.

Carbon deposits were seen on the fuel inlet to the incinerator primary chamber after some burns. The carbon is deposited from the fuel and it is likely that improving the operation of the incinerator will further reduce emissions of toluene. Improving the efficiency of the combustion process will also decrease CO emissions.

Reducing other emissions

Hydrogen chloride was only detected when plastics were incinerated. A reduction of the number and types of plastics burned would result in a reduction of HCl emissions. From an observation of the plastic waste, it is likely that uncontaminated food plastics (such as biscuit wrappers), personal bathroom plastics (such as shampoo bottles), and recyclable plastic waste (predominantly from field trips and Friday barbecues) could be removed from the 'burnable' waste stream.

The highest sulphur dioxide emissions occurred in burns that included magazine waste. It is possible that by removing magazines from the incinerator waste, sulphur dioxide emissions will decrease.

The Warren incinerator at Casey Station showed signs of disrepair. The first two weeks of site experimentation were hampered by mechanical failure. In addition, the refractory lining was cracked and broken and the door seal leaked. When an incinerator is not well maintained, emissions are generally higher (USEPA 1996b). The correct maintenance of the incinerator should reduce excess emissions.

A further means of potentially reducing emissions from incineration may be improved incinerator operator training. Some of the significant pollutants measured during these tests were as a result of burning material that should have been returned to Australia for disposal or burning only dry waste. Understanding factors influencing emissions would assist operators in achieving minimum emissions.

Conclusion

The motivation for this research was the hypothesis that 'waste incineration currently practiced at Australian Antarctic stations does not produce emissions that exceed existing environmental best-practice guidelines.' To test this hypothesis, incinerator operations and emissions were monitored at Casey Station as a case study for Australian Antarctic stations. The results were analysed to establish correlations between these operations and emissions. Further, to determine the significance of the emissions, the results were critically analysed with respect to both other station pollutant sources and existing environmental best-practice guidelines.

The study of incinerator operations and emissions was conducted between December 2000 and January 2001 at Casey Station, Antarctica. The emissions were sampled under controlled operational conditions and results were obtained for 16 burns. Incinerator operations monitored included: flue temperature; primary chamber temperature; burn length; fuel use; and waste characteristics (moisture content, weight, and composition). In addition, visual observations were made of the state of the incinerator and incineration practices.

Nine gaseous compounds from the flue and nine heavy metals in the ash were sampled from each burn. Gas emissions included the combustion gases CO, CO_2, and O_2, the hydrocarbons chlorobenzene and toluene, and the acid gases hydrogen chloride, nitrogen dioxide, and sulphur dioxide. The heavy metals in the ash included arsenic, cadmium, chromium, manganese, nickel, cobalt, copper, zinc, and lead. Mercury was also sampled as a composite sample of all burns. Other emissions often associated with incinerators, such as total particulates, dioxins, and furans, were not measured due to budget constraints but would be of interest for future studies.

The experimental results were analysed to determine the correlation between operations and emissions. Significant correlations existed between the following: HCl in the presence of plastics; copper, arsenic, and chromium in the presence of selected wood; NO_2 and toluene with the waste weight; and CO and toluene with very high proportions of dry waste. Correlations between gases were evident for: CO, O_2, and CO_2; and NO_2 with O_2, toluene, and HCl. Further correlations existed between heavy metals in the ash for: arsenic and chromium; and arsenic and manganese.

Comparative studies were conducted between measured emissions and environmental best-practice guidelines. The results of these studies indicated that CO emissions from the flue exceeded the USEPA guidelines for small municipal waste incinerators (USEPA 1995). In addition, arsenic and copper levels in the ash meant that the ash was categorised as 'hazardous waste for remediation' in accordance with the Tasmanian government guidelines (DPIWE 2002). Finally, a comparative study of the station incinerator emissions with respect to other station emission sources (powerhouse generators, boilers, and vehicles) was conducted. This study indicated that average yearly toluene emissions from incineration at Casey Station were 250% greater than the total hydrocarbon emissions from other station sources.

In conclusion, the results of measured emissions and the critical analysis of these results, indicate that waste incineration currently practiced at Australian Antarctic stations produces emissions that exceed existing environmental best-practice guidelines. There is no information on the overall status of emissions generated from the incinerators and how these emissions might impact the lichen and moss communities nearby or influence scientific programmes conducted at the station. However, there was no anecdotal or other evidence that the incinerator emissions were a problem.

References

AAD. 1997–2000. Incineration statistics. (Incomplete collection of incineration statistics from Davis, Mawson, and Casey stations, between 1997 and 2000; loose notes of incineration material presented to the researchers.) On file, Kingston, Tasmania: AAD.

AAD. 1999/2000. RTA manifests. Electronically submitted manifests for voyages 1–8 for season 1999/2000. On file, Kingston, Tasmania: AAD.

AAD. 2000. Antarctica online. http://www.antdiv.gov.au./ [26 February 2001]

Arens, M. 1994. *A waste management strategy for Australia's Antarctic operations.* Canberra: Commonwealth of Australia.

Bush S., L. Holmes, and L. Ho Trieu. 1995. *Australian energy consumption and production.* Canberra: Australian Bureau of Agricultural and Resource Economics (ABARE Research Report 95.1).

DPIWE. 2002. *Classification and management of contaminated soil for disposal.* Hobart: Government of Tasmania (Information Bulletin 105).

Headland, R.K. 2000. The Antarctic and Antarctic winter stations 2000. Unpublished document. Cambridge: Scott Polar Research Institute.

Kriwoken, L.K. 1991. Antarctic environmental planning and management: conclusions from Casey, Australian Antarctic Territory. *Polar Record* 27 (160): 1–8.

Metz, C.R. 1976. *Schaum's outline series: physical chemistry.* New York: McGraw-Hill Book Company.

National Environment Protection Council. 1998. *National environment protection measure for air quality.* Adelaide: National Environment Protection Council.

National Environment Protection Council. 2002. *Towards a national environment protection (air toxics) measure.* Documented at http://www.ephc.gov.au/nepms/air/air_toxics.html.

Perry, R.H., and D. Green. 1984. *Perry's chemical engineers' handbook.* 6th edition. Singapore: McGraw-Hill International: chapter 26.

Todd, J.J., and N. Sawyer. 1984. *Ultimate analysis of wood*. Hobart: Centre for Environmental Studies, University of Tasmania (Fuelwood Report 18).

USEPA. 1995. 40 CFR part 60: Standards of performance for new stationary sources and emissions guidelines for existing sources; municipal waste combustors. *Federal Register* 60 (243). Documented at http://www.epa.gov/ttn/atw/129/mwc/fr1295f.pdf [12 May 2001].

USEPA. 1996a. *AP-42 Fifth edition Vol 1*, Ch 1–10 External combustion sources. Documented at http://www.epa.gov/ttn/chief/ap42/index.html [1 October 2000].

USEPA. 1996b. *AP-42 Fifth edition Vol 1*, Ch 2–1. Solid waste disposal. Documented at http://www.epa.gov/ttn/chief/ap42/index.html [1 October 2000].

USEPA. 2000. 40 CFR part 60: New source performance standards for new small municipal waste combustion units. *Federal Register* 65 (235). Documented at http://www.epa.gov/ttn/uatw/129/mwc/fr899e.pdf [13 May 2001].