

# **IEA Bioenergy Task 36: Energy from integrated solid waste management systems**

## **Topic 2 Report**

### **Development of gasification, ash melting and high efficiency waste power generation technologies**

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## Abstract

Japanese energy policy places considerable emphasis on waste-to-energy to provide extra capacity for power generation in the future. However, many of the country's existing municipal solid waste (MSW) incinerators are small and do not recover energy. Under Japanese law, new waste incineration facilities must be equipped with an ash melting facility and must seek to utilise the slag produced from its ash melting facility. This requirement is intended to reduce pollution and to reduce the demand on Japan's limited landfill capacity.

Waste pyrolysis and combustion with ash melting is a promising technology for the generation of power from MSW in Japan. The technology not only provides high-efficiency waste-to-energy power generation, but also benefits the environment through lower dioxin emissions compared with standard incineration systems. This topic report describes the development of the technology in Japan through two New Energy and Industrial Technology Development Organisation (NEDO) projects carried out in collaboration with nine major industrial companies and the Institute of Applied Energy (IAE).

The first project, 'Development of waste pyrolysis and combustion with ash melting technologies', was carried out between 1998 and 2000. It aimed to enhance efficiency by reducing energy consumption throughout the system and improving the steam turbine performance.

The second project took place between 2001 and 2003, and focused on the development of waste pyrolysis, conversion and generation with gas engine technologies. The main aim of this project was to obtain high-efficiency power generation with small MSW incinerators by using gas engines rather than steam turbines.

The first project had six themes and the second project had four. One company was allocated to each theme. The companies conducted pilot-scale testing of the particular technological development at their own sites by adopting existing pilot plants.

Computer simulations performed by IAE found that a pyrolysis and gasification system with a gas engine type gave the best performance and economic analysis for plants smaller than 200 tons/day. Pyrolysis and combustion with a steam turbine had the best net efficiency for larger plants. A conventional stoker grate with a steam turbine performed less well due to the additional energy consumption associated with the requirement for ash melting.

Those technology developments considered technically and economically feasible are moving to commercialisation and are being gradually introduced in municipal facilities in Japan.

# Contents

<b>1</b>	<b>Introduction</b>	<b>4</b>
1.1	Current status of power generation from waste in Japan	4
1.2	Ash melting and slag	5
<b>2</b>	<b>Development of waste pyrolysis and combustion with ash melting technologies</b>	<b>7</b>
2.1	Efficiency enhancement by increasing the steam temperature	7
2.2	Ceramic high temperature air heaters	8
2.3	High temperature particulate removal from gas upstream of the boiler	11
2.4	High temperature steam recovery with fluidised bed and char combustion	14
2.5	Lower temperature DeNO <sub>x</sub> catalyst	17
2.6	Dehydrator for MSW with a high moisture content	22
2.7	Waste plastic blowing	23
2.8	Conclusions	24
<b>3</b>	<b>Development of gas engine technologies</b>	<b>26</b>
3.1	Pyrolysis process	27
3.2	Gas conversion process	28
3.3	Air preheater for syngas	30
3.4	Gas engine for syngas	34
<b>4</b>	<b>Performance and economical analysis of total optimised system for waste gasification and power generation</b>	<b>37</b>
4.1	Performance analysis	37
4.2	Economic analysis	39
<b>5</b>	<b>Potential of waste gasification and ash melting technologies</b>	<b>41</b>
	<b>Collaborators</b>	<b>43</b>
	<b>Acknowledgements</b>	<b>43</b>
	<b>Bibliography</b>	<b>44</b>

# 1 Introduction

Waste pyrolysis and combustion with ash melting is a promising technology for the generation of power from municipal solid waste (MSW) in Japan. The technology not only provides high efficiency waste-to-energy power generation, but also benefits the environment through lower dioxin emissions compared with standard incineration systems.

This topic report describes the development of the technology in Japan through two New Energy and Industrial Technology Development Organisation (NEDO) projects carried out in collaboration with nine major industrial companies and the Institute of Applied Energy (IAE).

- **Development of waste pyrolysis and combustion with ash melting technologies (1998–2000)**

This project was carried out by NEDO in response to the legal requirement to melt ashes to prevent pollution from MSW combustion, and the political requirement to achieve high-efficiency power generation. It included an evaluation of ways of increasing steam temperature and the development of a DeNO<sub>x</sub> (denitrification) catalyst activated at lower temperatures, a dehydrator for MSW with a high moisture content, the use of a char combustion furnace combined with fluidised bed gasification, and a waste plastic blowing system as a replacement for coke in shaft-type incinerators. Those technology developments considered feasible are moving to a commercial scale and are being gradually introduced in municipal facilities. In particular, increasing the steam temperature and dehydrating wastes will be utilised shortly.

- **Development of waste pyrolysis, conversion and generation with gas engine technologies (2001–2003)**

In addition to meeting the statutory requirement to melt MSW incinerator ashes, the aim of this project was to obtain efficient power generation with small incinerators. With this technology, power is generated by gas engines rather than by steam turbines and thus enhances the generation efficiency of small plants. This project included the development of a waste pyrolysis reactor, a gas reformer with ash melting reactor, an air preheater, and a gas engine based on reformed gas.

NEDO, one of the Japanese government's R&D centres, has been working to develop technologies aimed at enhancing the efficiency of power generation from waste since 1991, in studies supported by the Ministry of Economy, Trade and Industry (METI). Between 1991 and 1998, tests on ways of improving the efficiency of conventional boilers were performed in demonstration plants. These tests showed that new superheater materials allowed reliable furnace operation under steam conditions of 500°C and 9.8 MPa pressure.

## 1.1 Current status of power generation from waste in Japan

Japanese energy policy places considerable emphasis on waste-to-energy to provide extra capacity for power generation in the future. The target is to have a waste-to-energy power generation capacity of 4,170 MW (5,520 million litres of crude oil equivalent) by 2010. Waste-to-energy would thus provide 1% of the nation's primary energy supply by 2010. This projected extra capacity accounts for almost 30% of the total new energy capacity.

In 1999, Japan had 900 MW (1,150 million litres of crude oil equivalent) installed waste-to-energy capacity, which accounted for only 0.2% of the country's primary energy supply. To achieve the national goal, the installed capacity must increase five-fold from that in 1999 by 2010.

Most of Japan's 1,700 incinerators are old plants with a throughput of less than 100 tons/day and do not generate power or recover heat (see Table 1).

**Table 1 Number and capacities of existing Japanese incineration plant**

<b>Capacity (tons/day)</b>	<b>Incineration alone</b>	<b>With power generation</b>
≤100	1,353	1
100–200	229	14
200–300	61	27
300–600	49	84
≥600	8	58
<b>Total</b>	<b>1,700</b>	<b>184</b>

Source: IAE

Japan therefore needs to develop high-efficiency waste-to-energy technologies to replace its existing small incinerators. Any new incinerators must also comply with the ash melting regulation (see Section 1.2).

## 1.2 Ash melting and slag

Because the ashes from MSW incinerators contain pollutants, such as heavy metals, plant operators in Japan have traditionally take steps to prevent these pollutants from being discharged to the environment through techniques like ash solidification using cement.

The limited landfill capacity for ash disposal in Japan means that a cost-effective and safe use for the ash is needed. Melting the ash to form a slag is an effective method of reducing the risk of pollution from dioxins and allows beneficial use of the ash. In March 1998, the Ministry of Health and Welfare (MHW) announced that new waste incineration facilities must be equipped with an ash melting facility and must seek to utilise the slag produced.

MSW incinerator ashes that are melted, cooled and then solidified form a glasslike material (slag). Heavy metals with a lower boiling point evaporate and those with a higher boiling point become wrapped in mesh silica, a major constituent of the slag. This method prevents heavy metals from being discharged to the environment and the high temperatures required to melt the ashes result in the thermal decomposition of most of the dioxins present.

Melting the ashes requires energy to heat them. In some cases, the energy (eg electricity) is supplied from outside of the system. However, a combined waste gasification and ash melting process allows the ash to be heated using energy contained in the waste itself. In this process, gases derived from thermally-cracked wastes are combusted at a high temperature to melt ashes. Waste gasification and ash melting uses less electricity and can achieve higher

efficiencies compared with an electric ash melting facility system linked to a conventional incinerator (eg a stoker grate).

The slag has been confirmed as safe by the Japanese authorities and is currently used in Japan as a material for road construction and concrete. The diversion of the ash and slag from landfill also helps to prolong the life of the country's landfill sites.

Slag leaving an ash melting reactor is shown in Figure 1.

**Figure 1 Slag leaving an ash melting reactor**



Source: NEDO Report (2002) by NGK

## **2 Development of waste pyrolysis and combustion with ash melting technologies**

The following are essential to enhance the efficiency of a waste-to-energy plant with ash melting:

- reducing the heat liberated from condensers;
- reducing steam consumption;
- waste gasification and ash melting technologies designed to minimise heat loss.

The first NEDO project employed the following methods:

- increasing the steam temperature to enhance steam turbine efficiency;
- reducing the steam consumption by developing a low temperature denitrification (DeNOx) system;
- developing a dehydrator to dry wastes with a high moisture content (eg rural MSW) to reduce the energy required for this process and eventually to reduce the energy used to melt the ashes;
- reducing other fuel consumption when melting the ashes by developing a waste plastic blowing technology.

The project had six themes (see Figure 3), each of which was allocated to a separate company. All six companies undertook tests at pilot plants adapted from their existing pilot plants. The findings and results from these ideas are summarised below.

### **2.1 Efficiency enhancement by increasing the steam temperature**

Gases produced from wastes contain significant amounts of hydrogen chloride, which can corrode the internal surfaces of conventional boilers. Ashes melted on the wall surfaces of superheater piping walls can cause the temperature to become extremely high, leading to molten salt corrosion and a reduction in the wall thickness.

Three different technological approaches (see Figure 2) to combustion and heat recovery were therefore adopted in this project:

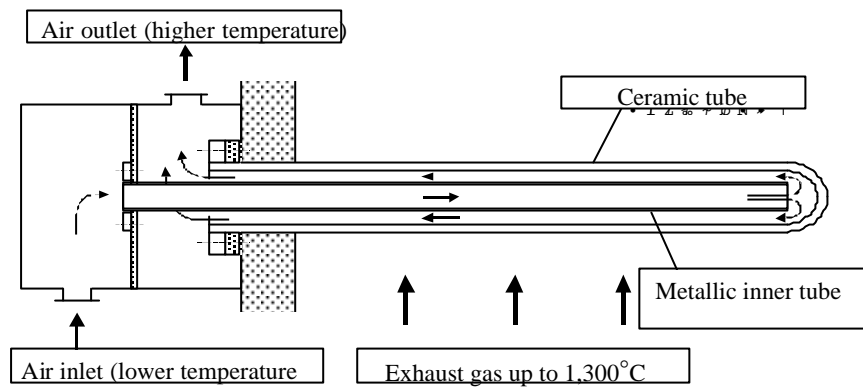
- ashes were removed upstream of the boiler using ceramic filters and heat was recovered (by developing a high temperature system for removing particulates);
- during fluidised bed gasification, high temperature heat was recovered in areas with a low concentration of hydrogen chloride (high temperature heat was recovered in a char combustion furnace);
- indirect superheating recovered high temperature heat (through the development of ceramic high temperature air heaters).





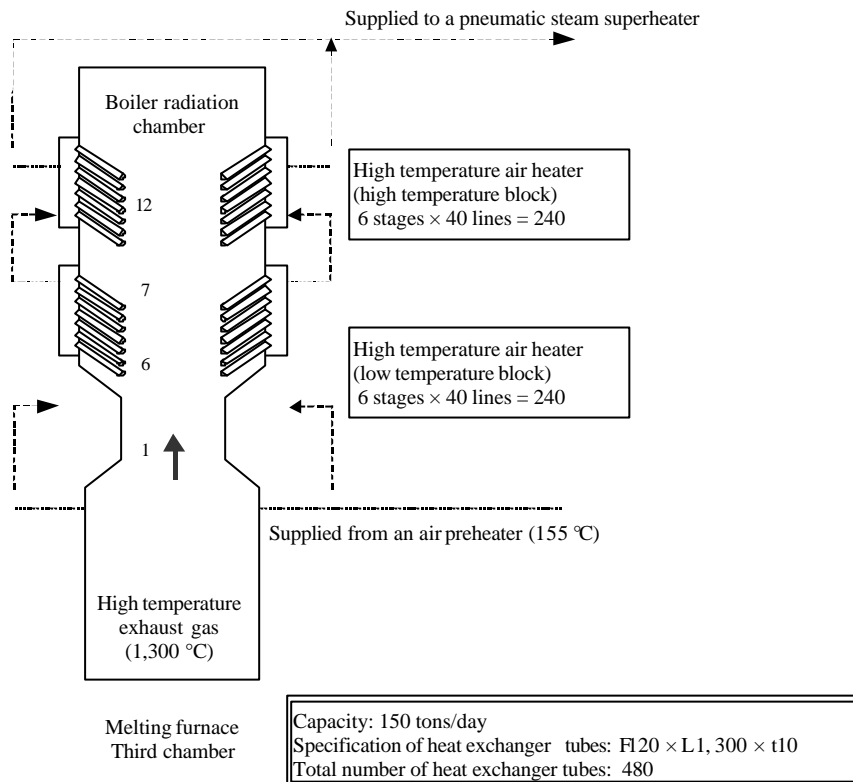
Existing systems for heat exchange between high temperature air and steam do not cause corrosion and are adequate for this purpose. R&D therefore focused on how to use a ceramic air heater to recover waste heat from the combustion gas. Figure 4 shows the structure of the ceramic air heater and Figure 5 shows how it would be mounted on a commercial scale.

**Figure 4 Structure of the ceramic air heater**



Source: NEDO Report (2000) by EBARA

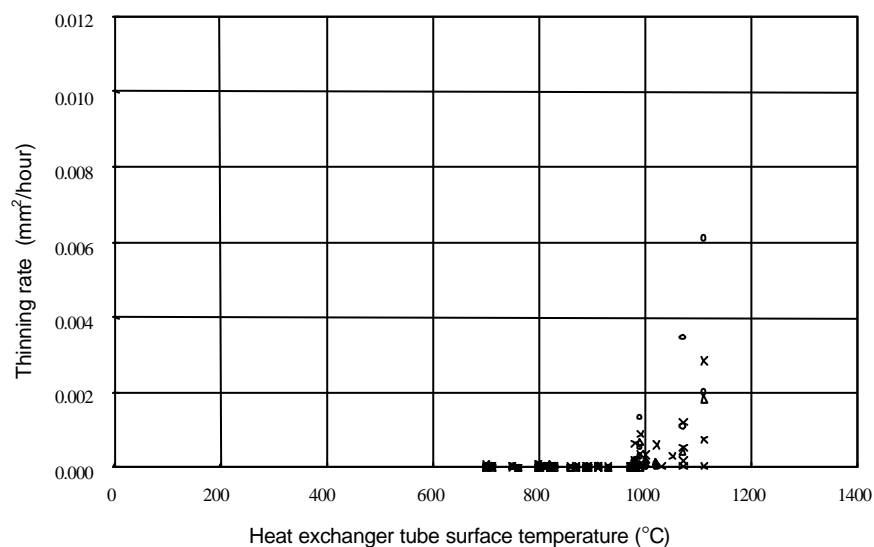
**Figure 5 Layout of ceramic air heater on a commercial scale**



Source: NEDO Report (2000) by EBARA

Because the heat exchanger tube surface temperature is below 1,000°C, the thinning rate (ie the rate at which the wall thickness decreases) is acceptable (see Figure 6).

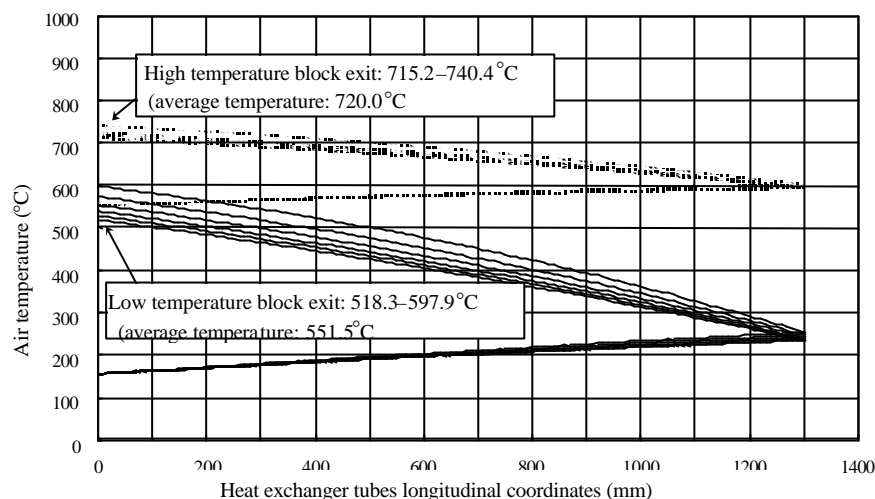
**Figure 6 Effect of heat exchanger tube surface temperature on thinning rate**



Source: NEDO Report (2000) by EBARA

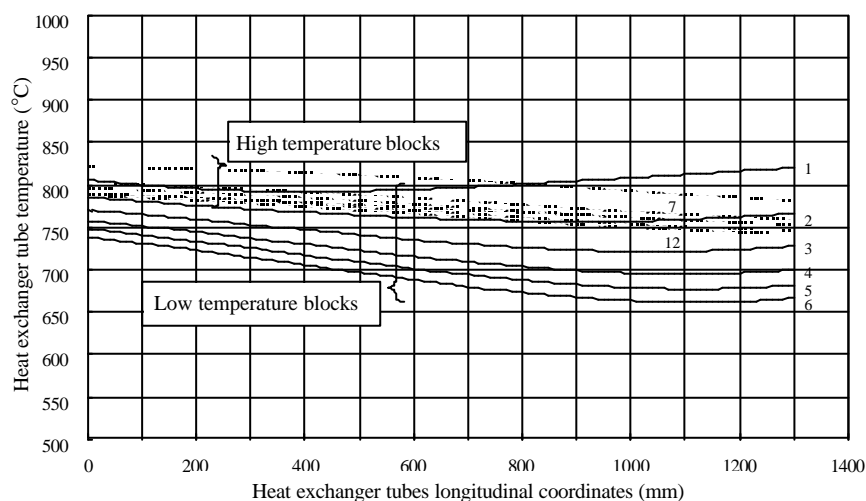
Calculations show that an air temperature of about 700°C would be required to keep the steam temperature above 500°C. In this case, the maximum surface temperature of the ceramic air heater heat exchanger tubes would be 800°C, ie well below 1,000°C (see Figures 7 and 8).

**Figure 7 Air temperature achieved by the heat exchanger tubes**



Source: NEDO Report (2000) by EBARA

**Figure 8 Surface temperature of the heat exchanger tubes**

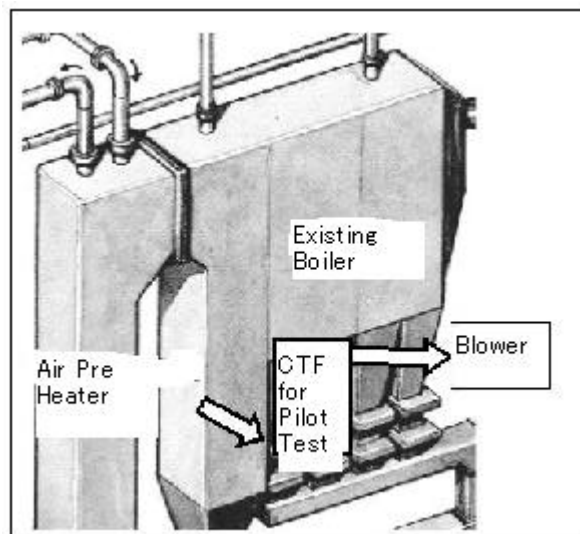


Source: NEDO Report (2000) by EBARA

## 2.3 High temperature particulate removal from gas upstream of the boiler

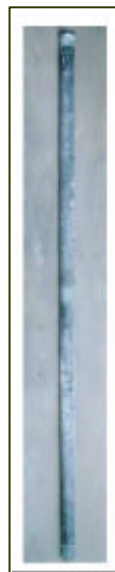
The aim of this work, by Mitsui Engineering & Shipbuilding Company, was to generate high temperature steam while preventing molten salt corrosion. Particulate deposition on the superheater tube surfaces is reduced by installing high temperature particulate removal equipment, such as a ceramic tube filter (CTF), in the upstream gas area of the boiler tubes (see Figure 9 and Figure 10).

**Figure 9 Position of high temperature particulate removal equipment**



Source: NEDO Report (2000) by MES

**Figure 10 Piece of ceramic tube filter**



Source: NEDO Report (2000) by MES

The feasibility of this technology was investigated by:

- installing probe tubes made from SUS310S both upstream and downstream of the CTF;
- measuring the thickness of the probe tubes;
- determining the melting points of ash deposited on the surface of the probe tubes.

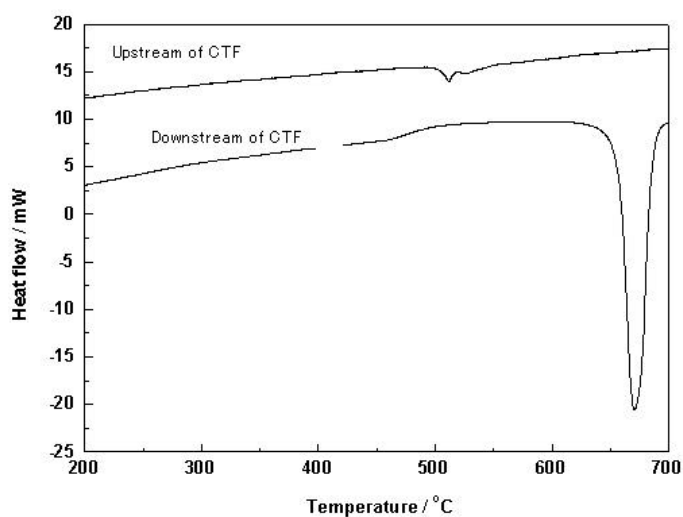
The results are shown in Table 2 and Figures 11 and 12. They suggest that, provided the surface temperature of the boiler tubes is less than 650°C, this technology could be used to generate 500°C steam without leading to a molten slag problem in the boiler tubes.

The research demonstrated that installing a ceramic tube filter upstream of the superheater would allow the production of high temperature steam without molten slag problems. However, this technology has not yet been applied on a commercial scale.

**Table 2 Results of feasibility testing**

	Maximum thinness due to corrosion ( $\mu\text{m}$ )	Ash melting point ( $^{\circ}\text{C}$ )
Upstream probe tube	115	504
Downstream probe tube	<10	650

**Figure 11 Ash melting points upstream and downstream of the CTF**



Source: NEDO Report (2000) by MES

**Figure 12 Probe tubes after testing: upstream of CTF (A) and downstream of CTF (B)**



Source: NEDO Report (2000) by MES

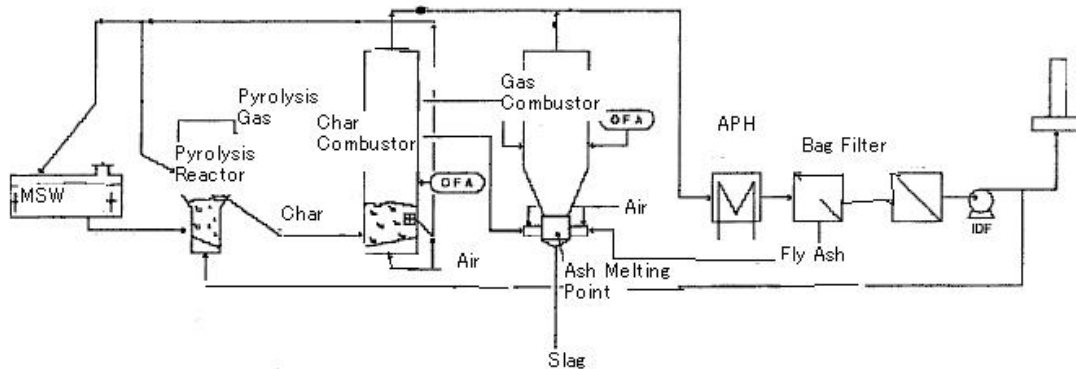
## **2.4 High temperature steam recovery with fluidised bed and char combustion**

This work, by Mitsubishi Heavy Industries Ltd, investigated the use of a char combustion furnace (char combustor) reactor to generate high temperature steam. The advantage of this system is the lower chlorine content achieved in a fluidised bed gasification system. Figure 13 shows the overall flow of the 20 tons/day pilot plant at Mitsubishi.

The chlorine content in the pilot plant's char combustor was 30–200 ppm compared with 400–1,500 ppm in a conventional grating stoker incinerator.

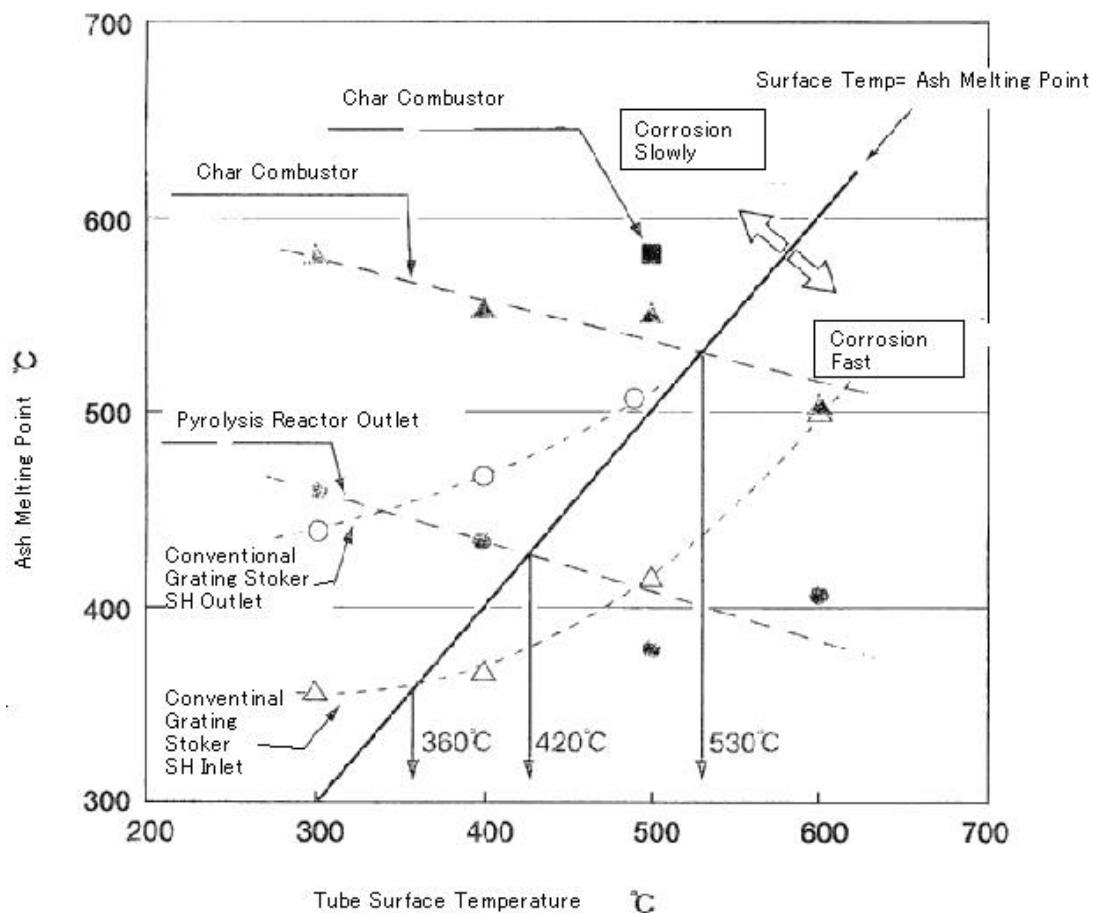
Figure 14 shows the ash melting points and tube surface temperatures at points equivalent to the positions of the superheater tubes in various types of combustion systems. When the superheater tube surface is at a higher temperature than the ash melting point, molten salt corrosion occurs and the corrosion rate is high. A temperature equivalent to the ash melting point is the upper limit for the surface temperature. In the pilot plant's char combustor, this surface temperature was 530°C.

**Figure 13 Schematic representation of the pilot-scale gasification plant with char combustor**



Source: NEDO Report (2000) by MHI

**Figure 14 Boiler tube surface temperature and ash melting points in char combustor and conventional grating stoker boiler**



Source: NEDO Report (2000) by MHI

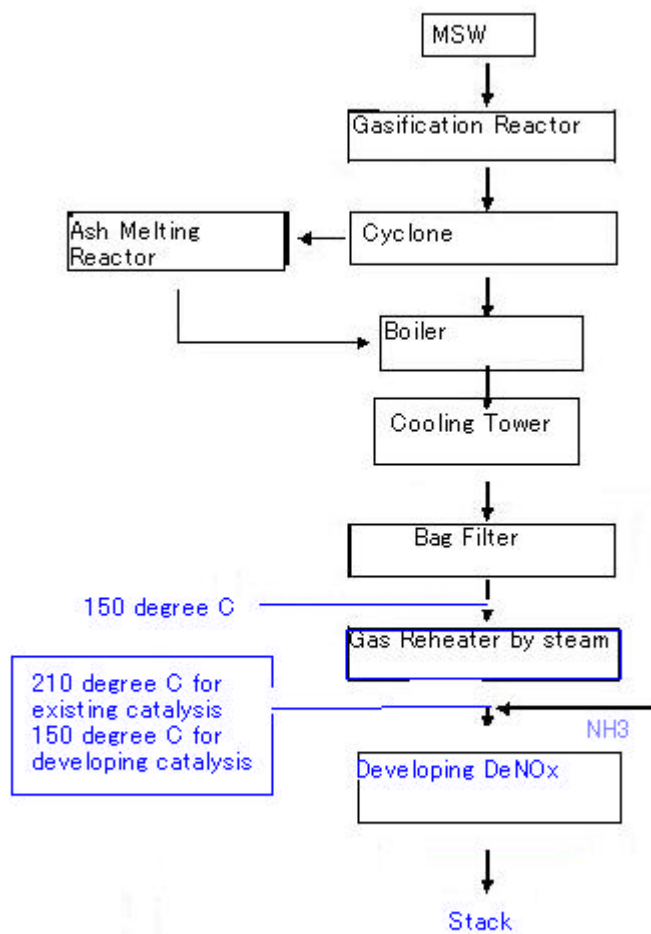
This pilot plant with its char combustion reactor provides a way of generating high temperature steam at 500°C without superheater corrosion. However, this technology has not yet been tested on a commercial scale.



## **2.5 Lower temperature DeNOx catalyst**

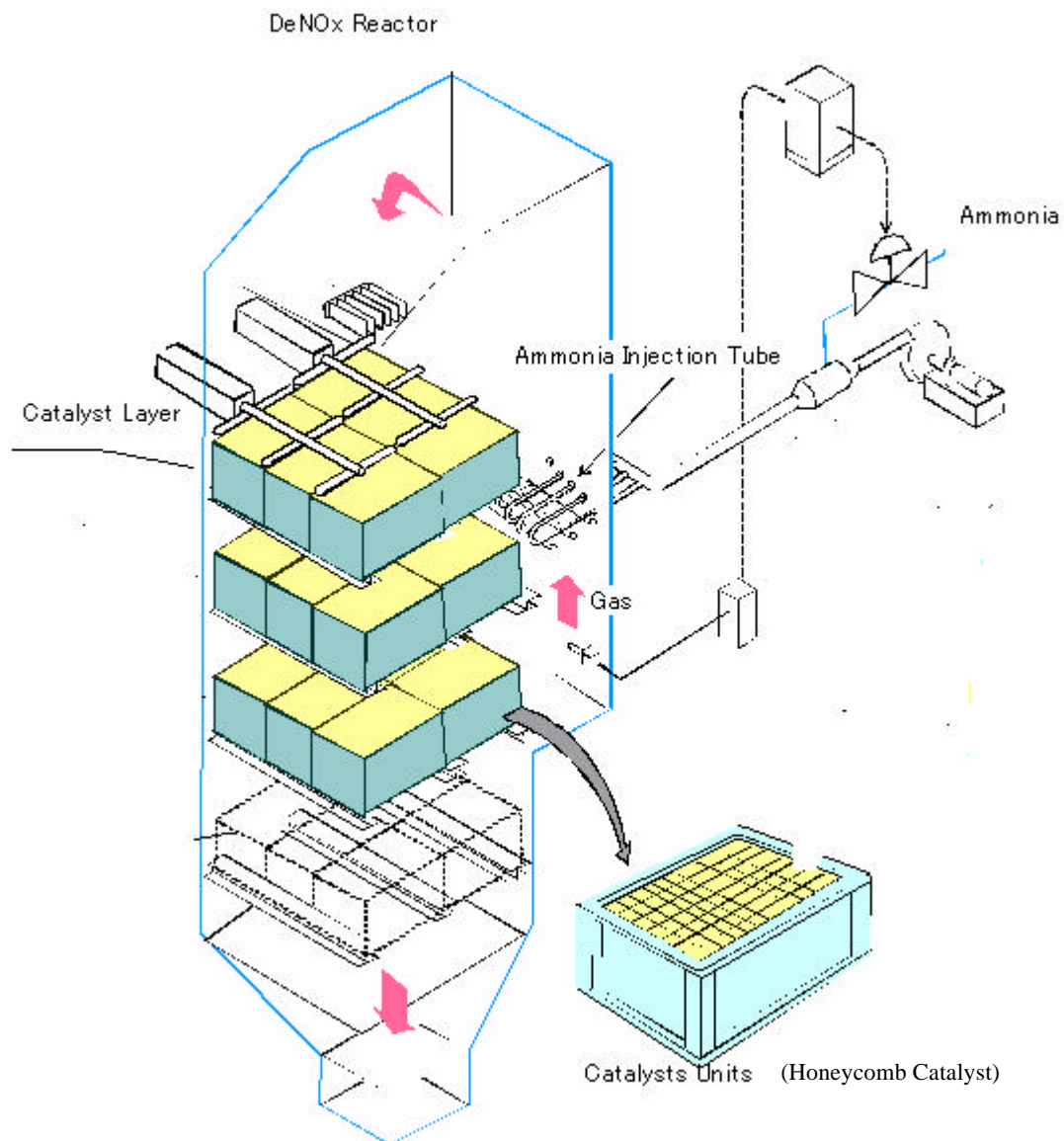
During the treatment of flue gas from a waste-to-energy plant, the flue gas is generally cooled to 150–170°C in order to convert hazardous material in the gas phase to the solid phase and thus allow it to be removed in a bag filter. After passing through the bag filter, the flue gas is reheated up at 210°C to remove nitrogen oxides (NO<sub>x</sub>) by selective catalytic reduction (SCR) in a denitrification (DeNO<sub>x</sub>) system. This higher temperature is necessary to achieve good activation of the DeNO<sub>x</sub> catalyst. Steam generated by a boiler is used as the source of heat to reheat the flue gas. Conventional DeNO<sub>x</sub> catalysts thus reduce plant efficiency to some extent.

The aim of this work, by Kawasaki Heavy Industries Ltd, was to reduce steam consumption by developing a DeNO<sub>x</sub> catalyst that could be activated at a lower temperature. The target temperature is 150°C. Figure 15 shows the overall concept of a high efficiency waste-to-energy plant based on such a catalyst and Figure 16 shows the DeNO<sub>x</sub> reactor composed of some honeycomb catalyst units in more detail.



Source: NEDO Report (2000) by KHI

**Figure 15 Concept of high efficiency waste-to-energy plant with DeNOx catalyst activated at a lower temperature**



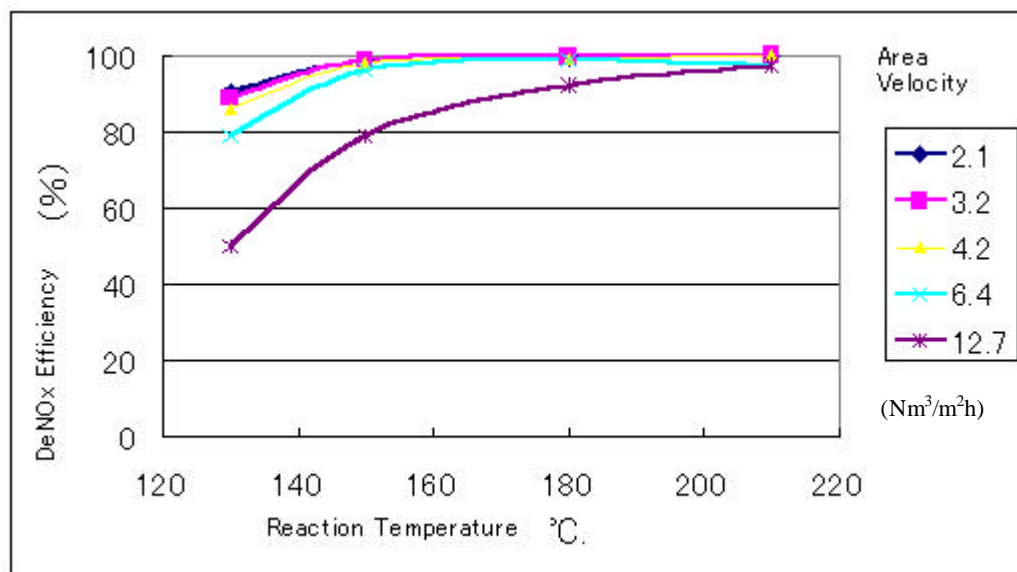
Source: NEDO Report (2000) by KHI

**Figure 16 SCR DeNOx reactor**

Initial laboratory tests were conducted with two types of DeNOx catalyst: a Ti-V catalyst and a Mn-Ti catalyst. However more development of manufacture technology of honeycomb catalyst is required for Mn-Ti catalyst at present.

These results indicated that adding some molybdenum to the Ti-V catalyst could enable a DeNOx efficiency of 80% to be reached at more than 150°C over for a short run (see Figure 17). This result was beyond the target DeNOx efficiency of 75%.

**Figure 17 DeNOx efficiency versus reaction temperature at different area velocities with a Ti-V-Mo catalyst**



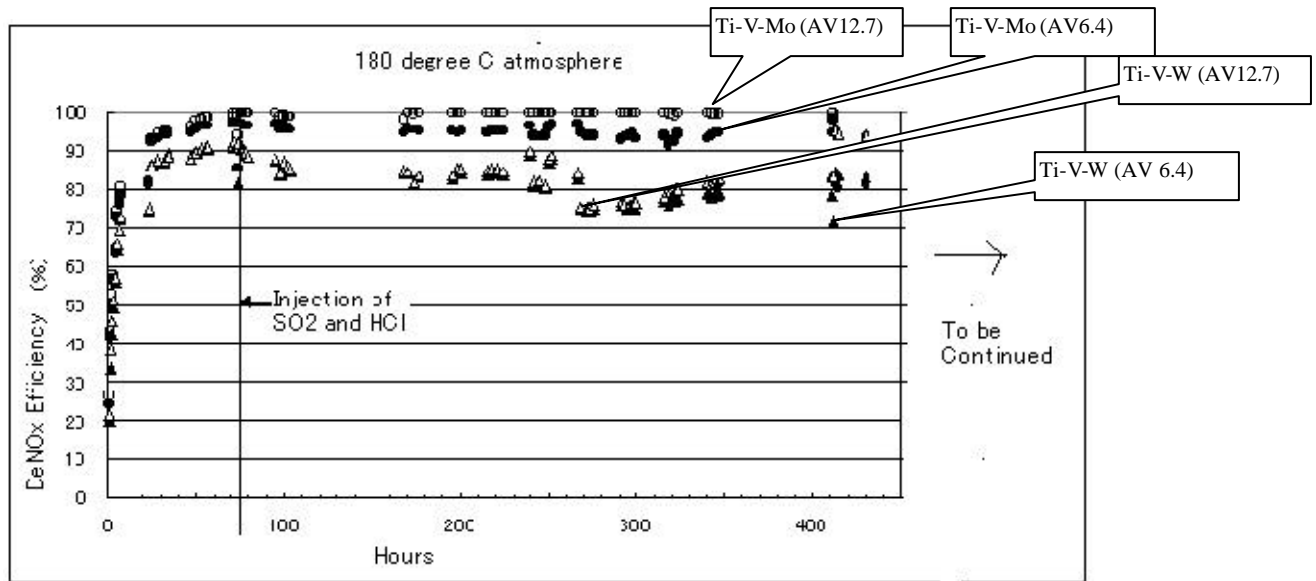
Source: NEDO Report (2000) by KHI

Following these laboratory tests, a long test run using the Ti-V-Mo catalyst unit was conducted with a gas ('mimic gas') that had a composition similar to that of the flue gas from a waste-to-energy plant. During this long test run, the test unit was sequentially exposed to:

- mimic gas at 180°C for 70 hours;
- mimic gas and injected sulphur dioxide (SO<sub>2</sub>) and hydrogen chloride (HCl) at 180°C for 380 hours to confirm degradation characteristics of the catalysts under an impurity gas atmosphere at 180°C;
- mimic gas plus SO<sub>2</sub> and HCl at 150°C for 150 hours to confirm the above characteristics at 150°C.

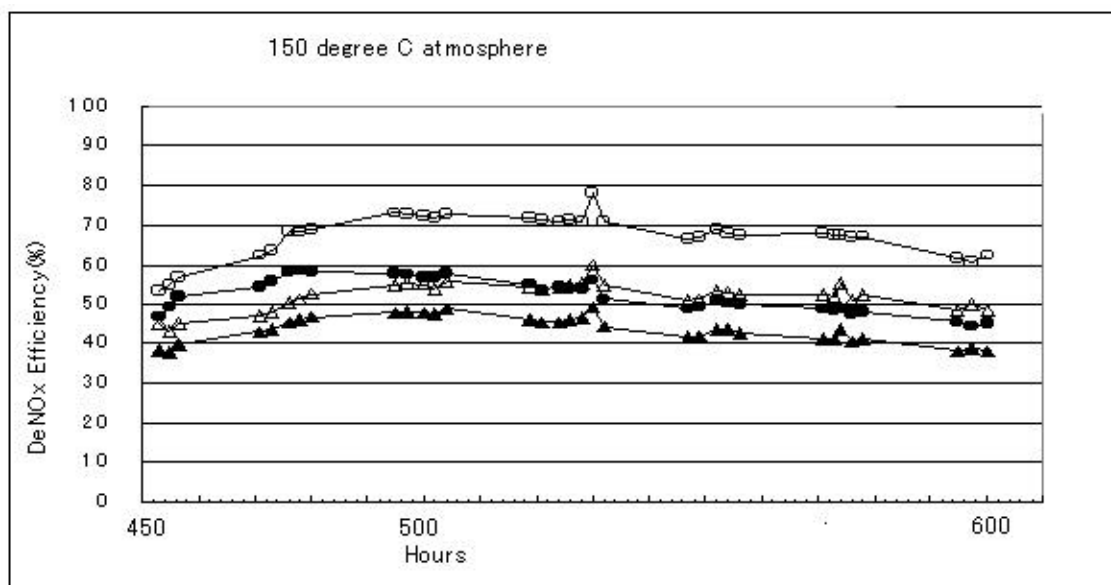
Figure 18 shows the changes in DeNOx efficiency with time for different area velocities (12.7 and 6.4 Nm³/m²h) at 180°C for the first 450 hours of the test run. For reference, Ti-V-W catalyst, which had been developed in previous year (1999), was exposed under the same conditions. Figure 19 shows the changes at 150°C for the final 150 hours.

The results show that there was very little degradation of the Ti-V-Mo catalyst at 180°C (see Figure 18), but that degradation was very high at 150°C (see Figure 19). DeNOx efficiency fell to as low as 60% for the catalyst that had experienced 150°C for 150 hours.



Source: NEDO Report (2000) by KHI

**Figure 18 Long test run results for the Ti-V-Mo catalyst unit at 180°C**



Source: NEDO Report (2000) by KHI

**Figure 19 Long test run results for the Ti-V-Mo catalyst unit at 150°C**

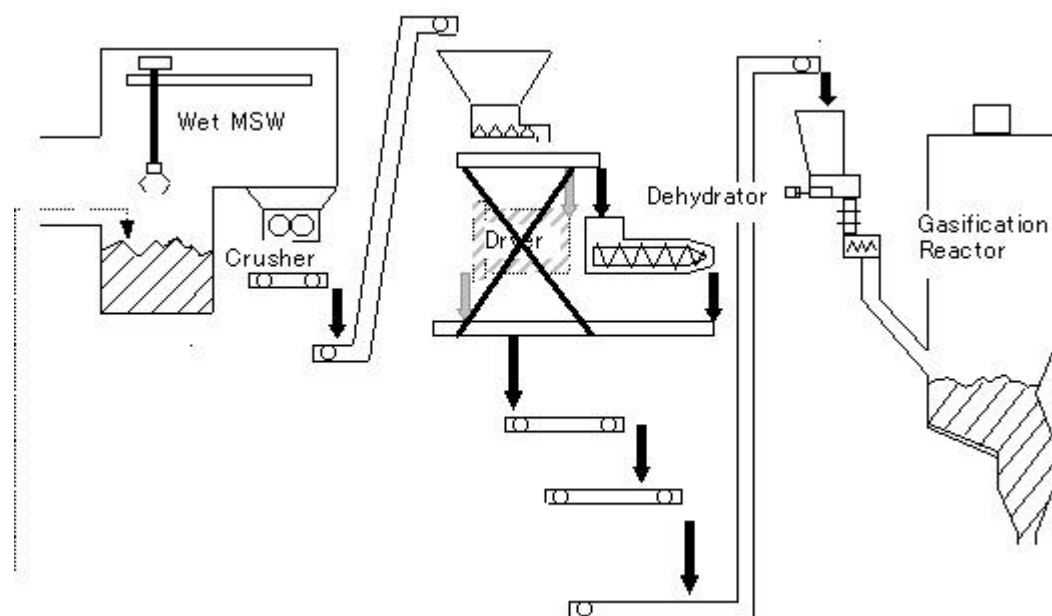
The tests suggest that a Ti-V-Mo catalyst activated at 170°C could endure the conditions in a DeNOx unit of a commercial high efficiency waste-to-energy plant in terms of catalyst degradation tendencies, taking account of the other test results. More research is needed to overcome the problems of catalyst degradation at 150°C before this activation temperature could be used successfully in a commercial plant. However, this technology will be applied in some Japanese commercial waste-to-energy plants within a few years and has been noted with interest by many companies.

## 2.6 Dehydrator for MSW with a high moisture content

Because most of the MSW from rural areas is food residues, it tends to have a high moisture content and a low LHV (lower heating value). In terms of the energy balance for the gasification process, it is necessary to increase the LHV of this MSW in order to obtain high enough temperatures to pyrolyse it.

High moisture content is a major barrier to the introduction of gasification plants in rural areas of Japan. However, installing a dryer to remove water from the MSW would be expensive and difficult in terms of plant layout. Moreover, a dryer would use considerable amounts of heat energy and thus reduce the plant's overall efficiency.

Hitachi Zosen Corporation has developed a dehydrator for high moisture content MSW and subjected the dehydrated MSW to demonstration tests in a pilot gasification plant (see Figure 20). In this pilot plant, the existing dryer was replaced with the dehydrator (indicated in Figure 20). Figure 21 shows the operation of the dehydrator in the pilot plant.



Source: NEDO Report (2000) by HZ

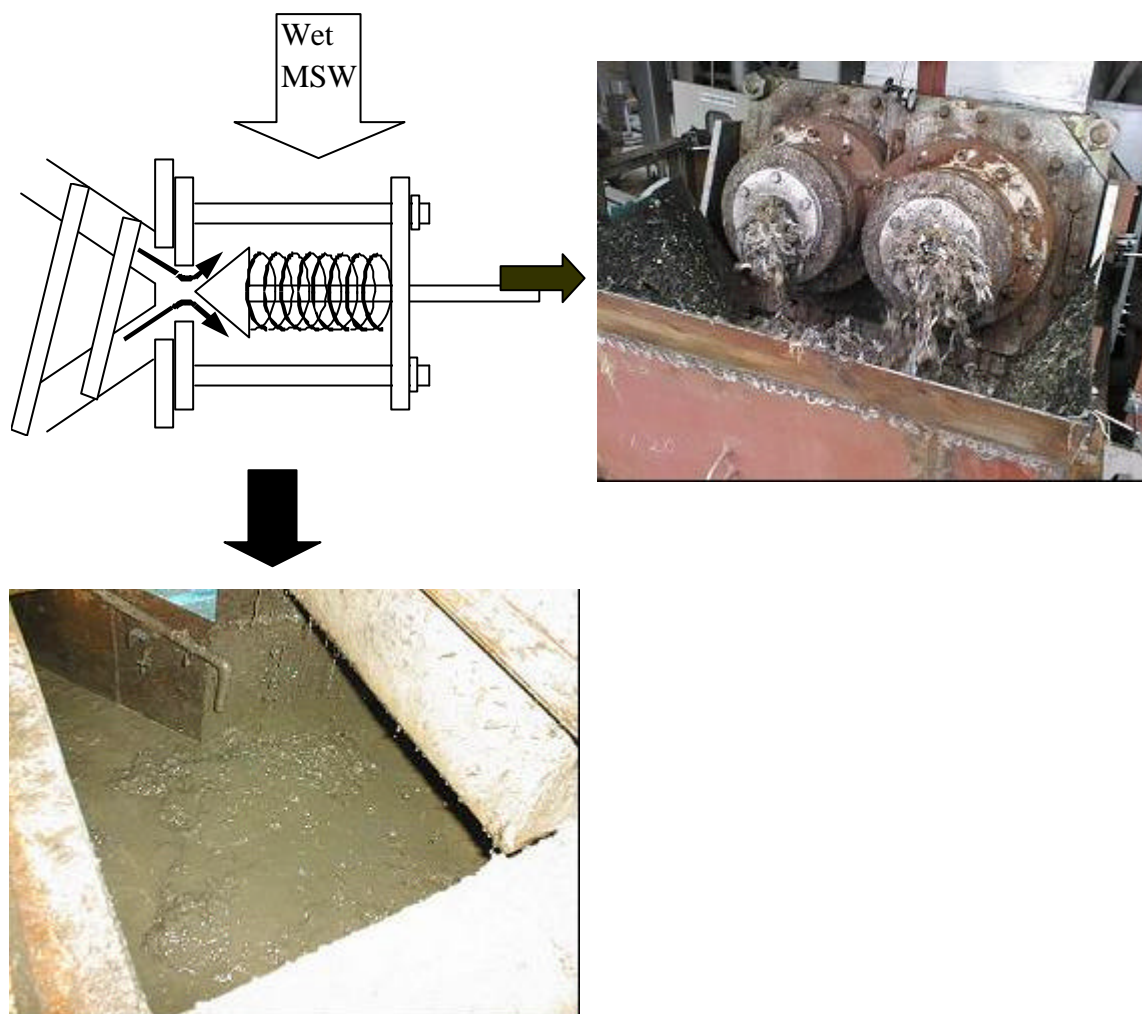
**Figure 20 Schematic representation of the pilot-scale gasification plant with dehydrator**

The technology has been applied to commercial waste-to-energy gasification plants in Japan. This involves:

- injecting wastewater and waste cake discharged from a dehydrator into the combustion area of a gasification reactor;
- holding hazardous constituents for over two seconds at temperatures greater than 850°C, to prevent the pollutants and odour being emitted from the plant.

The technology is, in general, applicable to MSW with moisture content of more than 45%.

**Figure 21 Dehydrator in operation**



Source: NEDO Report (2000) by HZ

## **2.7 Waste plastic blowing**

A shaft furnace (one type of waste-to-energy with an ash melting system) makes MSW melt directly. MSW is added to coke and limestone before being injected into the furnace. It is dried, heated, gasified and melted under the high temperature and reducing atmosphere generated by burning the coke in the furnace. The ash content is melted and exhausted to the bottom of the furnace as a slag. The pyrolysis gas is exhausted to the top of the furnace and burnt in a gas-fired boiler.

There is considerable experience of using this type of shaft furnace on a commercial scale in Japan. However, it has the disadvantage of requiring considerable quantities of coke. Nippon Steel Corporation therefore investigated blowing of waste plastic instead of coke into the furnace as a method of enhancing plant efficiency.

Results suggest that 30% of the coke could, in theory, be replaced with waste plastic. Figure 22 shows the waste plastic blowing demonstration plant at Nippon Steel Corporation.

**Figure 22 NSC's Waste plastic blowing demonstration plant at Kitakyushu city**



Source: NEDO Report (2000) by NSC

## **2.8 Conclusions**

The Institute of Applied Energy used the results obtained from the six studies in this project to carry out a virtual feasibility study and derive a total system, optimised in terms of performances with the maximum possible power generating efficiency (see Figure 23).

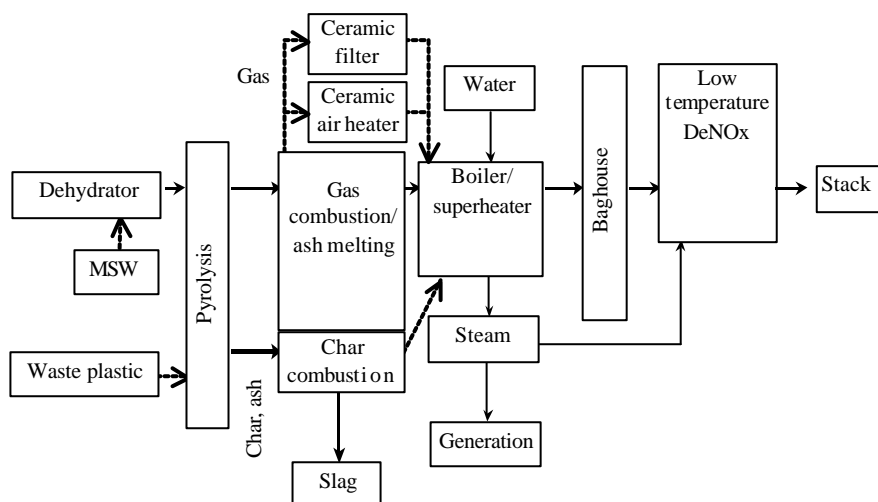
The dehydration of wastes (see Section 2.6) is particularly effective for MSW with high water content (>45%). Waste plastic blowing (see Section 2.7) is only applicable to shaft furnaces.

The feasibility study suggests that combining the virtual total waste gasification and generation system with the above developments in an optimised system would give a gross efficiency of 29% and a net efficiency of 24% for a 600 tons/day plant with a steam turbine generator operating at 500°C and 100 ata (atmospheres absolute). This compares with a gross efficiency of 25% and a net efficiency of 16% under the same conditions for a conventional grating stoker system (including conventional ash melting equipment with electricity).

The study also revealed that the cost (including construction and operation) of the gasification plant would be much lower than that for a conventional grating stoker system (assuming a 600 tons/day plant operating at steam conditions of 500°C and 100 ata, and ash melting).



**Figure 23 Optimised system for power generation from waste gasification and ash melting**



### 3 Development of gas engine technologies

The developments described in Section 2 allow consistently high efficiency waste-to-energy power generation systems with ash melting for medium capacity incinerators in Japan. However, most of the country's incinerators have a throughput of less than 100 tons/day and do not recover energy (see Section 1.1).

NEDO therefore turned its attention to establishing waste-to-energy technologies for small capacity plant that combined high generation efficiency and ash melting. To avoid the poor steam turbine efficiency associated with small waste-to-energy plants, NEDO initially considered a range of other generation systems, eg fuel cell, gas turbine and gas engines using waste conversion gas.

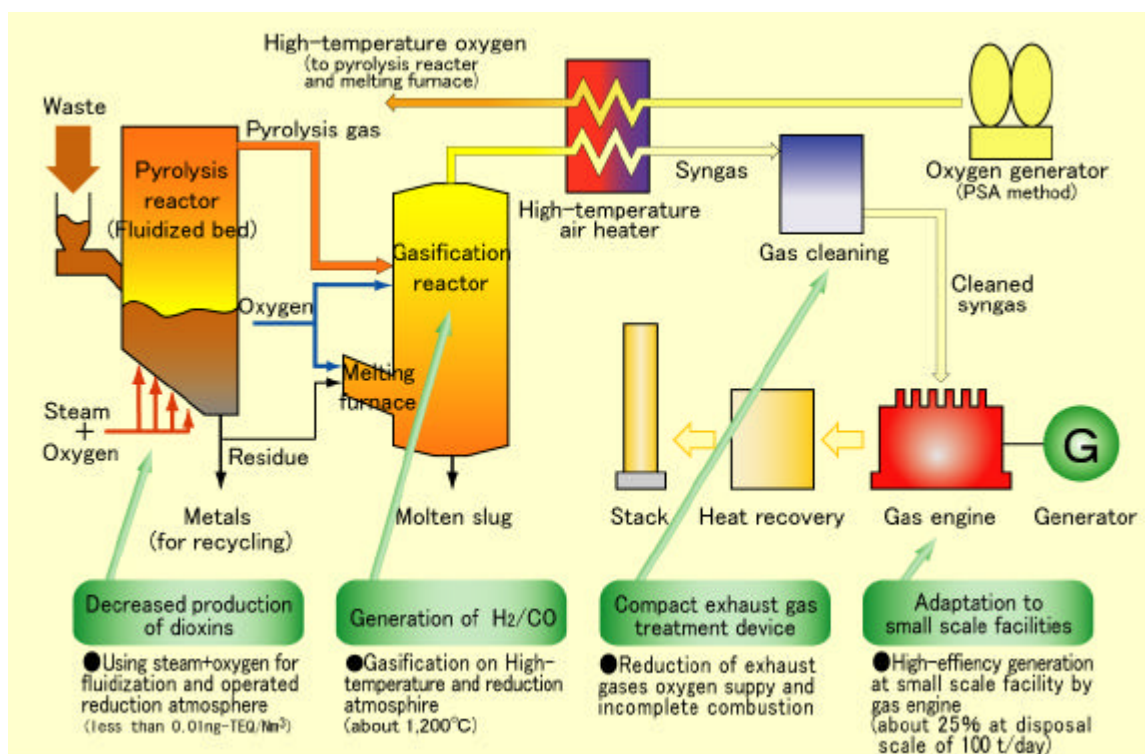
To reduce the technical risks, gas engines were selected as the power generation system for this project, which ran from 2001 to 2003. This system is expected to have a net power generation efficiency of 14% (as a 100 tons/day plant) and dioxin emissions of 0.01 ng-toxic equivalents (TEQ) per Nm<sup>3</sup> (the latter due to reducing atmosphere from the pyrolysis reactor to the gas engine inlet).

To enhance plant efficiency and reliability, the project had the following themes (see Figure 24):

- development of a pyrolysis process to reduce dioxin production in the pyrolysis gas;
- development of a gas conversion process to optimise gasification and the ash melting reactor;
- development of an air preheater for synthesis gas (syngas: a mixture of hydrogen and carbon monoxide obtained from the reforming of methane) to enhance plant efficiency;
- development of a gas engine for syngas adapted to waste gas conversion in small-scale facilities.

Each theme was allocated to a separate company. All four companies undertook tests at pilot plants adapted from their existing pilot plants. The findings and results from these tests are summarised below.

**Figure 24 Project themes: development of waste pyrolysis, conversion and generation with gas engine technologies**



Source: NEDO / IAE pamphlet

### 3.1 Pyrolysis process

The aim of this study was to optimise the pyrolysis process by enhancing pyrolysis efficiency, and reducing soot and tar in the pyrolysis gas by using a mixture of oxygen and steam in the pyrolysis reactor. Reducing soot levels in the pyrolysis gas should also reduce dioxin emissions.

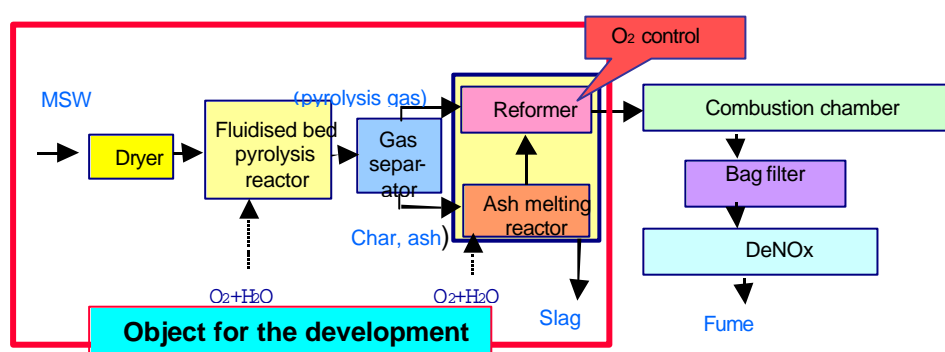
The gas conversion pilot plant at Mitsubishi Heavy Industries Ltd, which was also used for the char combustion furnace tests described in Section 2.4, consists of a fluidised bed pyrolysis reactor, a gasification reactor, an ash melting reactor, and a gas treatment facility. The mixture of oxygen and steam is injected into the pyrolysis reactor in order to maintain the fluidised bed zone and to reduce soot in the pyrolysis gas. Figure 25 shows the pilot plant, which is situated at Yokohama and has a capacity of 15 tons/day. Its fuel is MSW or refuse-derived fuel (RDF) from the city of Yokohama. The plant's layout is shown schematically in Figure 26.

**Figure 25 Pilot plant at Mitsubishi Heavy Industries at Yokohama**

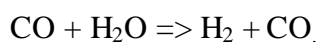


Source: NEDO Report (2003) by MHI

**Figure 26 Schematic representation of the pilot plant**



Pilot plant tests involved blowing high temperature steam and oxygen at 600°C or 650°C into the pyrolysis reactor. Pyrolysis gas can be converted to a hydrogen-rich gas by the following shift reaction:



Results showed that a steady pyrolysis reaction was maintained without the need for auxiliary fuel and that the soot content of the pyrolysis gas was less than 1%. In addition, the test indicated that a controlled oxygen supply at the reformer is an effective way of reducing both fluctuations in the gas composition and dioxins in the syngas. The dioxin concentration at the outlet of the bag filter was 0.01 ng-TEQ/Nm<sup>3</sup>.

### 3.2 Gas conversion process

The aim of this work, by NGK Insulators Ltd, was to enhance the gas conversion ratio by improving the performance of the gas reformer and the ash melting reactor.

NGK's pilot plant (see Figure 27) is at Handa City (near Nagoya City). It has a capacity of 4 tons/day of MSW from Handa City.

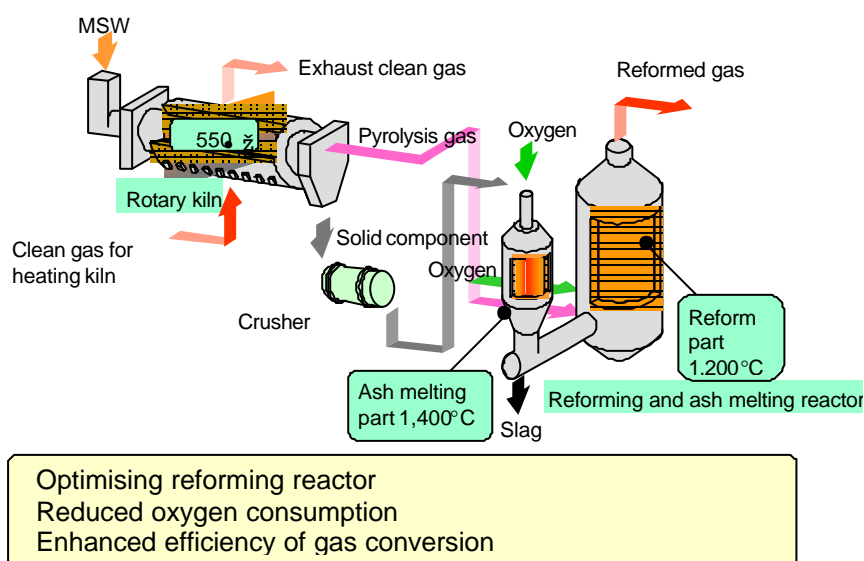
**Figure 27 NGK's pilot plant at Handa City**



Source: NEDO Report (2003) by NGK

Flows through the system are shown in Figure 28. In this system, the pyrolysis gas (derived from waste heated to 550°C in a rotary kiln) is converted to high calorific gas at 1,200°C in the reformer with steam and oxygen. The solid component is melted at 1,400°C to give slag.

**Figure 28 System flows through the pilot plant**



Source: NEDO Report (2003) by NGK

In a pilot plant test carried out in 2002, the gas conversion ratio was just 50% and did not reach the target value of 60%. This means that the gas volume was 83% (ie 50%/60%), so the power efficiency was 83% of what had been expected.

NGK reviewed the results (see Table 3) and adapted the pilot plant in 2003. This involved downsizing the reformer and replacing the oxygen and steam nozzles. It was confirmed for such adaptations to give a gas conversion ratio of 59% by the new pilot plant test in 2003.

**Table 3 Issues reviewed after the first pilot plant test**

Issue	Solution
Reduced heat radiation in the reformer	Decrease the volume of the reformer
Enhanced carbon gas conversion ratio	Improve the turbulence of oxygen, steam and products
Reduced oxygen consumption	Optimise the operational temperature

### **3.3 Air preheater for syngas**

The aim of this work, by Toshiba Corporation, was to confirm the reliability of a new design of air preheater for syngas. Adding an air preheater to a waste gas conversion system is a new concept in terms of enhancing plant efficiency.

The air preheater makes use of the sensible heat from syngas, which has a temperature of 900°C. This sensible heat accounts for as much as 20% of the heating value of cleaned syngas. The objective was to develop an air preheater that heats the air up to 600°C and whose metallic components had long-term reliability under pyrolysis gas, which has a reducing atmosphere. This development is a challenging and important element for achieving a high efficiency plant.

Toshiba's pilot plant (see Figure 29) is in Kawasaki City and has a capacity of 10 tons/day. Pyrolysis is performed in a rotary kiln and gas conversion involves high temperature air at the gas reformer (known as the 'gas cracker').

Toshiba initially conducted exposure tests for various alloys using the exhaust gas from an existing gas conversion pilot plant. Table 4 shows the composition content of the three alloys screened by exposing them for 3,000 hours to waste conversion gas from car shredder dust.

**Figure 29 Toshiba's pilot plant at Kawasaki City**



Source: NEDO Report (2003) by Toshiba

**Table 4 Composition of screened alloys**

(%)

Element	SUS310S	NAR-AH4	SUSXM15J1
Carbon (C)	0.04	0.072	0.06
Silicon (Si)	0.6	0.32	3.37
Manganese (Mn)	1.14	0.85	0.93
Phosphorus (P)	0.026	0.03	0.023
Sulphur (S)	<0.001	<0.001	<0.001
Nickel (Ni)	19.01	121.12	13.96
Chromium (Cr)	25.14	23.16	19.52
Nitrogen (N)	—	0.222	—
Lanthanum plus cerium (La + Ce)	—	0.034	—
Boron (B)	—	0.002	—

The demonstration air preheater was manufactured and installed on Toshiba's existing pilot plant. Its design was based on interim results from the exposure tests. The soot blower



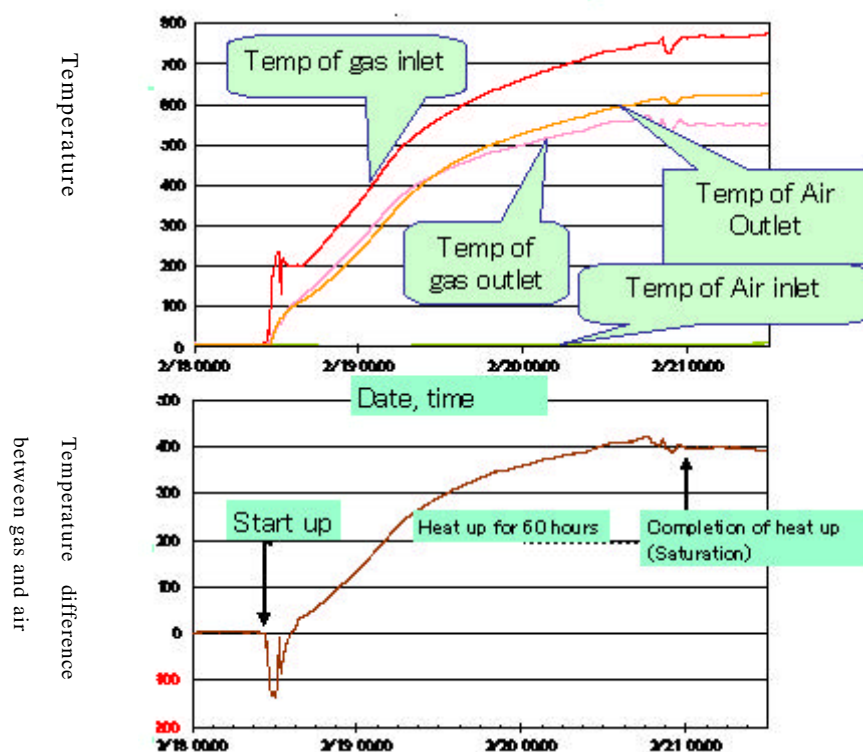
mechanism for removing some of the impurities in the syngas had to be contrived because the air preheater was installed upstream of a gas treatment facility.

The air preheater demonstration test was carried out in 2002 to confirm elements of its performance, such as the start-up characteristics of the air heating system. In this test, the plant system did not make use of the energy derived from the air preheater (the heated air was exhausted externally). However, the test revealed that the air preheater performance was such that the temperature of its outlet air could reach 600°C

Figure 30 shows the start-up characteristic of the demonstration test. This test revealed as follows.

- (1) The air preheater reached the thermal equilibrium for 60 hours from the start-up
- (2) The air preheater could heat the air to 600 degree C

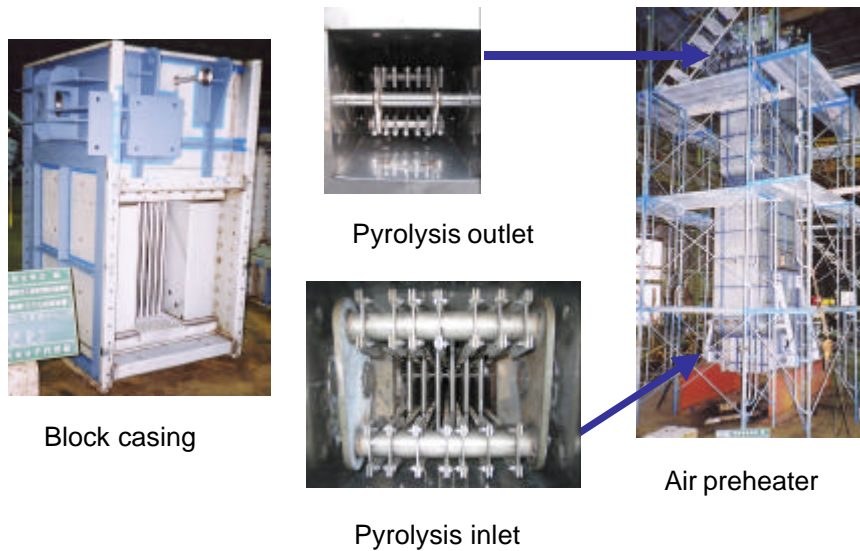
**Figure 30 Air preheater demonstration test: start-up characteristics**



Source: NEDO Report (2002) by Toshiba

Various elements of the air preheater are pictured in Figure 31 and views of the final installation are shown in Figure 32.





Source: NEDO Report (2002) by Toshiba

**Figure 31 Elements of the air preheater**



Source: NEDO Report (2002) by Toshiba

**Figure 32 Installed air preheater**

In 2003, the outlet air heated by the air preheater was obtained from the gas reformer and the plant made use of the sensible heat from the syngas. Both the exposure tests for materials and air preheater demonstration test with the new phase were carried out until November 2003. The results are as follows,

- (1) According to the exposure tests for 3200 hours, the corrosion of 3 alloys (SUS310, NAR-AH4, SUSXM15J1) could be acceptable level for a use of air preheater materials.

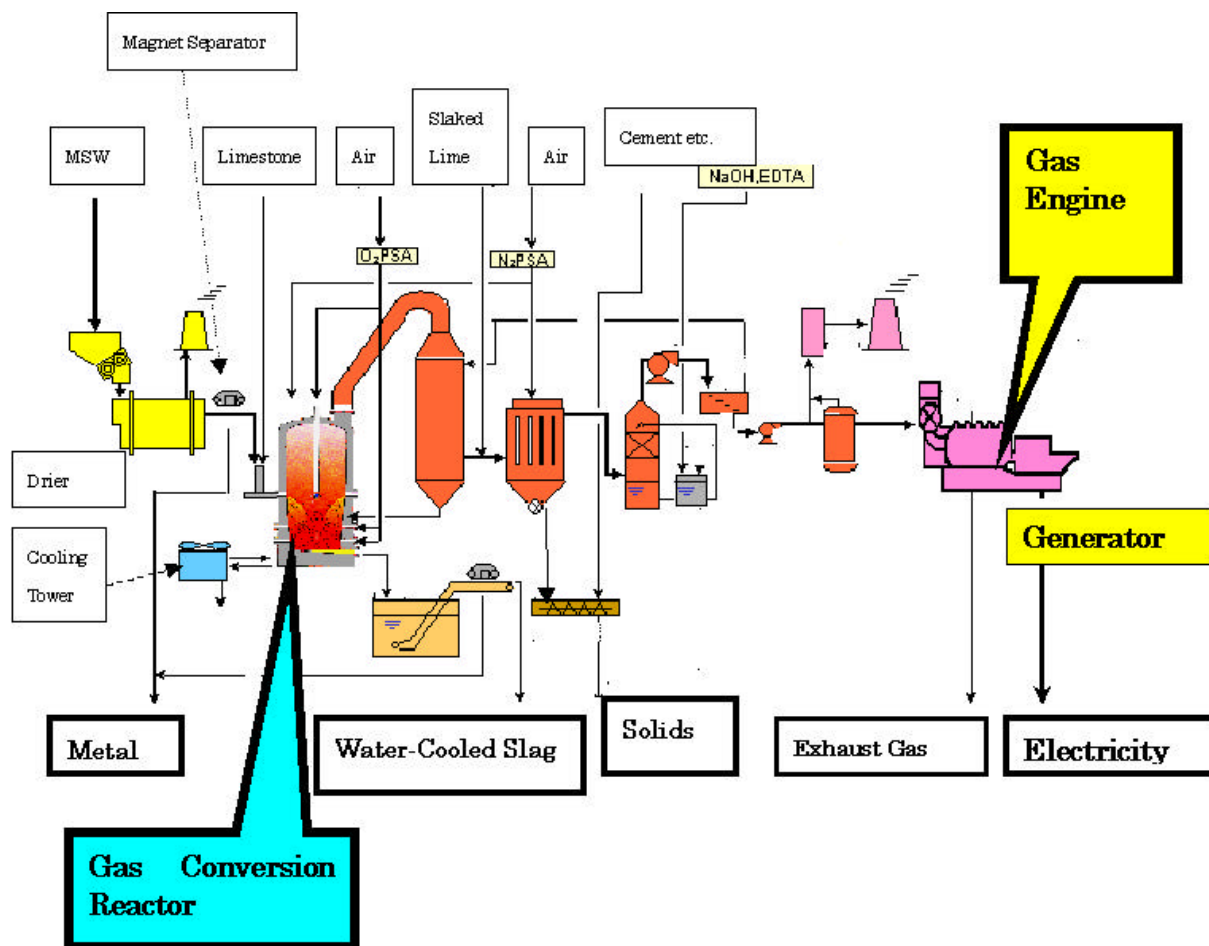
- (2) The air preheater demonstration test in 2003 confirmed that such system let gas conversion ratio of the total system enhance 5 %. In addition, such system has no problem of dioxins emission in a flue gas according to this test result.

### 3.4 Gas engine for syngas

The aim of this part of the project was to confirm the reliability of:

- a newly designed gas engine for syngas and its performance;
- total waste gas conversion with the gas engine system.

Sumitomo Metal Industries Ltd had already developed a waste gas conversion pilot plant without a gas engine. Its pyrolysis system is very different from other companies; using oxygen, waste is gasified directly with heat from the partial combustion of waste under a reducing atmosphere. The newly designed gas engine has now been added to this system (see Figure 33).

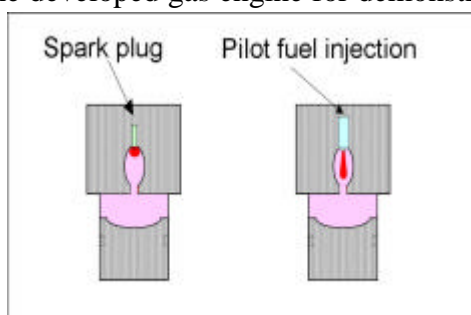


Source: NEDO Report (2003) by Sumitomo Metal

**Figure 33 Schematic representation of the waste gas conversion plant system of Sumitomo Metal**

The main disadvantage of using the gas engine with waste conversion gas is that the heat value of the gas is generally low, and fluctuates from 5 to 10 MJ/Nm<sup>3</sup> due to changes in the waste composition and amounts of waste treated. These problems were solved by developing a gas engine with a pilot oil ignition system (see Figure 34). This system is used with gas engine cylinders and can accommodate low heat value gases, such as waste conversion gas, because the ignition energy in the gas engine cylinder is 5,000 times higher than with a conventional ignition system.

The developed gas engine for demonstration run is pictured in Figure 35.



Source: NEDO Report (2003) by Sumitomo Metal

**Figure 34 Pilot fuel injection system**



Source: NEDO Report (2003) by Sumitomo Metal

**Figure 35 The developed gas engine for demonstration test combined with the waste gas conversion pilot plant at Sumitomo Metal**

The first phase of testing was concerned with adjusting the ignition timing and the supercharge pressure of the gas. For economic reasons, however, a mimic gas was used, which was a mixture of hydrogen and the exhaust gas from an ironworks.

In 2003, the gas engine was combined with Sumitomo Metal's waste conversion plant. A second phase of tests was performed using dried MSW and industrial waste. These tests showed that the gas engine could achieve the expected power efficiency for such wastes and its emissions (exhaust gas) were acceptable. The test results from the second phase of testing are given in Table 5.

**Table 5 Results of the second phase of gas engine testing**

Item	Target	Test result	Comments
Gross power efficiency	25%	26%	The target is likely to be reached.
Gas engine efficiency	36%	38%	At 7.5 MJ/Nm <sup>3</sup> of gas heat value
Dioxin content of outlet gas	<0.01 ng-TEQ/Nm <sup>3</sup>	Maximum 0.00092	Average 0.00026
NOx content of outlet gas	50 ppm	Maximum 70 ppm	DeNOx facility is necessary.
CO content of outlet gas	30 ppm	4, 400 ppm (10 ppm when a catalyst is used)	Catalyst is necessary.
Other emissions	Emission regulations	Satisfied statutory requirements	

## 4 Performance and economical analysis of total optimised system for waste gasification and power generation

The technical developments described in Sections 2 and 3 were analysed by IAE in terms of the performance and economics of a total optimised system. The analysis was based on a virtual representation of the total system and numerical simulations.

### 4.1 Performance analysis

Using the test data from the various pilot plant tests, IAE developed simulation program codes in order to undertake a total system analysis of:

- waste pyrolysis, combustion and generation with a steam turbine plant;
- waste pyrolysis, conversion and generation with gas engine plants for various pyrolysis reactor types.

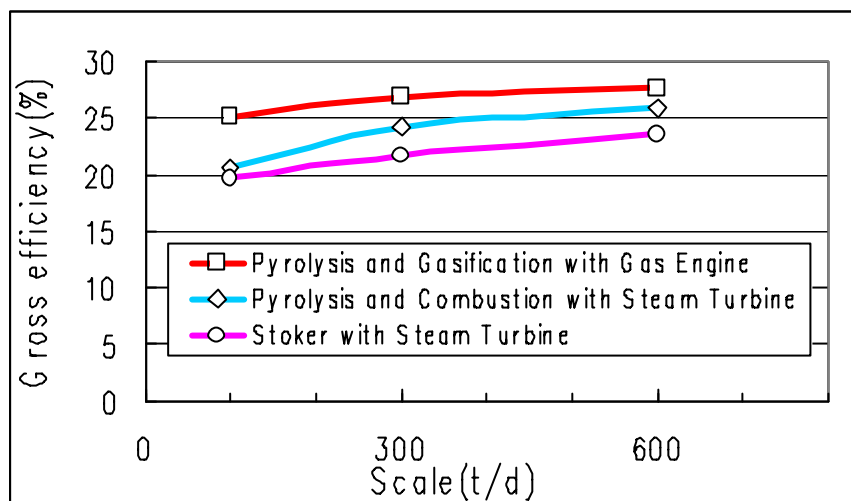
Model designs of a waste gasification plant, with both a steam turbine and a gas engine, were evaluated and compared with a state-of-art mass burn stoker boiler plant with a steam turbine. The assumptions used in the evaluation are given in Table 6.

**Table 6 Assumptions used in IAE's performance evaluation of the total system**

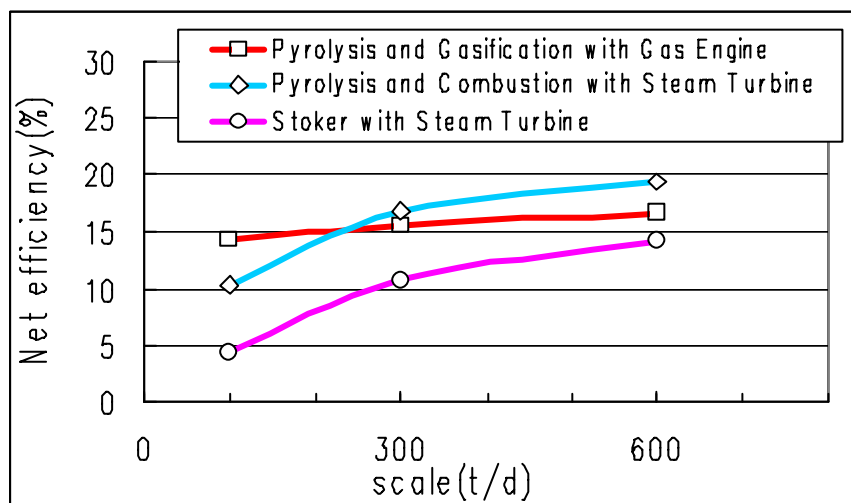
<b>Waste properties</b>	
LHV	8.8 MJ
Moisture component	42.0%
Ash component	5.5%
Combustibles component: of which	52.5%
Carbon	24.8%
Hydrogen	3.6%
Oxygen	23.2%
Nitrogen	0.4%
Sulphur	0.1%
Chlorine	0.4%
<b>Ash treatment</b>	All ash should melt to give a slag.
<b>Stack emissions</b>	
Dust emissions	<0.02 g/Nm <sup>3</sup>
Dioxins	<0.01 ng-TEQ/Nm <sup>3</sup>
NO <sub>x</sub>	<100 ppm
HCl	<30 ppm
SO <sub>x</sub>	<30 ppm

Simulation was performed for three types of system; gross and net plant efficiencies for these systems are shown in Figure 36 and Figure 37, respectively.

**Figure 36 Gross efficiency of waste-to-energy plants (IAE simulation)**



**Figure 37 Net efficiency of waste-to-energy plants (IAE simulation)**



These results revealed several things.

- Pyrolysis and gasification with a gas engine type gave the best performance of the three types in terms of gross efficiency, because this system has the smallest stack loss.
- The gas engine system has little merit at a larger scale. In terms of net efficiency, it has a performance advantage for plants with a throughput of less than 200 tons/day.
- A conventional stoker grate with a steam turbine has no performance advantage at any scale, because of the requirement under the Japanese ash treatment regulation for all new

MSW treatment plants to incorporate ash melting facilities. Stoker plants, which need additional energy for ash melting, are therefore at a disadvantage in terms of net efficiency.

- For waste-to-energy plants with a throughput of more than 1,000 tons/day, the need for reliability means that stoker-type plants and not gasification type plants should be selected. Stoker-type plants also have advantages for plants burning plastic-free residues, such as commercial biomass plants.

## 4.2 Economic analysis

The economic analysis carried out by IAE was based on data collection and the development of simulation program codes.

The analysis evaluated the economics of waste gasification plants with either a steam turbine or a gas engine, compared with a state-of-art mass burn boiler and generation plant with a steam turbine. The assumptions used in the economic analysis are given in Table 7.

**Table 7 Assumptions used in IAE's economic analysis of the total system**

<b>Construction cost</b>	Taking account of Japanese subsidy system
<b>Running costs</b>	
Power supply price to public utilities	8 JPY/kWh
Power purchase price from public utilities	1,600 JPY/(kWmonth)
Mains water	300 JPY/m <sup>3</sup>
Raw water	25 JPY/m <sup>3</sup>
Slaked lime	25 JPY/kg
Sodium hydroxide	50 JPY/kg
Urea water	60 JPY/kg
Ammonia water	55 JPY/kg
Sulphuric acid	25 JPY/kg
Heavy oil (only at start-up)	30,000 JPY/m <sup>3</sup>
Labour	8 million JPY/year (manager) 5 million JPY/year (supervisor) 3 million JPY/year (operator)
Other management fees	20% of labour costs
<b>Plant availability</b>	80%

\*108 JPY = 1 USD (22 June 2004)

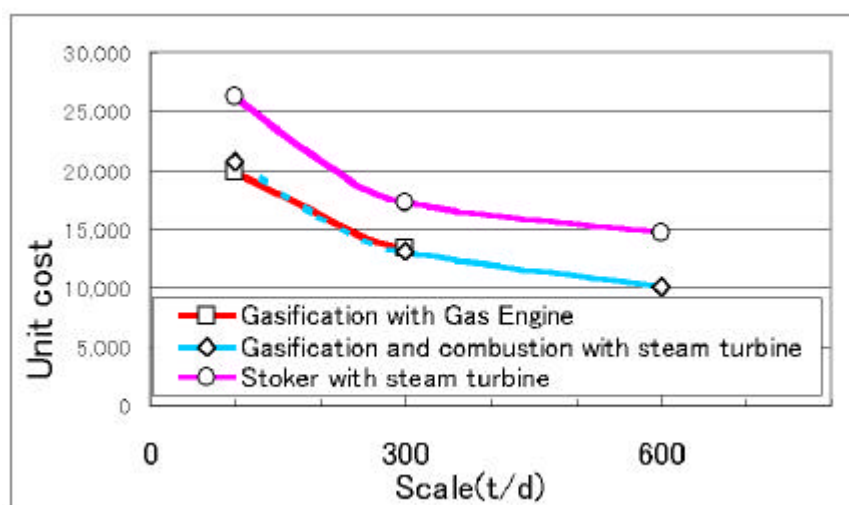
IAE carried out a feasibility study for the three types of system using unit costs defined by the following below formula:

$$UC = \frac{(CC + RC - RP)}{}$$

where:

UC	=	Unit cost (JPY/ton)
CC	=	Capital cost per year (JPY/year)
RC	=	Running cost per year (JPY/year)
RP	=	Revenue from power sales per year (JPY/year)
AW	=	Amount of waste treated per year (ton/year)

Figure 38 shows the units costs obtained for the three systems from the simulation.



**Figure 38 Unit costs of waste-to-energy plants (IAE simulation)**

The economic analysis revealed several things.

- Gasification with a gas engine has an economic advantage in plants processing less than 200 tons/day, as well as a performance advantage. This economic advantage is due to larger revenues from electricity sale than the other two types. This in turn is because the gas engine plants have a larger net efficiency at this scale of plant.
- The economic disadvantage of the stoker with steam turbine is due to the additional energy costs of the ash melting facility.
- The gas engine plant is the optimum system among the three types when the throughput is less than 200 tons/day. However, its reliability needs to be established at a commercial plant.
- Taking account of plant reliability, the gasification with a steam turbine has an advantage in having enough experience in Japan for plants of which capacities are more than 200 tons/day. In addition, at present, a state-of-art mass burn stoker boiler with a steam turbine should be selected for more than 1000 tons/day plant due to a plant reliability as well as no experience for such capacity plant.



## **5 Potential of waste gasification and ash melting technologies**

Waste gasification with a steam turbine is applicable to waste treatment facilities with a throughput of more than 200 tons/day. High-efficiency power generation using the technologies developed during the collaborative project led by NEDO is being promoted in Japan. In particular, the technologies used to increase the steam temperature and to dehydrate wet MSW are attracting considerable attention. Waste gasification and ash melting technologies with steam turbine power generation have been adapted for use in about half of new waste treatment facilities in Japan and have attracted interest from many Japanese municipalities. The reliability of such technologies has recently improved.

The second NEDO collaborative project sought to establish technologies featuring waste pyrolysis, conversion and power generation with a gas engine that were applicable to waste-to-energy facilities with a throughput of less than 200 tons/day. The main barrier to the uptake of such technologies is convincing local governments of their advantages and effectiveness for small waste treatment facilities. Their promotion is therefore essential because, unless the country's small incinerators implement waste-to-energy with ash melting, Japan is unlikely to meet its renewable energy target (including waste-to-energy) for 2010.

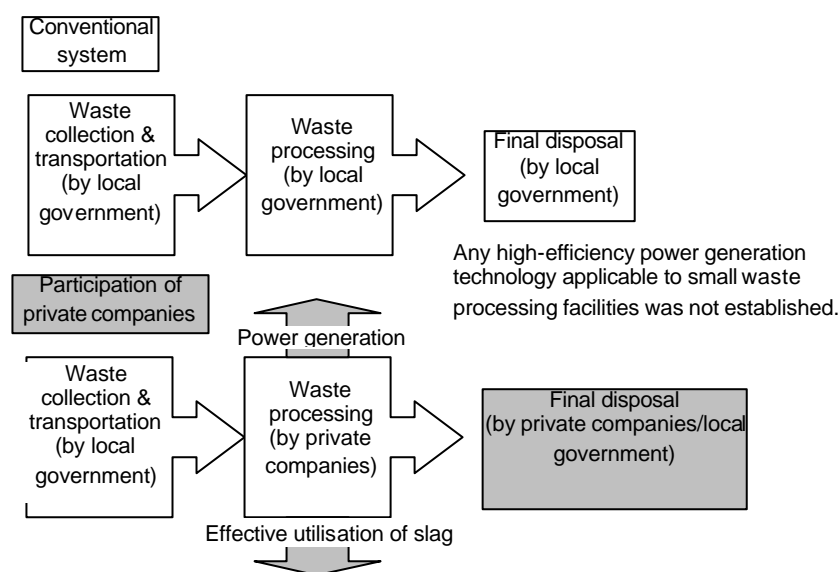
The advantage of these technologies is that they melt ash economically and enhance the efficiency of generating electricity from waste, even in small plants. The need for such technologies will increase, particularly in regions that become short of landfill capacity for waste and ash disposal and/or need to make more use of renewable energy sources to ensure the security of energy supplies.

One way of promoting these technologies is to open the way for participation by private sector companies in MSW treatment. Local governments are responsible for all waste management processes, from the collection and transportation to the final disposal of wastes, and view the introduction of waste-to-energy as just one option.

One possibility is for a scheme whereby private sector companies participate in waste treatment and disposal processes, but local governments remain responsible for the collection and transportation processes (see Figure 39). This would probably lead to incentives to create and develop the waste-to-energy sector. Utilisation of slag could also be increased to reduce landfill costs.

Private sector participation in waste-to-energy for MSW was not previously considered realistic because high-efficiency power generation technology had not been established for small waste treatment facilities. However, such schemes are expected to increase now that this development project has established the potential for high-efficiency power generation technology for all sizes of facility.

**Figure 39 Scheme for participation by the private sector in MSW management in Japan**



**Figure: 36 new scheme of private companies'**

Source: NEDO Seminar (2001) by H. Naramoto

For industrial waste, waste-to-energy technology is still at the development stage. However, the results from this project can also be applied to industrial waste. The problems are not technical, but rather centre on how to incorporate the technological developments into the existing waste treatment facilities. Most industrial waste treatment facilities in Japan are owned or operated by private sector companies, and are generally smaller than those for MSW. Under these circumstances, waste pyrolysis, conversion and generation with a gas engine is likely to be the preferred option for industrial waste treatment facilities.

## **Collaborators**

### **Development of waste pyrolysis and combustion with ash melting technologies**

- Mitsui Engineering & Shipbuilding Company Ltd (high temperature particulate removal)
- Mitsubishi Heavy Industries Ltd (char combustion furnace)
- Ebara Corporation (ceramic air heaters)
- Kawasaki Heavy Industries Ltd (lower temperature DeNOx catalyst)
- Hitachi Zosen Corporation (MSW dehydrator)
- Nippon Steel Corporation (waste plastics blowing)
- Institute of Applied Energy, Tokyo, Japan (feasibility study for total plant system).

### **Development of waste pyrolysis, conversion and generation with gas engine technologies**

- Mitsubishi Heavy Industries Ltd (pyrolysis reactor)
- NGK Insulators Ltd (reformer and ash melting reactor)
- Toshiba Corporation (air preheater)
- Sumitomo Metal Industries Ltd (gas engine)
- Institute of Applied Energy, Tokyo, Japan (feasibility study for total plant system).

## **Acknowledgements**

The authors are very grateful to those conducting the research described in this paper including Mitsui Engineering & Shipbuilding Company Ltd, Mitsubishi Heavy Industries Ltd, Ebara Corporation, Kawasaki Heavy Industries Ltd, Hitachi Zosen Corporation and Nippon Steel Corporation, NGK Insulators Ltd, Toshiba Corporation, Sumitomo Metal Industries Ltd and the Institute of Applied Energy.

In addition, the authors wish to thank Dr Asami, Mr Atoji, Dr Ogawa and Mr Ohmori for advice and assistance with data collection.

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### Note:

- (1) The sources of all figures (including pictures) in this report regarding each of technology developments are NEDO Reports described by each collaborators. These figures were provided by NEDO for use of describing this Topic 2 Report only.
- (2) All the original figures are written in Japanese. The authors translated them into English. Some figures were slightly modification by the authors for adequate description of the report.
- (3) “NEDO Report” in this report means each of the NEDO reports of “Development of waste pyrolysis and combustion with ash melting technologies” or “Development of waste pyrolysis, conversion and generation with gas engine technologies”. All of high efficiency waste power generation projects reports including the above 2 projects are released to the web site (<http://www.nedo.go.jp>) in Japanese only except for summary.