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MITSUBISHI ELECTRIC ADVANCE

Environmental Technology Edition

MITSUBISHI ELECTRIC

A Quarterly Survey of New Products, Systems, and Technology

●Vol. 87/Sep. 1999 Mitsubishi Electric **ADVANCE**

Environmental Technology Edition

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TECHNICAL REPORTS

"Advance" to Become Online Magazine

Readers are advised that this edition of Advance will be the last one to be printed as a traditional magazine. From December, Advance will continue to be available, as it is now, at the Mitsubishi Electric global homepage website (URL http://www.mitsubishielectric.com/ghp_japan/corporate_profile/advance/advance_index.html). It is hoped that the move to online format will speed publication and enable readers to print out only those articles of special interest to them.

Our cover illustration shows the symbol mark of the Mitsubishi Electric Group's environmental activities. First devised in 1993, it expresses our commitment to being an industrial group whose continued existence is justified by its contributions to a sustainable society — that is, one founded on recycling valuable resources.

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Overview

Time for a personal commitment to sustainable development

*by Ryoichi Yamamoto**

If Ernst Von Weizsächer is a realist, does that make Schmidt-Bleek an idealist? Weizsächer, Amory B. Lovins and his wife L. Hunter Lovins are co-authors of the book "Factor 4," while Schmidt-Bleek wrote "Factor 10," both of which have become best sellers around the world. Weizsächer stresses that to prevent the worldwide gap between poverty and affluence from opening up still further, we need to multiply the productivity of our energy resources immediately by a factor of four, while Schmidt-Bleek emphasizes that a fundamental solution to the world's environmental problems will require the absolute volume of the worldwide flow of materials to be halved and, if the quality of life in the OECD nations is to be maintained, the productivity of energy will have to be increased at least ten-fold by the year 2050.

However, there are those who say that with the population of the world in 2050 estimated at nine billion, it will take an improvement of a factor of 20 in energy productivity to provide for everyone. To achieve a factor of ten improvement certainly implies a factor of four improvement, so it is not really a matter of which estimate is right and which wrong. The real issue is that *any* foreseeable solution of environmental problems will require major revolutions in technology, and in social and financial systems.

I have only known the two authors for three years, but I am grateful to count them among my friends. Weizsächer is 60 years old, and Schmidt-Bleek is approaching 70, but I am overwhelmed by the enthusiasm, intellectual rigor, and intensity of their activities in the search for far-reaching and comprehensive solutions to the world's environmental problems, and by the wide circle of their supporters. Weizsächer, for instance, is never without a Lüfthansa flight schedule in his briefcase. Both of them take personally the problems of energy, the environment and poverty confronting mankind, and are utterly committed to comprehensive global solutions. "It needs to be done now and I need to do it" expresses a commitment that seems to derive from a sense of responsibility for modern culture, which owes so much to European influences. In discussions with members of the "Factor 10" club at Schmidt-Bleek's villa in Provence, in the South of France, I wondered why so few concepts or theories of how to save the world had originated in Japan. Sustainable development, eco-efficiency, environmental management, Factor 10, post-materialism, eco-design, life-cycle assessment... all of them are European proposals.

However, I certainly do not accept that the Japanese are lacking in creativity. For instance, the sophisticated culture of Japan's Edo era was by no means one of affluence, and I think we could properly stress the appeal of its non-materialistic nature to the world. Certainly, in the 21st century, one of the problems will be creating a rich post-materialistic culture.

At my first meeting with Weizsächer this year, he was saying how the productivity of energy resources in Japan was double that in Europe and America, and that this was one of the reasons he was urging ecological tax reform there. Isn't it time that the Japanese were more self-confident, and took up the challenge of sustainable development? ❏

Note: *Weizsächer is the son of a famous astrophysicist and the grandson of a President of Federal Germany. He currently heads the Wuppertal Institute for Climate, Environment and Energy. Schmidt-Bleek is an authority on environmental toxicity. After working on the OECD's regulations for toxic substances, he retired last year as deputy director of the Wuppertal Institute, and now, as the director of the Factor 10 Research Institute, he is active in eco-design consulting.*

**Dr. Ryoichi Yamamoto is a Professor at the Institute of Industrial Science & Technology, Tokyo University.*

Ecofriendly Ozone-Based Wet Processes for Electron Device Fabrication

*by Hirozoh Kanegae**

Mitsubishi Electric has developed ozone-based wet processes for fabrication of LCDs and other semiconductor devices. These low-cost and low-environmental-impact processes use tiny amounts of chemical reactants and can be conducted at room temperature. This report introduces technology for contamination-free production of high-density ozone and ozonated water, and discusses use of ozonated water as a substitute for a standard RCA cleaning process and for the removal of photoresist.

Public concern is driving manufacturers to reduce the environmental impact of their manufacturing processes. The imperative to manufacture good products at a low price is in transition to a new model of sustainable development in which consumers and manufacturers jointly participate.

Reducing the environmental impact associated with manufacturing processes is now taking importance alongside the more conventional objectives of making electronic equipment smaller, lighter and more power efficient. Novel manufacturing processes will consume smaller energy, chemical and gas supplies, reducing both cost and manufacturing wastes with small footprint installations.

This article introduces cost-effective and environmentally-friendly wet cleaning processes for semiconductor-device and LCD fabrication using ozonated water. Ozone is a strong oxidizing agent suitable for wafer cleaning and its only breakdown product is oxygen.

Ozone Gas and Ozonated Water

Ozone consists of three oxygen atoms joined by covalent bonds with a strength somewhere between single and double bonds. Its applications include disinfecting and deodorizing drinking water supplies, bleaching and removal of organics in wastewater, and surface treatment and oxidation of organic materials in industrial processes. All of these applications rely on ozone's powerful oxidation capabilities and harmless decomposition to oxygen.

Like other gases, ozone's solubility in water obeys Henry's Law. The amount of ozone that dissolves in water increases as the partial pressure of ozone rises and as the water temperature

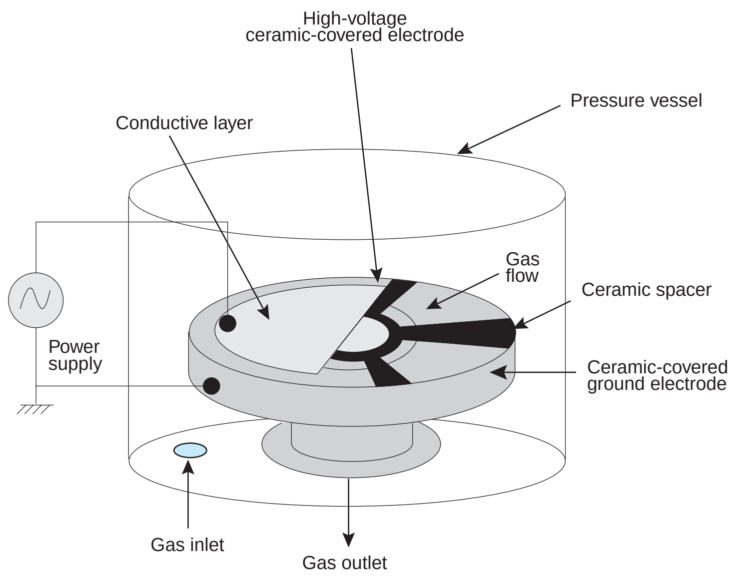

Fig. 1 General design of an ozonizer producing high-concentration contamination-free ozonated oxygen.

Hirozoh Kanegae is with the Advanced Technology R&D Center.

drops. The following rule for calculating dissolved ozone concentration is based on experimental measurements.

$Cw = 0.604(1+t/273)/(1+0.063t)\backslash Cg$ .... Eq. 1

where Cw is the dissolved ozone concentration in mg/l, Cg is the atmospheric ozone concentration in mg/l, and t is the water temperature in degrees Centigrade.

Ozone has three main mechanisms of chemical activity. First, it attacks the unsaturated bonds in double bonded and aromatic hydrocarbon chains by the well known Criegee mechanism yielding ketones, carboxylic acid and carbon dioxide. Second, it reacts with water to form the hydroperoxy radical (HO_2·) and hydrogen peroxide (H_2O_2) which attack saturated hydrocarbon chains. Third, it reacts with inorganic materials based on the difference in oxidation-reduction potential and oxidizes all metals except gold and platinum.

Controlling Contaminants

To replace the highly evolved manufacturing processes currently used for semiconductor production, ozone based processes will have to achieve comparable tact (or process "step") times and control contaminants that would adversely affect yields. High concentrations are required, and ozone and ozonated water generators must achieve the cleanliness required by today's high scales of integration.

Fig. 1 shows the basics of a system that produces clean, high-concentration ozone. A narrow discharge gap is formed by a conductive layer on the bottom surface of disc-shaped ceramic substrate and a ceramic-coated ground electrode separated by a ceramic spacer. The electrodes are housed in a pressure vessel. Oxygen gas supplied to the vessel passes through the discharge gap and exits through a port in the center of the ground electrode as ozonated oxygen[1],[2]. The discharge gap is extremely narrow to prevent temperature rise of gas in the gap and to control the number of low-energy electrons that could cause the ozone to break down. These features enables the system to achieve ozone concentrations over 230g/Nm^3 at a gas flow rate of 2l/min (Fig. 2).

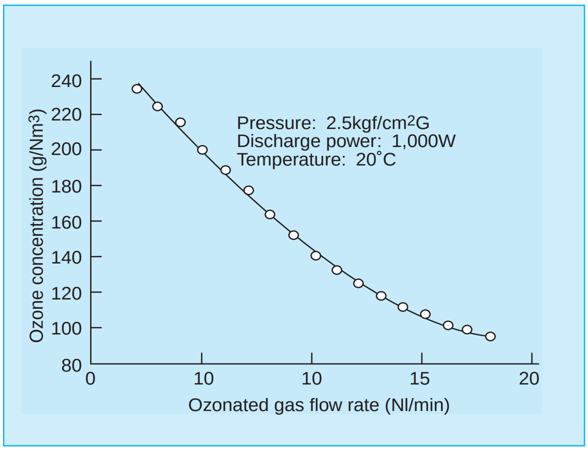

Fig. 2 Effect of gas flow rate on ozone concentration.

In addition to high concentration, ozone produced for semiconductor manufacturing must be free of metallic contaminants. This is achieved by ensuring that the gas contacts only ceramic surfaces. Metallic contamination of the ozonated water was measured at below the parts per trillion detection levels of microwave induced plasma mass spectroscopy and flameless atomic absorption spectroscopy (Table 1).

Wafers immersed in ozonated water were then tested for metallic contamination by total reflection X-ray fluorescence spectroscopy and typical contaminants including Ca, Cr, Mn, Fe, Ni and Cu were below the detection threshold of 1×10^{10} atoms/cm^2.

A particle counter at the ozone generator's outlet detected no particles over 0.27µm in diameter[3].

Table 1 Metallic Contaminants in Ozonated Water

Element	Na, K, Ca, Fe, Zn, Al	Mg, Ni, Cu	Cr, Mn
Concentration (DI water)	<50ppt	<20ppt	<10ppt
Conc. (ozonated DI water)	<50ppt	<20ppt	<10ppt
Detection threshold	50ppt	20ppt	10ppt

Ozonated Water Cleaning Technology

Control of particles and other contaminants is essential to maintain high yields in production of high-density memory devices. At present, this is accomplished using a series of chemical baths known as the RCA washing method[4]. Initially, a sulfuric acid and hydrogen peroxide bath (SPM) at 120~150°C removes organics and some metallics. Second, a bath of dilute hydrofluoric acid (DHF) at room temperature removes the oxide layer and incorporated metallic contaminants. Third, an ammonium hydroxide and hydrogen peroxide bath (APM) at 80~90°C removes particles. Fourth, an 80~90°C bath of hydrochloric acid and hydrogen peroxide (HPM) removes metals. Finally, dilute hydrofluoric acid is used to remove metallics from the oxide layer formed in the preceding step. Seven rinsings in deionized water follow for a total of 12 process steps (Table 2). LCD manufacture employs a similar process with fewer steps, but the large substrate size means larger baths that consume more chemical supplies.

Replacing these complicated cleaning procedures with ozonated water cleaning dramatically reduces use of chemical supplies, saving the cost of the chemicals and waste processing. Ozone processing also eliminates processing at elevated temperatures, avoiding the associated venting of vapors to the atmosphere. Reduced rinsing saves dionized water.

Ozone can oxidize organic residues from photoresist processes. Spin washing the wafers with ultrasonically activated ozonated water achieves cleaning performance equivalent to a sulfuric acid and hydrogen peroxide bath[5].

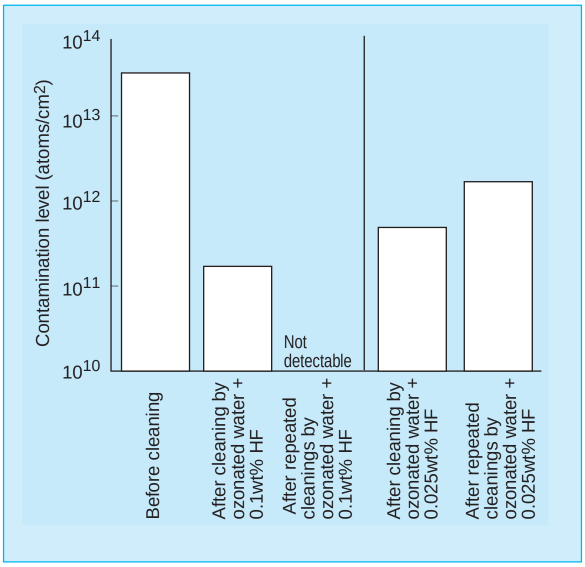

Fig. 3 Copper contamination on wafers before and after cleaning. The ozone concentration is 12ppm.

Ozonated water alone does not remove metallic contaminants incorporated into the oxide layer, but is effective when supplemented by a 0.1% hydrofluoric acid solution, a combination that has been thoroughly investigated[6],[7]. Fig. 3 shows that ozonated water bath with hydrofluoric acid reduces copper contamination with performance comparable to a conventional hydrochloric acid and hydrogen peroxide bath. The acid exposes metallic contaminants embedded in the oxide layer, so that an oxidation reaction can proceed. This forms metal ions that are drawn into solution. This constitutes a dramatic reduction in chemical usage.

Table 2 A Comparison of RCA and Ozonated Cleaning Systems

Method \ Target		Organic photoresist residue	Particles	Metals	Native oxides
RCA cleaning	Cleaning agent	SPM	APM	HPM	DHF
	Mechanism	Oxidative decomposition	Electrical repulsion	Dissolution	Etching
Ozonated water cleaning	Cleaning agent	Ozonated water			
	Mechanism	Oxidative decomposition	Dissolution		
	Acceleration method	Ultrasonic power	pH control and ultrasonic power		Add a little HF

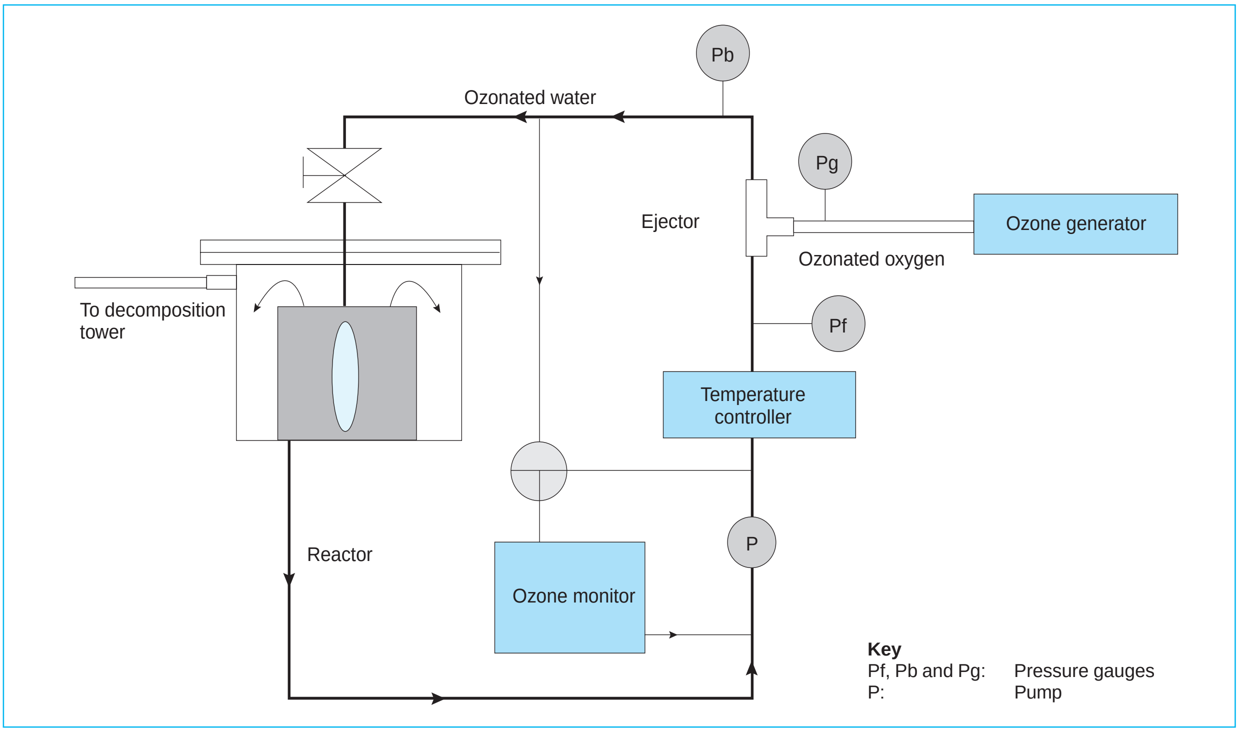

Fig. 4 Resist removal apparatus with ozone ejector

Use of ozonated water for particle removal has been investigated[7],[8]. The ammonium hydroxide and hydrogen peroxide bath normally used has a high pH so that particles receive a negative charge repelling them away from the negatively charged wafer. Since ozone water solutions are either neutral or mildly acidic, ozonated water processes will require activation by pH modifiers or ultrasonic energy. Replacing the ammonium-hydroxide based process eliminates a major source of ammonia contamination, increasing yields and reducing clean air consumption.

Ozonated Water for Photoresist Removal

Photoresists can be removed by oxygen plasma ashing (a dry process), by organic solvents, or in a sulfuric acid and hydrogen peroxide bath. For processing LCD panels, a mixture of dimethyl sulfoxide (DMSO) and monoethanol amine (MEA) is generally used.

Both the solvent and sulfuric acid process are performed at elevated temperature and vent fumes. In the widely used sulfuric acid peroxide process, Caro's acid (H_2SO_5) strips the resist, which oxidizes as soon as it is free. From an environmental impact perspective, trapping the fumes requires special equipment and the bath must be periodically replaced following depletion of the hydrogen peroxide.

An ozone-and-water method would not require the high temperatures or fume traps of the sulfuric acid method, reducing air costs and saving on dionized water—a much smaller environmental impact.

When an ozone concentration of 150~250g/Nm^3 and ozonated water flow of 4.0 *l*/min is used in the ejector-type resist stripping apparatus of Fig. 4, Fig. 5 shows the stripping performance for positive resist. The stripping rate is proportional to the water's ozone concentration and increases with temperature.

Fig. 6 shows the normalized resist removal rate as a function of temperature. R is inversely

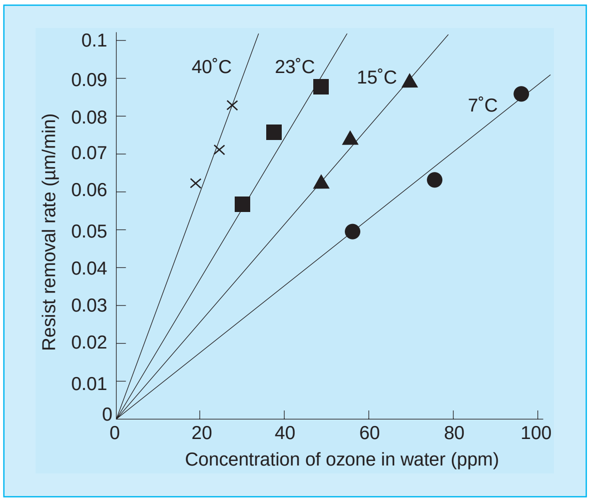

Fig. 5 Effect of ozone concentration on resist removal rate.

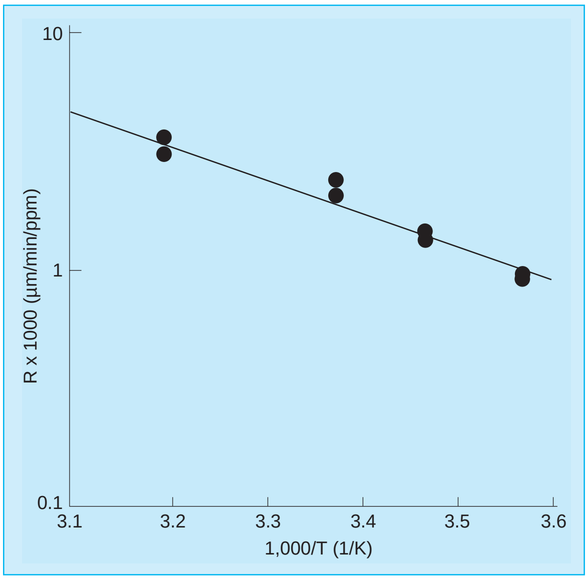

Fig. 6 Effect of water temperature on normalized resist removal rate.

proportional to T, expressed according to Arrehenius' equation:

$R = R_o exp(-E/kT)$ Eq.2

where R_o is the frequency factor, k is Boltzman's Constant, T is the water temperature (K) and E is the activation energy.

The activation energy calculated from Fig. 6 and Eq. 2 is 0.29eV, substantially smaller than the 4~5eV activation energy needed for carbon-to-carbon single and double bonds or carbon-to-oxygen single bonds, suggesting that one or more intermediate steps are involved[9].

The rate of reaction increases with temperature, but the dissolved ozone capacity reduces with temperature according to Eq. 1. For maximum resist removal speed, the processing temperature should be set to a level that matches the activation energy requirements of the resist. The type of resist, degree of baking, and the presence of ion implantation all affect activation energy. A key issue in ozone-based resist removal systems is achieving satisfactory removal speed.

Chemical-free, energy-saving room-temperature ozone-based processes promise to reduce the cost and environmental impact of semiconductor and LCD manufacture. Development of an efficient silent discharge ozone generator capable of supplying a high concentration of clean ozonated oxygen and a clean ozonated water generator promises to revolutionize semiconductor wafer and LCD cleaning and resist removal. ❑

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A Recycling Plant for Home Electric Appliances

*by Eiichi Hirasawa**

Basic Plant Design

The purpose of this project was to develop safe and efficient methods to recycle post-use home electric appliances, achieving a high rate of recovery of materials that can be reused as well as those that could have significant environmental impact. A key feature of this system is use of a primary disassembly process to remove major components prior to a chip-and-sort process for handling the remainder. Automation and mechanization have been introduced to ensure safe handling of large and heavy products. The disassembly line has the following key feature: Product model numbers are used to reference a database of disassembly information. The first time a particular product is disassembled, data is acquired at teaching stations and the database makes this information immediately available to processing stations throughout the plant. Details are recorded when disassembly problems arise, and the next time the same product model is received, it is routed to a teaching station and the database is updated with more accurate information. Table 1 lists the basic specifications of the recycling plant and Fig. 1 illustrates the concepts used to guide the design of the primary disassembly process.

Unloading

Table 2 lists specifications of a conveyer system that transports work from the truck bed to the sorting platform inside the plant building. Table 3 describes a second conveyer that uses ceiling-mounted rails for sorting and transporting work. A hoist and clamp fittings hold the work were specially developed for the application.

Table 2 Time and Capacity Specifications of the Unloading Unit

Hoist capacity	100kg
Max. turning radius	2,928mm
Hoist travel	2,756mm
Equipment height	3,331mm
Hoist speeds	2m/min, 9m/min
Operation times	
Arm movement	20s
Tool attachment	10s
Transport into plant	25s
Tool removal	5s
Total operation time	60s

Preprocessing Line

The preprocessing line prepares the appliances for transport by removing or modifying parts that could interfere with the conveyor. All AC cords, hoses, etc. are removed. Refrigerator doors, hinges, glass shelves, water collectors and metal handles are removed. Refrigerant gas is recovered from air-conditioner indoor units, while the connection pipes of the outdoor units are bent close to the body. The glass covers are removed from TVs. Washing-machine motor capacitors are removed.

Table 1 Specifications of the Recycling Plant

Appliance	External dimensions	Weight	Processing time	Components removed in primary disassembly
TVs	350 x 300 x 360mm min., 900 x 700 x 610mm max.	70kg max.	35 units/h (1.7 min/unit)	CRT (including band and electron gun), housing, deflection yoke, PCBs
Refrigerators	400 x 480 x 450mm min., 950 x 1,950 x 600mm. max.	100kg max.	25 units/h (2.4 min/unit)	Compressor, housing, CFC12, R502
Washing machines	520 x 394 x 780mm min., 860 x 660 x 1,030mm max.	60kg	27 units/h (2.2 min/unit)	Motor, plastic housing
Air conditioners				
Outdoor units	540 x 200 x 420mm min., 870 x 470 x 785mm max.	72kg	17 units/h (3.5 min/unit)	Motor, CFCs
Indoor units	698 x 109 x 235mm min., 1,200 x 294 x 450mm max.	32kg	17 units/h (3.5 min/unit)	Motor, fan, heat exchanger

**Eiichi Hirasawa is with the Home Appliances Recycling Business Development Office.*

Sorting Line

Fig. 2 shows the configuration of the sorting line. Four unloading stations allow work to be received from up to four trucks at a time. The product is identified and also whether or not the line can handle it is evaluated on the round conveyor. This allows processing tasks to be performed at a single location. The round conveyor sorts and distributes products to the appropriate processing lines, and has the additional ability to serve as a buffer in the case that one of the lines is delayed and work has backed up. A return conveyor allows lines to return pallets awaiting service to the round conveyor.

Product Recognition System

Installed on the round conveyor, this labor-saving system identifies the model number by measuring appliance size and shape and using image recognition technology to read the printed model number.

Table 3 Time and Capacity Specifications of the Sorting Conveyor

Hoist capacity	160kg
Hoist travel	8.9m
Hoist speeds	3.5m/min, 14m/min
Conveyer travel	40.2m
Operation times	
Initial movement	20s
Tool attachment	10s
Transport to round conveyer	24s
Tool removal	5s
Total operation time	59s

Appliance dimensions are measured by three cameras, two facing the front and one facing the top. Images are processed by a personal computer. Measurements were correct 90% of the time in tests of a wide variety of appliances.

The model number label is read by a separate

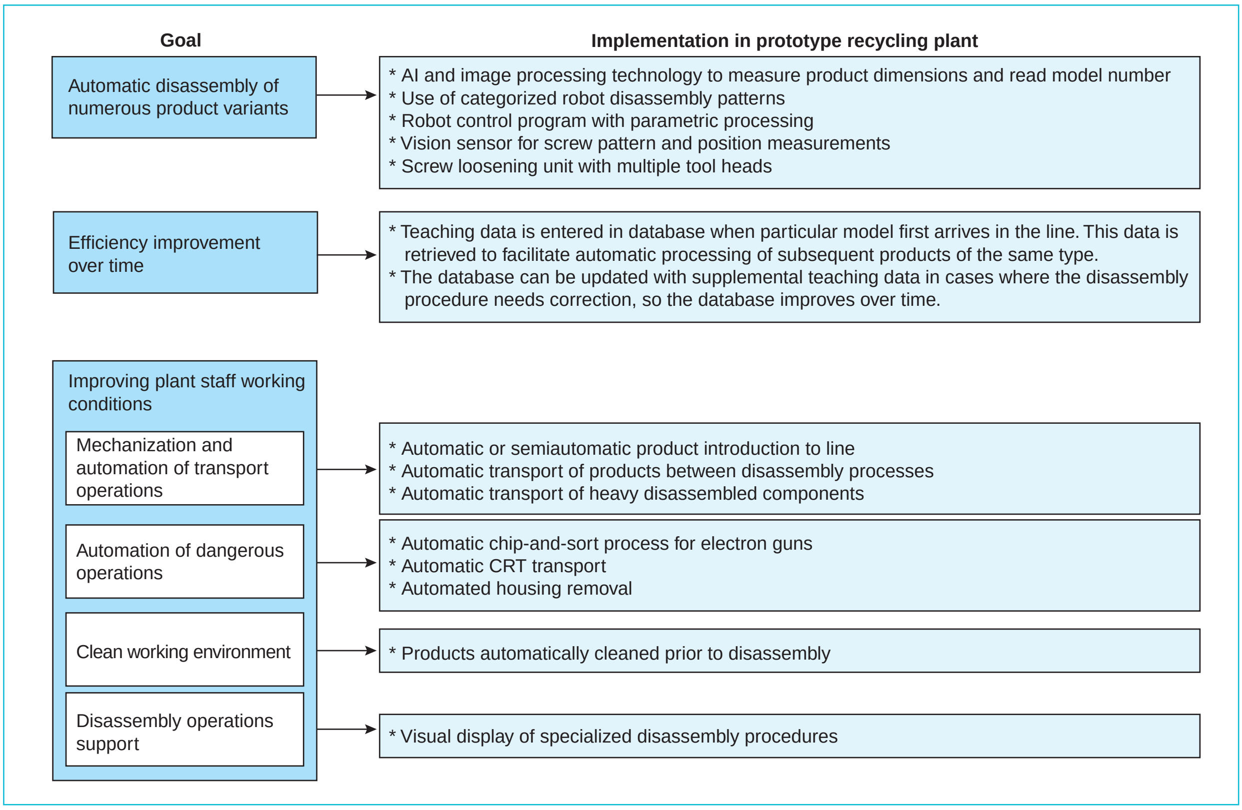

Fig. 1 Primary disassembly concepts.

Fig. 2 A view of the sorting line.

system consisting of a personal computer and five cameras: two facing the appliance front, two facing the rear and one facing the right side.

Primary Disassembly Line for TVs

Fig. 3 illustrates a primary disassembly line for TVs. The TV is clamped at four corners. The pallet has number flags identifying the pallet and the appliance it is carrying, and flags for managing the pallet's flow through the various processing stations.

Points on the TV's rear housing need to be identified to guide the subsequent cutting process. The teaching process used to locate these points only needs to be conducted once for each product model. The longer the line runs, the smaller the proportion of TVs requiring teaching. Fig. 4 shows the change over time in the number of teaching operations conducted during line testing.

The teaching data provides work coordinates and cutting-pattern data that guide operation of a six-axis robot with a saw head. The saw cuts the rear panel free, allowing its removal.

Personnel at manual work stations remove components not amenable to automated handling. Control screens allow easy control of cut height, depth and other cutting parameters.

Teaching is used to identify the location of the electron gun for crushing and removal, and to determine the location and type of the screws that attach the CRT to the chassis. Each TV

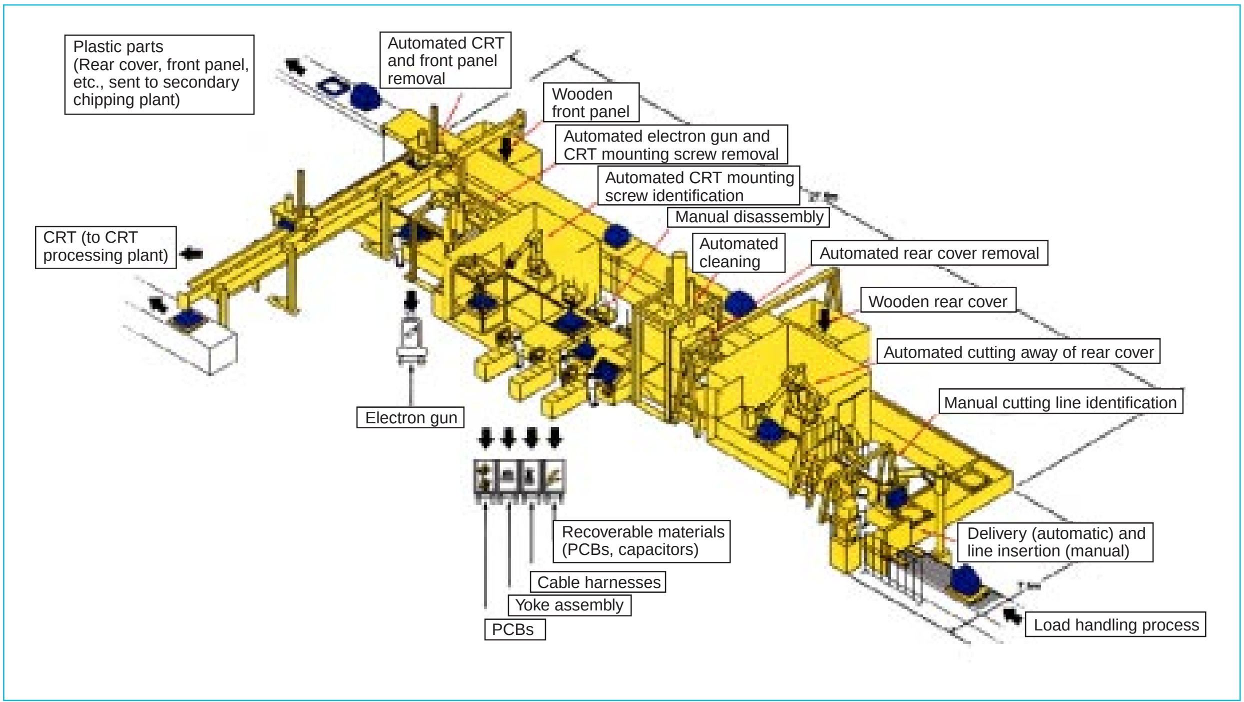

Fig. 3 The TV primary disassembly line.

must be measured individually to accommodate variations in screw position among products with identical model numbers.

The electron gun is removed by crushing it and vacuuming up the fragments. The crusher is inserted into the gun, and delivers shocks to the gun, bending and breaking it. The crushing and vacuum work together to capture fragments of the gun and surrounding glass. The CRT mounting screws are loosened, the CRT is held and lifted out of the chassis by a suction head, then is sent to a secondary processing plant. The remainder of the front panel is removed and sorted based on panel materials.

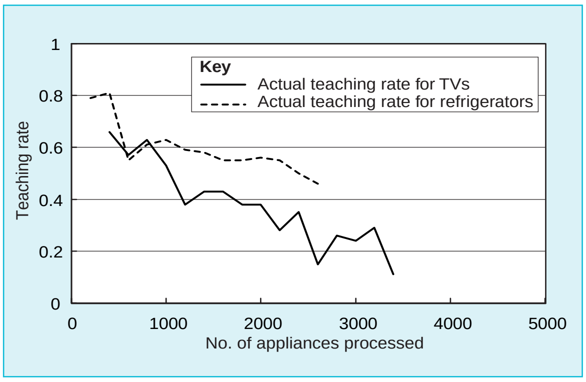

Fig. 4 Cumulative effects of teaching.

Primary Disassembly Line for Refrigerators

An incoming refrigerator and its pallet are turned onto their side and the refrigerator alone is carried into the line by a special conveyor with a tilt mechanism. The pallets are sent back to the sorting line. The location of the individual refrigerators on the line is electronically tracked.

Coordinates needed to guide a saw for cutting the compressor mounting plate are performed at a teaching station that takes measurements in three dimensions.

CFC refrigerant gas and lubricating oil are extracted together from the refrigerator's compressor. Each model requires a slightly different procedure. Three extraction stations make it possible for this relatively lengthy process to

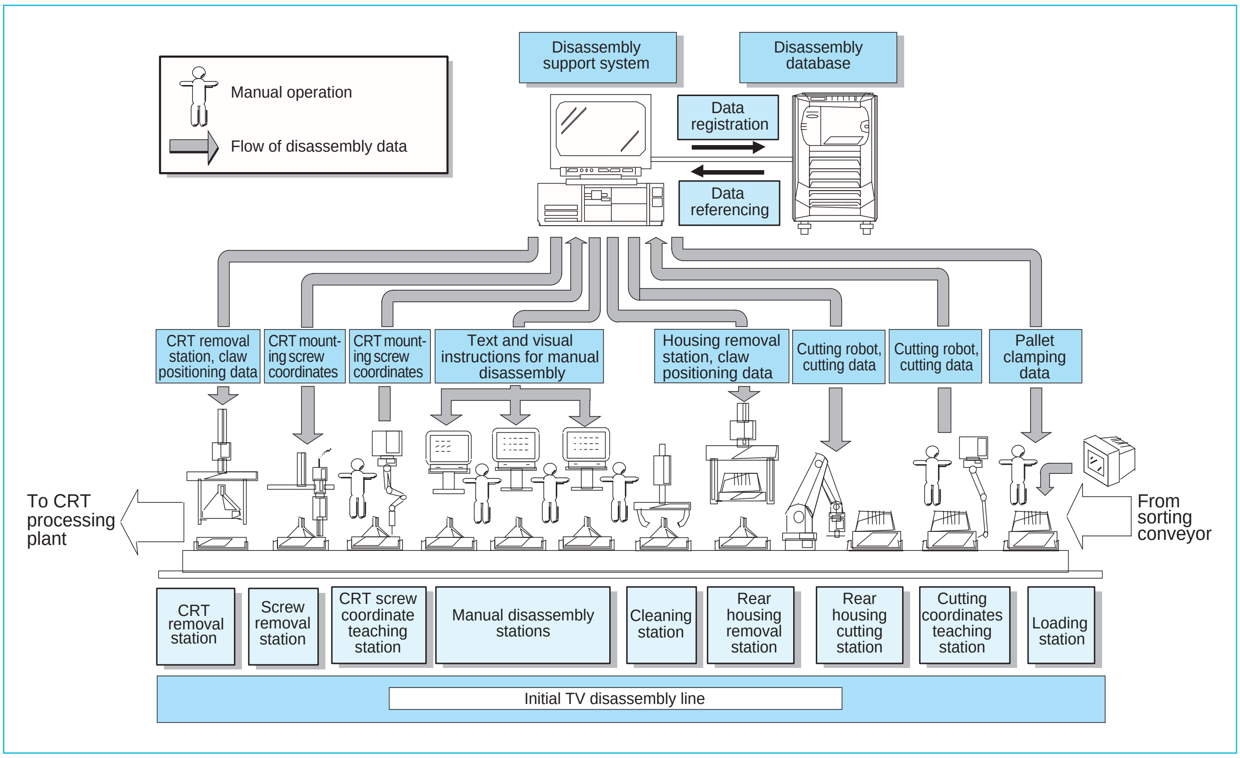

Fig. 5 Functions of the disassembly support system.

keep pace with the line. The extraction unit is semiautomatic. The operator places the head of the extraction unit at the lowest point of the cylindrical part of the compressor and drills a hole from which all contents in the refrigerant circuit are extracted. Heating and agitation are then used to separate the CFCs from the oil.

At the compressor removal station an automatically controlled cutting robot uses coordinates from the database to cut the compressor free from the chassis and then uses a hand to push the compressor down and out.

Additional Information Technologies

The disassembly support system automatically issues disassembly instructions for TVs, refrigerators, washing machines, and air conditioner indoor and outdoor units. Fig. 5 summarizes its functions.

The transport support system provides a video monitor to assist workers loading appliances onto the sorting line.

The materials-balance management system computes the relative weights of the post-use appliances going in versus the separated materials coming out of the chipper during the test operating period. Statistics are collected on product disassembly for various weight classifications. The weight classifications correlate with changing proportions of the product's constituent materials, and allow weight of the materials to be calculated from the weight of the product. The weight of materials recovered from secondary disassembly processes is also factored in.

The author would like to express his thanks to the Association for Electric Home Appliances, the Project for the Development of an Integrated Treatment and Recycling System for Post-Use Electric Home Appliances, and the companies that participated in the project. ❑

An Ecological Design Support Tool for Recyclability

*by Takao Bamba and Niall Murtagh**

The manufacturing industry must embrace global environmental issues if it is to remain vital. One avenue towards addressing these issues is design for environment (DFE), a design philosophy that considers the energy consumed in the production and use of manufactured goods and facilitates recycling of products at the end of their useful lives. This article reports on a product design support tool newly developed to evaluate product recyclability.

Design for Environment Support Tools

In addition to meeting conventional design criteria, products designed for minimal environmental impact should use recyclable materials, avoid harmful materials and minimize energy requirements during manufacture and use. Product design under this philosophy considers the cost of product recycling and disposal alongside manufacturing cost. The technology is capable of lowering the product's environmental impact as well as the cost over the entire product life cycle. Fig. 1 illustrates the basic concept of DFE.

DFE tools provide software support for developing products satisfying these criteria. These tools evaluate the environmental impact of a product's constituent materials and operation and the product's recyclability. Life cycle assessment (LCA) tools have been developed for evaluating the environmental effects of the phases of materials production, processing and product use, but do not cater for detailed evaluation of product disposal. The design support system described here relates product construction to recyclability. A complete DFE system will subsequently be achieved by integrating the system with conventional LCA tools.

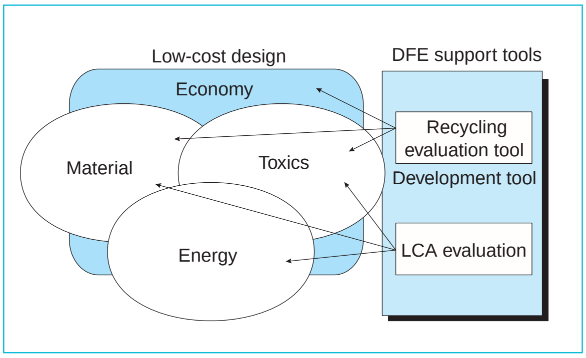

Fig. 1 The concept of design for environment.

Evaluating Recyclability

Current facilities for recycling electrical products use crushers and shredders to reduce old products to fragments which are then separated and recycled. While this approach minimizes processing costs, it is difficult to separate the materials effectively and offers limited possibilities for future improvements in the proportion of materials recycling. We therefore evaluate recyclability assuming a two-step recycling process in which certain components are removed in the first step, and the remainder of the product is then shredded and recycled conventionally (Fig. 2). From our survey of recycling technologies, we believe this approach will be adopted to varying degrees by manufacturers without substantial qualitative differences.

Four key components of recyclability were studied:

EASE OF COMPONENT REMOVAL. Primary dissassembly is the term used to describe the removal of certain components in the initial phase of recycling. These components are selected for their reusability, high recycling ease or value, for toxic materials content requiring separate disposal, or for the difficulty involved in crushing and shredding them. Recyclable materials are reused as materials of the same or lower grade. Reusable components are kept intact as far as possible. The ease of removal of these components is an important factor in recyclability.

RECYCLE RATE. This index describes the proportion of valuable materials such as iron, copper or aluminum that can be recovered, whether from individually removed assemblies, reused components, or shredded and separated materials.

RECYCLING COST. This figure includes the labor costs for primary dissassembly and the cost of processing toxic materials and residues from the crushing process offset by the sale value of the recovered materials.

**Takao Bamba and Niall Murtagh are with the Industrial Electronics & Systems Laboratory.*

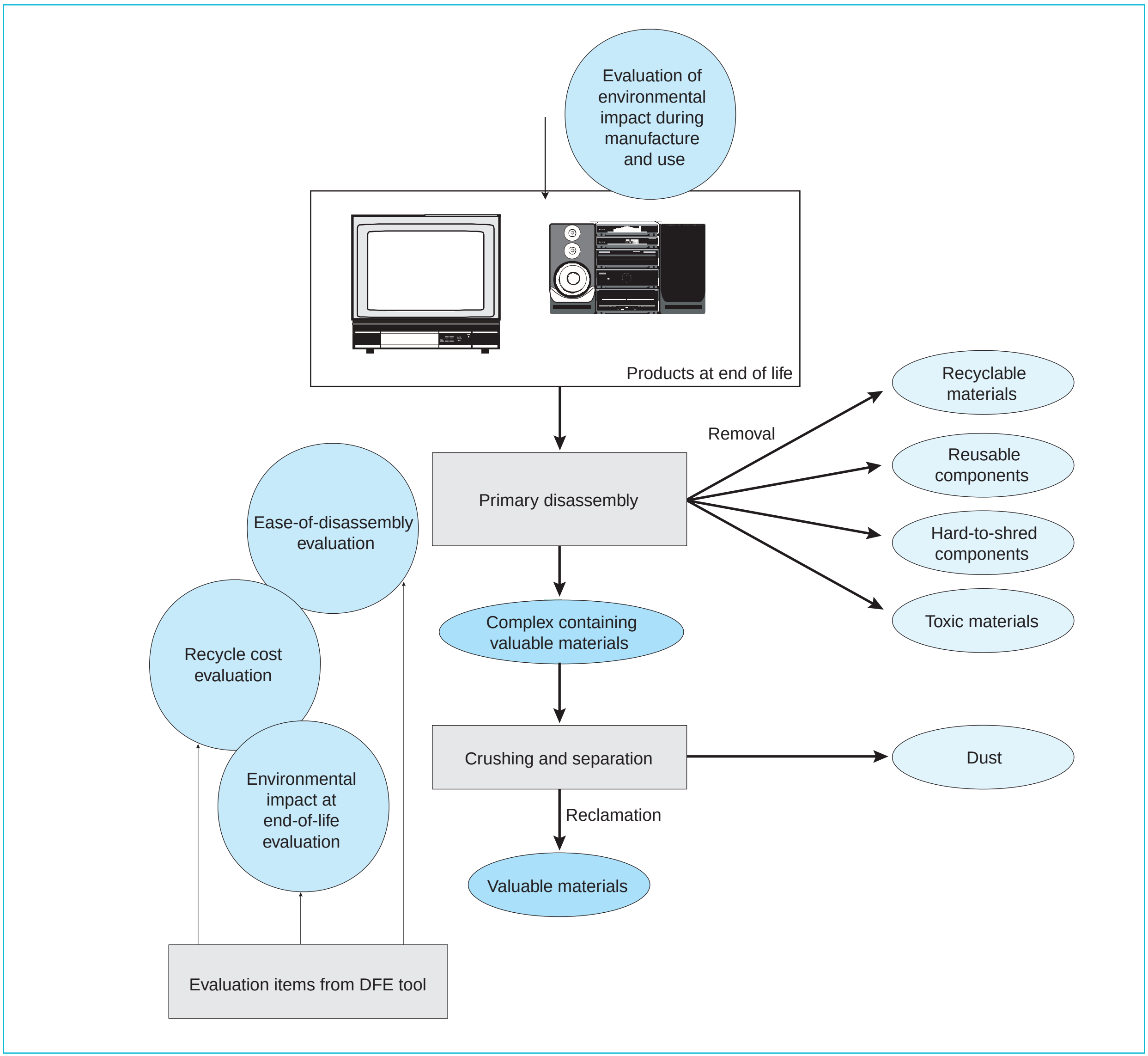

Fig. 2 Recycling process and DFE evaluation.

ENVIRONMENTAL IMPACT OF MATERIAL USAGE. This index reflects the overall environmental impact taking into account the anticipated processing method. The recycle rate and the residue processing method (landfill or incineration) affect the environmental impact. The design support tool reported here evaluates these factors during product design to facilitate product design and improvement.

System Concepts of Development Tools

Fig. 3 shows the configuration of the support tool. Two alternative input systems are being developed. In the first, the designer or product evaluator specifies components and defines disassembly procedures to be used in the evaluation. In the second system, product data files created by a 3D CAD system are processed for product construction and component informa-

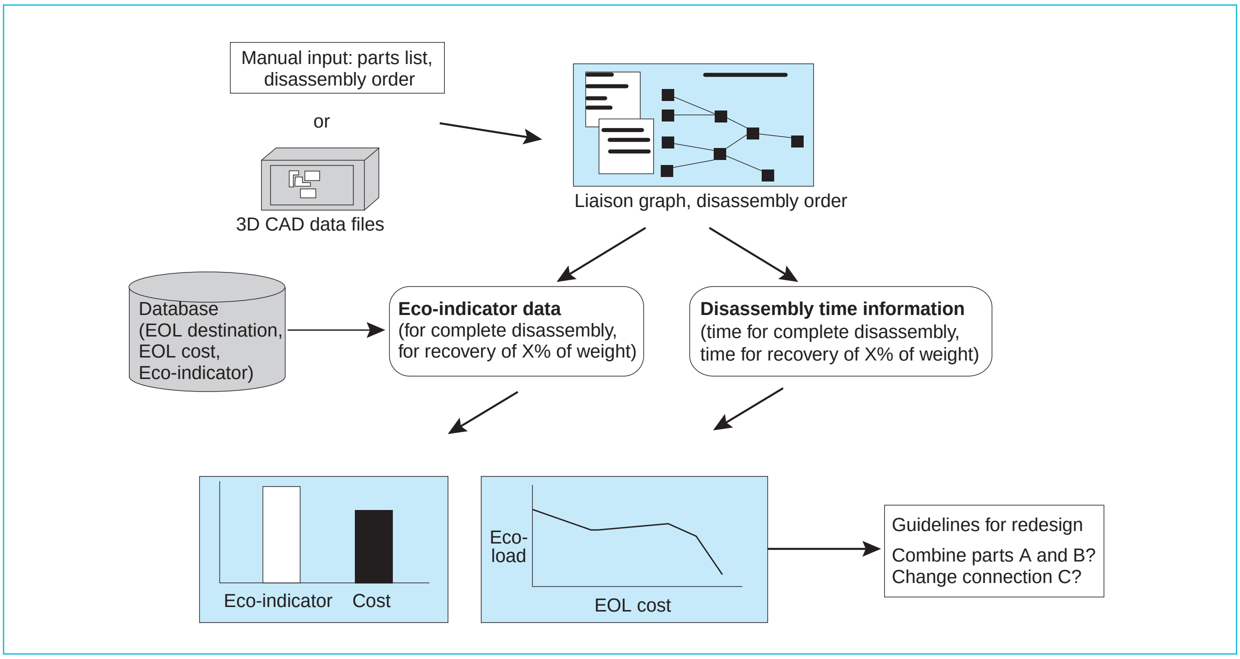

Fig. 3 System configuration.

tion, and disassembly procedures are generated automatically.

Component attributes in the system include component name, weight, external dimensions, material, method of disposal, environmental impact index (eco-indicator) and cost of disposal.

Manual input requires that the user enter the product name, weight, dimensions and material and specify the method of disposal. Current options include disassembly and removal of all toxic materials and/or reusable components, and disassembly to achieve a specified recycle rate by weight. These options help determine the depth of the primary dissassembly, that is how many components are removed before the product is crushed and shredded.

The above information is then used to compute the disassembly time, component environmental impact and recycling cost. These compu- tations utilize various databases: a list of the various materials that will be disposed of by recycling, landfill and incineration; an index of environmental impact for toxic materials, recyclable materials and incinerated materials; and a recycling cost database listing the value of reclaimable materials and costs of specialized processing.

The disassembly time is estimated on the basis of manual disassembly tests and can be determined more accurately if the user supplements disassembly procedures with data describing tools required and ease of access.

Environmental impact is evaluated using comprehensive evaluation indices developed in Europe. These indices describe the impact of each material on global warming, ozone depletion, smog, acid rain, eutrophication, air and water pollution as well as carcinogenic effects.

Fig. 4 shows a manual input screen for the system. Component name, weight, size, connection details and ease of disassembly can be readily entered. Manual input of the majority of these items can be eliminated using the output from 3D CAD data files.

The recycling cost and environmental impact (eco-indicator) indices can be determined using manually entered data and the system's internal databases. Figs. 5 and 6 show typical evaluation results.

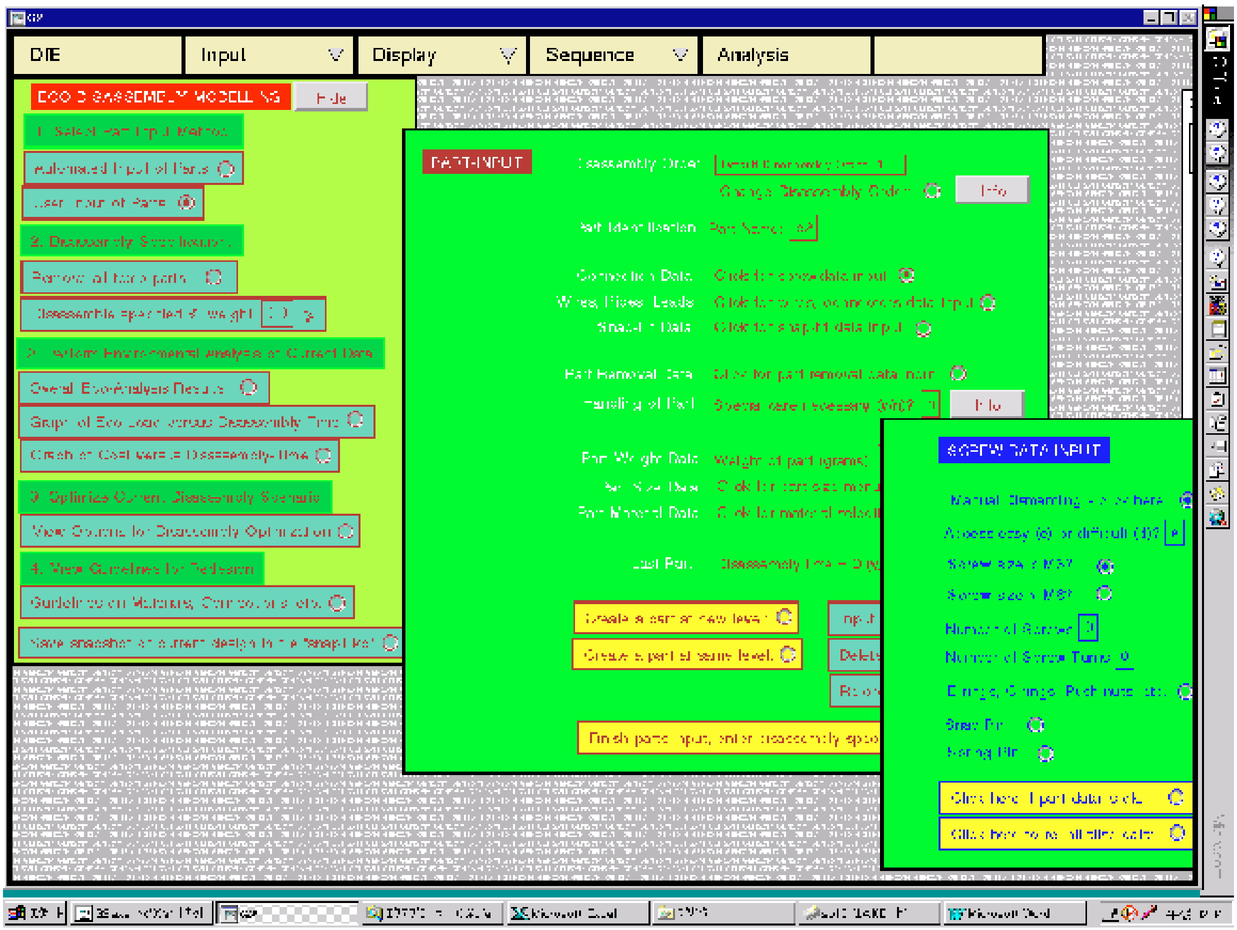

Fig. 4 Input screen.

The graphs in Fig. 5 show the relationship between disassembly time, environmental impact and recycling cost, which can be used to determine the effect of disassembly depth on environmental impact and recycling cost. Recycling cost is defined as labor costs of primary disassembly and the disposal costs of toxic and unusable materials offset by the value of reusable components and materials.

Fig. 6 shows totals for environmental impact index and disassembly time, displayed numerically and as bar graphs. Toxic materials data, disassembly procedure data and estimated recycle rate are also listed along with general redesign guidelines.

When carrying out the general design of a product, a recyclability evaluation can be conducted using manual data entry. Later, during the de-

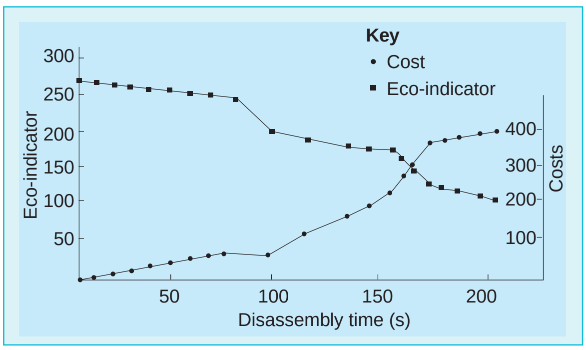

Fig. 5 Evaluation output graph.

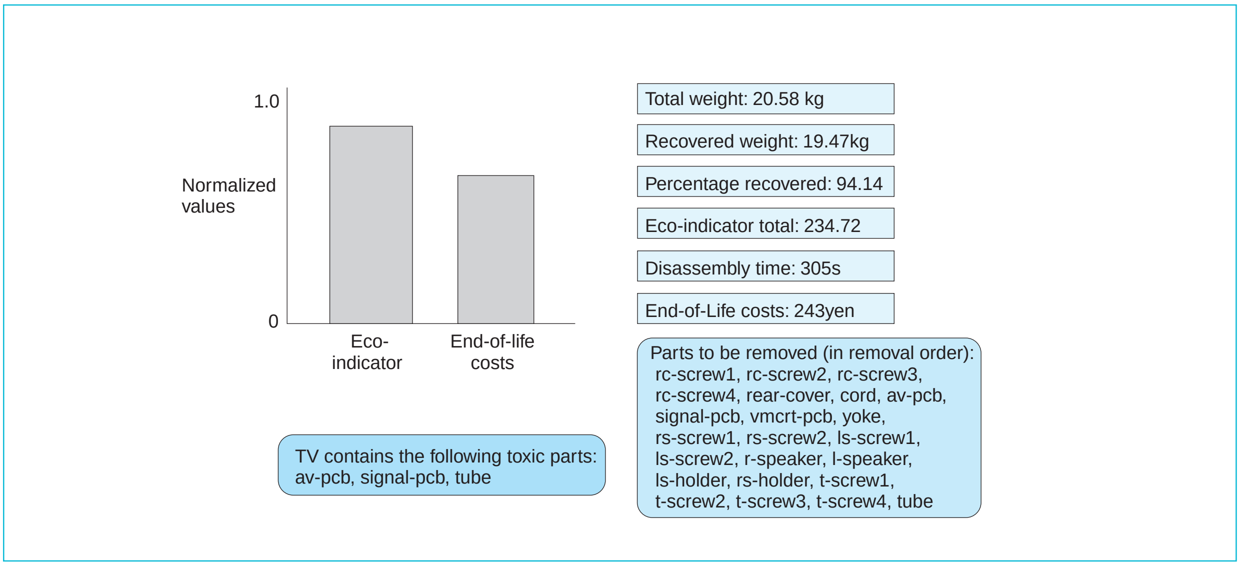

Fig. 6 Output information.

tailed design phase, more refined evaluations can be conducted based on information in 3D CAD data. We have developed software for extracting component information from 3D CAD model files and for generating information on the order of dissassembly. The 3D CAD system used to generate the model file was a commercial software package.

Applications and Discussion

The design support tool was tested in the design of consumer air conditioners. Fig. 7 shows predicted and measured values for disassembly times, a single parameter selected for ease of quantitative comparison. The vertical axis shows the removal time for various components listed along the horizontal axis. The calculated and actual removal times match closely, affirming the model's efficacy.

Issues to resolve in further development of the system include implementing an indigenous database of environmental impact indices for various materials and expanding the interface with CAD data. Fine-grained measurement of environment impact will become possible when

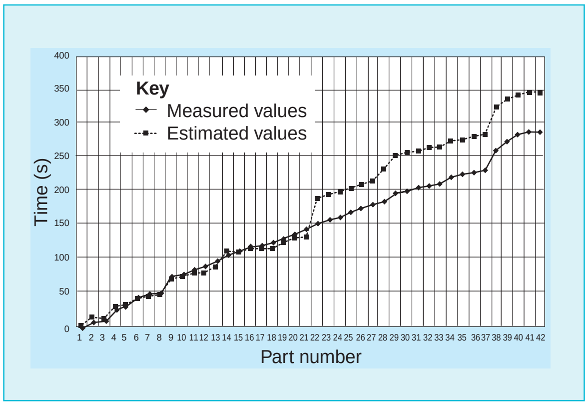

Fig. 7 Disassembly time, measured and estimated values.

the European environmental indices used in the model are supplemented by a Japanese standard database. The CAD data interface needs further development to handle the complexities of component shape information. Future work will improve the system's functions and a wider range of product applications will be considered. ❑

This research was partly carried out within the IMS/Gnosis project.

Ecomaterials

by Fumiaki Baba*

The production, use and disposal of electrical appliances and electronic equipment have substantial environmental impact because of the large volumes in which these products are manufactured. The use of ecomaterials can help to lower the environmental impact of products over all phases of the product life cycle. The design criteria for ecomaterials include compatibility with humans and the environment in addition to the traditional physical, mechanical and chemical considerations.

Ecomaterials

The production of large quantities of electrical and electronic products has had substantial environmental consequences that undermine the benefits these products confer on society. A systematic approach to lowering this environmental impact focuses on each phase of the product life cycle.

Materials used in manufacturing are first extracted from the environment, manufactured into products, and finally returned to the environment as wastes. The development of ecomaterials that can reduce the environmental impact is important to protecting the earth's natural environment.

The word "ecomaterial" is used for "environmentally conscious material" or "ecologically oriented material," which implies socially acceptable materials with minimal environmental impact. Conversion to ecomaterials is a vital means of addressing the environmental issues of resource depletion, materials recycling and reuse, global warming, ozone depletion and dioxin contamination.

Conventional materials analysis deals primarily with performance during product use. Ecomaterials must satisfy environmental compatibility and amenity criteria as well (see Fig. 1).

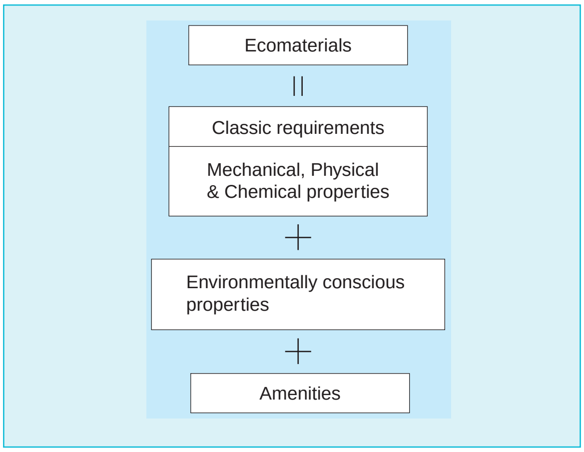

Fig. 1 The concept of ecomaterials.

ENVIRONMENTAL COMPATIBILITY. Ecomaterials are utilized to minimize the environmental impact over their life cycle of manufacture, distribution, use and disposal. Life-cycle assessment (LCA) facilitates development of ecomaterials by providing a quantitative measure of the environmental impact of materials and products over their respective life cycles. Evaluation of materials, for example, extends from mining through manufacturing to disposal—all steps of the product life cycle. This holistic approach to evaluation allows the development of materials and technologies with minimal environmental impact.

AMENITY CRITERIA. Performance criteria for resin materials used in product housings are currently limited to mechanical strength, moldability and appearance. Ecomaterials introduce an amenity index as an additional performance criterion. People encounter a variety of materials in their daily life. Ecomaterials have a degree of psychological and physiological impact, so the amenity index includes aesthetic considerations and tactility.

Development of Ecomaterials

Table 1 lists key categories of material for ameliorating environmental impact. Some materials are already regulated by law, others may be the target of future regulations, still others are essential to reduce the environmental impact of manufactured products. In Japan, the recently enacted Materials Recycling Law and Waste Processing Law encourage reclamation of materials and other steps to reduce the environmental impact of post-consumer products. Here we survey the state-of-the-art in ecomaterials development.

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Table 1 Materials Related Environmental Issues

Ozone depletion
Acid rain
Global warming
Atmospheric pollution
Ocean pollution
Soil pollution
Desertification
Ecosystem destruction
Dioxin contamination
Endocrine disruption
Depletion of non-renewable resources

OZONE DEPLETION. Mitsubishi Electric has eliminated the use of regulated chlorofluorocarbon (CFC) products through the introduction of alternatives. Hydrochlororfluorocarbon (HCFC) and hydrofluorocarbon (HCF) products are being used in refrigerant and foam-blowing applications. Water-based systems and zero-washing systems have been substituted for CFC solvents in cleaning systems for PCBs and precision components.

GLOBAL WARMING. Carbon dioxide is the greatest contributor to global warming. Large amounts of carbon dioxide are emitted by power generation facilities, manufacturing plants, and motor vehicles, and these join the already significant quantities of natural emissions. Reductions in product power consumption should be accompanied by similar consideration of product constituent materials.

The release of greenhouse gases (i.e., gases with high-global-warming potential) to the atmosphere can be lowered by designing products for reduced usage, by using substitute gases, and by adopting energy-saving, heat-conduction and thermal insulation technologies. Sulfur hexafluoride gas (SF_6) used in arc-extinguishing in-

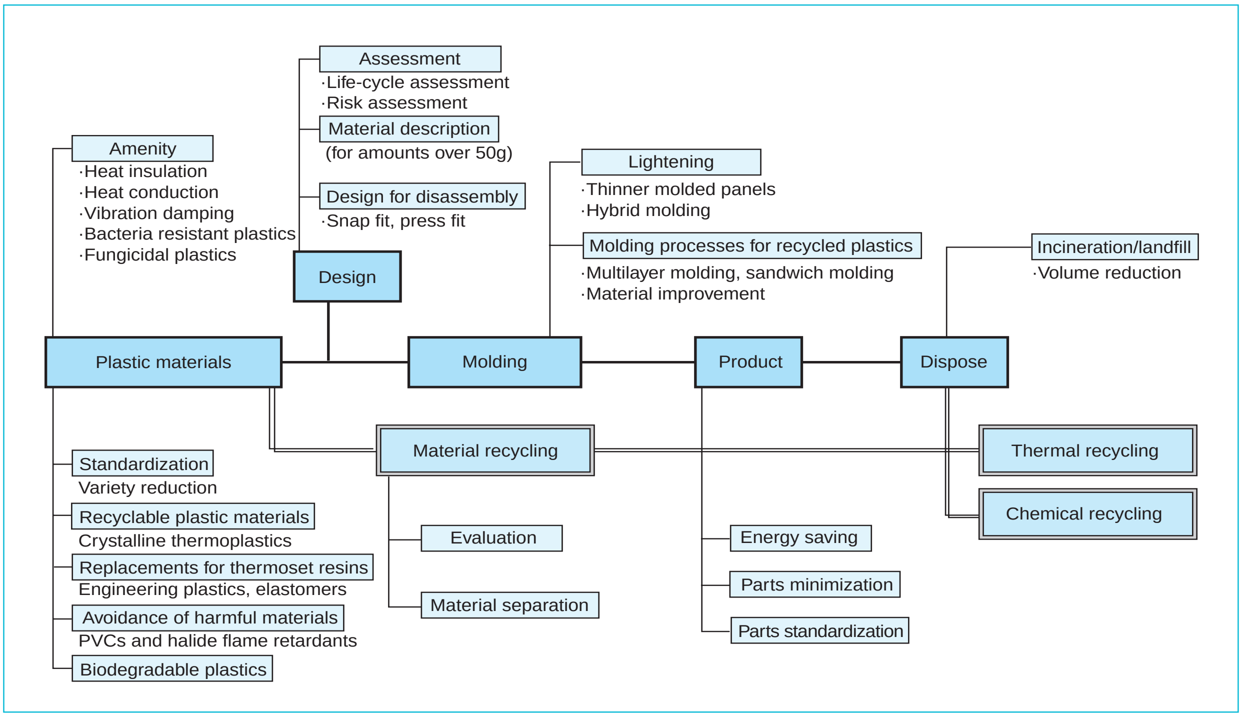


Fig. 2 Development roadmap for environmentally conscious plastics.

Table 2 Mechanical Properties of Plastic Recycled from Home Electrical Appliances

Plastic (appliance)	History	Tensile strength (MPa)	Flex strength (MPa)	Flex modulus (GPa)	Impact absorption energy (J)
Polystyrene (air conditioner)	Recycled	32.8	72.7	2.74	0.36
	Virgin	30.9	64.8	2.54	0.88
Polypropylene (refrigerator)	Recycled	27.8	48.3	2.09	0.57
	Virgin	27.8	47.1	2.05	1.06

sulating systems has a high global warming potential. Reclamation, leak prevention and detection technologies, coupled with studies of alternative insulation gases, are contributing to the reduced release of this gas.

REDUCED USE OF TOXIC MATERIALS. Lead is present in the solder used to mount electronic circuit components. Halide-based flame-retardant chemicals, which are also toxic, are found in plastics and glues. Because these materials have the potential to affect ecosystems and humans over all phases of their life cycle, their use must be reduced or eliminated. This will follow the implementation of international protocols and subsequent regulations, as with previous regulations enacted on the use of other harmful materials.

AN ECOMATERIAL APPROACH TO PLASTICS DEVELOPMENT. Because plastics are heavily used in household appliances and other electrical and electronic equipment, the reduction of their environmental impact has become increasingly important. Fig. 2 summarizes the work toward ecomaterials at Mitsubishi Electric. Impact evaluations and design reviews cover all aspects of the product life cycle from raw materials to product disposal.

Materials Recycling Technologies

Life-cycle analyses indicate the value of recycling in reducing product environmental impact. Materials and processes should therefore be designed to promote recycling. A high percentage of metal and glass is already being recycled, while the percentage for plastics remains low. Developing more efficient systems for plastic recycling is thus a high priority. Plastics may be recycled by chemical means to recover the monomer, incinerated to produce heat energy, or reused directly. The last approach, material recycling, is ideal in that the waste is almost entirely converted to a resource, which makes this option especially attractive. Plastics recycling technologies must address the comparative weakness of recycled materials, consider ways of handling contaminants and, finally, develop the technologies to utilize the recycled material.

The degradation of plastic materials is greatly influenced by their exposure to the environment, particularly to heat and ultraviolet radiation. Table 2 lists the results of mechanical tests on samples formed from both new and recycled plastic materials. Most of the measures of mechanical strength other than impact resistance show little deterioration. Mitsubishi Electric is working to improve material quality and develop new processing techniques that can increase use of this recycled resource.

The development of environment friendly materials will help reduce the environmental impact of product manufacture and consumption and promote the emergence of a high-recycling-rate society. The characteristics and functional behavior required of ecomaterials will almost certainly change over time. The movement toward products made of ecomaterials and the reduction of the environmental loads imposed by production will continue to control the direction of future technology development. ❑

An Electrically Operated EGR Valve that Reduces Automotive Emissions

*by Toshihiko Miyake and Hidetoshi Okada**

Automotive exhaust emission regulations are growing stricter in parallel with demands for greater fuel economy. The exhaust-gas recirculation (EGR) valve is one technology used to reduce the emissions of automotive engines. The authors developed EGR valves in which an electronically controlled stepper motor replaces the conventional vacuum-driven mechanism. The stepper motor system offers more accurate control over a wider range of engine operating conditions than a vacuum system, reducing emissions and improving fuel economy.

Automotive exhaust emissions include carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NOx). NOx is produced when nitrogen and oxygen from the air combine at temperatures over 2,000°C. Although high combustion temperatures result in better fuel economy and fewer emissions of hydrocarbons and CO due to the more complete burning that takes place at these higher temperatures, they also increase NOx production. The curves in Fig. 2 show the contrasting characters of these two emission-producing mechanisms.

EGR valves reduce NOx emissions by routing exhaust gases into the engine's intake manifold (Fig. 1). The presence of these unreactive gases in the cylinder during combustion serves to lower the combustion temperature. The EGR valve controls the amount of exhaust gas recirculation to suit engine operating conditions.

Fig. 3 shows NOx reductions achieved using a stepper-motor EGR valve developed at Mitsubishi

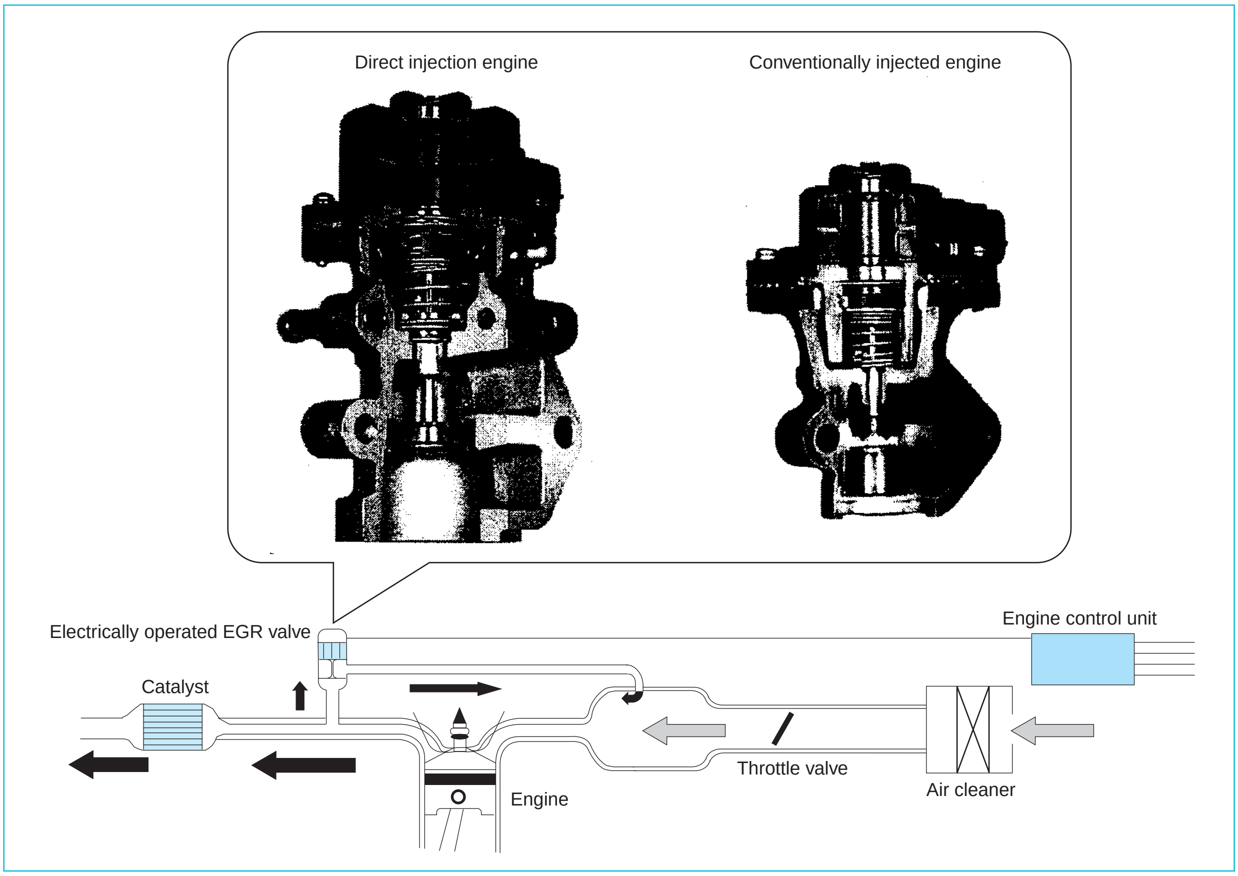


Fig. 1 Electrically operated EGR system.

**Toshihiko Miyake and Hidetoshi Okada are with Sanda Works.*

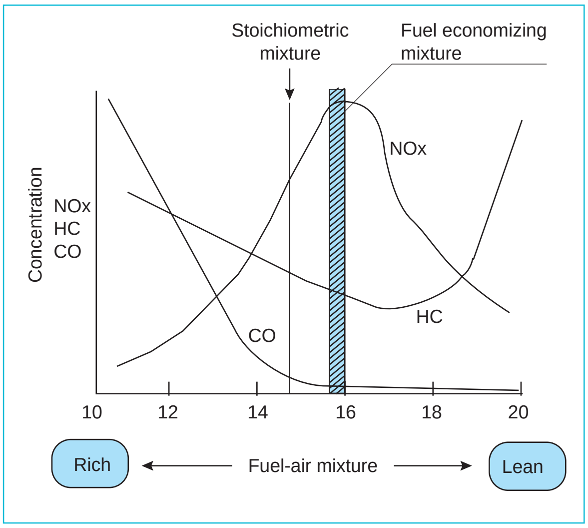


Fig. 2 Effect of fuel-air mixture on exhaust emissions.

Electric in the GDI engine manufactured by Mitsubishi Motors. According to papers published by Mitsubishi Motors, 97% of the NOx emissions present in the exhaust gases can be eliminated when recirculated exhaust gas comprising up to 30% of the intake air is used in conjunction with a lean-burn selective-reduction NOx catalyst. This emissions control performance is comparable to that of a three-way catalyst.

Fuel Economy Improvement

EGRs can improve fuel economy by reducing pumping losses. The accelerator pedal in a gasoline engine car controls a throttle valve that regulates the airflow through the intake manifold. Pumping losses occur when the engine is operating under low load and the throttle valve is nearly closed. Energy is wasted overcoming the resistance to airflow through this narrow passage. These losses can be reduced by a lean-burn combustion style in which the throttle valve is opened relatively wide in combination with a large EGR flow. The diluted-burn engine system developed by Mazda Motor Corporation uses this exact principle: it combines a large EGR ratio with a wide throttle opening that serves to reduce pumping losses (Fig. 4).

Problems with Conventional EGR Systems

The inadequacies of the vacuum-driven EGR valve make a strong case for an electrically operated valve. Conventional EGR systems operate the EGR valve using a diaphragm driven by the intake manifold vacuum. The vacuum is

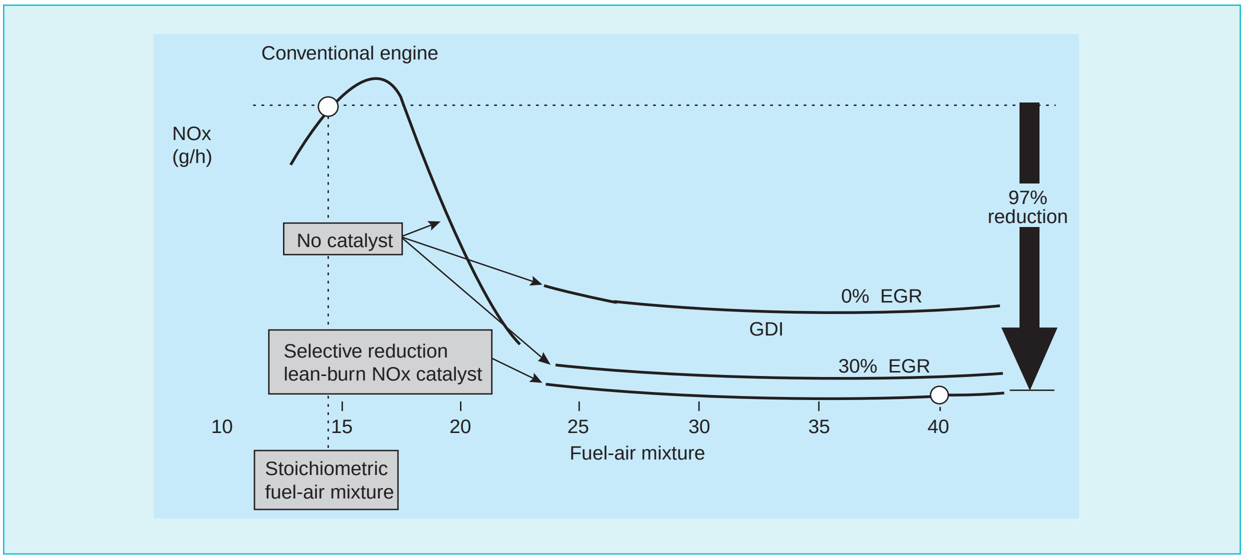


Fig. 3 Reduction of NOx emissions in GDI engine. Emission levels are for an effective vehicle speed of 40km/h.

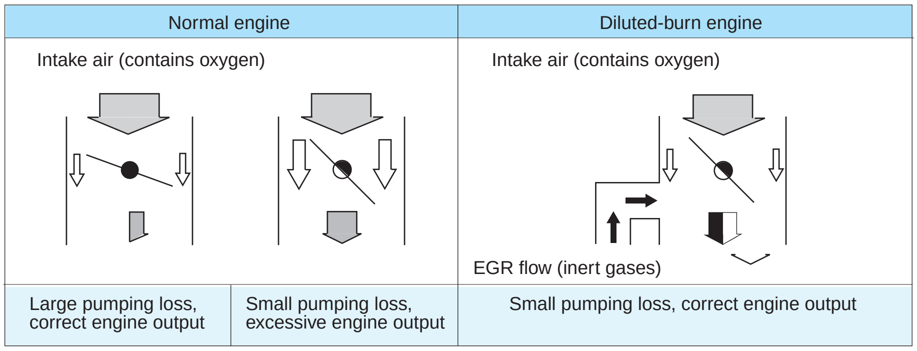


Fig. 4 The diluted-burn engine.

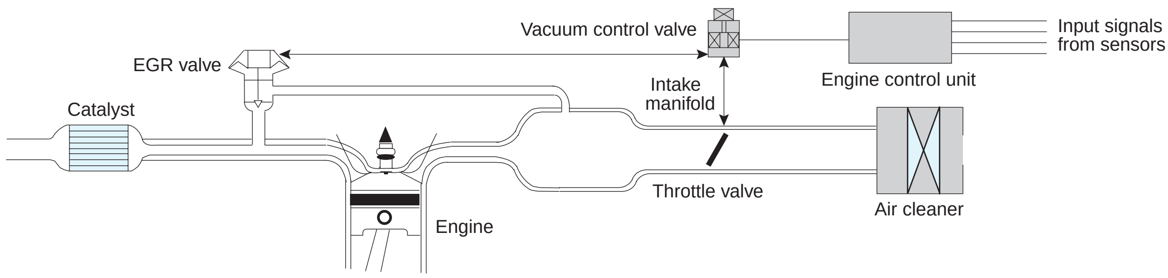


Fig. 5 A conventional vacuum diaphragm EGR system.

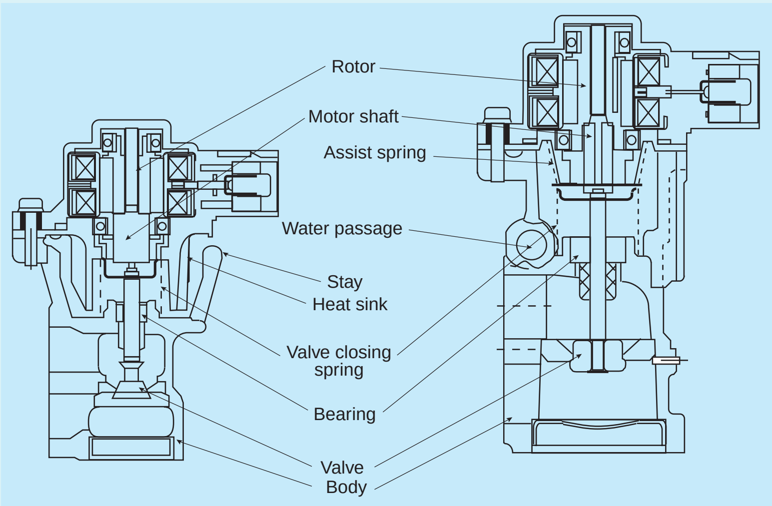
taken from the intake manifold downstream from the throttle valve. Because it depends on engine vacuum, this arrangement is useful for small throttle angles where a vacuum is present but not at wide throttle angles where the vacuum vanishes. It is not suitable under the low manifold-vacuum conditions that would reduce pumping losses (Fig. 5).

Electrically Operated EGR Valve

Mitsubishi Electric has developed an EGR valve driven by a stepper motor that will operate under all engine vacuum conditions. The stepper motor provides the best fit to the requirements of the EGR system: The power drain is modest, the valve opening is stable despite exhaust gas pressure pulses, no position sensor is required,

Table 1 Electrical Actuators

	Drive power	Valve stability	Position sensor	Cost	Weight
Stepper motor	High	Good	Unnecessary	Low	Light
Linear solenoid	Low	Fair	Required	Fair	Heavy
DC servo motor	High	Fair	Required	High	Heavy



a) Conventional fuel injection   *b) Direct injection*

Fig 6 Construction of electrically operated EGR valves.

the system is simpler than its vacuum operated counterparts, the cost is relatively low, and the system is suited to mass production.

Table 1 compares stepper motors against other electrical actuators that could be adapted to this application. A stepper motor offers three to four times the flow capability for the same drive power as a linear solenoid-operated valve.

Durability is also critical, because performance will suffer if carbon or oil sludge in the exhaust gases builds up in the valve-shaft bearing.

Construction

Fig. 6 shows the construction and Table 2 lists the performance of stepper-motor EGR valves developed for gasoline engines. We selected a push-open downward-opening design over a pull-open upward-opening design that does not require a special coupling between the rotor shaft and valve. Fig. 6a shows an EGR valve for conventionally injected engines, Fig. 6a a valve for direct-injection engines. We designed the system to be cost competitive with conventional EGR systems in order to support general-purpose applications as well as fuel-saving engine designs.

Table 2 Performance of Stepper Motor EGR Valves

Parameter	Conventionally injected	Direct injection
Motor type	Stepper	Stepper
No. of poles	48	48
Motor torque	0.035N.m	0.095N.m
Power consumption	13W	19.2W
Max. stroke	5mm	8.5mm
Max. flow at 6.7kPa	200l/min	800l/min
Resolution	4l/min	9l/min
Accuracy	8%	8%

Direct-injection engines typically require three to five times the EGR flow of conventionally injected engines. Our EGR unit for direct-inject engines uses a more powerful stepper motor to provide additional drive capacity for a larger valve. The operating load has also been reduced by introducing an assist spring that acts against the valve closing spring while the valve is open. The assist spring is inactive when the valve is closed, allowing the valve-closing spring to function.

A four-phase stepper motor is used for both types of application. A unipolar design reduces the load on the drive circuit. The external thread on the motor shaft and internal thread on the rotor convert the motor's rotary motion to linear motion. A single motor revolution of 48 steps drives the valve full stroke. The motor-driven solution provides rapid response for both opening and closing operations. Heat-resistant materials were used so the motor would tolerate the high temperatures caused by exhaust gases traveling through the valve body.

In the EGR valve for conventionally injected engines, the casting between motor and the valve body is supported by two narrow stays. Air flowing between the stays and over the heat sink below the motor provides sufficient cooling. A water-cooled aluminum heat sink in the valve for direct-injection engines provides additional cooling capacity to support the larger EGR flow.

The cost advantages of stepper-motor EGR valves are driving their introduction in general-purpose automotive applications. We expect demand for these valves to increase as lean-burn engines are used more widely, as fuel economy becomes more important, and as emission regulations are tightened. Although small, this advanced EGR valve can contribute significantly to preserving the global environment. ❑

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