Radiation Sources
EB and UV Curing Machines

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P11

ELECTRON BEAM PROCESSORS FOR RADIATION CURING APPLICATIONS

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INTRODUCTION

The electron beam (EB) curing system acquired an industrial reality in late 1960's when so-called low energy EB accelerators with industrial level performances became available. The process involves an instantaneous change in state of a liquid prepolymer-monomer mixture to a solid thin coating by free radical polymerization with crosslinked structure. Oxygen, being very reactive with growing radicals to form stable chemical species, inhibits the radical polymerization, which leads the system to be processed in an inert atomosphere using either (liquid) nitrogen or combustion gas.

Major advantages of the EB curing processes are as follows: a solvent-free system, less energy consumative, a much higher production rate, and a processing ability at ambient temperature. The equipment is very compact with resultant space savings and able to be easily controlled. Most of the commercialized products using this thechnology are also of improved qualities and the application areas of the technology are expanding.

This paper describes electron beam processors and related technologies for curing applications to facilitate those industrial personals who are trying to understand and evaluate the applicability and benefits of radiation curing to their products.

ENERGY DEPOSITION

The electron beam curing process is the result of a transfer of energy from the accelerated electrons as they penetrate the material which is being irradiated. The penetrating capability of electrons is shown in Fig. 1. As can be seen, the higher the kinetic energy of the electron beam, the greater the penetration depth will be into the material. Fig. 2 shows energy deposition profiles as a function of the accelerating terminal voltage. It can be understood that the majority of coatings are curable with irradition of electrons accelerated up to 300 keV. And, those accelerators in the range of 150 - 300 kV are called as low energy accelerators.

The measure of energy absorbed in a material is referred to as dose, of which unit is defined as rad or Gray (Gy) in SI unit.

1 rad = 100 erg/g, 1 Gy = 1 J/kg
100 rad = 1 Gy
1 Mrad = 10 kGy = 2.4 cal/g

Although the penetration depth of accelerated electrons is small, through collision to matter they generate X-rays which can penetrate far into materials. Therefore, the electron accelerator and its associated product treatment station must be shielded with either an exterior vault (vault-shielded or integrated structural housing of the unit (self-shielded). Accelerators operating in the energy range below 500 kV can be equipped with self-shielded models.

ELECTRON BEAM ACCELERATOR

The working principle of an EB accelerator is similar to the Braun tube for a television set, an electron gun for an electron microscope, or a large radio-valve. That is, electrons are generated by heating a cathode material (filament) and subsequently accelerated to a desired energy electrically in such a high vacuum as 10^{-6} Torr (Fig. 3). The accelerated electrons are then pass through a thin metal window, which is made from either titanium or aluminium foil, and must be cooled to prevent its melting.

Accelerators on the market can be devided in two types; scanned beam and non-scanned beam types, as shown in Fig. 4.

In the scanning types (Fig 4a), the electrons are emitted by a spiral cathode with a diameter of about 5 mm. and the beam spot is scanned across the material to be irradiated with a frequency of around 200 Hz. Since an accelerator of this type needs a scanhorn with a height of about 1 to 2 times the width of the material, it is often positioned horizontally.

As an example of scanning type, the specifications of the accelerator which has been installed at CAIR-BATAN as a pilot-pilot-demonstration line for wood coating since 1984 are shown below:

Type: Insulated gas sealed transformer
EB Energy: 300 keV max.
EB Current: 50 mA max.
Scanning width: 120 cm
Scan frequency: 200 Hz
Dose uniformity: ±5 % over a full scanning width
X-ray shielding: Self-shielded, shutter-type
X-ray leakage: below 0.2 mrem/hr
Conveyer speed: 2.5 - 25 m/min
Inert gas: Liquid nitrogen, 100 Nm^3/hr max

Non-scanning type machines as shown in Fig. 4 are also called as linear-cathode type, in which the electrons are emitted by one or more linear filaments, arranged across (Fig. 4b) or parallel (Fig. 4c) to the production line. Having no scanhorn, a machine of this type can be designed more compact than a scanning-type one. The acceleration voltage is limited upto 300 kV. Typical specification of these systems shown elsewhere are:

Voltage	150 - 300 kV
Width	15 to 250 cm
Dose	1 Mrad at 1500 m/min max
Uniformity	± 5%
Vacuum	5×10^{-7} torr
Oxygen Exclusion	5 ppm
Expected Filament Life	10,000 hrs
Maintenace schedules	
Air Filter	Every 2 weeks
Foil	4 months
Water Filter	2 months
SF_6 Pressure	2 months
Vac Pump Oil	9 months

There is another type of machine, where electrons are generated through secondary emission from a metal target (cathode) striken by high energy positive ions, as shown in Fig. 5. This type of machine can be operated at relatively low vacuum (10^{-2} Torr). The life of a secondary emitter can be considerably longer than a thermal emitter. Typical specifications of this type of machines are:

Voltage	150 to 250 kV
Current	.150 to 1.5 mA/cm² continuous 5 A/cm² pulsed
Window Areas	10 to 2000 cm²
Beam Uniformity	± 10%
Life	>20,000 hrs continuous 10^{10} shots pulsed
Efficiency	60 to 80% at 175 kV
Operating Pressure	10^{-2} Torr He

Quite recently, a German company which have three different EB units for its coating lines reported their experience on using them. The characteristics of the accelerators installed in the company are shown in Table 1. And, Table 2 shows maintenace time of the accelerators. It should be noted that the report concluded as follows:

"I (W. Karmann) wish to point out that the electron beam proceessors are accepted components of our coating line, which are employed particularly where high precision of production is required. The reliability is comparable to the other components of the lines."

IRRADIATION ENGINEERING

Automatic Control

Since an industrial electron accelerator is installed as an element of a production line, it should perform its functions without requiring the special attention of an operator. For this purpose, EB processors with automatic control system are available. Fig. 6 shows an example of such a system. By setting the required dose D, the comparator C determines the ratio of D of and signal T from the tachometer, which is proportional to the line speed v. The comparator then instructs the grid control G of the electron accelerator to adjust the beam current I according to the following relationship:

$$D = \frac{k \times I}{v}$$

where k is the yield factor of the processor (Mrad m min^{-1} mA^{-1}).

3-Dimensional Objects

It is generally considered that electon beams travel in straight lines and therefore are most suitable for processing flat objects. When they pass through the foil and gas layer, however, scattering of electrons occurs as well as energy loss.

The lower the energy of electrons, the greater the scattering. For example, the mean scattering half-angles of 200 keV electrons for various configus are shown below:

Configuration	$\theta_{1/2}$ (degree)
1/2 mil Ti window	21
1 mil Ti window	30
1/2 mil Ti window + 2.5 cm N_2	37
1/2 mil Ti window + 5.0 cm N_2	43

It can be seen that the mean scattering half-angle of electrons 5 cm below the window is more than twice of that at its back side. This means an increase in the front surface dose in spite of a decrese in the penetration depth of the electrons into the product. Fig. 7 shows the effect of the air gap on the gel content of a coating. It can be clearly seen that the coating can be most effectively cured at a very distanct place, not near the window. Moreover, it seems that the low energy electrons may possibly cure coatings on shaped matrials. In fact, it has been shown that it is possible to cure the coating on car wheel rims.

Fig. 8 shows a schematic diagram of EB curing of coatings on car wheel rims which was installed in West Germany. The pre-coated wheels with an water-based primer are stoved followed by spray application of and EB curable metallic paint to the outside of the rims. The coated articles are then admitted to the circular curing chamber which rotates to permit the coating be irradiated and cured under the accelerator.

Other potential processes for shaped materials are shown in Fig. 9 and 10.

Inerting System

Because the radical initiated polymerisation reactions are inhibited by the presence of oxygen, the irradiation zone must be maintained as an oxygen-free (inert) atmospher, typically with oxygen levels from less than 50 ppm to 500 ppm. This can be achieved by purging with inert gas usually from either liquid nitrogen or a gas generator. The prices for liquig nitrogen vary considerably from one geogrphical location to another, or with the amount to be used. The consumption of inert gas on a particular line depends on a number of factors such as the line speed, line width, thickness of the products, design of the curing chamber, etc. Anyhow, the cost for inerting is pointed as one of the major disadvantages of the EB curing technology.

A inert gas recycling system has been developed by a Japanese EB machine manufacture, with a consideration of the temperature rise in the irradition zone, in order to minimize the consumption of costful liquid nitrogen.

Table 3 shows the cost estimation for the inerting system with or without nitrogen recycling system, which is made on the following assumptions:

Acceleration voltage	200 kV
Beam current	300 mA
Max. temperature rise	25 °C
Oxygen concentration	<100 ppm
Price of liq. nitrogen	40 yen/Nm^3
Electric power for recycling	5.5 kW
Electricity cost	25 yen/kWh
Annual operation time	32,000 (16 x 200) hrs
Fresh nitrogen	100 Nm^3/hr
Recycled nitrogen	150 Nm^3/hr

It can be clearly seen that there is a lot of cost saving when the recycling symtem is used.

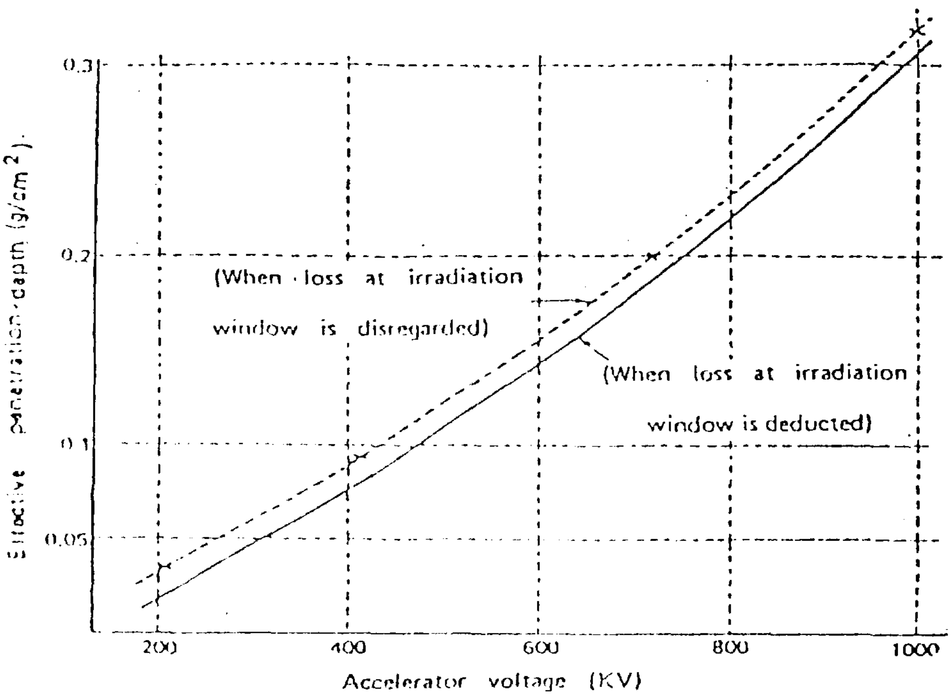


Fig. 1 Effective penetration depth

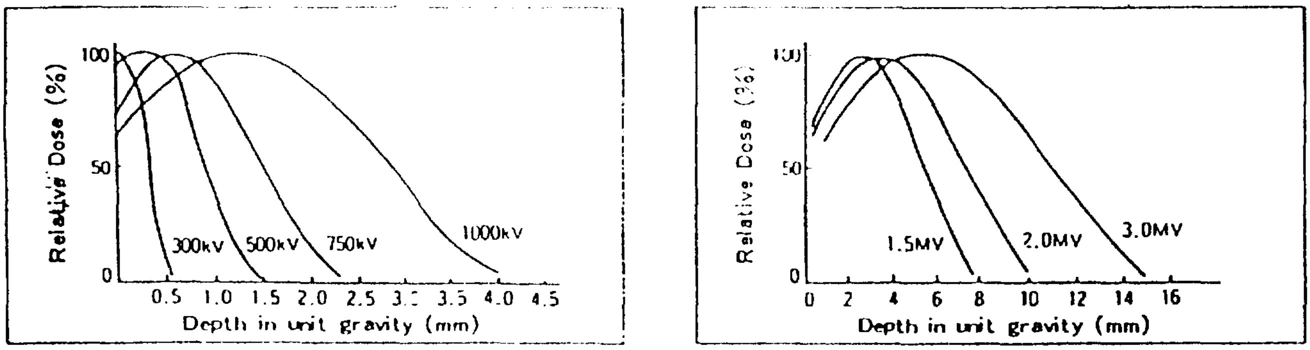


Fig. 2. Energy deposition profiles.

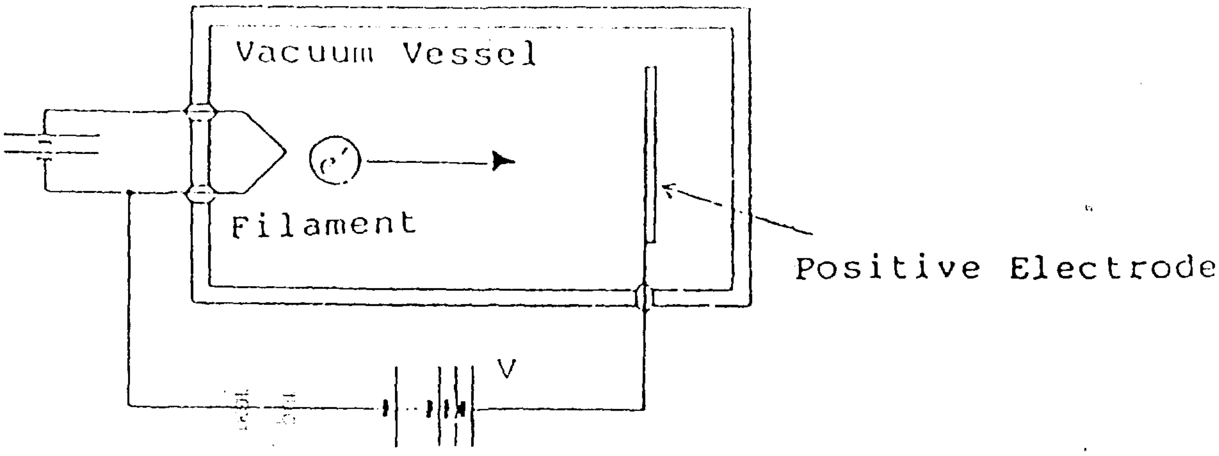
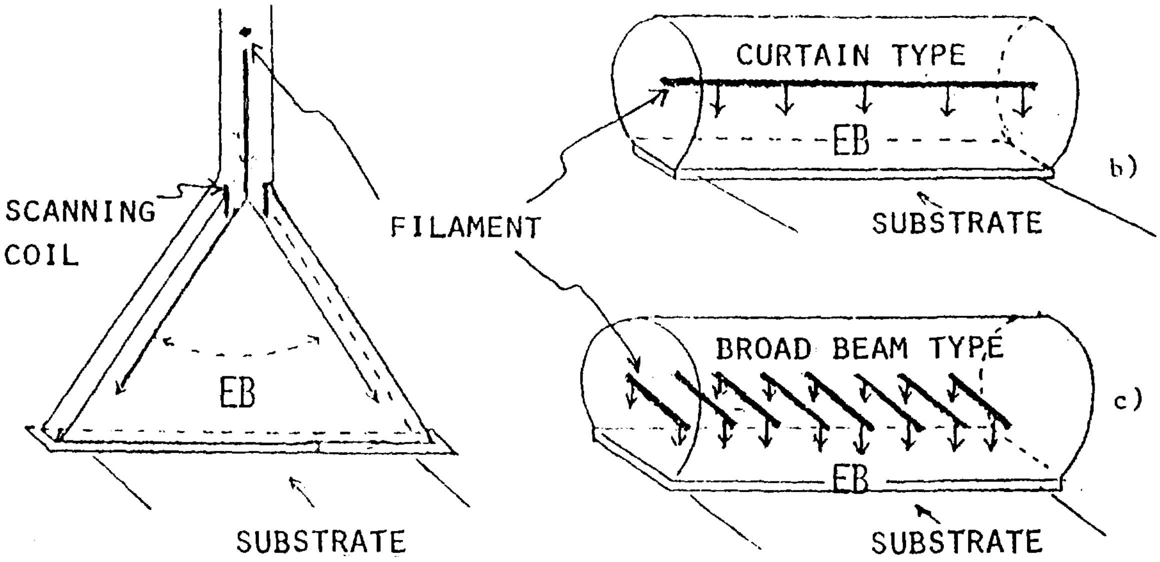


Fig 3. Principle of electron acceleration.



a) Scanning-type

Non - Scanning - type.

Fig. 4 Schematics of low-energy accelerators

P20

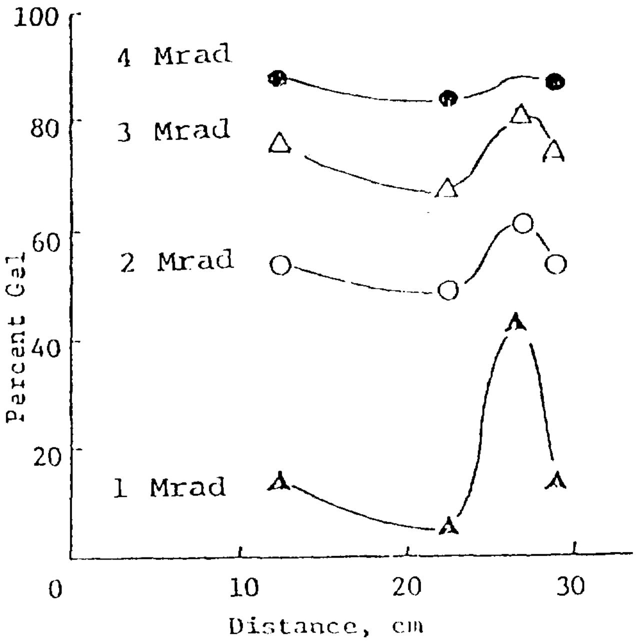


Fig. 7 Effect of distance (air-gap) on curing of an unsaturated polyester resin (300 kV scanner type)

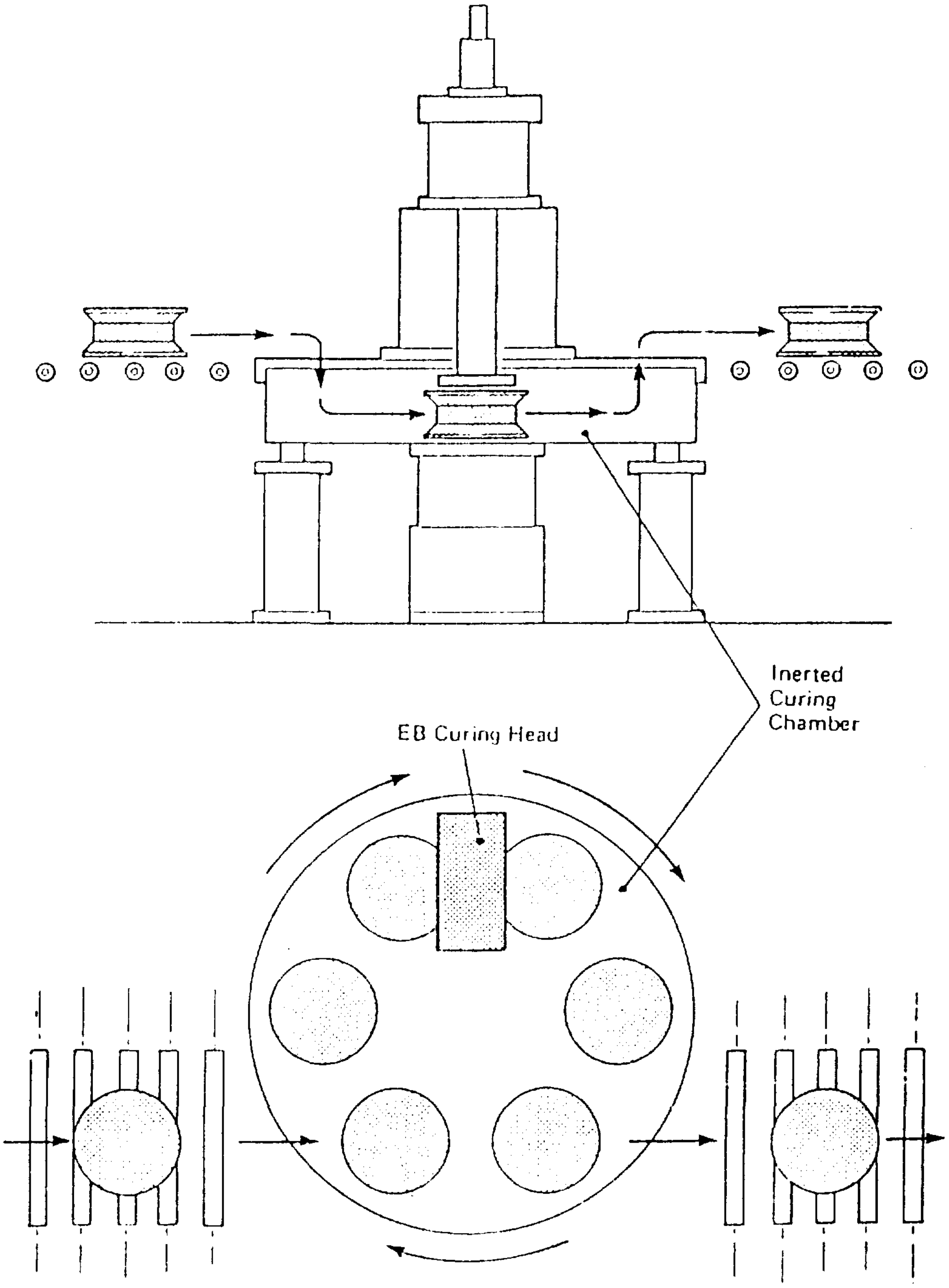


Fig. 8 Schematic diagram of EB curing of coatings on car wheels.

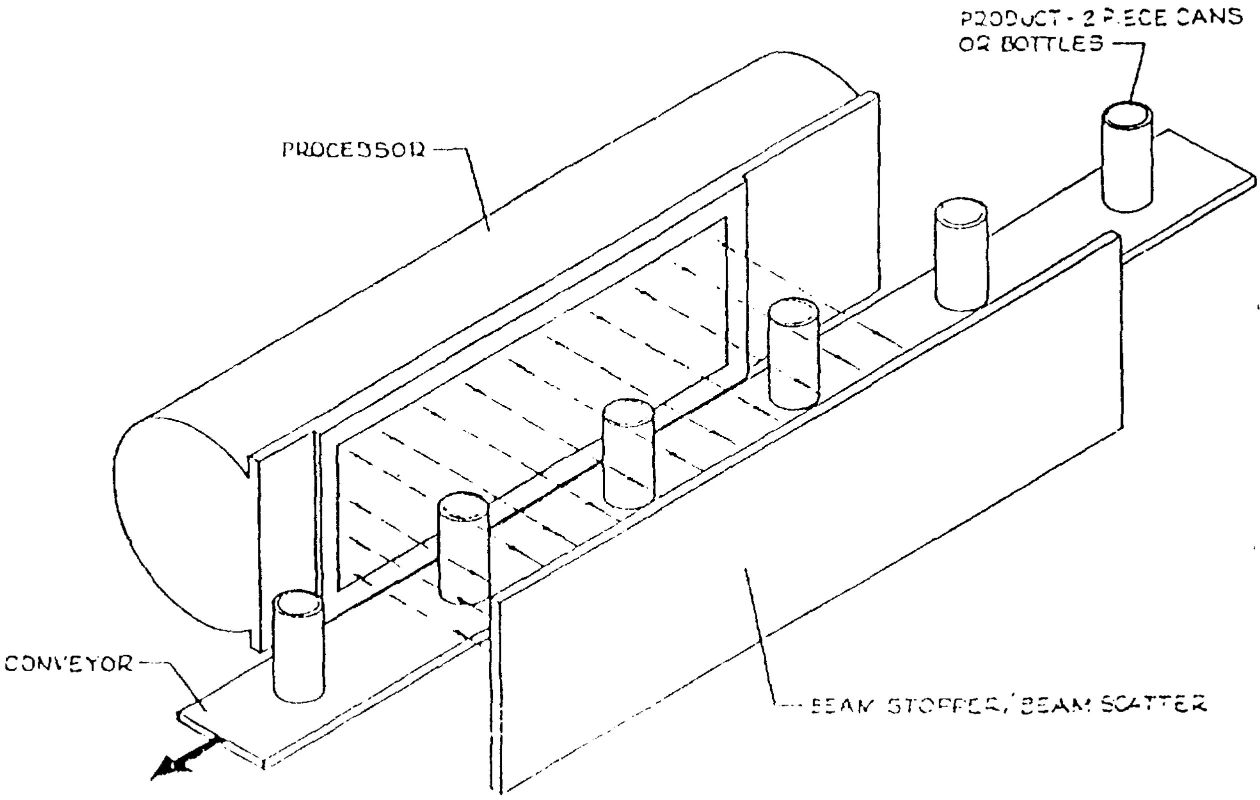


Fig. 9 Irradiation of two-piece cans.

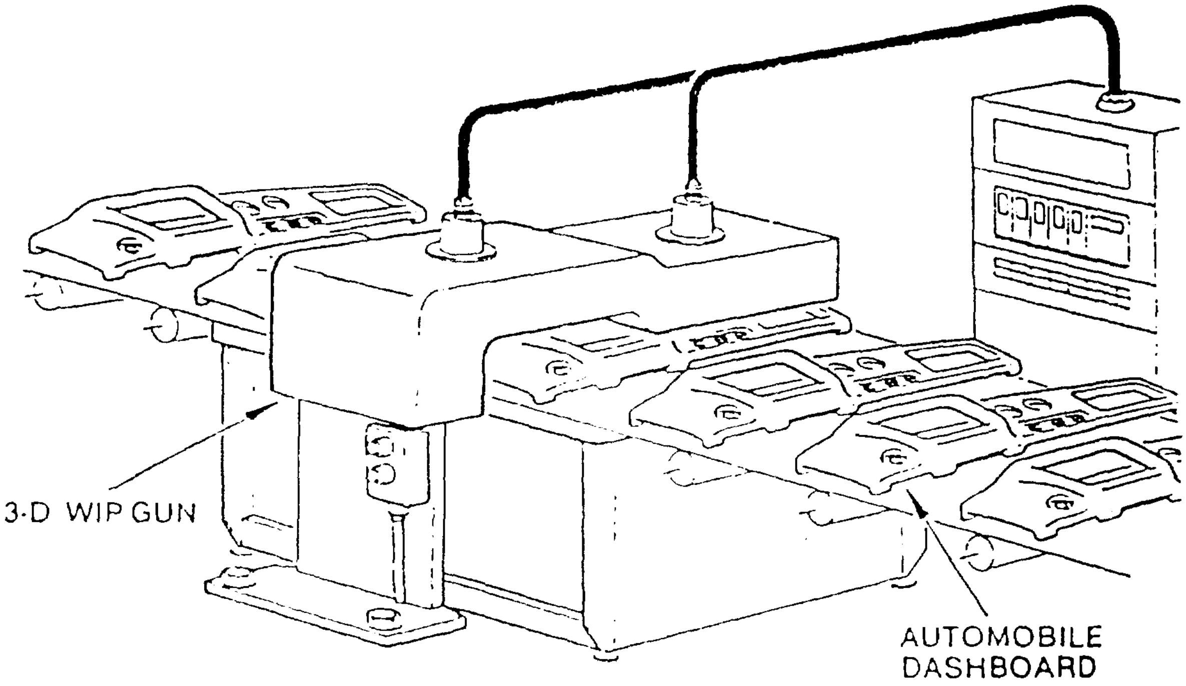


Fig. 10 Irradiation of automobile parts

Table 1 Charasteristics of Accelerators at Beiersdorf AG.

Made by	:	High Voltage Engineering Corp.	Polymer-Physik GmbH	Energy Sciences Inc.
Type	:	Scanning	Scanning	Linear Cathode
Cathode	:	Spiral	Spiral	Tranvers.Wire
Beam current controlled by	:	Temperature	Temperature	Grid-Voltage
Area weight of window + air gap	:	242 g/m^2	110 g/m^2	100 g/m^2
Support	:	none	drilled plate	lamellae
Beamwidth	:	1.22 m	1.35 m	1.35 m
Max. beam current	:	0.4 mA/cm	1 mA/cm	3 mA/cm
Rise time to maximum	:	45 sec	20 sec	15 sec
In operation since	:	1980	1983	1986
Hours of operation	:	11,000	18,000	8,500

Table 2 Maintenace time of the accelerators shown in Table 1

Made by	:	High Voltage Engineering Corp.	Polymer-Physik GmbH	Energy Sciences Inc.
Lifetime of cathode	:	>11,000 h	400 h	ca.3,000 h
Average time spent ✱	:	ca.2 days	1 h	24 h
Lifetime of window	:	250 h•	2,000 h·	>1,000 h·
Average time spent ✱	:	24 h	3 h	24 h

Explanations:

• usually broken by thermal stresses in the metal sealing ring
· usually changed preventively
✱ including reconditioning

Table 3 Cost estimation of N_2 recycling system

Nitrogen Recycling	YES	NO
Annual Nitrogen Consumption	320,000 Nm^3	800,000 Nm^3
Annual Nitrogen Cost (1000 yen)	12,800	32,000
Electricity for Nitrogen Recycling	17,600 kWh	0
Electricity Cost, (1000 yen)	440	0
Total Cost, (1000 yen)	13,240	32,000

U.V. EQUIPMENT

UV equipment suitable for curing is made up from the following components:

UV source
Reflectors
Ancillary Equipment

UV Source

Mercury Vapor Lamps

The mercury vapor lamp is normally a sealed transparent quartz tube into which has been introduced. The lengh of lamps vary up to 120 cm. Electrodes made of tungsten are loccated at either end. A typical lamp construction is illustrated in Fig. 1.

Low pressure mercury vapor lamps: This type of lamps operate at pressures in 10^{-2} to 10^{-3} Torr region, and at relatively low temperatures (40 °C). A small amount of argon gas is also introduced into the tube.The dominant wavelength emitted are 185 and 253.7 nm, the longer of the two being the more common.

Medium pressure mercury vapor lamps: These lamps are the most widely used for curing processes. The tube is constructed of transparent quartz and runs between 40 and 120 W/cm linear lamp with pressures of 10^{2} Torr. The surface temperature of the lamp being 700 °C, it needs to be cooled to control the temperature, whichi helps to maintain a steady spectral output. The efficient removal of any ozone produced should be ensured with appropriate extraction equipment. At the higher pressures and temperatures, a much wider spectrum output is produced than that of a low pressure lamp. Thus, the 253.7 nm line is relatively insignificant, but the 356/366 lines are very prominent and important for the UV curing process, since many photoinitiators have strong adsorption bands in this region.

High pressure Mercury Vapor Lamps: These lamps contain a mixture of mercury and xenon and operate above 10 atm. Under these conditions, the spectral output become a contininuum one. These lamps are normally small in dimensions, and used in photolithography.

Metal Halide Lamps

In order to modify and adjust the spectral output and to meet with specific applications, other meterials may be introduced into the tube. However, most of metals are less volatile than mercury and reactive to the elctrodes or silica walls of the tube. Among others, metal halides (normally the iodide) can be used because of being volatile and not chemically active. For example, magnesium iodide lamps supply 280, 310 and 385 lines and improve cure speeds. Gallium iodide enhances the 400-450 nm region and is suggested to be suitable for curing pigmented finishes.

Electrodeless Lamps

The electrodeless system activates the gas within the quartz bulb in a microwave field created by a small magnetron. The microwave energy (2450 Hz) excites the molecules within the tube very rapidly, and full power can be attained within 10 seconds, in contrast to the several minutes needed to start up electrode bulb. Most electrodeless bulbs are limited to 24 cm in length. For wider web processing, a series of these lamps are installed in a row.

Table 1 Comparison between Electrode and Electrodeless Lamps

	Conventional Electrode Lamp	Electrodeless Ultraviolet Lamp
Watt density:	120 watts/cm	120 watts/cm
Bulb length:	up to 2 meters	24 cm
Power source:	transformer and capacitor ballast	proprietary microwave system
Start-up time:	2 to 3 minutes	10 seconds
Stand-by condition:	half power	none required
Lamp warranty: (>85% output)	1,000 hours	3,000 hours

Reflector System

Intense light may be desirable in high speed, high throughput operation. In such case, the lamp can be positioned at one focal poin within an ellipsoid to concentrate ultraviolet light onto a target substrate. Since all UV sources also emit some visible and near infrared or heat energy, such light energy will also be concentrated at the focal point distant from an ellipsoidal reflector. In order to reduce this heat input, especially for heat sensitive substrates, a parabolic rerflector in which the bulb is positioned at its focal point can be used. The parabola can be desighed so that the light will be reflected outword in nearly parallel rays. Diffuse light is also desirable for dealing with shaped or three dimensional objects.

Ancillary Equipment

Cooling

There is an emission of some infrared or heat energy from any type of light sources. The temperature of an UV source must be controlled not only because of the need to maintain controlled temperature conditions in and around the bulb, but also because of substrate considerations. Therefore, UV sources are usually kept cooled by the circulation of air or air and water.

Shuttering

It is essential to be able to cut off the source of UV at a very short notice e.g. in the event of a line stoppage. This is particularly important where flammable or heat sensitive materials are being used. In such situations it is neccessary to fit a shutter to the UV assembly which will close automatically if the line is stopped.

Shielding

Exposure to UV radiation is extremely hazardous and must be avoided. It can cause temporary or even permanent blindness. Prolonged exposure to intense UV can result in skin canser. Therefore, it is essential to have effective shielding with appropriate interlocks to prevent accidental exposure.