Radiation Processing Technology in the 21st Century

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Introduction

Ionizing radiation was discovered by Roentgen in his discovery of X-rays in 1895, and its centennial anniversary was celebrated in many places in the year before last. Studies on chemical and biological effects of the radiation have been conducted since that time. The use of electron beams from the accelerators and gamma-rays from Co-60 produced by the nuclear reactors in the industrial processing started in between late 1950's and early 1960's and expanded world wide. Now, including the processing of various polymers, food irradiation, radioisotope production and so force, the radiation processing technology contributes greatly to industry, agriculture and medicine.

The radiation processing technology has made a great progress during the past 50 years. The progress in the next 21st century will also be great. The title of my today's talk is "Radiation Processing Technology in the 21st Century". This is too wide for me to cover all the progress which will happen in coming 100 years. The radiation processing technology is growing and will continue to grow to meet various requirements which will appear in future. At the Takasaki Radiation Chemistry Research Establishment(TRCRE), we are making an effort to give answers to anticipated future problems using the radiation processing technology. I would like to talk about some prospects for the future of the radiation processing technology with introducing current activities at the TRCRE to you.

Radiation Processing Technology Using Electron Beams and Gamma Rays

Towards the 21st century, we are required more and more to create innovative technologies to solve problems about environment, energy, natural resources, materials, health care, food and others which are the great concern to human beings. For the radiation processing technology to survive, it will be required to provide answers to those problems.

To fight against the environmental problems, the elimination of acid rain causing pollutants such as SO_2 and NOx from the flue gas of coal or oil combustion boilers by the irradiation with electron beams has long been studied in Japan. A schematic diagram of the process is shown in Fig.1. Under the irradiation with electron beams in the presence of ammonia, SO_2 and NOx in the flue gas are converted into sulfuric and nitric acid respectively, and solidified in a form of ammonium salts which can be used as fertilizer.

An economical assessment of the process for a coal-burning power station showed that both costs for plant and operation are estimated to be cheaper in the electron beam process than in the conventional lime-and-gypsum process. Construction of commercial plant is scheduled by the Chubu Electric Power Co., Inc., in Japan. Feasibility tests using a commercial scale plant are being conducted in China, and planned in Poland. The electron beam treatment is characterized in its simplicity of the process and the recycle use of eliminated pollutants as fertilizer. It will be a good example of the radiation processing technology which will meet requirements of the society in the 21st century by serving in both ways to the conservation of environment and the effective utilization of resources.

Other examples can be cited for cleaning of environment and recycling of resources as shown in Fig.2 and Fig. 3. Fig. 2 is a diagram of a process for purification of factory ventilation air to remove toxic volatile organic compounds such as trichloroethylene. For recycling of biological wastes, as shown in Fig.3, radiation can be used as an effective measure of disinfection in the process for composting of sewage sludge into fertilizer and conversion of oil palm wastes into animal feed.

The use of radiation for polymer modification will remain as an important field of the radiation application. It has been known that chelating resins containing amidoxime groups have an excellent capacity to recover metals from sea-water with a very high selectivity. Polyethylene fibers grafted with the amidoxime groups can collect metal components, cyclicly, such as uranium, titanium, vanadium and so force, which occur in the sea-water at very low concentrations(Fig.4&5). The nuclear power generation has been facing difficulties to gain a public acceptance in many countries, nevertheless, it will be inevitable for us to continue to use it as one of main sources of energy in the 21st century. The sea water will be able to provide fuel uranium with the aid of the radiation processing technology.

The radiation processing technology of polymers will provide high performance ceramic materials. Fig.6 shows a process for manufacturing of SiC fibers. Polycarbosilane(PCS) fibers are irradiated with electron beams for crosslinking and then pyrolized into SiC fibers. When the pyrolysis of the crosslinked PCS fibers is conducted under ammonia gas, silicone nitride fibers can be synthesized in place of silicon carbide. These ceramic fibers can be used as reinforcing fibers of ceramic-ceramic composites (C-C composite), as structural materials for a nuclear fusion reactor, space development and others. The radiation processing technology can similarly be applied for manufacturing of the composites. As shown in Fig.7, PCS is composed with woven cloth of SiC fibers, and then pyrolized into SiC after the irradiation with electron beams for crosslinking the part of PCS. This process is expected to give composites free from voids which cause usually a lowering in the mechanical strength of the composite materials.

Some other promising polymer processing can be cited as those which will grow in near future. For example(Table 1),

For environment technology

Polymeric fibers grafted with ion exchange residues to remove toxic metals for cleaning industrial waste water,

For health care technology

Crosslinked polyvinylalchohol hydrogel for wound dressing (Irradiation of hydrogel),

For high performance materials technology

Less-toxic crosslinked natural rubber latex (Irradiation of emulsion)

Abrasion resistant crosslinked PTFE (Irradiation at high temperature)

The radiation processing of polymers has been developed so far for solid polymers in most cases at room temperature. In the future radiation processing, the irradiation will be conducted to polymers at high temperature near melting point or in various states like hydrogel, emulsion and so force.

Ion Beams for the Radiation Processing Technology in Next Generation

Ion beams of relatively low energy ranging in between 200 and 400keV have been used in an industrial scale for LSI production. Those of MeV energy level are used for analytical purposes and radioisotope production for medical purposes. In general speaking, however, the application of ion beams for the radiation processing technology is still limited in a narrow area. In order to create new areas of the ion beam application, the ion beam facility called TIARA (Takasaki Ion Accelerator for Radiation Applications) was constructed at the TRCRE of JAERI. The TIARA consists of four ion accelerators, one AVF cyclotron and three electrostatic accelerators, and it can provide various ion beams covering a wide range of energy and mass number of atoms. Its features lie in the beam utilization. It can provide heavy ion microbeams, pulsed beams of nano-second width, irradiation to a wide area (100mm x 100mm) by beam scanning, dual and triple beams, and so on. Present research subjects using TIARA now cover studies on materials for the advanced technology like space development and a nuclear fusion reactor, biotechnology, functional materials, synthesis of novel radioisotopes, and ion beam technology (Fig.8&9).

Silicon(Si) is widely used in manufacturing various types of semiconductor devices. However, it has inherent drawbacks in connection with its application to high temperature, high power, high speed switching, and radiation resistant devices. Silicone carbide and diamond are expected as materials for LSI in the next generation. For the fabrication of SiC devices, it is important to control donor and acceptor impurities in SiC to regulate its electric conductivity. Nitrogen and aluminum are generally used as a donor or an acceptor impurity element, respectively. The ion implantation technique was found useful when the process temperature was kept higher than 800℃. Various defects formed during the implantation could be eliminated at temperatures over 1500℃ to form electrically effective pn junctions(Fig.10).

For the use of diamond for semiconductor devices, synthesis of a single crystal is a key technological problem at present. Ion beam deposition technique is expected to enable such synthesis with ultra high purity and high crystal perfection. Formation of thin film of diamond crystal on a Si substrate was performed using low energy C-12 ion beams. Energetic C-12 ions were mass separated and decelerated down to 10 or 100 eV. As shown in Fig.11, diamond single crystal was formed at the energy of 100 eV. It is interesting to note that the diamond crystal is formed after the amorphization in the mixed layers of Si and C at the surface of the substrate.

The use of ion beams in the processing of polymers is very limited at present. Only the particle track membrane(PTM) is used. But its performance is very low. In order to enhance the performance of PTM, the radiation grafting of environmental responsive polymers was conducted to the wall of the micro pores. Fig.12 is a photo of AFM observation to see the temperature responsiveness of the grafted pores. It shows an open state of the pore at 30℃, and a closed state at 0℃. We can also give other environmental responsiveness such as the responsiveness to hydrogen ion concentration, or electric field strength. These responsive pore membranes will be used for material diffusion control for pharmaceutical purposes.

The radiation application for agricultural purposes has a long history, but the use of ion beams is very scarce. In order to introduce a desirable genes from wild plants to cultivar, many works have been carried out, particularly in relation to disease- and insect-resistance. However, it is very difficult or almost impossible to get a viable plants between distantly related species, because of cross incompatibility or hybrid inviability. Recently, we found that pollen irradiation with ion beams was effective for overcoming these barriers. For example, in the case of tobacco plant, we found that the ion beam irradiation was characterized by the fact that it could exclude a concurrent unfavorable mutation which was inevitable, on the other hand, in the case of gamma-ray irradiation (Fig.13).

Further, ion beams was found effective to induced a novel mutant. An ultra-violet light resistant mutant which had never been obtained by other methods, was obtained by seed irradiation with C ion beams. Based upon these fundamental results, I would like to emphasize that the use of ion beams in the field of plant biotechnology will give us great profits in near future(Fig.14).

High Quality Radiation Sources in Future

I intended to show some future possibility which is foreseeable from the current studies at TRCRE. Now, I will touch briefly upon radiation sources in future. Synchrotron Radiation (SR) as well as X-ray laser, neutrons and positrons will appear to the area of the radiation processing. The SR and X-ray laser are electromagnetic radiation like gamma rays, and characterized by their very high intensity and coherency. They will give a great possibility for upgrading of the conventional radiation processing technology like LSI production. The JAERI has been engaged in the construction of those radiation sources. The latest SR-facility(SP-ring 8) having been completed by a joint work of JAERI and RIKEN began to operate in this month(Fig.15).

Neutrons will develop a novel field in the radiation processing technology where nuclear reactions play an important role, such as processing for annihilation of long-lived radioactive wastes produced in the nuclear power generation. The major facilities to be constructed are shown in Fig. 16, thus, 1) a super-conducting proton linac with proton energy of 1.5GeV and maximum beam power of 8MW for neutron production , 2) a linac with proton energy of 1.5GeV and maximum beam power of 5MW, allowing high intensity pulsed neutron beams for neutron scattering, and 3) research facility complex for accelerator-driven transmutation experiments, material irradiation and so force.

A positron is an antibody of electron. It has an unique mechanism for ionization. It can ionize material through the positron attachment followed by electron-positron pair annihilation. Thus, the ionization can be induced in a soft manner in a very low energy range from sub-eV to a few eV, and therefore, it is totally different from a violent manner by kinetic energy of energetic radiations. Positrons attach to chemically active groups which have large positron affinity and induce specified bond scission through the soft ionization. When it becomes possible, we could have a new tool for material manipulation. Under the positron project, positrons are produced by conversion of energetic electron from a linear accelerator of 100MeV and beam power of 100kW. High energy electrons are bombarded on an electron-positron converter, which causes a cascade shower of Bremsstralung and pair production reactions to generate energetic positrons. The energetic positrons are then moderated to be slow positrons. A tentative goal of the slow positron beam intensity is as strong as 10^{10}/sec(Fig.17).

Conclusion

The radiation processing technology will continue to provide possible technological solutions to the problems in the 21st century.

Table 2 shows the summary of my talk. In the field of environment, the electron beam cleaning of the flue gas will widely be accepted, because of its technological and economical benefits. Atomic power production can be sustained by fuel uranium from sea water. The radiation processing technology will also contribute to health care field by supplying new pharmaceutical polymer products. Interesting application of ion beams is expected in the field of biotechnology to enhance food production. Materials like SiC composites are expected as structural materials for the use under extreme conditions such as high temperature, intense radiation, possibly being capable for the use in space, nuclear fusion reactor. Electronic devices will also be more adaptable under severe conditions by introducing SiC and diamond as the basic semiconductor materials for the next generation LSI. Ion beam processing technology will be applied for their manufacturing.

As new radiation sources, Synchrotron Radiation(SR), neutrons and positrons which are characterized by their high quality and strong intensity will become available. Their present main interest is not necessarily in the application to the radiation processing technology, but they will certainly contribute to the progress in the radiation processing technology in future.

Fig.1

Schematic Digram of electron Beam Flue Gas Treatment

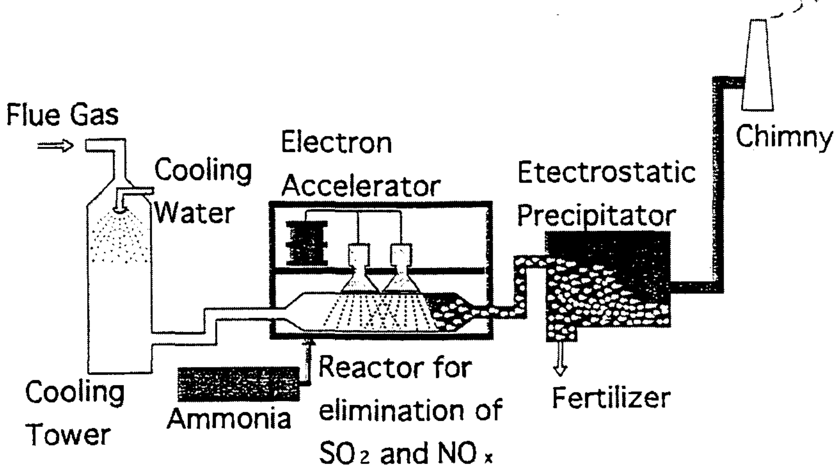


Fig.2

Removal of Volatile Organic Compounds in Ventilation Air

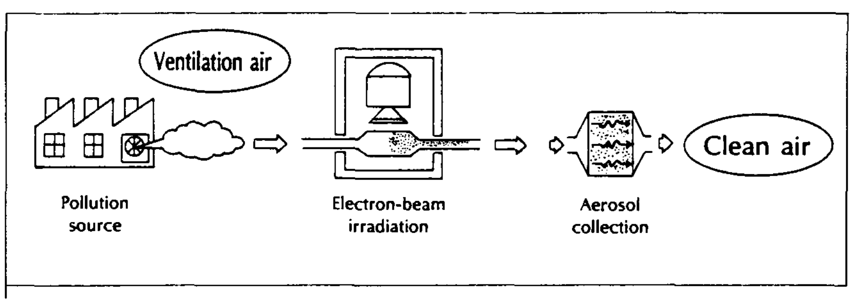
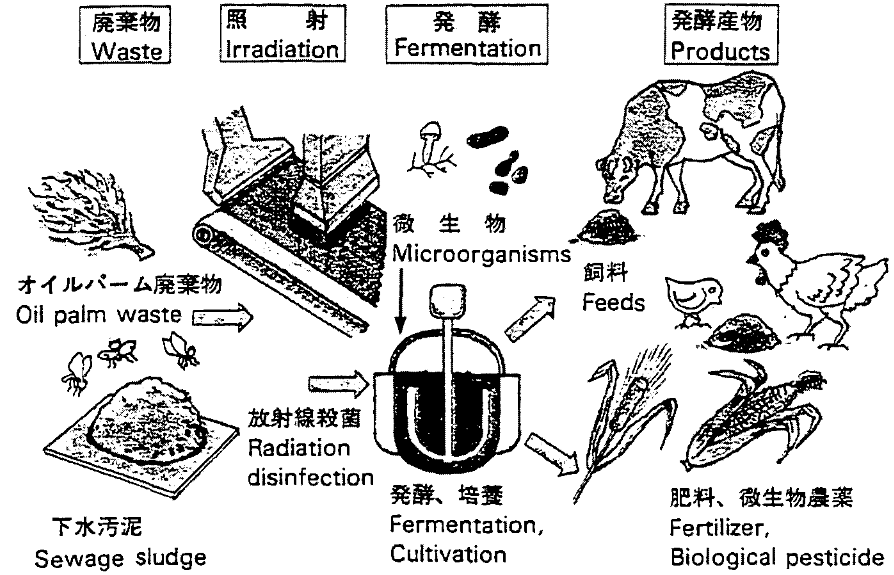


Fig.3



放射線による廃棄物の資源化
Upgrading of biological wastes by radiation

Fig.4

Development of adsorbent for recovery of metals from sea-water.

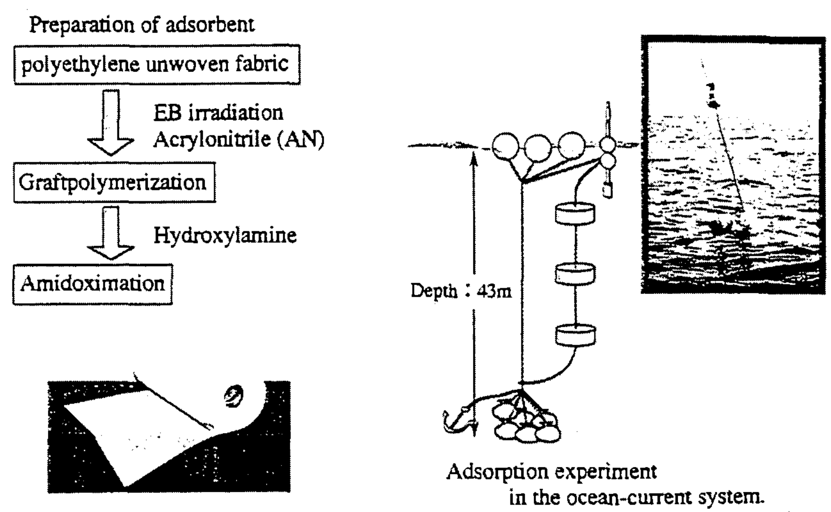
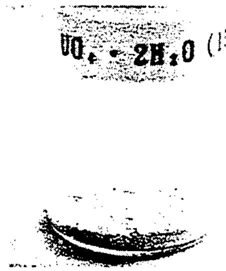


Fig.6

Performance of Adsorbent

Metals	Conc. in seawater µg/kg	Conc. in adsorbent g/kg	Conc. Ratio
Uranium (U)	3	~ 3	1×10^6
Titanium (Ti)	1	~ 2	2×10^6
Vanadium (V)	2	~ 6	3×10^6
Cobalt (Co)	0.1	~ 6	6×10^7

(Soaking period : 20 days)



Yellow-Cake from Sea-water.

Fig.7

Manufacturing of Ceramic Composites

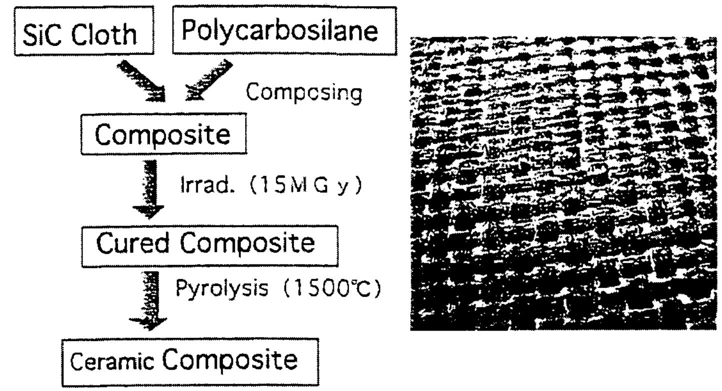


Fig.6

Preparation of Ceramic Fiber from Plastic Fiber

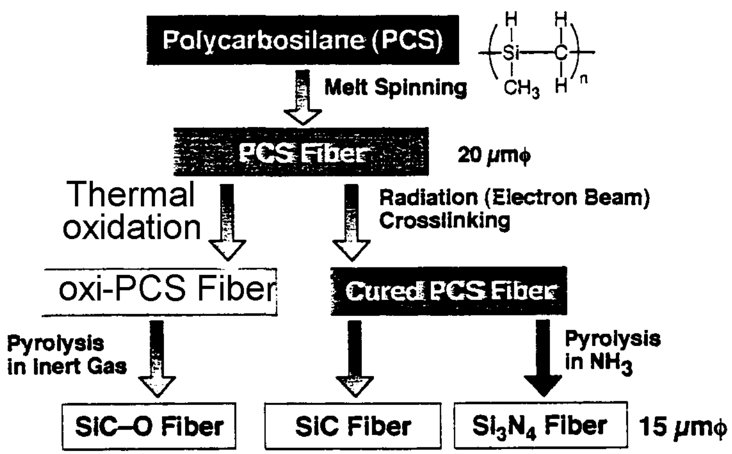


Table 1

For Environment

Polymeric fibers grafted with ion exchange residues to remove toxic metals for cleaning industrial waste water

For Health Care

Crosslinked polyvinylalchohole hydrogel for wound dressing

For High Performance Materials

Less-toxic crosslinked natural rubber latex

Abrasion resitant crosslinked PTFE

Fig.8

Accelerators and Beam Lines in TIARA

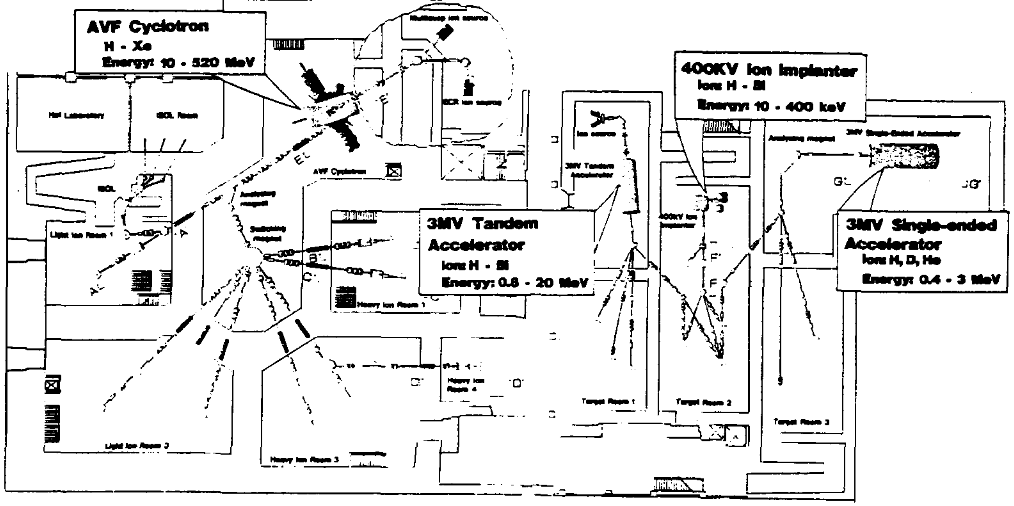


Fig.9

MAIN RESEARCH FIELDS OF THE ADVANCED RADIATION TECHNOLOGY PROJECT

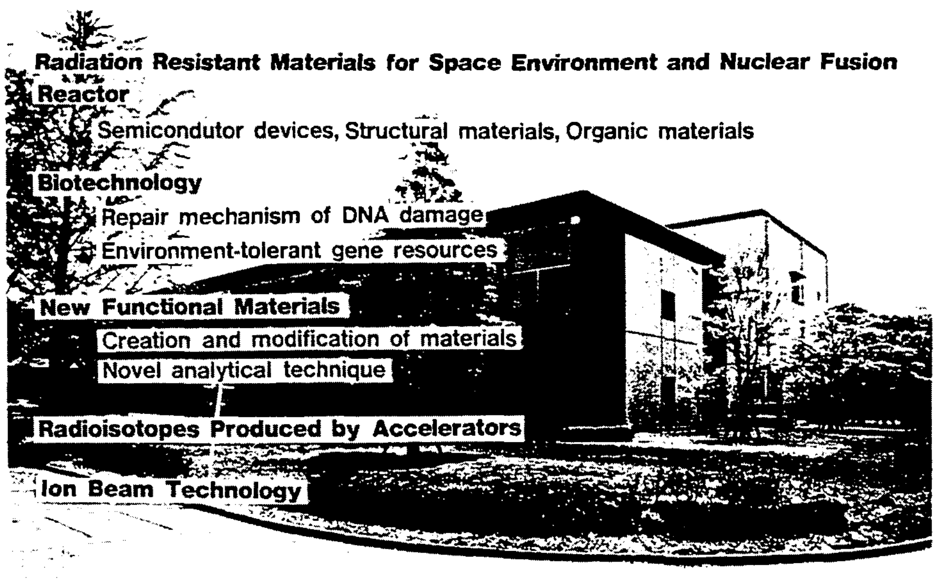


Fig.10

Hot-implantation of Nitrogen Ions on SiC

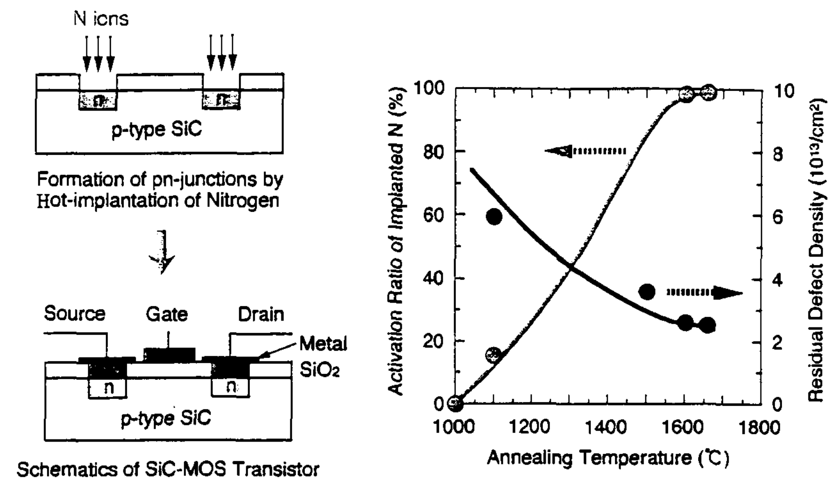
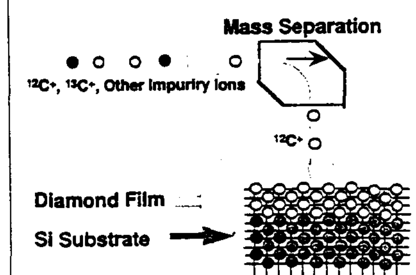


Fig.11

Synthesis of Diamond Thin Crystal Using Ion Beam Deposition Technique



Energy / Fluence (^{12}C / cm^2)	Synthesized Phase 10 eV	Synthesized Phase 100 eV
0	Si (111)	Si (111)
10^{15}	Cubic SiC +	Amorphous
10^{16}	Si (111)	Amorphous
10^{17}~10^{18}	Graphite Polycrystal	Diamond Thin Crystal

Fig.12

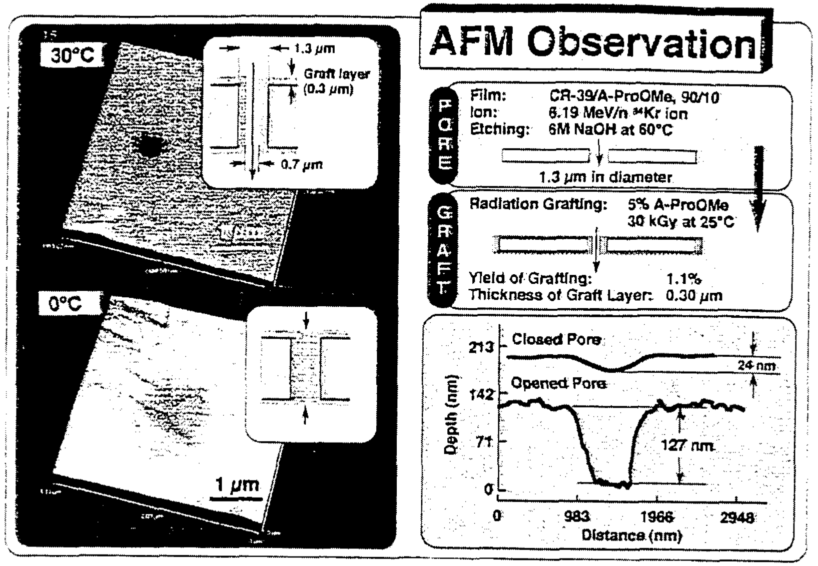
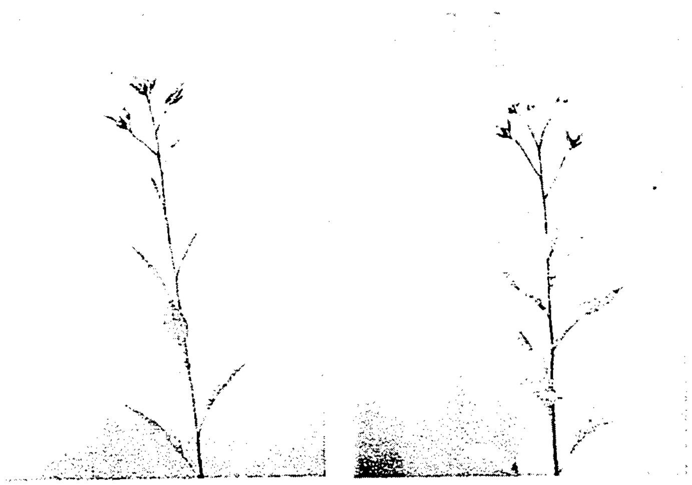


Fig.13

Tobacco plant



Hybrid (ion beams) Hybrid (gamma-rays)

Fig.14

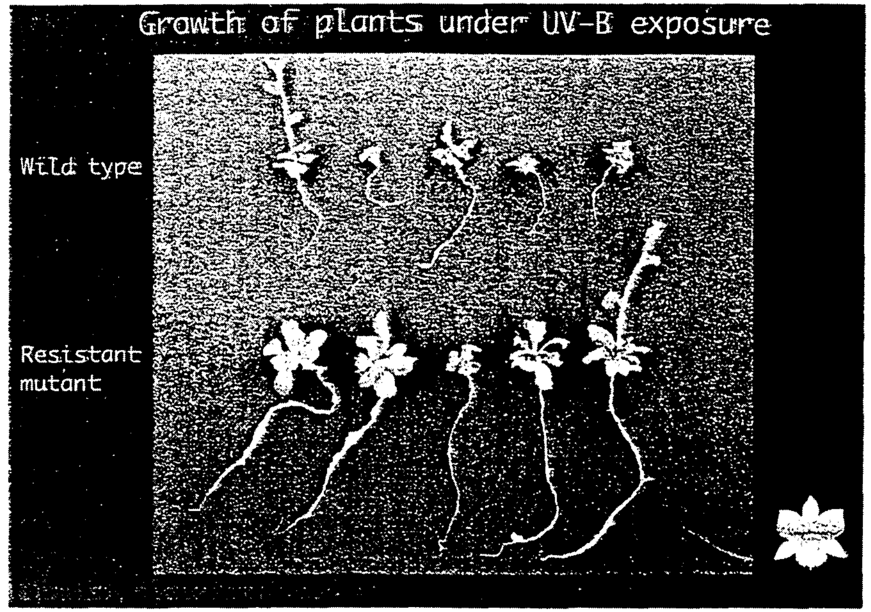


Fig.15

An aerial photograph of SPring-8 showing the linac(left), the synchrotron(left), and the storage ring(center).

Fig.16

Concept of Neutron Science Facility Complex

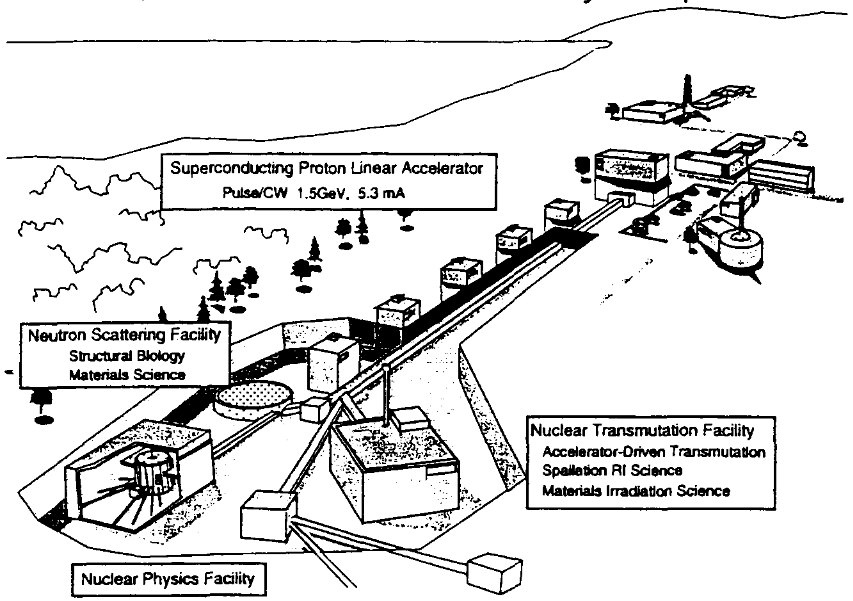


Fig.17

Outline of Positron Factory

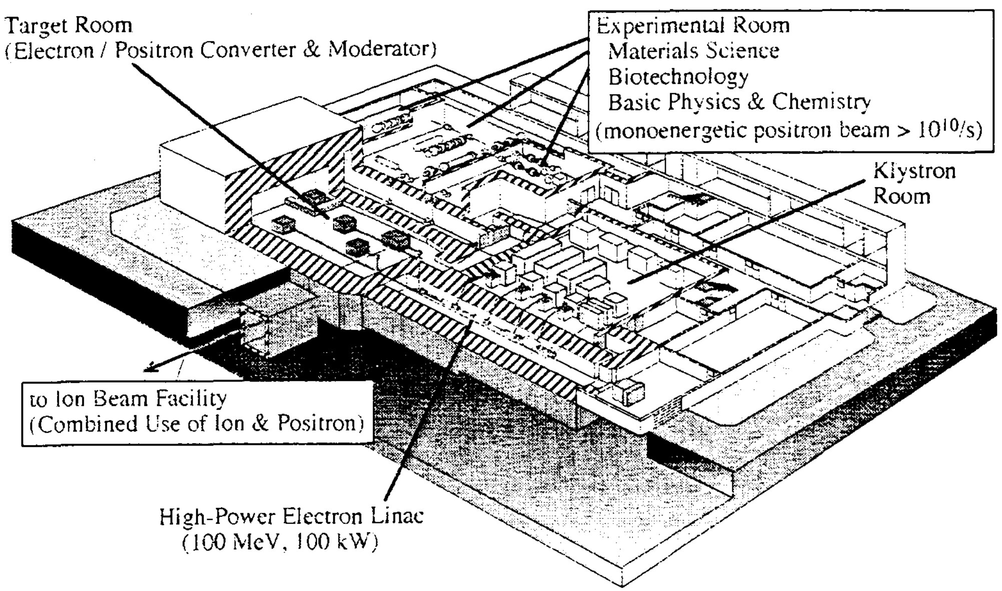


Table 2 Radiation Processing Technology Contributing to Human Life in 21st Century

Environment, Energy & Natural Resources
Cleaning of oil & coal combustion gas by electron beams (elimination of SOx, NOx)
Cleaning of industrial waste water (elimination of Pb, Cd and other toxic metals)
Cleaning of air (elimination of trace HCl, NH_3, amines and others in air)
Recycling of agricultural wastes, plastics and others
Recovery of useful metals from sea-water (U, Ti, V and others)
Health Care & Foods
Radiation polymerized or crosslinked clean polymers (drug delivery, wound dressing)
Radioisotopes for diagnosis and cancer therapy (positron emitting RI and others)
Mutation breeding & cell surgery by ion beams (new plant species for foods, flowers and others)
Materials
Ceramic fibers and composites (space development, nuclear fusion reactor, et. ct.)
Radiation Vulcanized Natural Rubber Latex (surgery and household uses, clean and safe)
Abrasion resistant crosslinked PTFE (industrial use, space development, et. ct.)
Manufacturing next generation LSIs (SiC semiconductor devices, single crystallin film of diamond)
New Radiation Sources
Synchrotron Radiation (LSI manufacturing, et. ct.)
Intense High Energy Neutrons (transmutation of long lived nuclides from nuclear power plants)
Intense Low Energy Positrons (material manipulation, et. ct.)