International Conference

Radiation Processing for Plastics and Rubber

15 to 17 June 1981

Bedford Hotel,
Brighton,
Sussex

THE PLASTICS AND RUBBER INSTITUTE
11 HOBART PLACE · LONDON SW1W 0HL

International conference

RADIATION PROCESSING FOR PLASTICS AND RUBBER

15-17 June 1981

Bedford Hotel, Brighton, Sussex, England

Organized for the PRI Meetings Committee by the following:

C1981 The Plastics and Rubber Institute
11 Hobart Place
London SW1W OHL
Telephone 01-245 9555
Telex 912881
Cables Plarubinst London SW1

VENUE

The conference will take place in the Sussex Room at the Bedford Hotel, Kings Road, Brighton, Sussex BN1 2JF (telephone 0273-29744, telex 877245 prefix Bedford). The hotel is situated on the seafront a short taxi-ride from the railway station.

TRAVEL

There are frequent trains from Victoria Station, London, and the journey takes about one hour. There is also a direct train service from Gatwick Airport.

SOCIAL FUNCTIONS

On the Monday evening the Mayor of Brighton has invited delegates for cocktails in the Banqueting Room of the Royal Pavilion from 1900 to 1945 (dress informal). Numbers are limited on this occasion to 220, and tickets will be allocated as registration forms are received. If your form was among the first 220 to arrive, your ticket will be enclosed with this booklet.

The Conference Dinner will take place at the Bedford Hotel on the Tuesday evening at 1900.

REGISTRATION

The conference registration desk in the main hall will be open from 1700 to 1900 on Sunday evening 14 June, and from 0815 on the morning of Monday 15 June. All participants are asked to call at the desk to collect a badge, list of delegates, and any other conference literature. Delegates may leave messages or seek information there but it is regretted that it will not be possible to contact delegates other than by showing their names on the message board. Coin-operated telephones are available at the hotel.

PROCEDURE AT SESSIONS

Speakers are asked not to exceed the time allocated to them on the programme, bearing in mind that this should be used for highlighting the important points in their paper. Projection facilities will be available for 35mm slides and overhead projection. All slides should be in boxes clearly marked with the contributor's name. These should be handed to the projectionist before the start of the appropriate session and be collected after they have been shown.

Chairmen are responsible for keeping authors and discussion contributors to the correct timekeeping

PUBLICATION OF PROCEEDINGS

It is hoped to prepare a general report on the conference for publication in a future issue of Plastics and Rubber International. The PRI claims the copyright for all the papers, and they must not be reproduced in part or in whole without written permission having first been obtained. All papers will be considered by the Journals Committee for publication in the Institute's quarterly 'Plastics and Rubber Processing and Applications'.

MEALS AND REFRESHMENTS

Coffees and teas will be served in the foyer. Lunches and dinners will be in the restaurant but with regard to dinners delegates should note that only the cost of the conference dinner on the Tuesday has been included in the conference registration fee. Delegates will need to make their own arrangements for dinner on the Sunday and Monday evenings, although this can of course be reserved at the hotel.

The bar in the hotel will be opening during normal licensing hours.

ENQUIRIES

Enquiries prior to the conference should be addressed to:

Patricia Barham
The Plastics and Rubber Institute
11 Hobart Place
London SW1W OHL (telephone 01-245 9555, telex 912881)

P R O G R A M M E

Monday 15 June 1981

Session A Chairman A A L Challis (PRI Vice-Chairman of Council; Chief Scientist, Department of Energy)

FUNDAMENTALS OF RADIATION PROCESSING

0915 1 Introductory paper
A Charlesby (Royal Military College of Science, Shrivenham)

0940 2 Radiation dosimetry
W L McLaughlin (National Bureau of Standards, USA)

0955 3 Pulsed NMR techniques for the study of irradiated polymers
A Charlesby (Royal Military College of Science, Shrivenham)

1010 4 Application of new NMR technique to a study of cross-links
J Sohma and M Shiotani (Hohhaido University, Sapporo, Japan) and T Yoshida (Government Industrial Development Laboratory, Sapporo)

1025 Discussion

1040 Coffee

1110 5 A study of crosslinking in polyethylene using mechanical and chemical measurement techniques
B J Lyons (Raychem, USA)

1125 6 Radiation induced graft-polymerization
A Chapiro (Laboratoire de Chimie Macromoleculaire sous Rayonnement CNRS, France)

7 Paper withdrawn

1140 Discussion

1200 Lunch break

Session B Chairman G Hall (Director, Brighton Polytechnic)

RADIATION SOURCES

1400 8 Radiation sources and their characteristics
G B Wills (BICC Research and Engineering Ltd)

1420 9 Low energy linear cathode electron processors
Urs V Lauppi (Charmilles - Energy Sciences International, Switzerland)

1435 10 Modern ICT electron processing systems
A Kuipers and J Stronckhorst (High Voltage Engineering Europa BV, Netherlands) and T B Fox (High Voltage Ltd)

1450 11 Electron radiation processing accelerators
P J Cracknell (Radiation Dynamics Ltd)

1505 12 Processing by gamma radiation - operation of a multi-purpose service
F J Ley and J Grant (Irradiated Products Ltd)

1520 Discussion

1540 Tea

Session C Chairman G R Shearer (Director, Tyre Manufacturing, Dunlop Ltd)

INSTALLATION AND ECONOMICS OF RADIATION FACILITIES

1610 13 Installation of radiation facilities
V J Boaler (Radiation Dynamics Ltd)

1630 14 Quality improvements and energy savings provided by electron beam processing of rubber and plastics
R L Malnati and C K Schmidt (High Voltage Engineering Corporation, USA) and H J Peters (High Voltage Engineering Europa BV, Netherlands)

1645 15 Electron beam processing of PE foam, PE film, calendered sheet rubber, and PE and PP bulk resins - the technological and economic advantages
R C Becker (Radiation Dynamics Ltd, USA)

1700 16 Low-voltage electron accelerators and their uses
P Holl (Polymer-Physik GmbH+ Co KG, FR Germany)

1715 17 Economics and processing with low-energy accelerators
J R Seidel (Energy Sciences International, Switzerland) and A Charlesby (Royal Military College of Science)

1730 Discussion

1900-1945 Cocktail reception at the Royal Pavilion

Tuesday 16 June 1981

Session D I Chairman Professor A Charlesby

APPLICATIONS

0930 18 Introductory paper by Professor J Silverman (University of Maryland, USA)

0950 19 Radiation sterilization of PVC medical components
M S Biggs, M J Gall and A E Thornton (BIP Vinyls Ltd)

1630 Open Forum

1900 Conference dinner at the Bedford Hotel

Wednesday 17 June 1981

Session D II Chairman J C Harrison (British Post Office)

0930 31 The use of irradiation for the production of shrink packaging materials
W G Baird Jr (W R Grace & Co, USA)

0945 32 Uniform electron beam crosslinking of polyethylene for foam production
A B Paterson (BXL Plastics Ltd)

1000 33 Irradiation of ultra-oriented high density polyethylene: effect of additives and drawing conditions
T Tincer, F Cimen, I Cimen (Middle East Technical University, Turkey) and G Akay (Cranfield Institute of Technology)

1015 Discussion

1030 Coffee

1100 34 A new radiolitically crosslinkable poly (vinyl chloride) insulation for telecommunications wire
E Scalco, W F Moore (Bell Laboratories, USA)

1115 35 Radiation cross-linked PVC jumper wire in the British Telecommunications (BT) part of British Post Office
P S Bridle and E R King (British Telecommunications)

1130 36 Gamma irradiation of electric cables
J Egan (BICC General Cables), A A Pinching and G B Wills (BICC Research and Engineering)

1145 37 Dose uniformity in electron beam irradiated cables and cores
R Bäuerlein (Siemens AG Research Laboratory, FR Germany_

1200 Discussion

1215 Summing-up
Professor J Silverman (University of Maryland)

1230 Lunch

RADIATION PROCESSING FOR PLASTICS AND RUBBER

INTRODUCTORY PAPER

Professor A. Charlesby R.M.C.S., Shrivenham, Swindon, U.K.

The study of materials exposed to high energy radiation has had a long history in academic circles; under such headings as radiation physics, radiation chemistry and radiobiology it is being continued very intensively in Universities and Research Institutes throughout the world. Thus 1200 papers on different aspects of radiation chemistry alone now appear annually. Radiation science taken as a whole occupies a central position, linking such apparently diverse subjects as basic physics (e.g. the basic interactions of radiation with matter), materials science, chemical reaction kinetics and biological effects, including radiation protection and medical treatment.

Industrial applications have appeared more recently, and have grown rapidly mainly in two fields - radiation treatment of plastics and rubber, and radiation sterilisation. These apparently very different fields are in fact related since in each case we are altering the chemical structure of macromolecules beneficially, and almost certainly relying on the same basis type of reaction. Here we are concentrating primarily on the former: radiation treatment of plastics and rubber now amounts to about 1000 million dollars per year, increasing at a rate exceeding 20% per annum.

The number of fields of application of radiation technology is also extending into such diverse topics as sewage treatment and food sterilisation. Nevertheless the main application still resides in the modification of macromolecules. My task at this stage is to outline the general aspects of the technology, and many of my comments will therefore be familiar to those who have worked in the field for a number of years. Fuller details and new advances will be given by later speakers.

The first point to be made is that radiation treatment of polymers has nothing to do with nuclear energy, which suffers from widespread public disapproval. It is in fact more closely related to photochemistry but with considerable differences and many advantages. Although some of the radiation sources used, especially in sterilisation, are radioactive, this is by no means essential, and most polymer processes involve high energy electrons. In any case mains electricity used in factories and homes may also derive from nuclear installations, but this does not mean that home cooking falls into the category of nuclear reactions. The reactions we are dealing with are those due to radical and ionic species, largely parallel to those involved in conventional chemistry, and no nuclear reaction or induced radioactivity is involved. To some extent this confusion with nuclear energy may have inhibited the growth of industrial applications. The best illustration I can give is that the use of relatively high doses of radiation for food preservation has now been accepted by such eminent bodies as the World Health Organisation, the Food and Agriculture Organisation, and the International Atomic Energy Agency. After many years of protracted and expensive research, it was concluded that radiation treatment of foodstuffs produces the same basic types of change as conventional cooking.

A second and most important feature is that radiation - induced modification of polymers and rubber can operate over a wide range of conditions such as temperature, and even in the solid state. It is also very easy to control geometrically. This can have a considerable effect on its applications since it now becomes possible to reverse the usual production sequence from raw material to final product. An object can be fabricated in its final physical shape, and then irradiated to initiate chemical reactions which give it further desirable properties whereas usually the chemical steps precede the physical ones. Thus the use of radiation techniques will frequently be a late step and in the hands of the fabricator, and not a chemical process producing a polymer which then has to be fabricated elsewhere.

The radiation technique is so very different from conventional chemical methods involving temperature changes and catalysts, that it is perhaps not surprising that chemical engineers of long experience have often been averse to its introduction. It is only with the widespread introduction of this new technique, and its obvious success that they are being forced to study its potentialities more closely. In fact radiation treatment, especially of polymers, is a remarkably simple process and it is often only lack of familiarity which has been a serious obstacle to its introduction. Another obstacle is sometimes that very early enquiries, made at a time when little was known or understood or economic sources were not available, led to premature judgements and these have not been re-examined. Recent conferences, especially those in Puerto Rico, Miami and Tokyo attracted considerable attendances from large industrial concerns, and led to a much wider understanding of the technique of its possibilities and limitations. We are confident that this meeting and the coming international meeting in Jugoslavia in 1982 will strive to extend this awareness, and bring to light new potential applications and fresh investigations.

The very early researches on radiation effects - some going as far back as over a century - used the two sources available at the time, fast electrons and X-rays, and the most widely used sources still fall into these categories - energetic electrons from accelerators and gamma radiation from cobalt 60. The choice depends on required penetration, dose rate (if this is relevant) and costs. Other forms of radiation such as fast neutrons, alpha radiation or other radiations present in reactors have been used for research purposes in polymers and lead to essentially the same type of chemical reaction. The energies used run from a fraction of a million to a few million electron volts for accelerated electrons and 1.3 million ev for cobalt 60 gammas. In their passage through matter the electrons or energetic photons lose energy by well-understood processes, in the course of which bonding electrons in the irradiated material are raised to higher energy levels (excitation) or stripped (ionisation). This leaves a trail of ions, electrons, broken chemical bonds, H atoms etc., and therefore radicals and ionic species. In photochemistry, where photons of only a few e.v. are used, absorption is selective, penetration is usually low and the energies inadequate for ionisation.

Since chemical bonds only require a few e.v. for destruction, it might be expected that incident radiation by particles of typically several million volt would cause bond destruction at random. In fact this is not so. For reasons which need not be discussed here, the reactions involved are remarkably selective, and it becomes possible to separate simple polymers into those where it is the backbone (-C-C-) linkages which are fractured (degradation) and those in which the sidechains (e.g. -C-H) are preferentially broken. The latter process can then lead by a series of later steps to crosslinking.

In spite of the great discrepancy in energies ($\sim 10^6$ MeV for incident electrons $\sim$10 ev for bonding electrons) the process is relatively efficient since each incident particle provides a large number of broken bonds. A typical figure is 30 ev per broken bond, comparable to the energy required to form an ion pair in air. This leads immediately to an estimate of efficiency. The G value is defined as the number of reactions per 100 ev, and is of the order of 3 (to within a factor of 3) in most polymers. Only in certain aromatics such as polystyrene is the figure very much lower ($<<1$) and this can be used to make radiation stable polymers. Since 1 Kwh = 2.25×10^{25}ev, each Kwh of energy absorbed produces $2.25 \times 10^{25} \times$ G/100 reactions, or typically about 1 mole. This allows us to make an initial comparison of radiation costs with those using chemical catalysts likewise capable of producing radical species. The rapidly decreasing cost of one Kwh from industrial radiation sources means that for some purposes radiation techniques are directly competitive with conventional chemical processes - quite apart from certain advantages such as lack of thermally dependent reactions, chemical residues etc. Up till now however, radiation has been used primarily in processes where more conventional chemical methods are difficult or impossible to apply.

Radiation doses have been expressed in terms of a unit - the rad or 100 erg/g of absorbed energy. Doses used in polymers and rubber treatment are usually a few megarads (1 Mrad = 10 joules/g = 2.4 cal/g). Thus 1 Kwh of absorbed energy can provide 1 Mrad to 360 Kg, or 2.5 Mrad to 144 Kg. In practice not all the energy produced is absorbed in the irradiated material. The cost per Kwh will of course depend on the size and type of radiation source and shielding amortisation, manpower, energy costs etc. Many industrial radiation sources are very economical users of energy, which in present and future planning can be of considerable importance. In many more conventional processes high heating costs are involved in raising the temperature of the entire specimen so that only a minute fraction of the chemical bonds can be broken.

Recently a new unit has been introduced - the Gray (1 Gy = 1 joule/kg or 10^{-4} Mrads). Thus doses involved in polymer treatment are of the order of tens of kilogray(kGy). May I take this opportunity of recording my sorrow at the ultimate decease of an old and faithful servant and friend - the megarad.

The immense flow of research papers on basic radiation chemistry has not yet been reflected in industrial applications on the same scale as those in plastics and rubber treatment. Why is this?

Basically radiation treatment is a means of producing reactive radicals (including H atoms), ionic species and trapped or free elctrons within the irradiated specimen. These may lead to simple reactions each involving a few, typically two radicals, or to a chain reaction initiated and often terminated by a radical. In the former case, with molecules of molecular weight M, 1 Kwh of absorbed energy will provide an average of one radical/ molecule in 2.25×10^{23} GM/$6.02 \times 10^{23} \sim 0.37$GM g. of irradiated product. If $G \sim 3$ and $M \sim 200$ this equals only 224 g, so that at present costs of radiation energy, the process is only economically feasible for products of high value. The same arguement of course applies to any conventional chemical process in which one catalyst molecule must be furnished per molecule to be modified. For polymers and rubbers however, where M may be of the order of 10^5, the same G value will result on a yield exceeding 100 Kg. It is already known from polymer theory that a single main chain scission or crosslink can greatly affect its physical properties. These will be discussed in fuller detail later at this meeting.

For chain reactions these considerations no longer apply, and many chemical processes such as chlorination become very feasible. It must be stressed however, that the radiation only intervenes in the initiating and/or terminating step - the propagation step is subject to the usual chemical limitations. However, radiation techniques may still be advantageous - lack of catalyst residues, complete temperature control, solid state reactions etc.

An outstanding example of such a chain reaction is of course polymerisation, which can be promoted and studied very usefully with radiation. The effect of temperature on the propagation step, the effect of radiation intensity (dose rate) and hence of radical concentration, the lifetime of radicals, ionic processes, the influence of additives, trapped radicals, ions and electrons, pressure effects etc., have all been investigated. One is still faced with the question of how such radiation - induced processes can be used on an industrial scale. One is now looking for reactions which cannot readily be initiated by more conventional means. The study of polymerisation reaction in the solid state has led to some surprising results, e.g. for some monomers polymerisation occurs more rapidly than in the liquid form; in others some structure may be present in the liquid state resulting in remarkably rapid polymerisation. Solid state polymerisation would of course give rise directly to oriented polymeric materials; however, early efforts to produce such materials on an industrial scale largely ceased due to general economic difficulties.

Much effort has been devoted to the production of graft copolymers, for which purpose low doses of the order of a Mrad (10 kGY) are usually adequate. Several methods are available - irradiation of a polymer in the presence of a monomer (in which case it is necessary to take measures to avoid homo-polymerisation); irradiation of polymers in the presence of oxygen to give oxidised products which on subsequent heating in the presence of monomer, yield reactive groups which then initiate the grafting reaction; irradiation of polymer "padded" with monomer; irradiation of polymer, and subsequent immersion in monomer, the reaction being initiated by radicals trapped in the original polymer. The major obstacle to the production of grafted polymers by these methods is basically the need to find large-scale applications. However, certain applications have been found. Surface or volume

grafting onto films provides membranes whose properties may be chosen to fulfil specific requirements of strength, permeability and selectivity. Textiles can be treated to make their surface more hydrophilic or dyeable. New classes of polymeric materials have also been prepared for bio-engineering applications, for example with different mechanical bulk properties and surface characteristics where these two requirements cannot be met by a single polymer. One application in widespread use is the production of wood plastic composites, though it is not certain that this is a true graft - it may be a mixture of two polymers, of which one has been polymerised in situ.

It is clear that in this aspect of radiation - induced reactions, a major need is the intensive search for further useful applications. The copolymerisation reaction is readily understood, and the doses needed are usually small. Unlike the situation for crosslinking or degradation, dose rate can be an important factor in polymerisation, and low dose rates tend to provide larger polymer or grafted chains.

By far the major industrial use of radiation in the polymer field is for crosslinking and degradation of plastics and rubbers. Polymers can be divided into those which form intermolecular bonds due to side-chain scission, and those which suffer a fracture of the main chains and hence a reduction in molecular weight. The distinction while not absolute, is remarkably sharp. Among the polymers which crosslink predominantly, polyethylene, poly dimethyl siloxane, natural rubber have been studied in greatest detail. Degrading (scissioning) polymers include Teflon, polymethylmethacrylate and polyisobutylene. Polypropylene is one of the few polymers which occupies an intermediate position. P.V.C. is anomalous in that some form of chain reaction via chlorine abstraction appears to be involved.

In spite of the wealth of published papers, the precise mechanism of crosslinking has not yet been generally agreed. Ionic mechanisms have been proposed, but there can be little doubt that the major reaction is via radicals. However, the doses used are quite inadequate to produce high local concentrations of radicals, such that two radicals on adjoining chains can meet to form a crosslink. It may be that two different reactions are involved, one immediately, the other via long-lived radicals (whose presence can be measured by E.S.R.) It is then necessary to propose some degree of radical mobility along and between chains. The practical results are however clear enough; at low doses the average (M_w) molecular weight increases, and a network (gel) begins to form when there is an average of one crosslinked unit per weight average molecule. Beyond this gelation dose, the network fraction increases, and the average molecular weight between crosslinked units M_c diminishes. The statistics of the process follows standard polymer theory and can be used to provide networks of different swelling or mechanical properties.

At extremely high doses, when M_c is sufficiently small, polyethylene can be converted to a glassy material, with brittle fracture. Depending on molecular weight, degree of crystallinity and to a small extent on temperature, the minimum dose to gel formation is a few megarads; the dose for good network formation is often about 10 - 20 Mrads. For rubber network formation also requires a few megarads, but for maximum tensile strength a dose of

40-50 megarads is needed. This is expensive, and the widespread use of radiation in the rubber industry either involves partial cure or the use of radiation sensitizers; synthetic rubbers may require smaller doses.

Radiation can promote crosslinking in fully saturated compounds such as n. alkanes, and therefore has considerable advantages over conventional chemical techniques. The ability to crosslink even at low temperatures also permits the utilisation of the so-called "memory" effect for many practical applications, to be discussed later in this meeting. This offers a challenge to industry, to discover and develop new applications.

Main chain scission results in a reduction in molecular weight, which can be accurately controlled by radiation dose. In polymethylmethacrylate, both main and side chain bonds are broken, and one would like to discover why the two broken chains, held in close proximity in glassy state, do not reunite. Teflon is especially sensitive to radiation, and irradiated, degraded Teflon is used for lubricants and other applications requiring lower molecular weight polymer than that initially produced.

There exists another class of radiation-induced reaction, partaking both of the crosslinking reaction of simple polymers and of the chain reaction as in polymerisation. It has the advantages of requiring very small doses (of the order of a megarad) yet producing a high density of crosslinking; it is also applicable to low molecular weight compounds. The basic requirement is that a radical on polymer molecule A links it directly or via a chain to polymer molecule B, but also creates a further radical species on B, allowing this to link to C etc., without the further expenditure of radiation-produced radicals. The requirements is for sufficient unsaturated bonds per molecule to allow both polymerisation and crosslinking steps to proceed in partnership. In evaluating the economic feasibility of this reaction - which I have termed enhanced crosslinking - it is necessary to take into account the cost of suitably unsaturated monomers or polymers.

This type of reaction has been widely used for crosslinking PVC - insulated cable for telephone communication networks. The cost of monomers is more than compensated for by the greatly improved product and the much smaller amount of material needed. The process also lies at the basis of radiation cured surface coatings prepared from low molecular compounds - the high density of crosslinks forms a dense network structure.

The possibility of producing valuable new properties by irradiation was first explored in detail in the very early fifties, and larger scale industrial products began to appear very few years later. Interest has continued to grow as the advantages of the technique became more widely known.

Many present and potential applications will be described in the following lectures. Further information can be found in the scientific literature, and especially in Radiation Physics and Chemistry, which aims to bring together the basic science, technology and present/potential applications. Comprehensive bibliographs are also published in this journal. Up-to-date overviews can be obtained in the proceedings of the international meetings

on Radiation Processing. These indicate clearly the range of subjects being considered, such diverse topics as rubber treatment, plastic foam, heat shrinkable tubing and sheet, electrical cable and components, wood-acrylic composites, lithography, hot water tubing for space heaters, surface grafting, food packaging materials, crosslinked fluorinated polymers, hydrogels, textile and leather modification, film foil and paper converting, biomaterials, food sterilisation and environmental improvement. I feel that major advances involve not only a good understanding of what radiation can achieve, but equally a search for novel and commercially desirable objectives to which the technique can be applied. The latter can best be found at meetings such as these, which bring together scientists and technologists from many industries, with very diverse outlooks, approaches and experience but sufficiently open minded to search and recognise new possibilities.

Further reading

Radiation Physics and Chemistry

International Meetings on Radiation Processing

Vol 9 (Puerto Rico 1976)
Vol 14(Miami 1978)
Vol 18(Tokyo 1981)

Synopsis only submitted Full paper may be available later.

DOSIMETRY

W L McLaughlin (National Bureau of Standards, USA)

Quality control of the radiation processing of materials is assisted by reliable measurements of absorbed dose distributions. Although control and proper adjustment of irradiation parameters serve to maintain satisfactory performance, it is useful to be able to measure precisely and accurately the energy deposition throughout an irradiated medium. Neither the monitoring of electron beam current or power, radionuclide decay, product dimensions can give sufficient information to assure irradiation values within specified absorbed dose limits.

Radiation processing dosimetry practice is generally divided into three parts: (1) calibration according to traceability to standard methods, such as calorimetry and reference chemical dosimetry= (2) the use in production of routine calibrated dosimetry systems, such as plastic or dyed plastic films= (3) the reading of dosimeters and evaluation of dose and dose distributions based on statistically reliable analysis of calibration factors and systematic uncertainties.

In the radiation processing of polymers, elastomers, laminated layers, textiles, etc, the sources of radiation energy usually are electron accelerators, although for some applications X- or gamma-ray photons are used. The lateral dose patterns and scattering profiles, as well as the shape of penetration curves of radiation dose with depth determine the three-dimensional dose distributions in the product, which in turn affect the success of the process. Not only is the relative dose uniformity important, but also information about the spectral characteristics of the radiation must often be taken into account. Because of diffusion by scattering, oblique beam directions, charge trapping in insulators, charged-particle straggling, and other secondary scattering effects, the definitions of spectral and spatial radiation distributions are sometimes a difficult matter. It is therefore useful to map detailed dose distribution patterns in an irradiated medium, since spectral distributions at different locations are poorly known. Small dosimeter size greatly determines the ability to register accurately dose distribution patterns, as is explained by cavity theory considerations.

A bulky sensor can be considered an intruding probe, which displaces a portion of the medium of interest with a discontinuity. If the probe is of essentially the same density and atomic constituency as the host medium, it is capable of measuring dose realistically, as long as it was calibrated in a similar medium of thickness corresponding to an electron equilibrium layer. If, on the other hand, it had been calibrated bare in a 60co gamma-ray field, a very thin dosimeter would give a higher dose interpretation than say a more bulky chemical dosimeter. In the