RADIATION DAMAGE STUDIES FOR DETECTOR MATERIALS

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ABSTRACT

Radiation damage studies, and consequently R & D work, in identified fields have to be a crucial part of any project concerned with detector development for the next generation of hadron colliders.

The paper presents the programme of radiation damage studies of the LAA project, in which mainly two fields of activities appear: i) scintillating materials based on organic compounds or crystals, and ii) semiconductor materials for detectors and electronics. A review of the present knowledge is given, as well as the problems arising with parameters which influence radiation damage, such as radiation type, time and atmosphere.

1. INTRODUCTION

Studies of radiation hardness of materials used in installations for high-energy particle physics have in the past been concentrated on materials and components used in the primary beam areas of the accelerators. Very little or practically no consideration has been given to detector materials, because the radiation doses in present fixed target or collider beams are in most cases far below any damage level.

Exactly the opposite will be the case for future hadron colliders in the multi-TeV energy range where the accelerator will have to operate with low beam losses and hence low radiation doses, whereas in the collision region of the detector the doses will be in the order of 10^4 to 10^6 Gy (1 to 100 Mrad) per year and therefore similar or higher than normally accumulated in present primary beam areas in more than 10 years. To illustrate this fig. 1 shows the doses accumulated in the CERN 450 GeV Super Proton Synchrotron (SPS) during 10 years of operation (1) and fig. 2 the doses expected in one year in a detector of a future multi-TeV collider (2). Note that in fig.2 the doses were calculated for an integrated luminosity of 10^{40} cm^{-2} and that the doses increase linearly with luminosity. Further it must be noted, that most of the commonly used detector materials (plastic scintillators, semiconductors, electronics) are many orders of magnitude more sensitive to radiation than materials used in the accelerator tunnels (magnet coils, cables, hoses, etc.).

Therefore radiation hardness tests of detector materials and components are an integral part of the LAA project (3). In the first stage of the project this included development and selection of components which fulfil the sometimes very restrictive requirements and carry out radiation tests in parallel or at a later stage; these are mainly routine accelerated radiation tests. At a later stage long term ageing tests and R & D work in identified fields (e.g. semi-conductor detectors) need to be itensified.

A new aspect to be considered will be the detector design itself, where radiation-sensitive equipment (e.g. electronics) has to be placed in positions with lower radiation doses, e.g. laterally instead of in foreward directions (see fig. 2). Also the detector layout should allow a reasonably easy replacement of the most vulnerable components, and built in high dose dosimetry is necessary.

Before describing in more detail the programme of LAA radiation hardness tests, some information is given on experience from radiation tests on accelerator components and parameters which influence radiation effects.

2. EXPERIENCE FROM RADIATION TESTS OF ACCELERATOR COMPONENTS

Large experience has been gained especially at CERN on radiation effects on accelerator materials along with the tender and construction period of the main CERN accelerators and storage rings e.g. ISR, SPS and LEP. With this a large amount of radiation damage test data became available, which are compiled and documented (4). This documentation is also of interest for future detectors, where in some places the doses will be higher than in present accelerators, as stated above. Figures 3 and 4 give a schematic presentation of radiation resistance of a large variety of insulation materials which are used in high-energy particle engineering (4).

Even more important than routine accelerated radiation damage tests is the experience with radiation ageing of the materials during the operation of the accelerators. In order to be able to do this, more than 1000 passive integrating dosimeters are distributed in the primary beam areas of the CERN accelerators and the results are published regularly (5). This allows to check the dose calculations and the validity of the accelerated tests during construction; it also allows to decide on preventive change of damaged components and to make predictions for new projects.

Therefore it is strongly recommended to foresee in the design for future detectors a built in high dose dosimetry system. Also dosimetry in existing collider experiments (SPS, LEP and HERA) would be very useful. Again experience gained from the accelerator high dose dosimetry will be benificial (5).

A further outcome of an over 20 years activity in radiation testing of accelerator components are extensive contacts with industry, other institutes active in the field and international organizations like IAEA (International Atomic Energy Agency) and IEC (International Electrotechnical Commission). This contributed to the understanding of radiation effects in accelerator materials (6) and allows to standardize radiation tests (7). This standardization includes specification of materials to be tested, the radiation type, dose and dose rate and the atmospheric conditions. All these parameters are also of great importance for detector materials where a lot remains to be done in the standardization of radiation damage tests.

3. PARAMETERS WHICH INFLUENCE RADIATION EFFECTS

3.1. Radiation type and sources

The most commonly used device for radiation damage tests are the 1.2 MeV gamma rays from a ^{60}Co-source. Also X-ray sets, nuclear reactors, electron and proton accelerators and spallation neutron sources are used. By doing radiation tests in different sources and when comparing afterwards the results, one must be aware that the equal dose to equal damage principle does not apply for all materials. This is in particular true for semiconductor devices and electronics where the displacement damage by neutrons and protons may be much more pronounced than ionization damage by gamma rays. For organic insulating materials however, as shown in figs. 3 and 4 the damage is mainly dependant on dose, irrespective of the type of irradiation.

Important errors and confusion may be created when converting fluence to dose from neutron or proton irradiations in order to compare the damage effects. This conversion may depend on materials and energy. For example the neutron fluence to dose conversion for the Standard Neutron Irradiation Facility (SNIF) at ASTRA reactor (8) is for scintillators 2 x 10^{-11} Gy/n/cm^2 and for electronics it is 10^{-12} Gy/n/cm^2 for a neutron energy > 0.1 MeV. For neutrons of different energy (e.g. 14 MeV) another factor of 10 in difference may occur. For radiation damage tests with neutrons it is therefore essential to know the energy and to avoid conversion to dose for damage interpretation and comparison. In any case dosimetry must be an important and integral part of any radiation damage test programme (9).

Further, it must be noted that severe restrictions in sample size exist in most irradiation facilities. For example the container of the above cited SNIF has a diameter of 56 mm and a length of 120 mm only. Typical dimensions of standard Gammacell irradiation facilities are 150 mm diameter and 200 mm length. Therefore in most cases only small samples can be irradiated and not whole devices.

For future detectors it is most desirable to gain experience with damage in the radiation field around high-energy particle accelerators. For this reason parasitic irradiations are carried out behind an SPS target area at CERN and the construction of an irradiation facility near the PS is under study. In the latter the sample size needs to be small again, but irradiations can be carried out under more controlled conditions.

3.2. Radiation dose and dose rate

One of the basic problems of radiation damage tests is, that, in order to make predictions in time, they have to be carried out in an accelerated procedure. It is however not guaranteed that a material which receives a very high dose in one hour will exhibit the same damage when exposed to the same dose in a detector within one or several years. By consciously or unconsciously overlooking this most errors and wrong conclusion are made in present radiation damage studies for future detectos. The differences may involve orders of magnitudes and may go either way: less damage or more damage. This is demontrated in figures 5 and 6. Figure 5 shows the reduction of elongation at break of a conventional thermoplastic cable insulating material where reduction in dose rate, e.g. increase in time, severely increases the damage effect. Exactly the opposite is the case for radiation induced losses in an optical fibre cable, which at low dose rates exhibits less damage effects due to recovery (fig. 6, from ref. 14). Recovery with time is an important factor for many optical fibres, scintillators and crystals, therefore the time between end of irradiation and measurement needs also to be considered.

Extensive work has been carried out for high energy particle accelerators and nuclear power stations in the understanding of long term ageing effects in a large variety of materials and procedures and methods are proposed to eliminate the errors made by accelerated tests (10). For detector materials, especially scintillators, a large amount of work remains to be done.

3.3. Atmosphere

Like radiation type and dose rate also the surrounding atmosphere may influence radiation effects. In many cases it could be shown that the diffusion of oxygen into the sample enhances the radiation effect in organic materials. The fast degradation at low dose rate in the example given in figure 5 is explained by the presence of oxygen, which diffuses into the sample with time and which reacts with metastable peroxy radicals and catalyses further degradation. Therefore in many cases irradiation in inert atmosphere, e.g. N_2, or in vacuum reduces the radiation damage.

Detector materials which are most concerned with radiation effects in different atmospheres are scintillators and scintillating fibres. Unfortunately the results obtained so far are confusing and not well understood: Oxygen may not only enhance radiation damage as explained above but may also reduce it. Figures 7 (from ref. 12) and 8 (from ref. 13) show an example. More work is still required to understand this and take preventive measures for future detectors.

4. LAA RADIATION DAMAGE STUDIES FOR FUTURE DETECTORS

LAA is at present the only project in which systematic R & D work and prototype construction of all components of a future multi-TeV detector are carried out (3). Radiation hardness is one of the key objectives within this project; therefore the LAA units which have to use components in radiation fields are involved in radiation hardness studies. Table 1 gives a summary of the present status of these studies.

From Table 1 appear mainly two fields of activities:

i) scintillating materials based on organic components or crystals,

ii) semiconductor materials for detectors or electronics.

Performance and damage mechanism in these two fields are entirely different and have therefore to be dealt with by different groups of experts.

It must be stated that the present programme contains with same exceptions no activity which can be considered to be proper research into radiation hardness of detector materials. What is rather done are radiation tests in parallel with the selection of materials and components for which of course radiation hardness is an important criterion.

Apart from the activities within the LAA Units described above the LAA Unit 10: Radiation Hardness, has the task to coordinate the radiation studies within the project and maintain contacts with the Units concerned. In addition the following activities are going on:

- An X-ray source was made operational at CERN to carry out irradiations of electronic components.
- The construction of a facility at the PS is under study for irradiation of electronics and other small components.
- The acquisition of a powerful X-ray and gamma source for irradiation tests is under study.
- Contacts are being established with the Department of data processing and electronics of Hahn Meitner Institute, Berlin, on the subject of radiation tests on electronics and with the organic materials Department of SANDIA National Labs, on radiation degradation studies of polymer based scintillating fibres.
- Contracts exist with three irradiation facilities: Austrian Research Centre, Seibersdorf, Conservatome, Montluel and Hahn Meitner Institute, Berlin, for routine irradiations.
- Parasitic irradiations are carried out near a SPS target area.
- High dose dosimetry is carried out for radiation tests.

The ongoing activities in the other LAA Units listed in Table 1 are briefly described below. More details can be found in reports of the cited Units and in ref. 3. Some presentations are also included in the proceedings of this meeting.

4.1. Unit 1A, gaseous detectors

Two topics are considered in this Unit. The first was to study the ageing of the Multi-Drift-Modules (MDM) filled with high-purity Dimethylether (DME) when continuously exposed to X-rays. The relevant parameters monitored were: current, voltage, temperature and gas quality. This programme which was carried out in collaboration with Florida University, Gainsville is terminated and the results are published (15). Up to 10 kGy (1 Mrad) the results were very satisfactory.

The second part concerns the read-out electronics for the MDM. Irradiations were carried out on four unpowered chips (4 independent channels per chip) with gamma rays and reactor neutrons. Two different types were proposed: a Fujitsu preamplifier MB 43 458 and a preamplifier-discriminator from LeCroy TRA 402 and MVL 407. The latter survived 10^4 Gy (1 Mrad) gamma irradiation and 10^{15} n/cm^2. This is a very satisfactory result.

4.2. Unit 1B, Scintillating fibres

This Unit has an extensive radiation test programme for plastic scintillators and scintillating fibres. This comprises base materials such as polystyrene, PMMA and PVT and the commercial scintillators SCSN 38, SCSN 81, NE 110, and of course the new scintillator found, which is PMP in a polystyrene and PVT matrix. Irradiations are carried out at various sources: gamma, neutron, and near the CERN accelerators. Some samples were also irradiated in an inert atmosphere (N_2). Irradiations have been carried out up to 10 kGy (1 Mrad). The results have shown that PMMA is less suitable as matrix material than polystyrene and PVT. For the scintillating material good results have been obtained for SCSN 38, SCSN 81 and NE 110, whereas the PMP doped samples show some absorption, which can however be mostly recovered in oxygene atmosphere after one month. Investigations to improve the radiation resistance of PMP are in progress.

4.3. Unit 1C, GaAs microstrip detectors

Gallium Arsenide microstrip detectors are considered as an alternative to standard silicon detectors with the advantage to be more radiation resistant. Some examples of test structures have been built so far to measure the electric characteristics of GaAs. Samples have been irradiated to ^{60}Co gamma rays and at CERN up to 10^4 Gy. Irradiations to high doses are planned.

4.4. Unit 2A, High-precision electromagnetic calorimetry

As can be seen from fig. 2 doses in the calorimetry part of the detector become only important in forward direction at small angles. Radiation effects on Barium Fluoride crystals (BaF_2) and read-out electronics.

Long-term gamma irradiation of a 2 x 2 x 5 cm^3 BaF_2 crystals up to 3 x 10^5 Gy (30 Mrad) were carried out. No significant radiation damage occurred. Irradiations at CERN are in progress.

4.5. Unit 2B, Compact electromagnetic and hadronic calorimetry

This group produces the component known as spaghetti calorimeter (SPACAL) consisting of 1 mm diameter scintillating fibres embedded in a lead module. Important radiation damage tests are in progress in collaboration with LIP in Lisbon. Transmission and scintillating efficiency are measured. Irradiations have started on 15 kind of fibres from different companies (Kyowa, Optectron, Bicron, Cunz) at 5 dose rates and in 4 different atmospheres to doses up to 10^5 Gy (10 Mrad). The programme and first results have been presented at this meeting (16).

4.6. Unit 4, Leading particle detection

The components of this Unit need to be placed at small angles and very close to the beam. The expected doses are therefore extremely high (>10^6 Gy per year). A research collaboration has been established with the University of California, Santa Cruz, to develop radiation-hard compact VLSI electronics.

The project includes analog and digital devices. The analog part consists of the development of a fast amplifier-discriminator system with a dielectric isolated bipolar technology. This has to be faster (40 nsec pulse width for the

prototype) than previously available circuits. It is expected to be radiation hard even without the application of (secret) foundry techniques for hardening.

The digital part consists of a pipeline, buffer and read-out system, matched in speed to the analog part and designed in CMOS. It will be radiation hardened (contract with a specialized firm) and will serve as a yardstick for the overall LAA radiation-hardening programme. First results have been presented at this meeting (17).

4.7. Unit 5A, Subnuclear multichannel integrated detector technologies

This Unit essentially deals with silicon detectors and micro-electronics, both very sensitive to radiation. Some of these devices need to be placed very close to the beam line (2 cm), where doses are expected to be in the order of 10^5 to 10^6 Gy per year (see fig.2). This clearly shows that important R & D work is required on the one hand to obtain radiation-hard components and on the other hand to design systems that allow exchange of degraded devices.

At present only a modest programme of radiation tests is going on test components and on a 16-channel version of the AMPLEX low-noise amplifier, all made in standard CMOS technologies from 2 firms (Faselec, CH, and Mietec, B). Irradiations with X-rays have started.

At a later stage of the LAA project a rather extensive hardening project may have to be given to specialized manufacturers for certain circuits once the functioning of such circuits and their precise location are established.

Unlike for electronics, industry has little research power or interest in silicon detector devices. Detector fabrication technologies, in particular pixel detector development, needs to be carried out within the LAA project. Radiation tests on such detectors are planned to be carried out together with the irradiation and test programme described above for electronics.

4.8. Unit 5B, New radiation-resistant technologies

This project is based on a collaboration with Uppsala University and the Swedish Institute of Microelectronics. The goal is to design read-out electronics circuits in a silicon on sapphire CMOS process with a radiation resistance exceeding 10^4 Gy (1 Mrad). Irradiations are carried out with gamma rays and neutrons. The present programme is specified in two stages:

Stage 1 includes design and production of test structures on transistor level. These will then be measured and irradiated repeatedly to characterize the process and such basic structures with respect to radiation damage both in transistor parameters and in noise performance. The results from these studies will be used to make simulation models, allowing accurate predictions of circuit behaviour after radiation.

Stage 2 consists of design and production of more complex structures, such as amplifier stages, storage cells, compensating bias networks, etc., to be studied and measured with respect to electronic performance and radiation hardness. These structures and studies should then form a base of knowledge for the construction of complete read-out chips for high-energy physics experiments with predictable radiation lifetimes.

It is planned to continue this investigation further by producing a complete read-out chip and test this under real conditions.

4.9. Unit 6, Real time data acquisition and analysis

Complex electronic equipment has to be placed close to the tracking and calorimetry part of the detector for data acquisition and analysis. A number of pilot projects are being built up in order to explore the possibility to handle the high data rates as expected from a multi-TeV detector using commercially available designs of general or special-purpose processors. Both the choice of designs and the possibility of integrating them into custom-designed electronics are being actively investigated. At the present stage of these projects the requirement of radiation hardness is kept in mind during research work in collaboration with industry and institutes but it would be premature to carry out radiation tests. Therefore no activity in this respect is at present going on.

5. SUMMARY

1. Much work has been done within the LAA project and interesting results have been obtained. From these results it appears, that by careful selection of components the objectives can be obtained at least for the initial defined 10 kGy (1 Mrad). For materials placed at small distance and low angles as well as for luminosities exceeding 10^{33} cm^{-2} s^{-1} much work still remains to be done.

2. As regards to radiation resistance scintillator materials are better off than electroncis and semiconductors (figs 9 and 10).

For electronics an extensive amount of work is available from military and space projects. Collaboration with experienced institutes and industry needs to be intensified to get access to radiation hard components.

On scintillators extensive studies have recently started. Further work is required into the understanding of radiation effects and long term ageing.

3. Semiconductor detectors (silicon or Gallium Arsenide) for use in high radiation areas are not yet available.

4. Apart from scintillators and electronics auxiliary equipment (e.g. cables, structural materials, etc.) need not to be forgotten. The large experience with radiation effects on accelerator components is most beneficial in this respect for future detectors.

5. When radiation hard components have been found during R & D and prototype work the problem need not necessarily be solved. It must be assured that those items are available in large quantities at a reasonable price.

6. During detector design one should always keep radiation hardness in mind. Once the geometry and layout for a future multi-TeV detector is defined in more detail the following steps need to be done:

- new dose calculations,
- identify radiation sensitive materials and their position within the detector,
- radiation test need to be standardized in procedure, radiation source and dosimetry,
- radiation test and research into understanding of radiation effects need to be intensified,
- high dose dosimetry system needs to be integrated in detector design.

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Table 1

SUMMARY LAA RADIATION HARDNESS STUDIES

Status Septembre 1989

LAA UNIT	Materials and components	test carried out at	Status
1A Gaseous Detectors	Multi-Drift-Module	Gainsville	Terminated
	Readout electronics	CERN	In progress
1B Scintillating fibres	Scintillators and Scintillating fibres	CERN CERN	In progress
1C GaAs Microstrip	GaAs Microstrip detectors	CERN	In progress
2A High precision em calorimetry	Scintillators: BaF_2	CERN	In progress
	$KMgF_3$	CERN	Planned
	Electronics	CERN	Started
2B Compact calorimetry	Scintillating fibres:	LIP Lisbon	Terminated
	15 kind of fibres irradiated at 5 dose rates in 4 atmospheres	LIP Lisbon	Started
4 Leading particle detection	VLSI electronics	Santa Cruz	In progress
	Multiplexer for LPS	CERN	In progress
5A Silicon detectors	Electronics	CERN	In progress
	Pixel detector	CERN	Planned
5B Rad. hard technologies	New radiation-resistant technologies based on SOS4 CMOS	Uppsala	In progress
6A Data acquisition	Electronics for data acquisition		No activity yet
10 Radiation hardness	See Chapter 4		
11 Particle Identification	Bipolar analogue chip CMOS digital readout chip	CERN	Planned

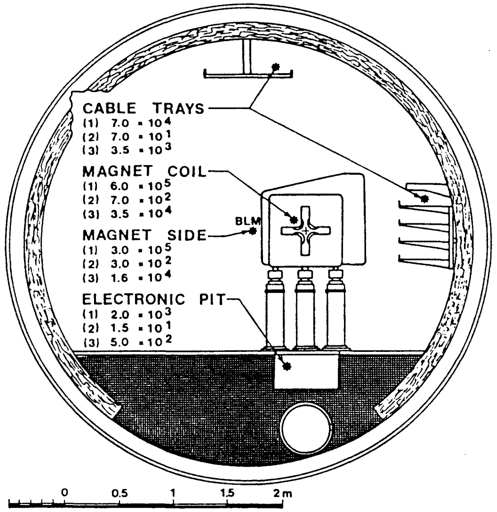


Fig. 1 Cross-section of the SPS tunnel with dosimeter positions and doses (in Gy) measured during 10 years of SPS operation (1976-1986). (1) Maximum and (2) minimum doses measured at this position. (3) Mean dose from 216 dosimeter positions. Number of accelerated protons: 17.5×10^{19}.

(Ref. 1)

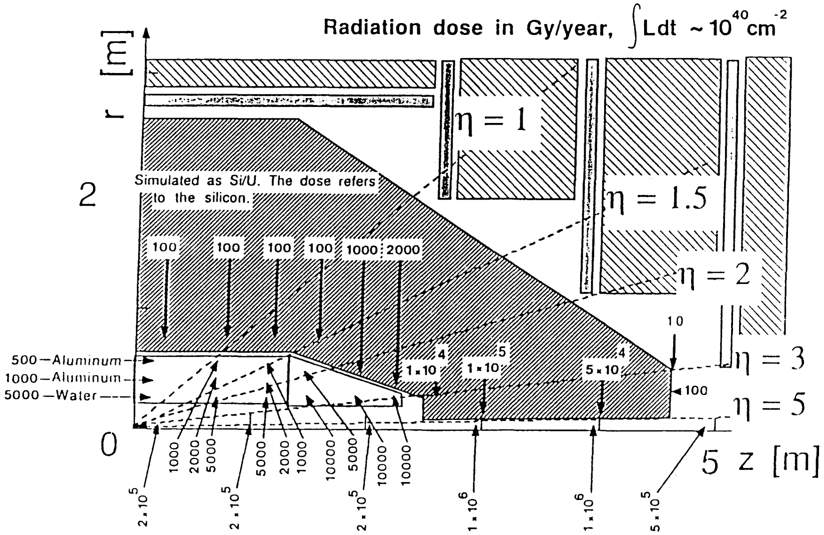
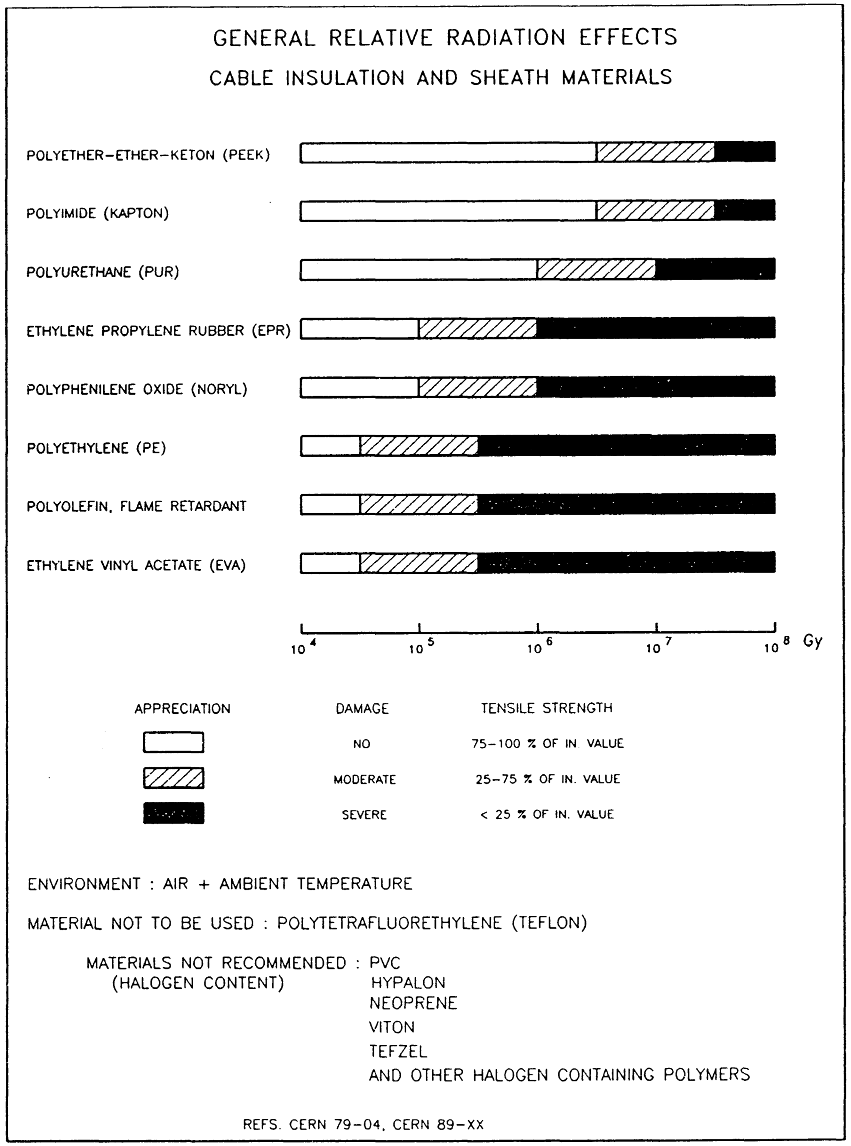


Fig. 2 Annual dose rates estimated at points within a TRD and calorimeter detector system

(Ref. 2)



APPRECIATION	DAMAGE	TENSILE STRENGTH
☐	NO	75-100 % OF IN. VALUE
▨	MODERATE	25-75 % OF IN. VALUE
■	SEVERE	< 25 % OF IN. VALUE

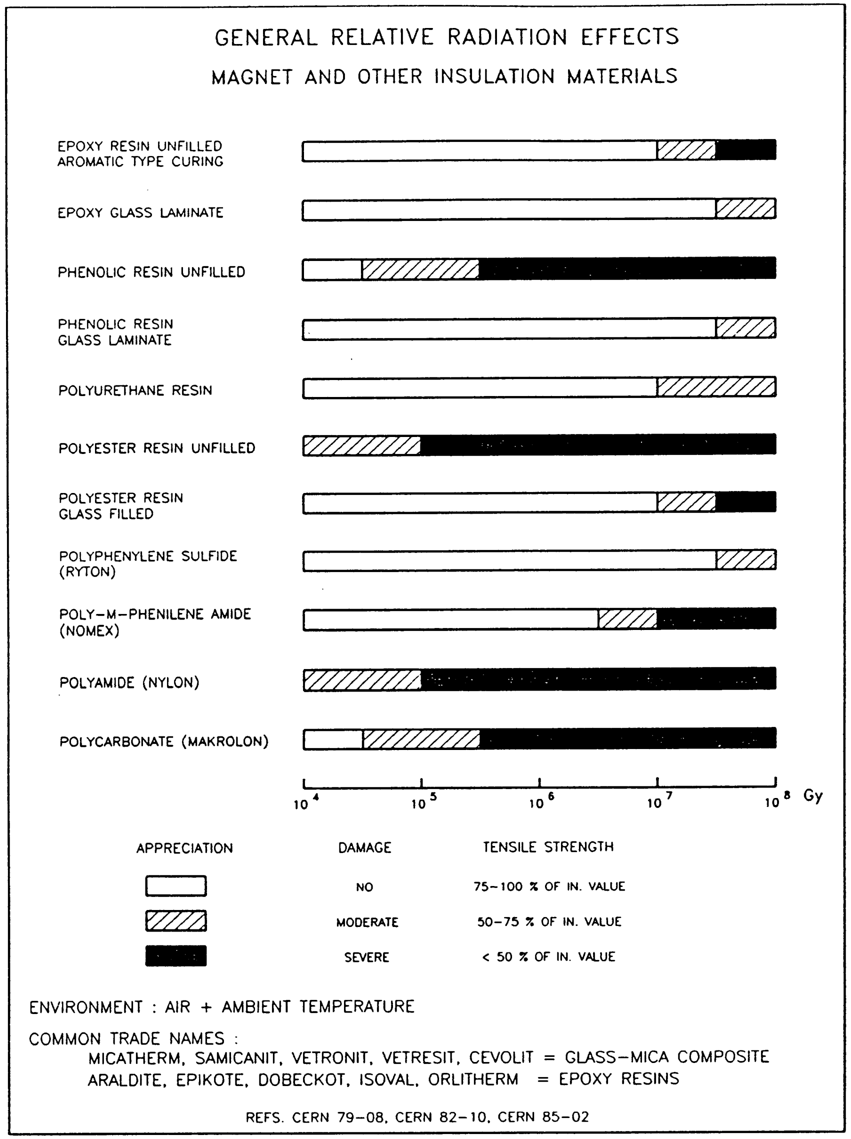
ENVIRONMENT : AIR + AMBIENT TEMPERATURE

MATERIAL NOT TO BE USED : POLYTETRAFLUORETHYLENE (TEFLON)

MATERIALS NOT RECOMMENDED : PVC
(HALOGEN CONTENT)
HYPALON
NEOPRENE
VITON
TEFZEL
AND OTHER HALOGEN CONTAINING POLYMERS

REFS. CERN 79-04, CERN 89-XX

Fig. 3 General relative radiation effects of cable insulation and sheath materials. The appreciation can only serve as general guideline. Atmosphere and other environmental conditions may influence the results.



APPRECIATION	DAMAGE	TENSILE STRENGTH
☐	NO	75-100 % OF IN. VALUE
▨	MODERATE	50-75 % OF IN. VALUE
■	SEVERE	< 50 % OF IN. VALUE

ENVIRONMENT : AIR + AMBIENT TEMPERATURE

COMMON TRADE NAMES :
MICATHERM, SAMICANIT, VETRONIT, VETRESIT, CEVOLIT = GLASS-MICA COMPOSITE
ARALDITE, EPIKOTE, DOBECKOT, ISOVAL, ORLITHERM = EPOXY RESINS

REFS. CERN 79-08, CERN 82-10, CERN 85-02

Fig. 4 General relative radiation effects of magnet and other insulation materials. The appreciation can only serve as general guideline. Atmosphere and other environmental conditions may influence the results.

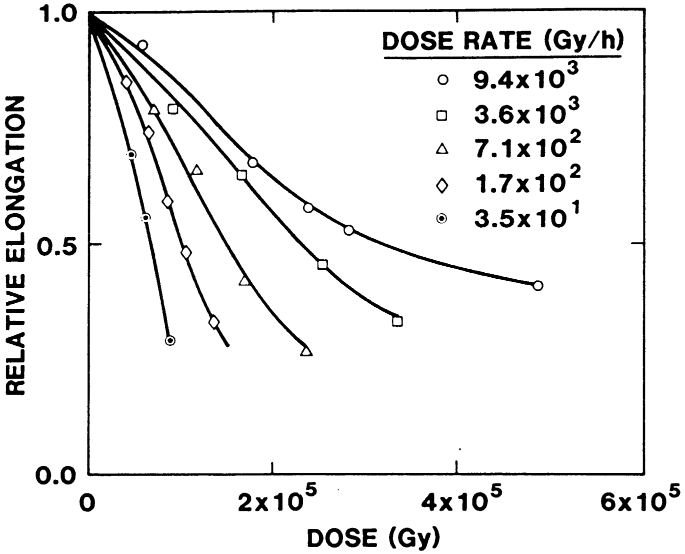


Fig. 5 Change of relative elongation of a thermoplastic cable insulating material irradiated in air at different dose rates.

(Ref. 11)

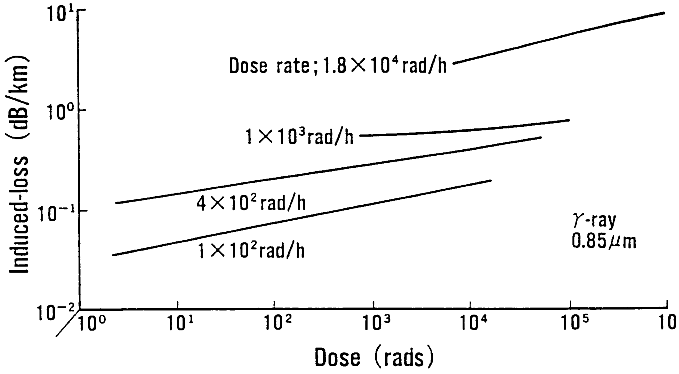


Fig. 6 **Gamma-ray induced loss of the multi-mode graded index fibres with germanium-doped silica core fabricated by VAD process and synthetic silica cladding.**

(Ref. 14)

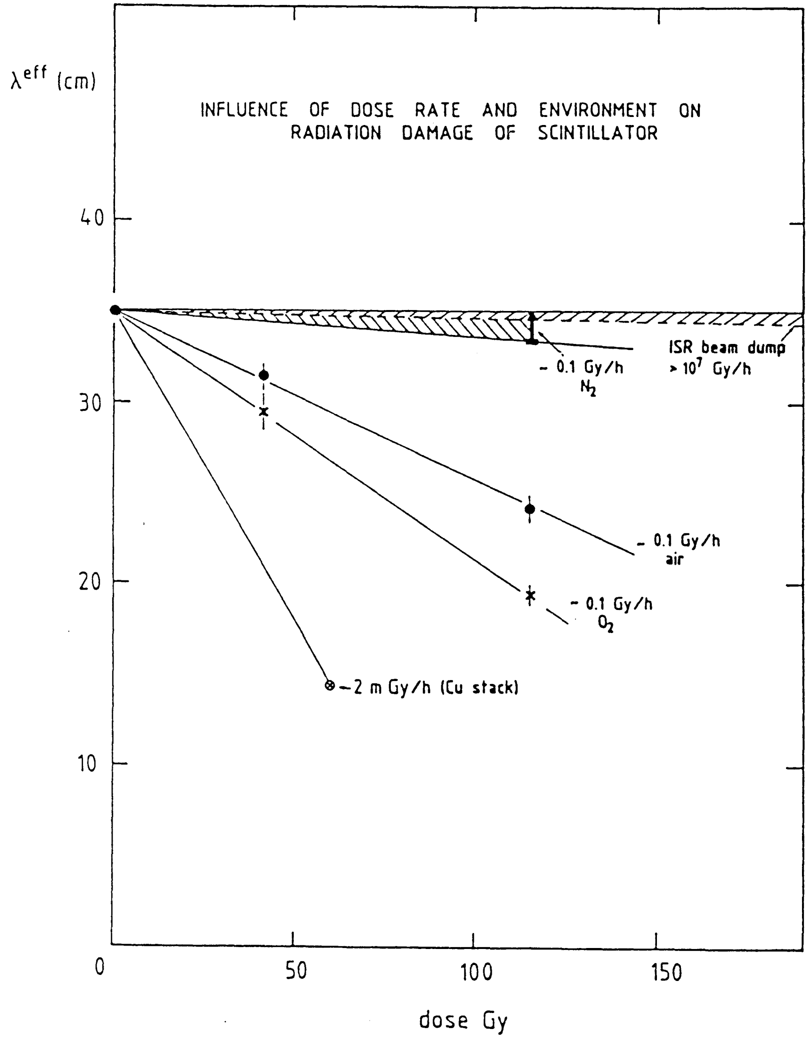


Fig. 7 The effective attenuation length as a function of total absorbed dose, for different dose rates and various environments. The curves are drawn to guide the eye.

(Ref. 12)

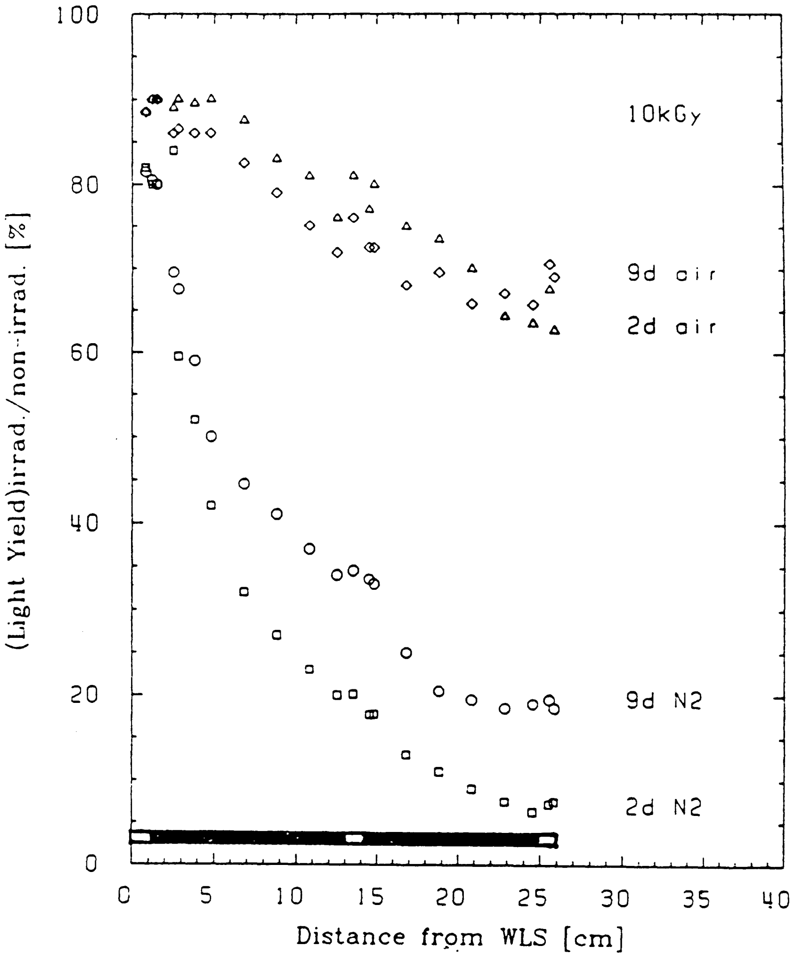


Figure 8 Radiation damage studies for 2.5 mm thick plastic scintillator SCSN-38. Shown is the pattern of irradiation and the ratio of pulse height measured by excitiation with light from a Xenon lamp after and before irradiation. Data presented for irradiation with 10 KGy of 25 MeV protons for material stored in air and nitrogen. Measurements have been done 2 days and 9 days after irradiation.

(Ref. 13)

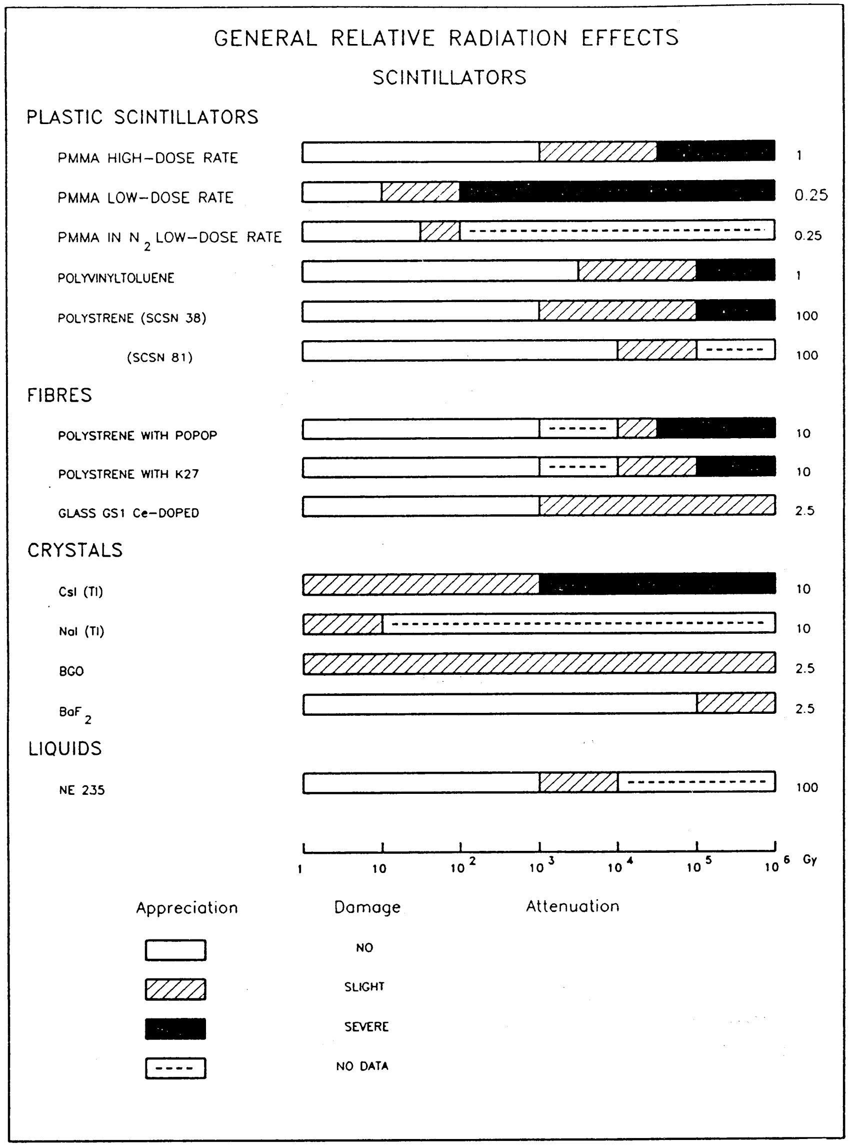


Fig. 9 General relative radiation effects of some current scintillator materials. The appreciation can only serve as general guideline. Atmosphere and other environmental conditions may influence the results.

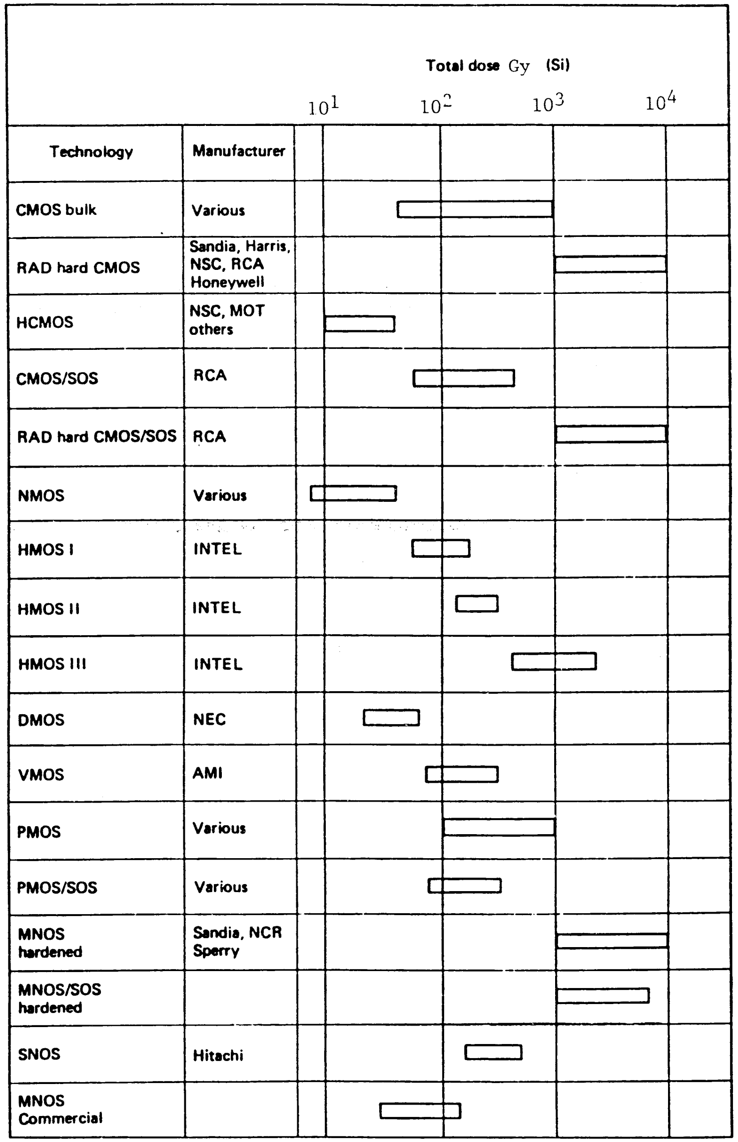


Fig. 10 **EFFECTS OF RADIATION ON ELECTRONIC SYSTEMS**