The s
cript has been authored
the U. S. Government
o. W-31-109-ENG-38.
. Government retains a
free license to publish
ublished form of this
v others to do so, for
oses.
Fermilab Library
0 1160 0009671 3
ANL-HEP-CP-92-46

ANL-HEP-CP-92-46
For the Proceedings of the
International Conference on Radiation-
Tolerant Scintillators and Detectors
Florida State University, Tallaahassee, FL
April 28 - May 2, 1992

CONFERENCE SUMMARY

James Proudfoot*

High Energy Physics Division, Argonne National Laboratory
9700 South Cass Avenue, Argonne, IL 60439 USA

ABSTRACT

It is my task to summarise the great variety of topics (covering a refreshing mix of physics, chemistry and technology) presented at this conference, which has focused on the effects of ionising radiation on scintillators and other particle detectors. One of the reasons and the central interest of many of the participants was the use of such detectors in experiments at two future large hadron colliders: the Superconducting Super Collider to be operating outside of Dallas in the United States by the turn of the decade and its European counterpart the Large Hadron Collider to be operating outside of Geneva in Switzerland on a similar time scale. These accelerators are the "apple of the high energy physicist's eye". Their goal is to uncover the elusive Higgs particle and thereby set the cornerstone in our current knowledge of elementary particle interactions.

This is the Quest, and from this lofty height the presentations rapidly moved on to the specific questions of experimental science: how such an experiment is carried out; why radiation damage is an issue; how radiation damage affects detectors; which factors affect radiation damage characteristics; which factors are not affected by radiation damage; and how better detectors may be constructed. These were the substance of this conference.

PHYSICS MOTIVATION - THE DETECTORS

The physics is the discovery of the Higgs or the "certain new physics" at the Electro-Weak Symmetry Breaking mass scale and was discussed by Green and Reucroft. For the weak coupling, ee $\rightarrow$ WW, the coupling strength α_ϕ is a function of this mass scale , given by the equation

$$\alpha_\phi = \alpha_W/4\pi\left(\frac{M}{M_w}\right)^2$$

This coupling is of order 1 for masses, M, of order 1.6 TeV. Therefore, at this mass scale new physics is "certain". This may be the discovery of the Higgs particle as described within the "Standard Model" of fundamental interactions or the discovery of some new phenomenon indicating unexpected substructure.

To reach this mass scale requires high energy interactions. As was discussed by Reucroft, high energies are most readily achieved by colliding two counter rotating beams of protons rather than the use of a single beam on a fixed target. As an

example, for a 20000 GeV proton beam energy (the SSC design energy), the center of mass energy in a colliding beam configuration is ~40000 GeV, to be compared with only ~200 GeV in a fixed target experiment. A further requirement is that of high luminosity as the effects sought have low cross section.

The characteristics of a typical detector were discussed by Green and Reucroft. It comprises a tracking system to measure charged particles, a calorimeter to measure electrons and neutrals and an external detector to measure penetrating particles (such as muons). The experimental technique used is to infer the existence of the underlying quarks, leptons and bosons of the theory by measuring the particles produced in the interactions between pairs of protons:

Quarks		via	Jets
Leptons		via	Tracks and Showers
Gauge Bosons:	gluons	via	Jets
	gammas	via	Electromagnetic showers
	W, Z IVBs	via	Leptons and Jets

The key performance issues are efficiency, precision and uniformity as the goal is to extract very small signals from very large backgrounds.

Radiation damage enters the picture as the more mundane interactions between the high energy protons have very much larger cross sections. Therefore at the high luminosities required for reasonable signal rates at the LHC and SSC, the products from these processes deposit large amounts of energy in regions of the detector. This can vary from a few KRads/Year to a few MRads/Year [1]. This energy deposition is certain to degrade detector performance and the groups involved in designing the experiments have already invested much effort in understanding how severe this degradation can be (see for example the talks by de Salvo, Henriques and Byon-Wagner in these proceedings).

Several papers were presented on the effects of neutron radiation on scintillating fiber tracking systems. Such a detector is extremely simple in function [2]. A charged particle traversing a scintillating fiber deposits energy, which is converted into scintillation light, propagates along the fiber and is detected as a hit by a photon detector if the signal is above some discriminator threshold. Radiation damage has the simple effect of steadily increasing the attenuation of the signal. The final damage limit was obtained at a dose of 1MRad, where the fiber becomes totally inefficient.

The performance of the calorimeter has been studied for many styles of device as indicated in Fig. 1. The technique used by all groups has been to measure the performance of test devices as a function of radiation dose, model the light collection using a Monte Carlo program and model the expected performance of the actual calorimeter design to high energy particles, using a high energy shower Monte Carlo program. As an example of this technique, Fig. 2 shows the measured and fitted light loss for transmission and emission in a Lead/Scintillating Fiber calorimeter [3]. The fit is then used in a Monte Carlo including hadron and electromagnetic shower development to estimate the limiting value of the energy resolution of the device. For a 20% loss in signal at electromagnetic shower maximum, the limiting value of the calorimeter energy resolution is 2%. The specific models are detector dependent and the reader is referred to the many papers presented at this meeting for a complete survey of results. All groups essentially reached the

same conclusions. In an electromagnetic calorimeter, where precision is an essential requirement, a maximum dose of between 1 and 4 MRad is (barely) acceptable.

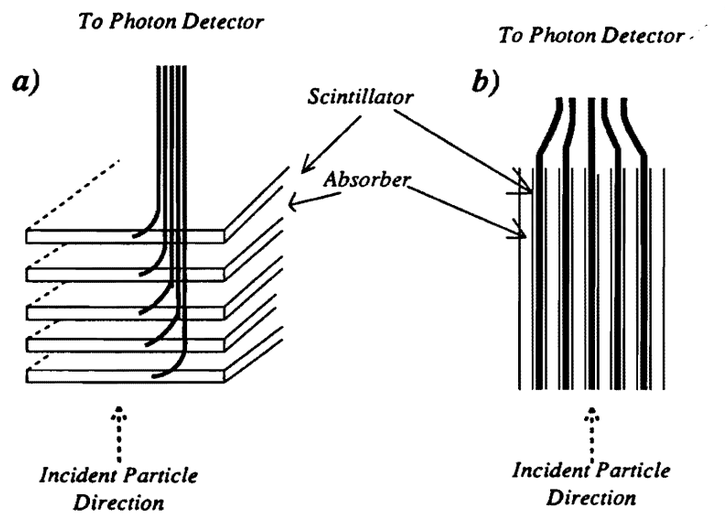

Fig. 1 Two classes of scintillator calorimeter:
a) with absorber normal to the direction of incidence to the incoming beam and liquid scintillator or scintillator tile read out via wavelength shifting fiber;
b) with absorber approximately parallel to the incoming beam and scintillating fiber embedded in the absorber matrix (a "spaghetti calorimeter").

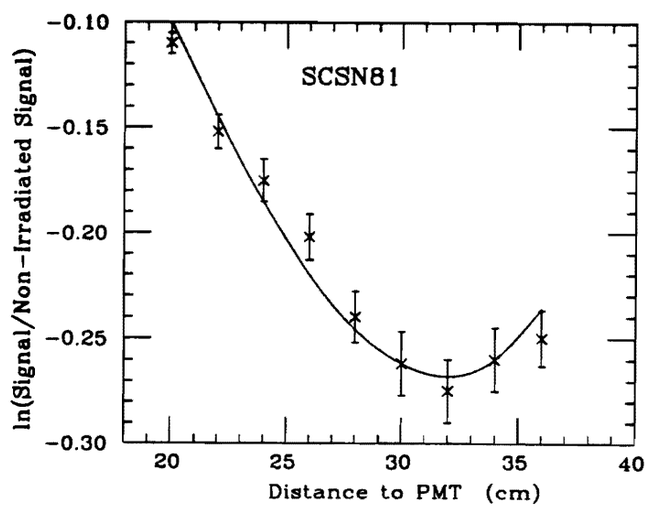

Fig. 2 Measured and fitted light loss as a function of shower position in a lead/scintillating fiber "spaghetti" calorimeter.

This performance is not sufficient to allow the forward regions of such detectors to pass the rather stringent test of survivability for 10 years at 10 times design luminosity - hence the efforts underway to improve scintillator materials. The "ideal" scintillator/wavelength shifter system is one in which the wavelength of the scintillation light is 450-500 nm and is matched to a wavelength shifter whose absorption peak is in this region, and whose emission peak is approximately 550 nm. This system should have an overall decay time constant of 3-5 nsec and should yield < 10% drop in signal following 1 MRad absorbed dose in a 10 cm × 10 cm tile

read out with 50 cm of wavelength shifting fiber. The design characteristics which can be modified are concisely stated as:

Base Material	-	selection or modification
Fluors	-	selection and combination
Additives	-	choice of stabilisers and loading elements
Processing Method		
Cost		

Each and every one of these is impacted by the high radiation levels to be accommodated.

The central topic of interest at this meeting was on the development of improved scintillators to reach the performance of the ideal system. The focus was on three areas of specific research: development of a reliable model for the damage and recovery mechanisms; implementation of the understanding gained from the development of this model in the synthesis of new plastics; development of new fluor systems to avoid particular regions of high radiation induced absorption.

DEVELOPMENT OF IMPROVED SCINTILLATORS

Damage to the Polymer Base

The picture of the damage mechanism centered on the color center products formed by ionising radiation. These comprise radical ions, radical ion products and conjugate bonds along the backbone of the polymer chain. The scattering strength and absorption of these centers is a strong function of wavelength : Red <<<< Green << Blue < U.V. Figure 3 [4] shows the absorption spectrum in irradiated polystyrene. The strong absorption band at approximately 520 nm can be associated with two absorption bands (at 512 and 554 nm) of an expected radical ion (cyclo-hexadienyl).

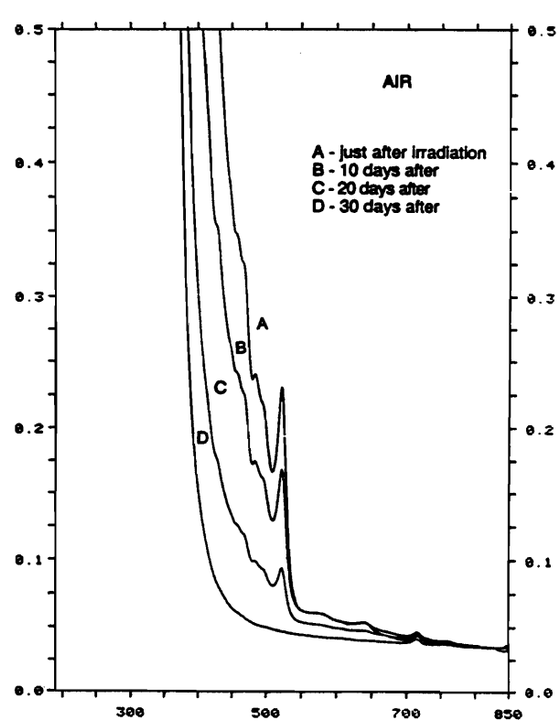

Fig. 3 Absorption spectra for pure polystyrene following a 10 MRad radiation dose.

The observed recovery of transmission with time (the annealing process) was identified with arising from a mixture of two competing processes [5]: oxygen diffusion and quenching of radicals to form non-colored products (Fig. 4) [4]; radical ion movement and re-combination to form non-colored products.

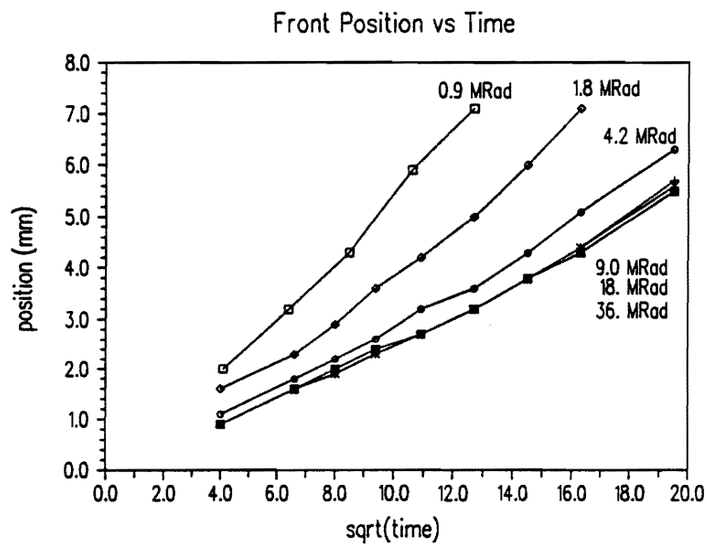

Fig. 4 Position, as a function of dose, of the bleaching front associated with oxygen diffusion and quenching of radical ion color centers in polystyrene.

However, many additional factors have been identified. They can most easily be summarised by representing the transmission as function of wavelength by a matrix transformation, d_{ij}

$$T(\lambda, \text{polymer}) = f(\lambda,\text{polymer}) \,.\, d_{ij}\, p_j$$

where, $T(\lambda, \text{polymer})$ is the transmission of the plastic

$f(\lambda, \text{polymer})$ is characteristic of the non-irradiated material and

$$p_j = \left\{ \begin{array}{l} \text{Radiation Dose} \\ \text{Radiation Dose Rate} \\ \text{Time} \\ \text{Temperature} \\ \text{Glass Transition Temperature} \\ \text{Permeability} \\ \text{Molecular Mobility} \\ \text{Additives /Stabilisers} \\ \text{Atmosphere During Irradiation} \\ \text{Atmosphere Following Irradiation} \\ \text{Surface /Volume Ratio} \\ \text{Plate /Fiber Geometry} \\ . \\ . \\ . \end{array} \right\}$$

Data on all of these factors were presented at this meeting and I will only summarise the key points as I perceived them. The demonstration that this understanding is close to the truth is the observation that polymers modified according to this model do indeed show the expected change in resistance to radiation dose. However, at present much of the interpretation of data is complicated by the fact that these factors are not orthogonal and the correlations have not yet been fully unfolded.

Dose Rate Dependence

Much effort has been expended studying dose rate effects as, due to time limitations, the dose rates required to achieve high total dose must be significantly higher than any dose rate expected in the real detector situation. There has been some disagreement between experimental results in this area over the past few years. Unfortunately, this has as yet not been wholly resolved.

Table 1

			$\Delta\mu/D$ in 10^{-6} cm^{-1} Gy^{-1}			
UVA	dose rate	dose	after 5 d	100 d	330 d	416 d
nm	Gy/h	Gy				
332	2640	5900	3.3	3.0	0.7	0.3
332	6.7	2790	2.8	2.8	0.0	-0.2
360	2640	5900	3.2	2.9	0.2	0.2
360	6.7	2790	2.9	3.0	0.3	0.0
380	2640	5900	18.0	15.3	5.1	4.7
380	6.7	2790	18.0	13.9	0.7	0.3
396	2640	5900	29.5	28.5	13.7	13.4
396	6.7	2790	28.7	27.9	1.4	0.6

Giokaris [6] reported results on scintillator bars doped with a variety of blue and green fluors. These were irradiated to a total dose of 1.6 MRad at dose rates of 250 Rad/hr, 10.5 kRad/hr and 1 MRad/hr. The net loss of transmission along a 20 cm bar varied from about 10% for the green dyes to about 40% for the blue dyes. No dose rate dependence was observed. This result is opposite to that reported by Zorn [7], who carried out an similar series of experiments using fiber geometries. Holm [8] reported measurements for the ZEUS detector on wavelength shifter sheet. The dose rate dependence of transmittance along a sheet is shown is Table 1. No effect is observed. Other data presented at this meeting included implicit dose rate dependence. Overall, no significant effect was observed for the majority of these tests. However, Gillen [5] warned that one should still be wary as the measurements see a competition between two processes (bleaching and radical ion recombination) and reported significant dose rate dependence in pure polystyrene as a function of temperature (Fig. 5).

Kinetics of Annealing

As was discussed above, the two main annealing processes are considered to be a result of oxygen diffusion and radical ion mobility. The rate of both of these processes can be increased by increasing the permeability and radical ion mobility

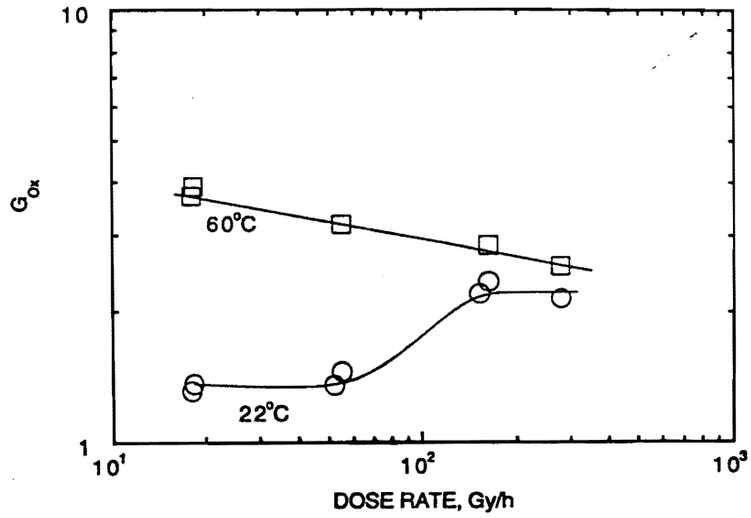

Fig. 5 Concentration of oxidised radicals, G_{ox}, as a function of dose rate and sample temperature, for pure polystyrene.

of a polymer by reduction of it's glass transition temperature (Tg) [9]. Several possible approaches were proposed: addition of side chains; addition of plasticiser agents; use of a copolymer in which one polymer has a low Tg. Two clear examples were shown in which this general philosophy succeeded in yielding a plastic base with high resistance to radiation dose. Figure 6 shows the result of annealing a copolymer with Tg = 53 C in air [10]. The final recovery is approximately 95% (much improved over pure polystyrene) and little dose rate dependence is observed on this plateau. Figure 7 [11], shows the use of an additive (in this case 30% silicone oil) to increase mobility and thereby yield a scintillator with excellent radiation resistance. The conclusion is that the model describing the kinetics of annealing does indeed appear to give positive direction to the development of plastic bases with improved radiation tolerance.

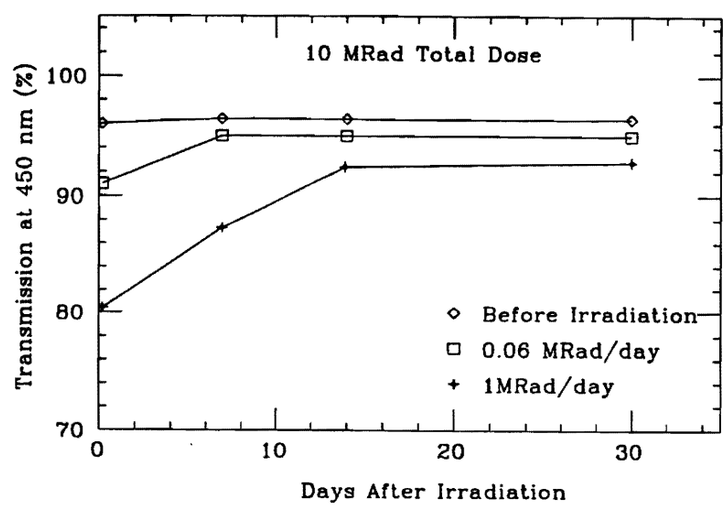

Fig. 6 Recovery of isobutyl methacrylate after 10 MRad total dose accumulated at dose rates of 0.06 MRad/day and 1 MRad/day.

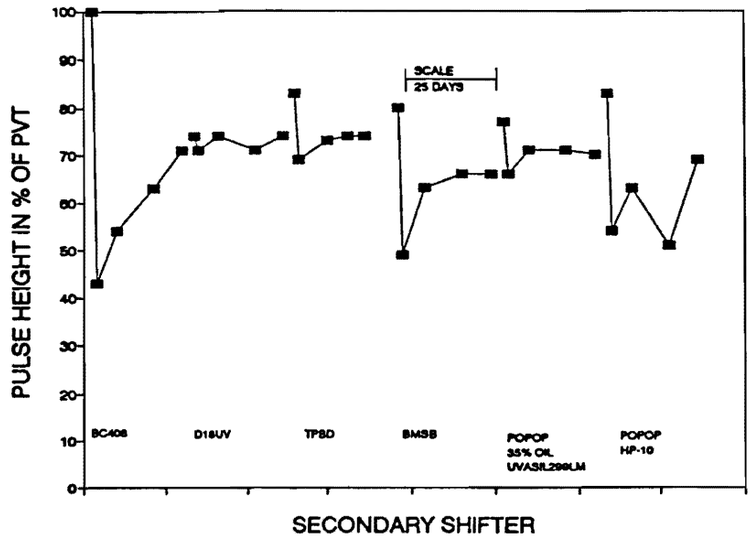

Fig. 7 Annealing rates for various choices of secondary shifter following a 10 MRad dose. All scintillators contain 30% silicone oil, except where noted.

Atmosphere

The role of the atmosphere in which materials are surrounded was discussed in many of the presentations. The issues being addressed generally reflected the role of oxidation processes occurring during irradiation versus those occurring following irradiation. In the former case, the oxidation products themselves may be the subject of further damage with the possible formation of permanent damage sites. To further obscure this issue, there is a (probably temperature dependent) competition between this bleaching process and radical ion re-combination. Details of this intricate balance and some modeling of the resulting effects were given in the talk by Gillen. [5] Experimentally, the clearest statement was presented by Gomes [12]. Figure 8 shows the recovery of SCSF81 fiber in air following irradiation in either nitrogen or air. The initial damage is seen to be much

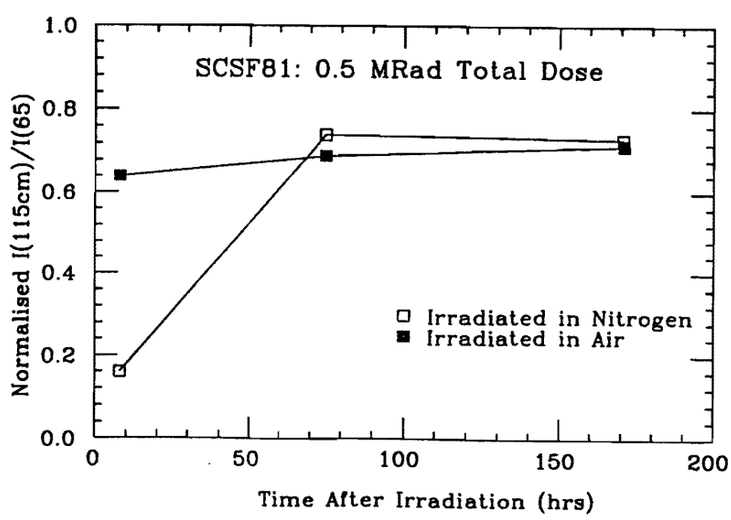

Fig. 8 Normalised light yield as a function of annealing time in air, for SCSF81 polystyrene scintillating fiber following 0.5 MRad dose in nitrogen or dry air.

less severe in the case that oxygen is present during irradiation to immediately bleach colour centers, while, the level of permanent damage is comparable for both cases. A similar result was obtained by the ZEUS group [8]. With these newer data, the conclusion on atmosphere with respect to detector design is becoming somewhat clearer, with a distinct preference being for a simple dry air environment.

Alternative Materials and Implementations

Alternatives to rather conventional scintillation calorimetry, were discussed mainly in terms of liquid scintillator contained in silica glass capillaries [12] and scintillating glasses [13]. Although the performance of the liquid scintillator approach was somewhat more radiation resistant than the tile or fiber approaches, the most outstanding results of the conference were from a "spaghetti" style lead calorimeter using the detection of Cerenkov radiation in silica glass fibers as the sampling technique [14]. This device, designed for heavy ion physics, showed no degradation in performance following a total dose of 2 GRads. Such a device, though not appropriate for the high performance region of an SSC or LHC detector, is eminently matched to the physics of the forward regions of the detector, where the radiation dose is the highest.

DEVELOPMENT OF NEW FLUOR SYSTEMS

In much of the detector design work for SSC and LHC detectors, conventional photon detectors have been assumed due to their history of successful operation in past experiments. However, a signification limitation due to the use of such devices is their spectral response. This forces the emission wavelength of the waveshifter fluor to be in the green and that in turn forces the emission spectrum of the scintillator to be in the blue. Therefore, following irradiation of the base polymer, all radiative photon transfers occur by propagation through damaged material and are attenuated. One obvious solution is too move to longer wavelengths, which then requires the use of photon detectors with good quantum efficiency in the far green and red parts of the spectrum.

Many candidate dye laser exist which have the right spectral characteristics and can be obtained from catalogues of major chemical manufacturers. Dye synthesis is an advanced art and several presentations were given on the details of dye molecule modification [15]. By careful tuning of the actual dye molecule it is possible to shift its fluorescence emission frequency to progressively longer wavelengths whilst retaining high quantum efficiency (as necessary.) This approach in principal allows the detector designers to choose arbitrary wavelengths for the various calorimeter and tracking detector options. Red sensitive photon detectors are also now becoming available to the private sector at reasonable cost. The spectral response of one such candidate photocathode, which has in been developed for night vision glasses is shown in Fig. 9 [16].

This approach has already been tested in a calorimeter [16]. Figure 10 shows the increased radiation resistance obtained by using a 3HF scintillator tile (yellow light) read out via an O2 wavelength shifter fiber (orange light) using a red sensitive photocathode. A modest 20% loss of signal is observed after an accumulated dose of 3 MRad. With the correct choice of dyes and photon detector it is thus envisaged that even visible light detectors of good radiation hardness can be designed. Furthermore, the absorption in the infrared is even less (especially in the

region 630-700 nm) and it was advocated that this might be the operational region of a detector with maximum radiation hardness.

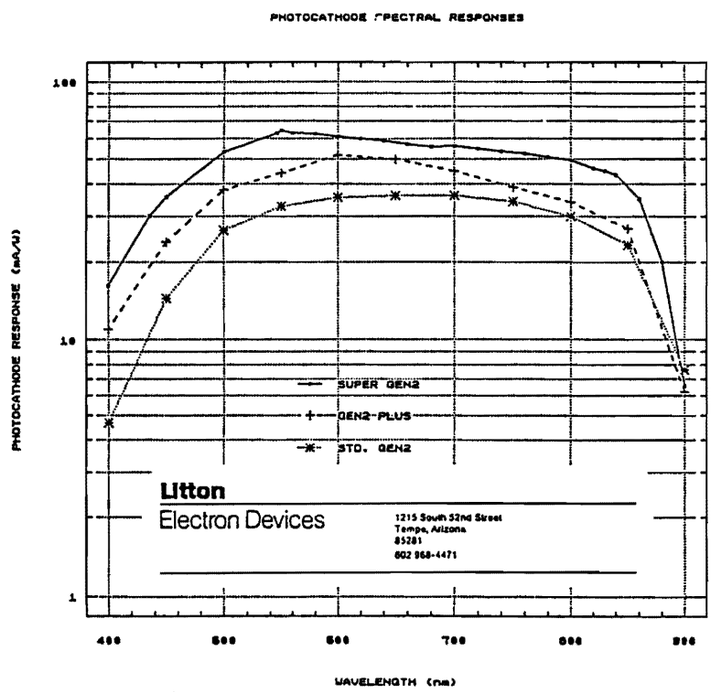

Fig. 9 Spectral efficiency of one family of red sensitive photon detectors, marketed by Litton.

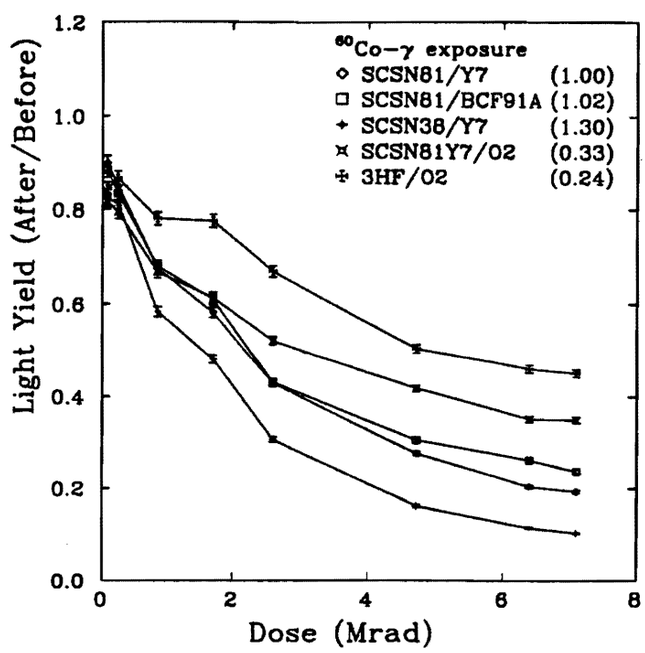

Fig. 10 Radiation hardness for a series of tile/fiber test calorimeters using a variety of scintillator/wave shifter/PMT combinations (e.g. blue/green SCSN81/Y7, yellow/orange 3HF/02).

Conclusion

In summarising the results presented at this workshop, I have realised that it is impossible to justly review all the data from such a diverse range of topics. Personal bias has limited me to leave out many of the interesting and relevant details. These include many of the techniques and measurements done to develop the understanding of the subject of radiation damage: theoretical model development and associated test experiments; the chemistry and radiation chemistry of dyes and polymers; resonance spectroscopy to identify radiolysis products; the relationship between energy deposition by photons, electrons and neutrons, and the intricacies of precision timing measurements. My personal perspective has been that of a high energy physicist, whose objective is to participate in the design of a detector for the SSC. At this conference we have heard why such an experiment will yield insight into the structure of our universe. The cloud obscuring part of this picture is the absorption of light signals in our calorimeters and tracking detectors. With present detector technology, this cloud will limit the performance of the detector by either degrading its performance or by limiting its useful lifetime. Several viable technology improvements have been proposed and demonstrated at this meeting. In the plastics we have heard of polymers with low glass transition temperature and moderately high radiation resistance. We even understand to large extent why these properties are connected. In the fluor system we have heard about options to design more efficient fluors at longer wavelengths and therefore gain another factor of 2-4 in radiation hardness. Lastly we have heard of alternative approaches, most especially silica glasses, which may be considered for use in the harshest of all environments and will survive to tell the tale. In the next year or so these new developments should be further studied and their performance confirmed. The experiments proposed for the LHC and SSC will then not be limited in what they may see.

Finally, on behalf of the participants to this Workshop, I would like to thank the organisers, Roger Clough, Kurtis Johnson, and Peter Sonderberger, for an excellent and most topical meeting. We also thank the secretarial staff, Melissa Loggins, Sherl May, Kathy Mork, and Sherry Reyback, for their tireless efforts and assistance.

* Work supported by the U.S. Department of Energy, Division of High Energy Physics, Contract W-31-109-ENG-38.

REFERENCES

1) Groom, D. E. , H. Hirayama, and W. R. Nelson, SSC-SR-1033, SSCL-285.
2) Reucroft, S., these proceedings.
3) Henriques, A., these proceedings.
4) Wallace, J. S., these proceedings.
5) Giller, K. T., these proceedings.
6) Giokaris, N., these proceedings.
7) Zorn, C., these proceedings.
8) Holm, U., these proceedings.
9) Harmon, J. P., these proceedings.
10) Taylor, A. G., these proceedings.
11) Markley, F., these proceedings.
12) Gomes, A., these proceedings.
13) White, J. T., and K. Young, these proceedings.
14) Gorodetzky, P., these proceedings.
15) See for example the talks of, A. Pla, M. Kasha, J. Schleroff, and P. Cahill, these proceedings.
16) Byon-Wagner, A., these proceedings.