RADIATION ACCIDENTS AND DOSIMETRY

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ABSTRACT

September 2nd 1982 one of the employees of the γ-irradiation facility at The Institute for Energy and Technology (Kjeller, Norway) entered the irradiation cell with a 65.7 kCi ^{60}Co-source in unshielded position. The victim received an unknown radiation dose and died after 13 days.

Using electron spin resonance spectroscopy, the radiation dose in this accident was subsequently determined based on the production of longlived free radicals in nitroglycerol tablets borne by the operator during the accident. He used nitroglycerol for heart problems and free radicals are easily formed and trapped in sugar which is the main component of the tablets. Calibration experiments were carried out and the dose given to the tablets during the accident was determined to 37.2 ± 0.5 Gy. The general use of free radicals for dose determinations is discussed.

INTRODUCTION

According to United Nations Scientific Comittee on the Effects of Atomic Radiation (UNSCEAR) (UN 81) a number of occupational exposures to ionizing radiation (in some cases with fatal result) have been reported during the last 30 years. In most cases a true reconstruction of the accident appears difficult and consequently the determination of the radiation dose involved is rather uncertain. In this paper a dosimeter, based on the formation of free radicals, will be presented which proved useful in the case of a radiation accident which recently took place in Norway.

On September 2nd 1982 one of the operators at the γ-irradiation facility at the "Institute of Energy and Technology" (Kjeller, Norway) entered an irradiation cell with the ^{60}Co-source (approximately 65.7 kCi or 2.43 PBq) in unshielded position. The operator was alone during the accident and received an unknown radiation dose. The exposure resulted within minutes in nausea and vomiting and the man died after 13 days.

Attempts were made to determine the radiation dose based on a film dosimeter which the operator carried in his pocket (trousers). The film was black implying that the radiation dose was well above 5 rad (0.05 Gy). Further attempts made to arrive at a more rigorous dose determination from the film dosimeter were unsuccessful.

The doserate at different positions within the irradiation cell is well known. Attempts were therefore made to estimate the dose from time-studies of the operators movements within the irradiation cell during the accident. Information about the latter was attained by interview with the operator in hospital the day after the accident. This "time study"

approach, which appeared to be very uncertain, yielded a dose of the order 100 rad (1 Gy). The weak point is the information provided by the operator and in particular his statement about the length of time he spent inside the irradiation cell (he claimed this to be less than 30 seconds, whereas our measurements showed that he must have been exposed for more than 5 minutes).

An attempt was also made to determine the radiation dose based on the chromosome damage induced (No 66). Brøgger and van der Hagen (Br 52) found large chromosome aberrations in lymphocytes from blood samples taken respectively 1 day and 5 days after the accident. The number of cells was small, but the restricted material suggested a dose of more than 1 krad (10 Gy).

For dose determination in radiation accidents, based on physical methods, we have to rely on some permanent or long lasting effects such as crystal imperfections and color centers in inorganic materials and long lived free radicals in the case of organic or biological materials. It is well known that ions and free radicals formed by radiation are very reactive with lifetime in solutions and cells far less than a second. However, in solid material (waterfree) the secondary reactions are slowed down considerably with the result that the radical lifetimes increase to hours, days, and even years. The formation of radicals as well as their stability vary from one compound to another. It can, however, be concluded that free radicals are formed and trapped in solid organic materials. These species can be observed and studied by electron spin resonance (ESR) spectroscopy.

ESR has been used to study radiation induced radicals in organic compounds since the pioneering work of Gordy and his coworkers in 1955 (Go 55). The technique with all its new facets has yielded a wealth of information about radical structures and the kinetics of the secondary radical reactions (He 76). The use of ESR for quantitative measurements such as yield determinations appears to be rather uncertain and has played a minor role during the years compared to qualitative measurements. The early experiments showed that free radicals are formed in amino acids, peptides, proteins, and sugar-molecules with radiation yields (G) of up to 10 and more (Pr 61, Mü 62, He 63a).

The dose-effect curves for the formation of free radicals in organic compounds are linear in the dose region of from zero to about 10^5 rad whereupon they gradually curve off at higher doses. In the study of molecular damage to compounds of biological interest doses in the megarad region are used and no particular attempts have been reported to perform quantitative measurements for doses below a few krad.

The dose-effect curves are adequately described by the general formula:

$$N(D) = \sum_{i=1}^{n} N_{io} \left(1 - \exp(- k_i D)\right)$$

where N(D) is the total number of ESR centers observed after a radiation dose D. For some compounds n is equal to 1 whereas in the general case n is 2 or larger. The interpretation is that in those cases two or more different radicals are formed simultaneously which exhibit different saturation levels.

The stability of the radicals was found to vary from one compound to another. In some compounds they may be surprisingly stable at room temperature. The detailed time-course studies revealed that in the initial period after exposure secondary radical reactions may take place. Samples which were followed for days and months showed a decay in the number of radicals which followed the formula:

$$N(t) = a\ln t + b$$

where N(t) is the number of ESR centers as a function of time after exposure and a and b are constants characteristic for the compound in question. Some compounds were followed for a period of 3 years and the logarithmic form of the decay curve indicates that in solid substances the radiation-induced ESR centers may be stable for a long period (infinitely) at room temperature (He 63b).

As a conclusion it can be stated that ESR centers are formed by radiation and that this formation may serve the purpose to be used for dose determinations. For adequate dose determinations two properties must be under control: a) The detailed course of the dose-effect curve (i.e. a calibration curve must be worked out). b) The stability of the induced ESR centers.

In the recent accident we found ESR signals induced in several of the effects borne by the operator during the accident such as shoe, buttons and even in his trousers. However, due to some heart problems the operator used and carried with him (in his pocket) som nitroglycerol tablets. These tablets consist mainly of sugar which is a suitable compound for dosimetry since radicals are formed in high yields and with good stabi-

lity at room temperature. The radiation dose to the tablets borne by the operator during the accident have been determined, and the details of this are given in the following.

MATERIAL AND METHODS

a) The ESR spectrometer and the samples used

Each of the ESR samples used consists of one nitroglycerol tablet in powder form (they were crushed in a mortar) kept in a quartz sample tube (precision NMR-tube, type WILMAD) with air present.

All samples were given the same position in the ESR-cavity (reflection-type, TE_{102}-mode). The ESR spectra were recorded at room temperature using a Bruker Spectrospin spectrometer of type ER-200 MRD connected to an ASPECT 2000 computer. The spectrometer operates in the frequency region from 9 to 10 GHz (X-band). The spectrometer settings used in the present experiments were as follows; microwave power = 0.2 mW, magnetic field modulation = 2.5 gauss, sweeptime = 200 seconds and the time constant = $1 \cdot 10^{-3}$ sec/gauss. The spectra were digitized (2048 points per spectrum, 12 bit A/D-converter). In order to increase the signal to noise ratio spectral accumulation and summation were carried out. All calculations and measurements (integrations and amplitude measurements) are based on digitized spectra via programs for the ASPECT 2000.

Care was taken to ensure that the parameters used (in particular the microwave power and the field modulation) were well below the threshold values for spectral distortions.

b) The Nitroglycerol tablets.

The employee of the γ-irradiation facility involved in the accient used nitroglycerol tablets from two different sources: A) From Dumex (Denmark) with the trade name "Nitromex" and B) From Apothekernes Laboratorium (Oslo, Norway) with the trade name "Nitroglycerin A-L".

A) Nitromex-tablets have the following composition: 0.5 mg nitroglycerol, 83.3 mg lactose, 0.05 mg sodiumriboflavinphosphate, 0.43 mg macrogol (polyethylenglycol), and 1.75 mg confectioners sugar. The weight of the tablets was 83.7 ± 4 mg. The tablets are yellow and have a relatively soft consistency with the result that the small metal box used by the operator to store the tablets contained some yellow powder worn off from these tablets.

B) Nitroglycerin (A-L) tablets have the following composition: 0.5 mg nitroglycerol, 192.0 mg sorbitol, and 7.5 mg macrogol. The weight of these tablets was 201.6 ± 7 mg. These tablets are white and quite hard packed.

c) The calibration exposures

In order to work out "dose-effect" curves, tablets of the same type were obtained and irradiated with ^{60}Co-gamma rays to controlled doses in the range from 500 rad to 10 krad. The doses were determined by T. Wøhni at "The State Instite of Radiation Hygiene" using thermoluminescence dosimetry. The doses determined are "exposure doses" given in roentgen (R). For conversion to absorbed doses given i rad a conversion factor of 0.93 was used (Jo 56).

RESULTS

A. Nitromex-tablets.

In Fig. 1 is shown the ESR spectra obtained from unirradiated as well as irradiated Nitromex tablets. The resonances are recorded as the first-derivative of the absorption spectra. In the first place, it can be concluded that these tablets yield an ESR spectrum in the unirradiated form. The origin of this background resonance is not known. In this connection it can be mentioned that saccharides used for pharmaceutical purposes sometimes contain small amounts of metal oxides which may yield ESR signals. Furthermore, Kashiwagi and Enomoto (Ka 80) have shown that free radicals are formed in lactose when heated (70°C and higher) or exposed to UV. We have no information of the pretreatment of the lactose used in the Nitromex tablets and can therefore not ascribe the "background signal" to a particular step in the manufacturing procedure. The background signal (Fig. 1, top) is stable and has no influence on the calibration data. It is evident that due to this signal the dose-effect curve will not go through origin. Another effect caused by the background signal is that the spectra from the irradiated tablets showed small changes with dose in the low-dose region. This is marked on the spectra in Fig. 1 by arrows pointing at a couple of lines for which the relative intensity ratio changed with dose. In fact, this behaviour can be used to give a visual estimate of the radiation dose to the tablets irradiated during the accident. Thus, the data in Fig. 1 show that the dose involved must have been larger than 1.78 krad.

The parameter used to determine the irradiation dose is the number of radicals formed by radiation, which are stabilized in the tablets. The number of radicals is proportional to the area under the absorption

curve. Since first-derivative spectra are recorded a double intergration is necessary. This is automatically carried out by the ASPECT 2000 computer.

In Fig. 2 the dose-effect curve is presented. The number of radicals (given in relative units) is plotted versus the irradiation dose. A number of independent measurements are carreid out for each dose value used and the standard deviation in the measurements are given by vertical bars in those cases where it is larger than the symbol used. It is evident that the dose-effect curve is linear in the dose region examined.

One comment about the stability of the induced radicals appears appropriate. Within a period of from 1 day to 4 weeks after exposure we observed no spectral changes whatsoever including both qualitative and quantitative changes.

The tablets borne by the operator during the accident were measured under the same conditions. They yielded a result (given by a star in Fig. 2) which correspond to an absorbed dose of 3.7 krad (37 Gy).

B. Nitroglycerin A - L tablets.

The white Nitroglycerin A-L tablets yield no resonance when unirradiated. The radiation induced signal, however, showed spectral changes with time after exposure as shown in Fig. 3 upper part. The quantitative results are given underneath. A decrease in the number of radicals of 11% was observed in the period of from 2 hrs to 3 weeks after exposure. The data in Fig. 3 are given in a plot with a logarithmic scale along the

abcissa (the time-axis). It can be noted that the present data follow the equation discussed above for the stability. This suggests a decay of 17% in one year and 27% in 100 years.

The radicals induced in the tablets have not been identified. We assume that sugar radicals (more than one) are responsible for the spectra. The spectral changes together with the quantitative data (Fig. 3.) suggest that one radical is transformed into another one in the initial period after exposure rather than a rapid simple decay of one of the species.

Since the tablets exposed in the accident had been stored for 3 weeks before we got the opportunity to do ESR-measurements we decided to make the calibration curve on tablets stored for 3 weeks after exposure. The qualitative and quantitative results are given in Fig. 4. Again a linear dose-effect curve is obtained. The tablets exposed during the accident gave a spectrum corresponding to an absorbed dose of 3.8 krad (38 Gy).

The dose to the operator.

The dose given to the nitroglycerol tablets (the average value of those for Nitromex and Nitroglycerin A-L) in the accident was determined to 37.2 ± 0.5 Gy. This is the dose given to a position (the pocket of the operator) approximately 80 cm above the floor. One question which can be raised is whether an average body dose can be arrived at from these ESR results. Attempts are being made with phantom measurements, but several uncertainties exist. For example, due to the position of the ^{60}Co source the dose within the irradiation cell varied with the height above the floor. Thus, if the operator was in an upright position during the

accident the dose to a position 130 cm above the floor (i.e. the position of the chest) would be approximately 80% of that observed in the present experiments. Furthermore, we have no information to what extent the tablets were shielded by the body during the accident. Even though the operators movements within the irradiation cell are unknown the present results show that he must have been there for at least 5 minutes.

Dose determinations in radiation accidents

It is of course a strange coincidence that the victim of this accident suffered from heart problems and used tablets which subsequently could be used for dose determination. In the general case we must rely on some other compounds which poseas potentialities to be used as a dose monitor. Free radicals must be formed which in turn are stable at room temperature and in the presence of oxygen (air). We observed weak ESR signals in buttons, shoe and trousers, and it may be possible with some efforts to use these signals for dose determinations. A couple of requirements seem appropriate for a system which should be used as a dose monitor in radiation accidents. In the first place, it should be possible to determine the dose within the first day after exposure (i.e. radical lifetimes of the order of hours are necessary). And secondly, from a medical point of view with regard to treatment (such as bone marrow transplant) it seems important to determine doses in the range 0.5 to approximately 1 krad.

Based on the recent accident and the ESR experiment carried out we suggest that the following systems should be explored:

In the case of radiation workers a suitable compound (for example an amino acid such as glycine) in the form of a tablet can be included in the personal dosimeters used. The nature and stability of the radicals induced in glycine are well known (in other suitable compounds they can be explored) and calibration curves can easily be obtained.

2. In the case of the general public we suggest the possibility to use finger nails. Some preliminary experiments have been carried out in this laboratory. Finger nails (from the authors) have been cleaned by ultrasound in an ethanol bath and exposed to 50 kV X-rays to doses of the order 0.5 to 5 krad. Some results are displayed in Fig. 5. The following observations are made:

A. Unirradiated finger nails seem in general to exhibit a weak ESR signal. The extent of this background resonance varies from one person to another (Fig. 5A).

B. An ESR signal is induced by radiation. The main part of this resonance is a broad unresolved line with a peak to peak linewidth of approximately 10 gauss centered at a g-value of about 2.006. In addition a low field "wing" is observed. (Fig. 5B).
These data seem to suggest that the resonance in part is due to peroxyde protein radicals. The radiation induced signal seems to be independent of the donor person.

C. An example of a dose-effect curve is given in Fig. 5C. This curve is obtained by repeated exposures to one particular sample (taken from T.H.).

The data presented in Fig. 5 warrants the following conclusion: Free radicals are induced and stabilized in finger nails when exposed to ionizing radiation. With present days ESR spectrometers it seems possible to observe radiation induced radicals for doses down to 200 to 300 rad. The "nail dosimeter" is now being explored in more detail in our laboratory.

FIGURE LEGENDS

Fig. 1: First-derivative ESR-spectra of irradiated and unirradiated (top curve) Nitromex tablets. The amplification factors (relative gain) used are given on each spectrum. The two sets of vertical arrows point at spectral positions which exhibit changes with dose. The samples were measured at room temperature.

Fig. 2. The dose-effect curve for Nitromex tablets. The calibration curve is obtained by irradiating Nitromex tablets (the main component is lactose) at room temperature with ^{60}Co γ-rays to the doses indicated. The doses were determined by TL-dosimetry. The number of radicals, as determined from the area under the absorption curve, is given in relative units. Tablets irradiated during the accident yield a resonance with an area marked by a star.

Fig. 3. Effect of postexposure time on the ESR spectrum of "Nitroglycerin A-L". A tablet was exposed and measured 2 hrs. after exposure (top resonance). The tablet was then stored at room temperature and remeasured several times during the first 3 weeks (504 hrs) after exposure.

The lower part of the figure yields the number of radiation induced radicals as a function of time elapsed after the end of the exposure.

Fig. 4. First-derivative ESR spectra of irradiated "Nitroglycerin A-L" tablets observed 3 weeks after the end of the exposure (top part). The calibration curve, yielding number of radicals versus dose, is given underneath. Otherwise as for Fig. 2.

Fig. 5. First-derivative ESR spectra from unirradiated (A) as well as irradiated (B) finger nails. The results for two different persons (T.H. and H.T.) are given. The lower part (C) yields the dose-effect curve for a "nail dosimeter" obtained after repeated exposures to one particular sample (taken from T.H.). The ESR observations are made within 20 minutes after the exposure. The peak to peak amplitude is the parameter used which in turn is proportional to the number of radicals.

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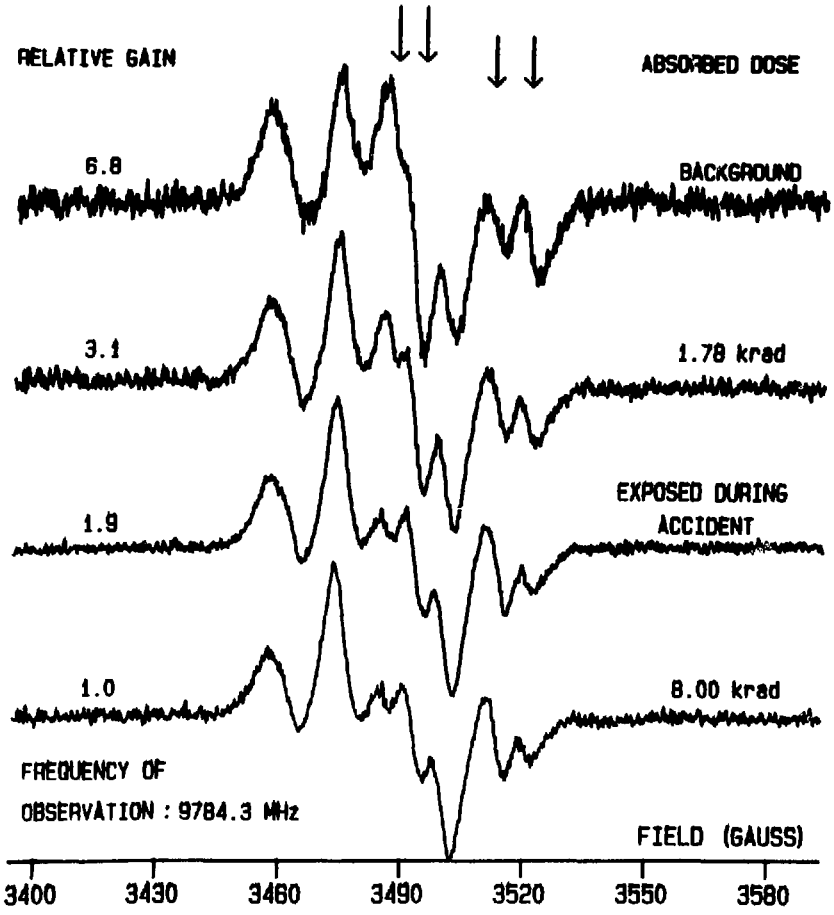
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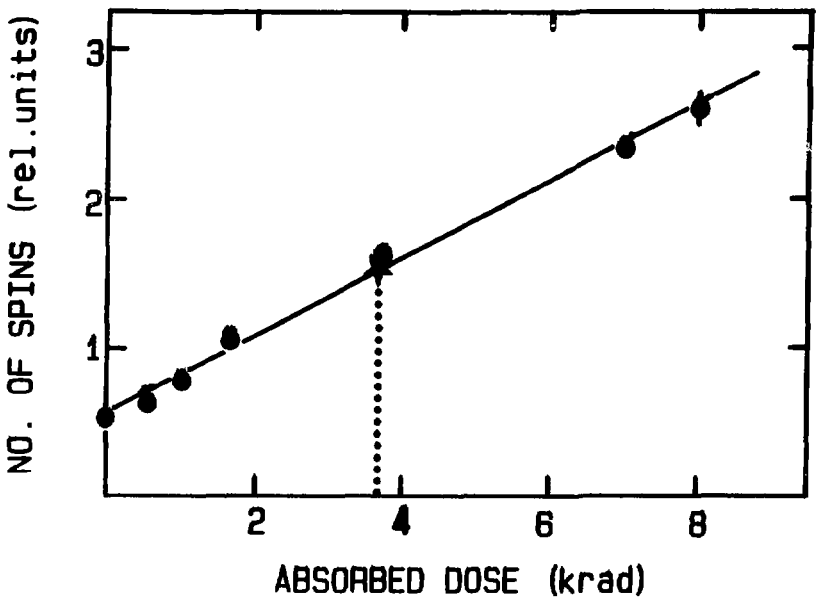
3550
3580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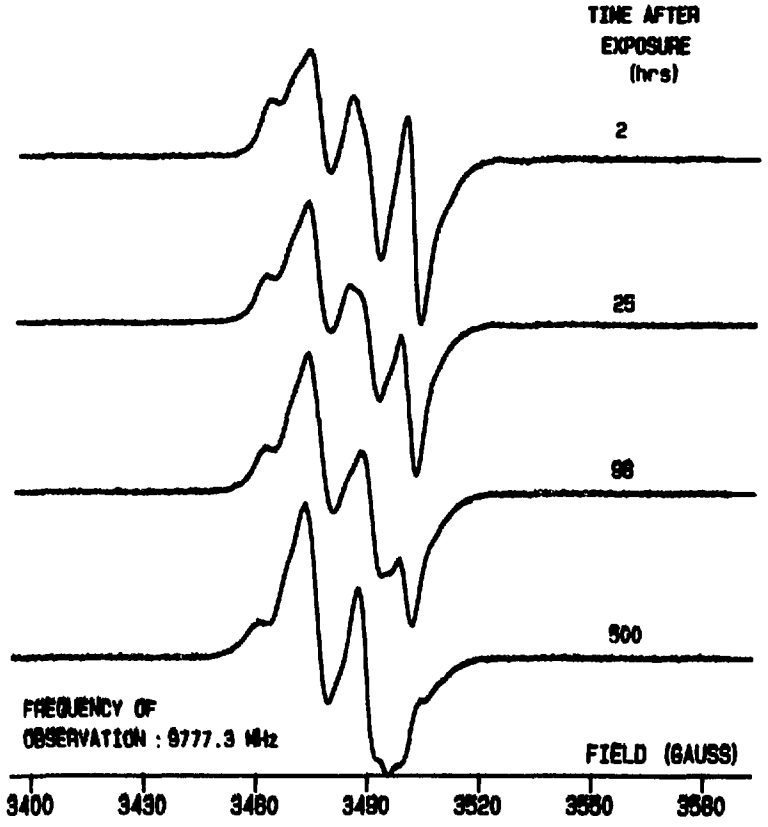
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(hrs)
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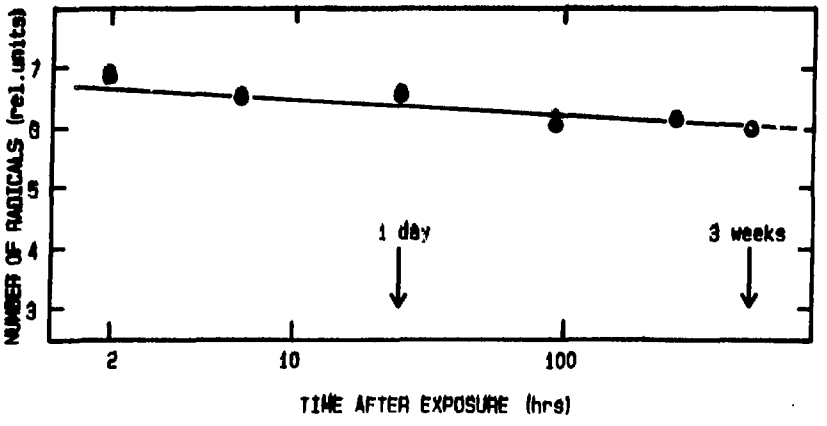
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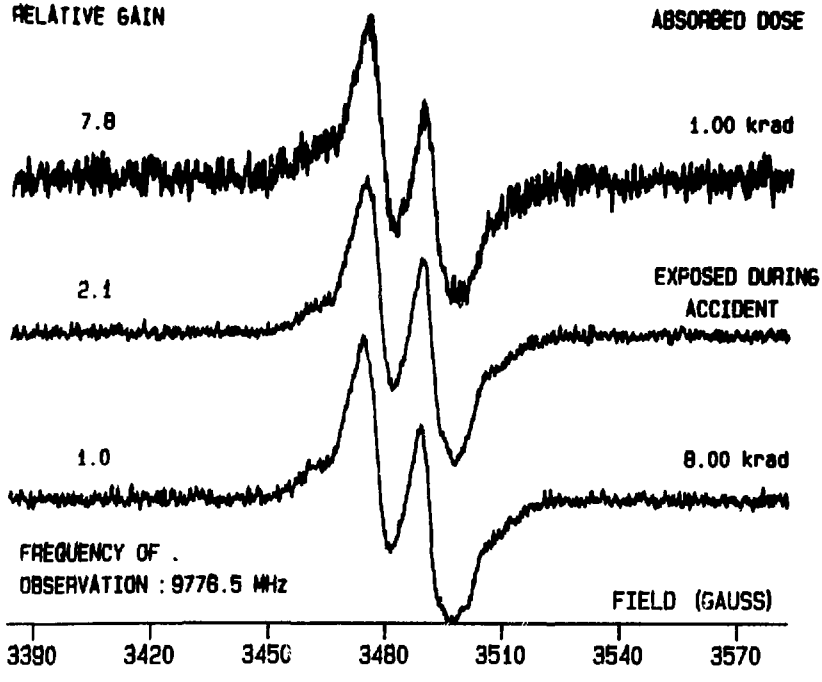
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2.1
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1.0
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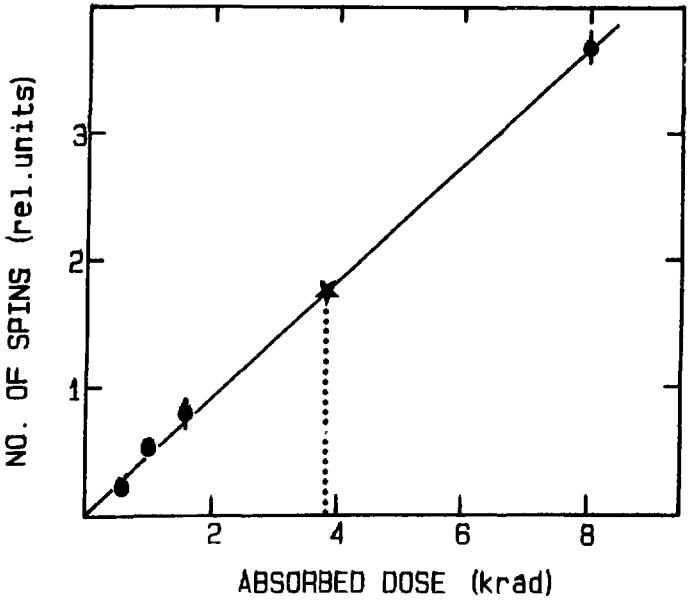
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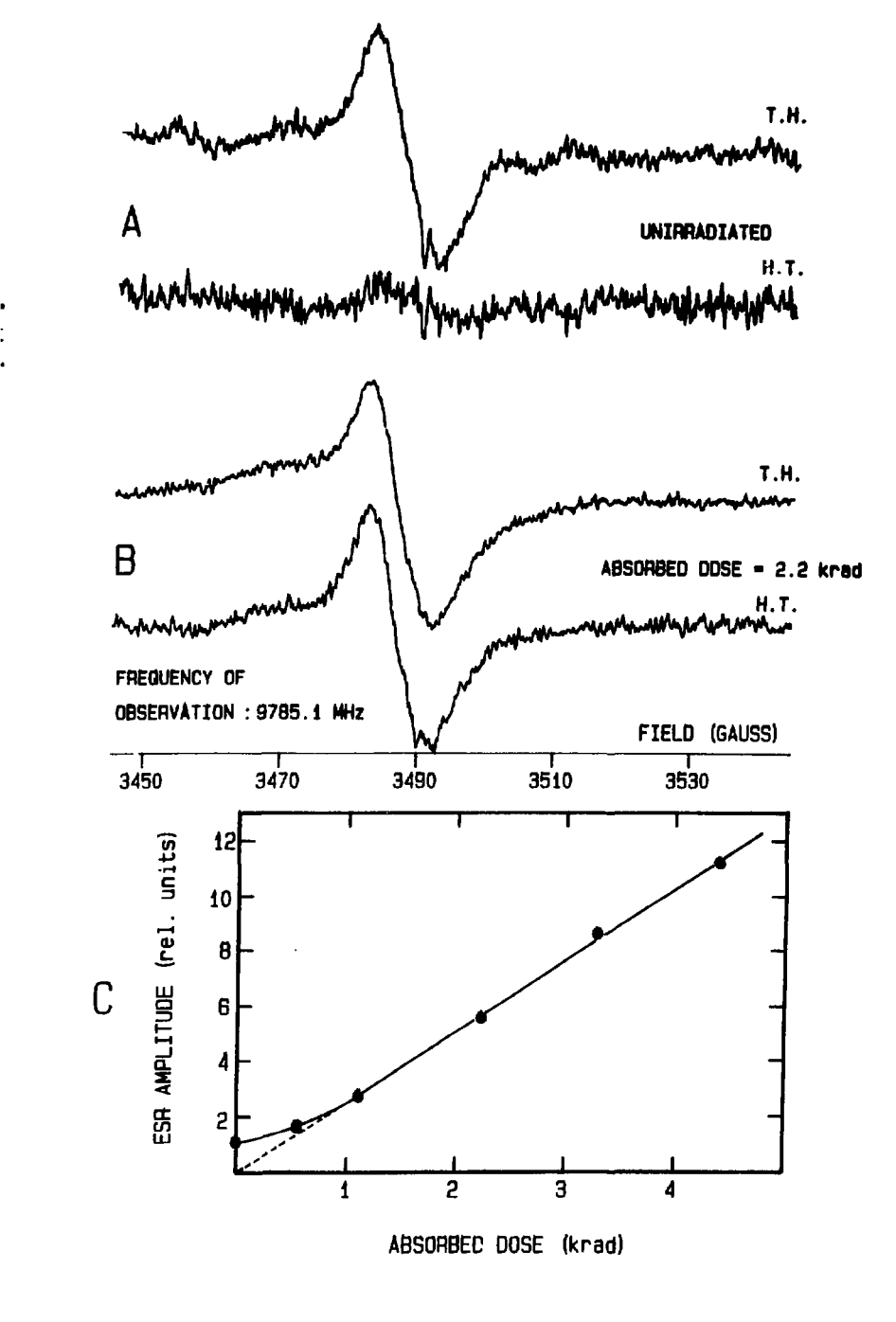
T.H.
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H.T.
T.H.
B
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H.T.
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OBSERVATION : 9785.1 MHz
FIELD (GAUSS)
3450
3470
3490
3510
3530
C
ESR AMPLITUDE (rel. units)
12
10
8
6
4
2
1
2
3
4
ABSORBED DOSE (krad)