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ACCELERATOR DEPARTMENT

Annual Progress Report

1 January - 31 December 1982

Abstract. A description is given of work in the fields of irradiation chemistry, physical dosimetry, radiation physics and technological application of radiation, radiation bacteriology research and irradiation technology, as well as of the operation of various irradiation facilities.

INIS-descriptors: ACCELERATOR FACILITIES; BACTERIA; DOSEMETERS; DOSIMETRY; IRRADIATION DEVICES; RADIATION CHEMISTRY; RESEARCH PROGRAMS; RISOE NATIONAL LABORATORY.

CONTENTS

PREFACE

The objective of the Accelerator Department is to contribute to research, development, and the implementation of processes based on ionizing radiation; thus, the following activities are carried out:

- Radiation chemistry research of fundamental and applied problems in chemistry. The applied techniques include pulse- and steady-state radiolysis as well as computer simulation.

- Radiation dosimetry research with respect to proper application of dose meters as well as to basic understanding of radiation absorption processes.

- Radiation bacteriology research mainly in relation to radiation sterilization problems and radiation-resistant microorganisms, and also to increase basic knowledge of the radiation resistance mechanism. Production and supply of bacteriological standard preparations for control of irradiation sterilization plants.

- Operation and maintenance of the irradiation facilities (three electron accelerators and three ^{60}Co-units).

- Development and construction of equipment for radiation experiments and for customer irradiation services. Upgrading of irradiation facilities.

- Customers services, including test and pilot irradiations, control and measurements, and advisory assistance.

The principal activities in these fields are described in this report which covers the period from 1 January to 31 December 1982. The contributions marked with * are abstracts of published articles.

1. RADIATION CHEMISTRY

1.1 Rate constants and products of the reactions of e_{aq}^-, O_2^- and H with ozone in aqueous solutions[*]

(K. Sehested, J. Holcman and E.J. Hart (Port Angeles, WA, USA))

Ozonide ions, identified by their optical absorption band at 430 nm, form in electron irradiated aqueous ozone solutions by the reactions: $e_{aq}^- + O_3 \rightarrow O_3^-$ and $O_2^- + O_3 \rightarrow O_3^- + O_2$. Both reactions are quantitative and the rate constant for the hydrated electron reaction with ozone was determined in competition with oxygen to be $k(e_{aq}^- + O_3) = (3.60 \pm 0.2) \times 10^{10}$ dm^{3}mol^{-1}s^{-1}. The rate constant for the peroxy radical reaction with ozone was measured from the pseudo-first order buildup of the ozonide ion to be $k(O_2^- + O_3) = (1.52 \pm 0.05) \times 10^9$ dm^{3}mol^{-1}s^{-1}. The rate constant of hydrogen atom reaction with ozone was measured in acid solution, pH 2, by competition with oxygen to be $k(H + O_3) = (3.65 \pm 0.40) \times 10^{10}$ dm^{3}mol^{-1}s^{-1}. The initial product is an OH radical.

1.2 The reaction of the hydroxyl radical with ozone

(K. Sehested, J. Holcman and E.J. Hart (Port Angeles, WA, USA))

The reaction of the OH radical with ozone has been measured by Bahnemann and Hart to be $k(OH + O_3) = 3 \times 10^9$ dm^{3}mol^{-1}s^{-1}. This rate constant was obtained by competition kinetics in the acetate-ozone system, measuring the absorbance at 350 nm (the acetate radical absorption) as function of the acetate-ozone ratio. As this rate constant is 75-fold greater than the gas-phase value, they suggested that a new species, presumably $HO_4(O_4^-)$, is formed.

We measured the formation of the O_3^- radical ion in a N_2O saturated ozone solution at pH 9-10.5. The formation kinetics and yields of O_3^- is dose rate dependent, indicating a second order recombination rate of the new species of the order of 10^{10} dm^{3}mol^{-1}s^{-1}. By extrapolating the yields and the kinetics to ∞ ozone concentration, a value of 1.1×10^8 dm^{3}mol^{-1}s^{-1} for the O_3^- formation is obtained from both. The experimental conditions were refined to avoid the second order reactions by using single pulses of 50 rd pulse^{-1} and by integrating 15-30 single traces by computer. With this technique it was shown that the formation of the O_3^- radical ion is first order with ozone concentration, and full yields of O_3^- according to initial radical yields are obtained. A second order rate constant for O_3^- formation of $(1.3 \pm 0.3) \times 10^8$ dm^{3}mol^{-1}s^{-1} was found.

An identical rate constant was obtained in the carbonate-ozone system, pH 10.3, by following the relative yields of the carbonate radical and the O_3^- radical as function of the carbonate concentration.

As a consequence of these findings it appears that $HO_x(O_x^-)$, if formed, possesses the same properties as the OH radical with respect to recombination rate and reactivity towards carbonate. Moreover, the decaying transient spectrum observed in UV during the O_3^- radical ion formation corresponds to the sum of the spectra of ozone and the OH radical. Thus, the only experimental argument for the existence of the $HO_x(O_x^-)$ species is the high rate constant determined in the acetate system (see next paragraph).

1.3 Pulse radiolysis of the ozone-acetate-N_2O system
(K. Sehested, J. Holcman and E.J. Hart (Port Angeles, WA, USA))

Our experiments in the ozone-acetate-N_2O system show that the acetate radical reacts with ozone forming the O_3^- radical. The O_3^- radical absorbs at 430 nm, but has an extinction coefficient at 350 nm of about 2/3 of the acetate radical. The rate constant measured for the buildup of the O_3^- at 430 nm is k = $7-8 \times 10^8$ dm^{3}mol^{-1}s^{-1}. It is also found that oxygen inhibits the formation of O_3^- in this system. The acetate radical ion is known to react with oxygen $\overset{\bullet}{C}H_2COO^- + O_2 \rightarrow \overset{\bullet}{O}_2CH_2COO^-$ with k = 3×10^9 dm^{3}mol^{-1}s^{-1}. Thus inhibition of the O_3^- formation by oxygen can be rationalized in terms of low reactivity of the peroxyacetate radical with ozone. Further examinations of the absorbances at 350 and 430 nm lead to the conclusion that the formation of O_3^- is the second step in the reaction between acetate radicals and ozone. The mechanism for the O_3^- formation is tentatively explained by the following reactions:

$$OH + CH_3COO^- \rightarrow \overset{\bullet}{C}H_2COO^- + H_2O$$

$$\overset{\bullet}{C}H_2COO^- + O_3 \rightarrow O_3\overset{\bullet}{C}H_2COO^-$$

$$O_3\overset{\bullet}{C}H_2COO^- \rightarrow CO_2 + H_2O + \overset{\bullet}{C}O_2^- \text{ (or } H_2CO + O_2 + \overset{\bullet}{C}O_2^-)$$

$$\overset{\bullet}{C}O_2^- + O_3 \rightarrow CO_2 + O_3^-$$
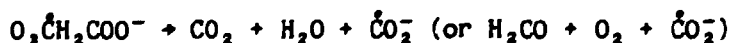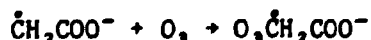
The rate constant k = 3×10^9 dm^{3}mol^{-1}s^{-1} for the OH + O$_3$ reaction, was measured in the ozone-acetate-N$_2$O system from the dependence of the absorption yields at 350 nm on the [O$_3$]/[CH$_3$COO$^-$] ratio without taking the above mentioned reactions into account. Rough calculations on the system have shown that the dependence of the absorbance at 350 nm to some extent can be accounted for even though the OH radicals react exclusively with the acetate. The results depends more on the oxygen/ozone ratio, as the acetate radical reacts with both. Our results invalidate the ozone-acetate system for a determination of k(OH + O$_3$). Therefore, it is concluded that the reaction of the OH radicals with ozone can be described as:

$$O_3 + OH \rightarrow O_2^- + H^+ + O_2$$

$$O_3 + O_2^- \rightarrow O_3^- + O_2$$
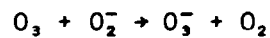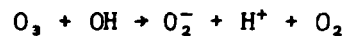
with k(OH + O$_3$) = $(1.3 \pm 0.3) \times 10^8$ dm^{3}mol^{-1}s^{-1}.

1.4 Molar absorptivities of ultraviolet and visible bands of ozone in aqueous solutions[*]

(E.J. Hart (Port Angeles, WA, USA), K. Sehested and J. Holcman)

The molar absorptivities of aqueous ozone solutions are reported for the wavelength ranges 190-300 nm and 350-900 nm. At the maxima of these bands, $\varepsilon_{260}(O_3)$ = 3292 ± 70 M^{-1}cm^{-1} and $\varepsilon_{590}(O_3)$ = 5.1 ± 0.1 M^{-1}cm^{-1}. The analyses for ozone were carried out by absorbance measurements of the gas at 253.7 nm and by oxidation of ferrous sulfate in sulfuric acid solution followed by back-titration of excess ferrous ion with potassium permanganate. Spectrophotometric analysis of ferric ion was also used at low ozone concentrations. A stoichiometric ratio, Fe^{3+}/O$_3$, of 1.996 ± 0.036 was found. The visible spectrum of aqueous O$_3$ is compared with that of ozone gas.

1.5 Formation of ozone in the reaction of OH with O$_2^-$ and the decay of the ozonide ion radical at pH 10-13[*]

(K. Sehested, J. Holcman, E. Bjergbakke and E.J. Hart (Port Angeles, WA, USA))

Ozone forms in aqueous alkaline solutions, pH 10-13, by a reaction between OH and O$_2^-$ radicals. The reaction OH + O$_3^-$ → O$_3$ + OH$^-$ is only a part (about 30%)

of the total reaction, the other reaction being $OH + O_3^- + OH^- \rightarrow 2O_2^- + H_2O$. The ozone formation is demonstrated by the high-pressure pulse radiolysis technique using a 4 µs, 40 krd pulse. The ozone disappears fast in a reaction with the simultaneously formed O_2^- reforming O_3^-. The mechanism for the O_3^- decay is based on these reactions. The final product from the O_3^- decay is only the peroxy radical, O_2^-. The overall rate constant for $OH + O_3^-$ is determined to be $k(OH + O_3^-) = (8.5 \pm 1.0) \times 10^9$ $dm^3mol^{-1}s^{-1}$. Computer simulations of the high-pressure system as well as the atmospheric-pressure oxygenated system with high and low pulse intensity support the suggested mechanism for the O_3^- decay. The protonation rate of the O_3^- radical ion is measured to be $k(O_3^- + H^+) = (9.0 \pm 1.0) \times 10^{10}$ $dm^3mol^{-1}s^{-1}$.

1.6 The Mechanism of O^3P atom formation in Y-ray irradiated and UV photolyzed aqueous solutions[*]

(E.J. Hart (Port Angeles, WA, USA), Weldon G. Brown (San Diego, CA, USA), and E. Bjergbakke)

O^3P atoms form by excitation processes in the radiolysis and photolysis of the oxyhalate ions, BrO_3^- and ClO_4^-. However, the mechanism for O^3P formation by the radiolysis of dilute alkaline solutions involves non-excitation processes. Evidence for this conclusion is provided by a comparison of "direct effect" calculations on these systems. They demonstrate that the relative yield of O^3P from OH^- is 15-fold greater than that of BrO_3^- thus indicating a more effective mechanism for O^3P formation in alkaline solutions. The expected increase in $G(H_2)$ from the postulated excitation decay reaction:

$(OH^-)^* = O^3P + H^-$ followed by $H^- + H_2O = H_2 + OH^-$ could not be confirmed. Neither water nor OH^- produce O^3P when irradiated at 184.9 nm. However relatively high yields of O^3P form in alkaline H_2O_2 solutions photolyzed at 253.7 nm. A possible reaction is: $O^- + OH = O^3P + OH^-$. The participation of sub-excitation electrons in aqueous radiolytic excitation phenomena is further explored in the radiolysis of formate solutions.

1.7 Computer simulation of the reactions in the Fricke dosimeter with varying Cl^- concentrations

(E. Bjergbakke)

This work is performed in collaboration with J. Swallow, Christie Hospital and Holt Radium Institute, Manchester, and B. Parsons, Kelterston College, North E Wales Institute.

The work on the computer simulations of the reactions in the Fricke dosimeter was continued. The reaction between HO_2 and Cl_2 improved the computerfit, but the mechanism is still not complete.

1.8 Dissociation and dioxygen formation in hydroxide solutions of tris(2,2'-bipyridyl)iron(III) and tris(1,10-phenanthroline)iron(III): Rates and stoichiometry*

(G. Nord, B. Pedersen (Chemistry Lab. I, H.C. Ørsted Institute) and E. Bjergbakke)

The fast redox reactions of the title Fe(III) complexes in basic solutions give the Fe(II) complexes and coordinated ligand N-oxide as primary products. Further reactions by parallel paths include dissociation to give the free ligand N-oxide and catalysis ty hydroxy-Fe(III) complexes leading to dioxygen. No O_2 is produced when dissociation of tris(2,2'-bipyridyl)Fe(III) is suppressed by addition of excess ligand; the dependence of the O_2 yield on the degree of dissociation of this complex can be reproduced using the rate constants for the parallel catalyzed and uncatalyzed decay of the first product.

1.9 Pulse radiolysis of Cl^- solution

(J. Holcman, E. Bjergbakke, and K. Sehested)

The buildup at the 350 nm band observed in neutral or slightly alkaline, N_2O saturated, concentrated (above 0.2 mol dm^{-3}) Cl^- solutions is ascribed to a new reaction (1) $ClOH^- + Cl^- \rightarrow Cl_2^-$. The rate constant for this reaction was obtained from computer simulation to be $k(Cl^- + ClOH^-) = 2\times10^5$ $dm^3mol^{-1}s^{-1}$. A reaction with such a low rate constant cannot be studied by conventional techniques due to the interference of second order radical-radical reactions. Therefore computer integration of 20-30 single traces with dose per pulse as low as 30-50 rd has been applied. Using this technique a first order character of the buildup is demonstrated and the order of magnitude of $k(ClOH^- + Cl^-)$ is confirmed. However, the yields of Cl_2^- obtained in these experiments are lower than the full yield of the initial radicals and increase with the Cl^- concentration. These findings are tentatively explained by the equilibrium $H_2O + Cl_2^- \rightleftarrows ClOH^- + Cl^-$. Work is in progress in order to verify this hypothesis.

1.10 Radiolysis of oxyanions of nonmetallic elements

(U. Kläning (Institute of Chemistry, Aarhus University) and K.Sehested)

Properties of the adducts of the hydrated electron with selenate, tellurate and arsenate, and of the OH and O^--adducts of selenite, tellurite and arsenite were studied by pulse radiolysis.

It was found that spectra and reactions of e_{aq}^--adducts in general are very similar to the spectra and reactions of OH or O^--adducts formed at the same pH. The O^--adduct of selenite and the e_{aq}^--adduct of selenate at pH > 13 dissociate to selenite and O^-. At pH < 11 the OH-adduct of selenite and the e_{aq}^--adduct of selenate disappear in a second order process. The e_{aq}^--adduct of selenate and O^-/OH adducts of selenite react with carbonate forming the carbonate radical ion. The e_{aq}^--adduct of tellurate and the O^-/OH adducts of tellurite react with O_2 forming O_2^-. The e_{aq}^--adduct of tellurate reacts with the bicarbonate ion with formation of the carbonate radical ion. The corresponding reaction of O^-/OH-adducts of tellurite, at pH 10-11, with bicarbonate does not go to completion, an observation which indicates that more than one O^-/OH-adduct is formed at these pHs. No reaction of e_{aq}^--adduct of tellurate and O^--adduct of tellurite with carbonate was observed.

The O^--adduct of arsenite forms a complex with oxygen, a complex which in a subsequent reaction yields arsenate and O_2^-. In contrast to selenite and tellurite, arsenite reacts with the carbonate radical ion under formation of the OH-adduct of arsenite.

1.11 Reaction of OH and O^- with chlorate and bromate

(U. Kläning (Institute of Chemistry, Aarhus University), Elfin Larsen (Chemistry Department), and K. Sehested)

Based on pulse radiolysis experiments and measurements of exchange of oxygen isotopes between solvent water and the solutes, chlorate and bromate, it is concluded that the rate constants of the reaction of OH and O^- with ClO_3^- and BrO_3^- are less than 10^5 $dm^3mol^{-1}s^{-1}$.

1.12 Reaction of hydroxyl radicals with hydrogen at elevated temperatures. Determination of the activation energy[*]

(H. Christensen (Studsvik Energiteknik AB, Sweden) and K. Sehested)

The reaction of hydroxyl radicals with hydrogen in aqueous solutions has been studied in the temperature range 20-230°C. The rate constant of the reaction was determined either by competition kinetics, using Cu^{2+} as the competitor, or through the measurement of the formation rate of O_2^- in aqueous solutions of oxygen and hydrogen. The rate constants at 20 and 230°C are $(3.4 \pm 0.3) \times 10^7$ and $(7.7 \pm 1.5) \times 10^8$ $dm^3 mol^{-1} s^{-1}$, respectively. The activation energy of the reaction is 19 kJ mol^{-1} (4.6 kcal mol^{-1}).

1.13 Activation energy of the reaction $e_{aq}^- + e_{aq}^-$

(H. Christensen (Studsvik Energiteknik AB, Sweden) and K. Sehested)

The spectrum of the hydrated electron is measured in the temperature range 14-200°C. The maximum absorption wavelength shifts to the red as the temperature increases in accordance with literature. The maximum absorbance and half width change very little over this temperature range, indicating that the radical yields are almost constant up to 200°C and that the solvation shell does not change significantly. The second order recombination rate gives an activation energy of about 5.3 kcal mol^{-1} (~22 kJ mol^{-1}) although the reaction is not pure second order above 150°C. The experiments are performed at pH 13 with high pressures of hydrogen. The OH radicals are converted to hydrogen atoms, which successively convert to the hydrated electron by OH^- reaction.

1.14 Activation energy of $O^- + H_2$ and $H + OH^-$

(B. Hickel (Saclay, France) and K. Sehested)

The temperature-pressure cell technique was used to determine the activation energy of the $O^- + H_2$ and $H + OH^-$ reactions. The measurements were performed in alkaline solutions, pH 13-14, with hydrogen at high pressure following the build-up of the hydrated electron at 700-900 nm. As the hydrated electron simultaneously decays, the experimental data are computer simulated to evaluate the rate constants at the various temperatures. The activation energy for $H + OH^- \rightarrow H_2O + e_{aq}^-$ is determined to be 6.4 kcal mol^{-1} (27 kJ mol^{-1}).

1.15 Reactivity of OH and O⁻ with aqueous methyl viologen studied by pulse radiolysis[*]

(S. Solar and N. Getoff (Institut für Theoretische Chemie und Strahlenchemie der Universität Wien, Austria), W. Solar (Ludwig Boltzman Institut für Strahlenchemie, Wien, Austria), J. Holcman and K. Sehested)

The behavior of aqueous MV^{2+} (containing 3×10^{-2} mol dm^{-3} N_2O) towards oxidizing radicals (OH and O⁻) was investigated in the pH-range from 6 to 14 by means of pulse radiolysis, combined with a semi-linear optimization method. In neutral and weak alkaline solutions (pH = 6 to ≤ 9) the OH-attack results mainly (92%) in the formation of OH-adducts on the ring carbon atoms of MV^{2+} (R_1 species) and the rest of OH is abstracting an H-atom from the $-CH_3$ group (R_2 species). The first type of transients (R_1) are produced with k = (2.3 ± 0.2)×10⁸ $dm^3mol^{-1}s^{-1}$ and decay with 2k = (1.3 ± 0.2)×10⁸ $dm^3mol^{-1}s^{-1}$, possessing λ_{max} = 470 nm (ε_{470} = 2000 ± 70 m^2mol^{-1}). The R_2 radicals are formed with k = (2.0 ± 0.3)×10⁷ $dm^3mol^{-1}s^{-1}$ and disappears with 2k = (1.0 ± 0.2)×10⁸ $dm^3mol^{-1}s^{-1}$.

In strong alkaline solutions (pH ≥ 13.8; 3×10^{-2} mol dm^{-3} N_2O) the O⁻ radical anions react preferentially (80%) with the $-CH_3$ group by H-cleavage (k = (1.2 ± 0.1)×10⁹ $dm^3mol^{-1}s^{-1}$) forming R_2-transients, which decay mainly by reaction with OH⁻ (k = 2.8 ×10⁶ $dm^3mol^{-1}s^{-1}$) to produce R_3 intermediates. The last ones have absorption maxima at 392.5 and 605 nm ($\varepsilon_{392.5}$ = 3400 ± 100 m^2mol^{-1}; ε_{605} = 1630 ± 70 m^2mol^{-1}) and are very long lived species. A small fraction of R_2 transients is disappearing by formation of dimers (k = (1.0 ± 0.2)×10⁸ $dm^3mol^{-1}s^{-1}$).

The remaining 20% O⁻ attack MV^{2+} on the ring carbon atom (k = (3.0 ± 1)×10⁸ $dm^3mol^{-1}s^{-1}$) resulting in O⁻-adducts, which have λ_{max} = 470 nm (ε_{470} = 880 ± 50 m^2mol^{-1}) and can decay by reaction with OH⁻ (k = (1.35 ± 0.2)×10⁴ $dm^3mol^{-1}s^{-1}$) or by dimerization (2k = (1.0 ± 0.2)×10⁸ $dm^3mol^{-1}s^{-1}$).

1.16 The reaction of N,N-dimethylaniline radical cation in strongly alkaline solution[*]

(J. Holcman and K. Sehested)

The N,N-dimethylaniline radical cation is formed in pulse radiolysis of strongly alkaline (pH = 13-14) solutions in an one-electron oxidation of the N,N-dimethylaniline (DMA) by the $(CNS)_2^-$ radical, k(DMA + $(CNS)_2^-$) = 1.3×10⁸

$dm^3mol^{-1}s^{-1}$. The radical cation thus formed loses its methylic proton in a reaction with OH^- forming the corresponding substituted methyl radical, $k(DMA^+ + OH^-) = 1.0\times10^5$ $dm^3mol^{-1}s^{-1}$.

1.17 Contract work for Studsvik Energiteknik AB

(H. Christensen (Studsvik Energiteknik AB, Sweden), E. Bjergbakke and O. Lang Rasmussen (Computer Installation))

The work consists of program development and computer simulation of a) Radiation chemistry in connection with radioactive waste disposal, and b) Reactor chemistry in a LOCA (Loss of Coolant Accident).

1.18 References

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2. RADIATION PHYSICS, PHYSICAL DOSIMETRY, AND TECHNOLOGICAL APPLICATION OF RADIATION

2.1 Experimental and calculated response of the radiochromic dye film dose meter to high-LET radiation[*]

(J.W. Hansen, M. Wille, and K.J. Olsen (Dept. of Radiophysics, University Hospital of Copenhagen, Herlev))

The dose-response characteristics of biological systems and physical detectors change with the linear energy transfer, LET, of the impinging charged particle, so that the response to high-LET radiation may either be larger or smaller relative to the response of low-LET radiation for the same absorbed

dose. Most physical detectors, however, show a decrease in relative response with increase in z_{eff}^2/β^2. Once 2 or 3 parameters can be obtained from low-LET radiation experiments with a given detector, the theory of track structure (1) predicts its high-LET dose-response characteristics. The theory is based on the assumption that the ratio in response for high-LET particles to that for low-LET radiations, RE, is due mainly to the inhomogeneous dose distribution around the path of that particle. The radiation effects of interest are due primarily to the absorbed dose of the δ-rays ejected from the ion path. Radiation effects from low-LET radiation, e.g. γ-rays and high energy electrons, are also due to absorbed dose from δ-rays, i.e. low energy electrons.

Dose-response characteristics were measured for the FWT 60 nylon-base radiochromic dye-film dose meter irradiated with ion beams of 3 and 16 MeV protons, 10 MeV α particles, 21 MeV ^{7}Li-, 42 MeV ^{14}N-, and 64 MeV ^{16}O icns. These characteristics were compared with the response to reference low-LET radiations, i.e. ^{60}Co γ-rays and 10 MeV electrons. The ion beams covered an initial LET range of 28-5434 MeVcm^{2}g^{-1} corresponding to an average LET in the detector of 28-6740 MeVcm^{2}g^{-1}. The experimental relative effectiveness, RE, decreased monotonically with z_{eff}^2/β^2 from 1.00 for 16 MeV protons to 0.81, 0.55, 0.47, 0.36, and 0.28 for 3 MeV protons, α particles, ^{7}Li, ^{16}O$^-$, and ^{14}N ions, respectively.

The radial dose distribution around the ion path was calculated using two different range-energy relations for the δ-rays: a linear relation $r = k_1 \cdot \omega$ and one based on a power law $r = k_2 \cdot \omega^\nu$ where r is the range and ω the energy of the δ-rays. Calculations of theoretical RE values, based on the track structure theory of Katz and coworkers, were in good agreement with experimental results. The best agreement (-6.2% to + 14.3%) was obtained by using a power-law range-energy relation.

2.2 Detection of individual tracks of heavy ions in the dye film

(J.W.Hansen, R. Katz (University of Nebraska-Lincoln, U.S.A.))

Prediction of relative effectiveness of high-LET particles in matter involves calculations of the radial dose deposition around the path of the penetrating particles. By bombarding the dye-film dose meter by 2.02 GeV uranium ions we hope to be able to test part of the calculations experimentally. These densely ionizing particles leave tracks in the film which, according to calculations, are visible in a microscope. The irradiation is recently done at GSF, Darmstadt (G. Kraft).

2.3 Experimental and theoretical track segment investigations of 64 MeV oxygen ions in the dye film

(J.W. Hansen and K.J. Olsen (Dept. of Radiophysics, University Hospital of Copenhagen, Herlev))

In a recent study of the high-LET response of a FWT 60 radiochromic dye film using a 50 µm thick film we have found a very good agreement between the experimental and calculated relative effectiveness, RE, for ions covering a range in average LET of 28-6740 MeV cm^2/g. In the case of irradiation with the highest LET used in that study, the film was a thick detector in which the particles were completely stopped. The present experiments were designed to test the calculations in detail, particularly in the Bragg-peak of the slowing-down particles.

The irradiation was carried out with a number of FWT 60 films, 5-7 µm in thickness, packed in a stack sufficiently thick to stop the 4 MeV/amu oxygen ions used in the present experiment. The dose to the films was calculated from measured beam fluence and the recent published stopping power data of H.H. Andersen and Ziegler. The effective charge of the ions when penetrating the film samples was calculated from the formula of Ziegler. The response of the film to ionizing and exciting radiation is given by the change in optical density per unit film thickness (∆OD/mm) measured at the wavelength of 601 nm.

The experimental and theoretical uncertainty in calculations of dose and RE is mainly determined by the accuracy of the data for stopping power and the effective charge of the ions. Both become more and more inaccurate below 1 MeV/amu and data in the vicinity of the Bragg-peak may be particular inaccurate.

Our radial dose distribution calculations have been compared to published data, and excellent agreement is found both with experimental data and calculations using a Monte Carlo code of Paretzke for a 0.53 MeV [79]Br-ion. An excellent agreement is also found with a calculated dose distribution around the path of a 2 MeV/amu ^{12}C-ion.

The curves in Fig. 1 show the average dose to the film samples calculated: a) from particle fluence and stopping power, b) from the measured response and the calculated RE values, and c) from the measured response and the dose-response calibration curve for the reference radiation.

Figure 2 shows: a) the measured film response, b) the theoretical response as calculated from average absorbed dose and RE values for the film samples, and c) response, if the absorbed dose was due to the reference low-LET radiation.

Fig 1

Fig 2
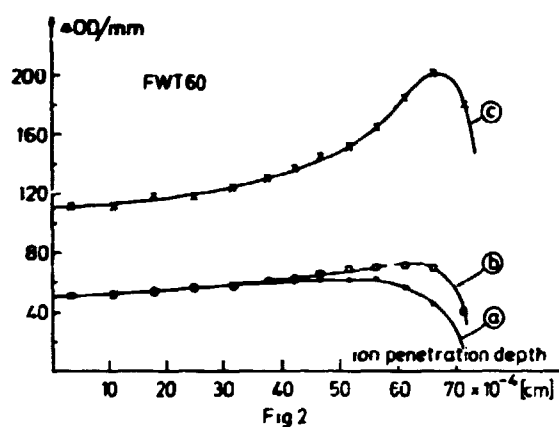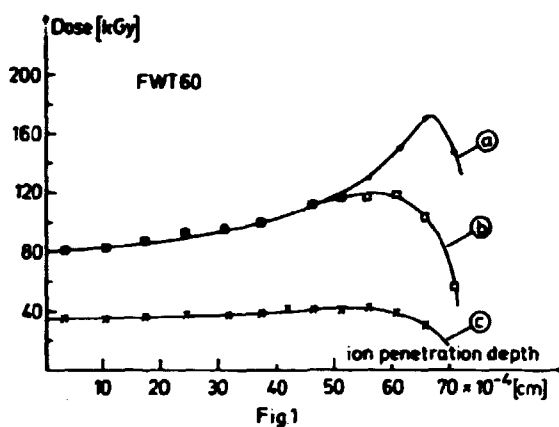
The data in Figs. 1 and 2 show that the theory is able to calculate with good accuracy the dose response over most of the particle range. The RE values that are too high calculated below 1.5 MeV/amu cannot be corrected for by changing the parameters in the theory without affecting the initial part of the curve where perfect agreement is observed. In an earlier study of 3 MeV/amu ^{14}N-ions stopped in a 50 μm FWT 60 film, the calculated RE values were 14% too high. The most likely explanations are that at low energies relatively more of the absorbed energy is deposited as excitation energy and that the film though sensitive to excitation is more sensitive to ionization.

2.4 Dose intercomparison with alanine

(L. Verhey (Dept. of Radiation Medicine, Massachusetts General Hospital, Boston, U.S.A.), R. Katz (University of Nebraska, Lincoln, USA), F. Bermann (CEA-STEP/STEPD, Fontenay aux Roses, France), M. Waligorski (Inst. of Nucl. Physics, Krakow, Poland), K.J. Olsen (Dept. of Radiophysics, University Hospital of Copenhagen, Herlev), and J.W. Hansen)

Dose intercomparison measurements with alanine dose meters are initiated including laboratories in Poland, France and U.S.A. The cooperation is motivated from difficulties in stipulating the relative biological effectiveness, RBE, in the spread Bragg-peak of a proton beam. The Harvard accelerator, Boston, is being used for radiotherapy by the Harvard Medical School. Biologically they find that the proton RBE's range from 1.05 to 1.25, while track structure calculations predict 1.03. This discrepancy may be due to problems with the proton dosimetry. One way to check this is with alanine dose meters exposed to a certain dose at the proton accelerator and read out at the participating laboratories. At the same time calculations on predicted relative effectiveness, RE, for the proton beam in question in alanine will be performed by the participants. Theoretically the RE for the alanine dose meter, which is a one-hit detector. cannot exceed 1, and if by measurements we find that it does exceed 1, we can conclude that the proton dosimetry is wrong.

The ESR measurements will be performed on a Varian E-3 ESR spectrometer, which is borrowed from the Institute of Chemistry, Aarhus University, for an indefinite period of time.

The spectrometer will be used in an investigation of the alanine dose meter for which work is in progress. In the Nordic Recommendation for External Beam Therapy is stated the necessity of having a tertiary standard dose meter for se in calibration of radiotherapy machines. The Danish State Institute for Radiation Hygiene has expressed its interest in investigation of alanine for this purpose and for use in calibration of food irradiation facilities.

2.5 Investigations on the dye-film dose meter[*]

(J.W. Hansen, M. Wille and K.J. Olsen (Dept. of Radiophysics, University Hospital of Copenhagen, Herlev))

During an investigation of a theory of particle track structure using the radiochromic dye-film dose meter as a detector, it was found that the knowledge of the behaviour of the dose meter was lacking in several respects. Previous investigations of the dye film have mostly been concerned with dose levels, where the response is linear. We have exposed the dose meter to doses up to 1-2 MGy, which saturates the formation of dye molecules with low-LET radiation. The film has been irradiated with both ^{60}Co γ-rays, 10 MeV electrons and heavy charged particles covering a range in initial LET of 28-5434 MeV cm^2g^{-1}. Our investigations have covered: the optical absorption spectrum at various dose levels and radiation qualities, kinetics of build-up and fading of coloration after exposure to high and low doses, the saturation dose-response level, bleaching at very high doses, the dose-response after irradiation in air or vacuum, dose rate effects at high doses, and temperature dependence of the dose-response. The dose-response characteristics have been measured mainly at 510 nm and over a dose range of $1-10^4$ kGy which is from the lowest detectable dose to above saturation.

The dose-response has been found to depend strongly on: the time span between irradiation and measurement, the irradiation temperature, and the dose rate at doses above 50 kGy for low-LET radiation. Irradiation in vacuum (< 1Pa) and open air produced same dose-response. This work supplements previous investigations of the dye film mainly carried out at lower doses.

2.6 The model of track structure applied to radiotherapy[*]

(J.W. Hansen and K.J. Olsen (Dept. of Radiophysics, University Hospital of Copenhagen, Herlev))

Heavy charged particles and neutrons are used in radiation therapy, mainly treatment of cancer diseases, to an extent controlled by economic considerations. By using high-LET radiation several advantages are obvious, namely enhanced concentration of dose deposition, enhanced effectiveness, RBE, in cell killing per unit dose deposited, and a reduction of the oxygen enhancement ratio, OER. The OER denotes that at low-LET radiation the cells are approximately 3 times less sensitive to radiation when irradiated under normal oxygen tension than when irradiated under anaerobic conditions. Tumor cells accumulate relatively more oxygen and are as such less sensitive to

cells accumulate relatively more oxygen and are as such less sensitive to low-LET radiation than normal cells. A problem connected to the use of high-LET radiation is the prediction of overall cell killing by fractionation doses. We have incorporated the model of track structure, which predicts cell killing for high-LET radiation, into the Cohen model, which is the most frequently used model for fractionated dose planning in radiotherapy, Risø-R-477. We have so far no experimental evidence for the validity of our model, which, however, may be tested by means of bacteria cultures available from the bacteriological laboratory at the Accelerator Department.

2.7 Radiochromic dye film dose meters

(A. Miller, W. Batsberg Pedersen (Chemistry Dept.), and W.L. McLaughlin (National Bureau of Standards, Washington, D.C., USA))

Thin-film plastic dose meters are produced using commercially available dye precursors as well as dye precursors synthesized at the Chemistry Department of Risø. The properties of the dose meters are investigated, in part under a research contract with the IAEA (2883/RB), particularly with respect to electron beam irradiations. One finding is that a previously observed instability of the response seems to be due to relative humidity. The dose meter films have been used for dose and dose distribution measurements.

2.8 Lyoluminescence

(A. Miller)

An apparatus for measurement of lyoluminescence has been modified with an improved system for water injection, and this is being tested. We participated with this dosimetry system in an international dose intercomparison organized by the IAEA as a part of that agency's program for high dose standardization. The properties with respect to dose rate, temperature, humidity and storage are being investigated.

2.9 Calorimetry

(A. Miller, and W.L. McLaughlin (National Bureau of Standards, Washington, D.C. USA))

For both of the dose meters above, and also in more general terms, it is important that irradiation conditions are well defined and calibrated. For our cobalt-sources calibration is made by standard ferrous-sulphate (Fricke) dosimetry, while calorimetry is used at the electron accelerators. The water calorimeter, which serves as the reference at the linear accelerator, has been tested in an intercomparison involving National Bureau of Standards, Washington, D.C., Physikalisch-Technische Bundeanstalt, Braunschweig, and National Physical Laboratory, London. The measurements, which were also part of IAEA's program for high dose standardization, are not yet concluded. In connection with the measurements on the water calorimeter, a graphite calorimeter with similar dimensions was constructed. It is more sensitive than the water calorimeter and can be used at lower doses on the linear accelerator, but it is intended for use also at the 400 keV electron accelerator. Part of this work is carried out under the IAEA research contract.

2.10 Calculation of the energy dependence of dose meter response to ionizing photons[*]

(A. Miller, and W.L. McLaughlin (National Bureau of Standards, Washington, D.C., USA))

Using a program in BASIC applied to a desk-top calculator, simplified calculations provide approximate energy dependence correction factors of dose meter readings of absorbed dose according to Bragg-Gray cavity theories. Burlin's general cavity theory is applied in the present calculations, and certain limitations of the theory are considered. Examples of the use of the program are given for ^{60}Co γ-ray irradiation of a LiF dose meter held in aluminum and for evaluation of the influence of changes in broad γ-ray spectra on the response of several dose meters. The BASIC program and typical data plots as given here are available for certain dose meter prob materials and combinations used with intermediate energy photon spectra (0.01-100 MeV).

2.10.1 A program in BASIC for calculation of cavity theory corrections[*]

(A. Miller, and E. Bugge Christensen (Technical University, Copenhagen))

A program in BASIC for a desk-top calculator HP 9830A is described. The pro-

gram allows calculation of cavity theory corrections according to Burlin's general cavity theory. The calculations are made by using tabulated values for stopping powers and energy absorption coefficients, stored either as coefficients to a fitted polynomial or as the actual table data.

2.11 IAEA training course
(A. Miller)

As a part of the IAEA's program for high dose standardization, a training course was arranged at Risø, 20 September - 1 October, 1982. 17 participants from all over the world got an impression of the latest developments in dosimetry during lectures and practical exercises. Most of the staff in the Accelerator Department was involved in getting through the seminar, which also had lecturers from Health Physics Department, Safety Department, Danish agencies and firms, and from USA, Hungary, England, and the IAEA.

2.12 Commercially oriented activities
(A. Miller, and W. Batsberg Pedersen (Chemistry Dept.))

Commissioning dosimetry was carried out at a 250 keV Electrocurtain accelerator temporarily installed at the Printing Division in the Danish National Bank. The measurements which were carried out with radiochromic dye films (commercial FWT-60 and home-made PVB) showed a lower nominal dose than specified, but good agreement with nominal depth dose, dose uniformity and relation between dose and paper speed was found.

Other dose measurements were carried out for Danish and foreign firms, as were test-irradiations and pilot-scale industrial irradiations. In one case we have irradiated materials in larger quantities.

We have assisted the National Food Institute in the preparation of a report describing the current status of food irradiation, and we have assisted two students, who for the final exams had projects on food irradiation. We have also assisted an industry research project on development of specialized rubbers for medical applications.

Measurements of radioactivity induced in products at 10 MeV electron irradiations are being carried out. Reasonable agreement with theoretical predic-
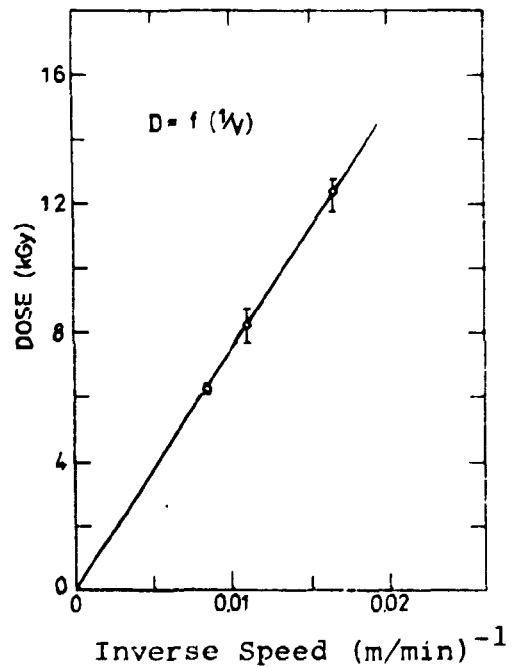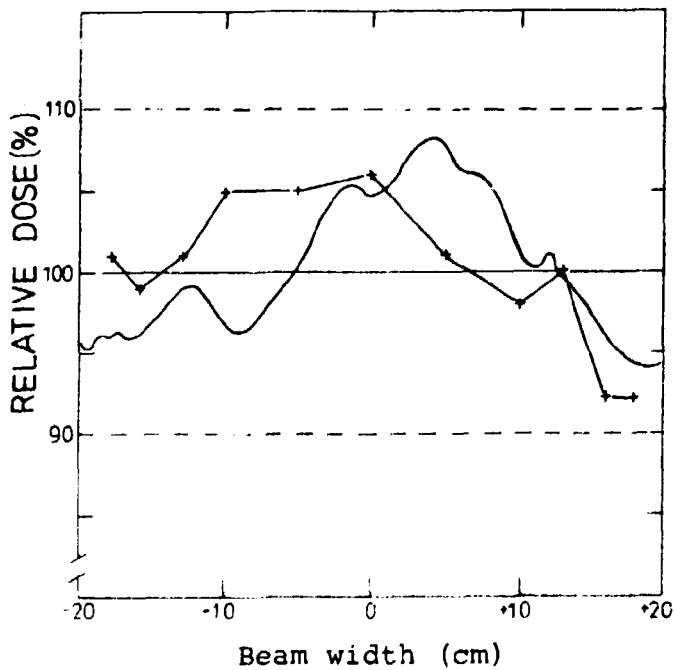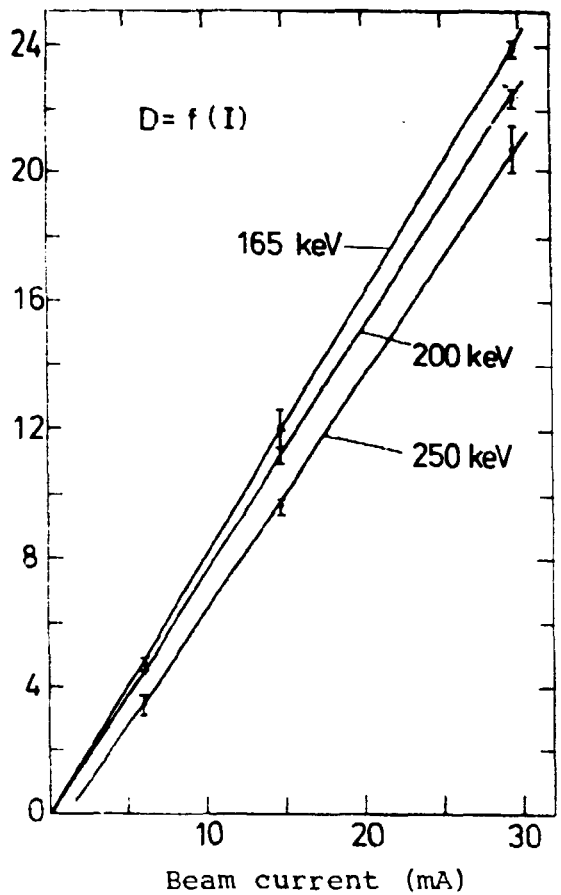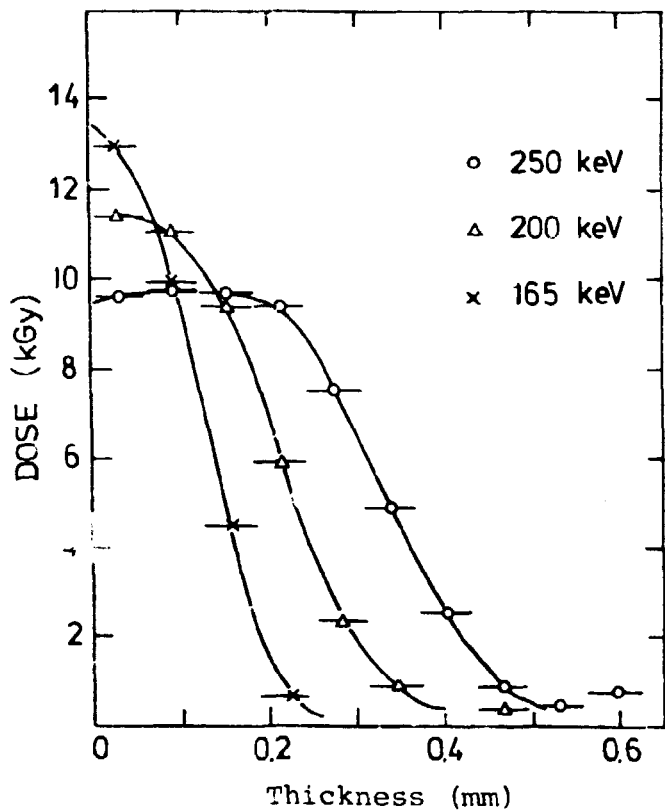
Commissioning dose measurements on an Electrocurtain
accelerator installed in the Danish National Bank.

tions have been found, but some questions about the reactions leading to thevery small amounts of radioactivity remains.

2.13 References

J.W. Hansen and K.J. Olsen, Experimental and Calculated Response of a Radiochromic Dye-Film Dose Meter to High-LET Radiations. Accepted: Rad. Res.

J.W. Hansen, M. Wille, and K.J. Olsen, Problems Associated with the Use of the Radiochromic Dye-Film as a Radiation Dose Meter. Accepted: Radiat. Phys. Chem.

J.W. Hansen and K.J. Olsen, Experimental Investigations of the Delta Ray Theory for Heavy Ions Applied to Thick Detectors. To be presentated at the 7th International Congress of Radiation Research, July 1983.

J.W. Hansen, Medium Range Dosimetry by ESR Spectroscopy of Alanine. To be presented at the 11th Nordic Meeting on Clinical Physics, May 1983.

J.W. Hansen and K.J. Olsen, Relative Effectiveness of High-Let Radiation in a Tissue Equivalent Physical Detector. To be presented at the 11th Nordic Meeting on Clinical Physics, May 1983.

3. RADIATION BACTERIOLOGY RESEARCH

Bacteriological research concerns the developing and testing of radiation sterilization processes, as well as the giving of advice and assistance on specific projects to prospective users of radiation sterilization. Research interests are concentrated on the mechanisms of radiation resistance.

3.1 Sensitivity of Escherichia coli acrA mutants to psoralen plus near ultraviolet radiation*

(M.T. Hansen)

The sensitivity to psoralen plus near ultraviolet light (PUVA) was compared in a pair of E. coli strains isogenic except for the acrA locus. AcrA mutants were forty times more sensitive to the lethal effect of PUVA than the wild type. Free λ phage exposed to PUVA survived as well when plated on acrA mutants as on the wild type. In contrast, λ CI857 ind⁻ was very sensitive to PUVA when carried by lysogenic acrA strains. The hypersensitivity of bacterial and λ DNA, when inside acrA cells, was paralleled by an increased photobinding of radio-labelled psoralens in the mutant. Binding was increased specifically to DNA rather than to nucleic acids in general. The acrA-determined difference in psoralen binding ability persisted after permeabilizing treatment of the cells. The data suggest that the acrA mutation causes an alteration in the environment of the cellular DNA so as to allow increased intercalation and photobinding of psoralens.

3.2 Rescue of mitomycin-C or psoralen inactivated Micrococcus radiodurans by additional exposure to radiation or alkylating agents*

(M.T. Hansen)

The processing of damaged DNA was altered in a mitomycin-C sensitive mutant (mtcA) of Micrococcus radiodurans. The mutant, which retains resistance to UV radiation, did not show the characteristic wild type excessive DNA degradation and cell death after sublethal doses of either UV light or mitomycin-C followed by incubation with chloramphenicol. After exposure to ionizing radiation, which introduces DNA strand breaks by direct, non-enzymatic action chloramphenicol did, however, promote loss of viability equally in wild type and mutant strain. The data suggest constitutive synthesis of an enzyme system responsible for wild type proficiency in the repair of mitomycin-C induced damage.

An alternative system able to repair damage caused by mitomycin-C was demonstrated in the mtcA background. In the mutant, additional damage inflicted upon the cellular DNA effected a massive rescue of cells previously inactivated by mitomycin-C. Thus, a dose of 200 krd of ionizing radiation increased the survival by a factor of a thousand from 10^{-4} to 10^{-1}. Similarly, efficient rescue was provoked by UV radiation or by simple alkylating agents.

Cells treated with psoralen plus near ultraviolet radiation could be rescued only when inactivation was due primarily to psoralen-DNA interstrand crosslinks rather than to monoadducts. Rescue of inactivated cells was prevented in the presence of chloramphenicol. These results can most readily be interpreted in terms of an alternative repair system able to overcome DNA interstrand crosslinks produced by mitomycin-C or psoralen plus near ultraviolet light, but induced only by the more abundant number of damages produced by radiation or simple alkylating agents.

3.3 W-reactivation in Acinetobacter calcoaceticus[*]
(D. Berenstein)

Weigle(W)-reactivation was demonstrated in A. calcoaceticus for the UV-irradiated lysogenic phage P78. The reactivation factor (survival of irradiated phage on irradiated bacteria/survival on unirradiated bacteria) reached a maximum value of 20. This was obtained at UV-doses giving phage and host survivals of about 5×10^{-6} and 1×10^{-1}, respectively. Intracellular development of W-reactivated P78 was followed by one-step growth experiments. Conditions which allowed maximal W-reactivation also extended the period of phage production and yielded a somewhat reduced burst size.

3.4 Genetic mapping of Acinetobacter calcoaceticus
(D. Berenstein)

The genetics of A. calcoaceticus is almost unknown. A transducing phage and conjugation system have been described a few years ago, but no linkage between different markers could be demonstrated. A. calcoaceticus strains containing plasmids able to mobilize bacterial chromosome have been obtained from Dr. A. Vivian, Thames Polytechnic (London). The plasmids have been introduced into our own A. calcoaceticus strains that are now being used for genetic mapping of A. calcoaceticus, especially for genetics of radiation resistance. Preliminary results show that there is chromosome mobilization of our own Acinetobacter strain, Ac.78, by a plasmid originally isolated from an Acinetobacter strain: pAV1.

4. OPERATION AND MAINTENANCE OF IRRADIATION FACILITIES

4.1 HRC electron linear accelerator
(J. Fenger and B. Lynggård)

The accelerator has been in operation for a normal number of hours. About 70 per cent of the time the facility was used for experimental irradiation, mostly in connection with the pulse radiolysis equipment. Twenty per cent of the time was used for service irradiation on the beam conveyor belt. Maintenance of the facility covered about 10 per cent of the time. The following maintenance works have been carried out:

Injector system: Flash-over problems in the high-voltage injector (reported in the Annual Progress Report for 1981) extended into 1982. As reported an insulating stand-off and newly designed light links were destroyed by flash-over. The problems could be due to insufficient insulating properties of a temporary stand-off and of the transformer oil. Replacements have solved the problem. By the end of the reported period new spare light links, delivered by the usual supplier, were tested in the injector. Unfortunately, one of the light links was destroyed due to flash-over. The reason could be impurities trapped on the inside of the light link cable. The light links were cleaned by evacuating at 80°C for several days and afterwards impregnated with transformer oil. The processed light links will be tested in the installation at the next inspection of the injector system.

Beam scanning system: The scanner for the electron beam (22 years old) was renovated. The heat radiation from the high power electron tubes in the electronics slowly destroys the insulation material and connectors. The linearity and symmetry of the scanned electron beam were improved. The system is not up to date, the electron tubes are expensive, but the use is limited to service irradiation 20 per cent of the time, and at the moment we have no plans for a renewal. The aluminum scanner window was replaced. A new spare coil was delivered.

Cooling system: After 6 years in operation a general overhaul of the accelerator cooling system was carried out. The cooling tower and air cleaner were anti-rust treated. The temperature regulator of the secondary cooling loop was replaced by a new pneumatic unit.

Microwave system: In the Annual Progress Report for 1981 it was mentioned that the klystron seems to be near exhaustion, but it is still in operation after 4300 hours; it was installed medio 1978. Increasing DC input power is needed to obtain full microwave output power.

4.2 Febetron, field-emission accelerator

The field-emission accelerator was used for pulse radiolysis of gases and for Raman spectroscopy. Only minor repair-work was needed.

4.3 ICT, low-energy accelerator

The low energy accelerator was used for dosimetry and polymerization experiments. The operation was trouble-free.

4.4 10,000 Ci ^{60}Co-facility

The 10,000 Ci ^{60}Co-facility was used for radiation research and for customer services. It further serves as a reference source for microbiological efficiency testing according to the IAEA's recommendations for the radiation sterilization of medical products.

Some pneumatic hoses and valves were renewed. The personal security system was renovated in cooperation with the health physics authorities.

4.5 5,000 Ci ^{60}Co-facility

The 5,000 Ci ^{60}Co-cell, presently located in the Control Department of the Danish Serum Institute, Copenhagen, was used for bacteriological research.

4.6 3,000 Ci ^{60}Co-facility

The 3,000 Ci ^{60}Co-cell was used for research in radiation chemistry, radiation bacteriology, and customer services.

A new motor for the rotation drive was installed. The rotation speed is no longer variable.

5. EXPERIMENTAL EQUIPMENT

5.1 910 nm nanosecond light pulser
(J. Fenger)

A 910 nm GaAs light pulser has been developed for testing of infra-red detectors. Rise and fall time ~5 ns.

5.2 Infra-red solid state detector
(J. Fenger)

For the pulse radiolysis detecting system the response characteristics of various solid state detectors were tested. It was found that the overall response time is not a simple exponential function, but consists of a initial fast response (~5 ns) followed by a much slower response (~10 μs) rising to the maximum amplitude of the input signal.

5.3 PDP-8 computer installation
(B. Lynggård)

A Biomation 8100 transient recorder was incorporated in the system, decreasing the shortest sample interval from 50 ns to 10 ns.

The program was modified as follows:

The signal/noise ratio can be improved by averaging data from several identical experiments in each individual point.

Data for increasing light transmission can now be handled.

A "calculator mode" was included, so that the terminal can be used as a normal calculator.

Testing of the light detecting system was made easier.

6. EDUCATIONAL ACTIVITIES AND PUBLICATIONS

6.1 Lectures

D. Berenstein, Strålesterilisation af Medicinsk Engangsudstyr (Radiation Sterilization of Disposable Medical Equipment) (for students at Danmarks Sygeplejeskole). Risø, 9 February.

D. Berenstein, Studies in Acinetobacter Calcoaceticus. Thames Polytechnic. London, England, 19 May.

D. Berenstein, Initiering og Kontrol af Kromosomreplikation, Strukturen af oriC og Minikromosomer (Initiation and Control of Chromosome Replication, the Structure of oriC and Minichromosome). Mikrobiologisk Institut. København, 2 November.

A.E. Buenfil-Burgos, R.M. Uribe, A. de la Piedad, W.L. McLaughlin and A. Miller, Thin Plastic Radiochromic Dye Films as Ionizing Radiation Dosimeters. 4th International Meeting on Radiation Processing, Dubrovnik, Yugoslavia 4-10 October.

H. Christensen and E. Bjergbakke, Radiolysis of Groundwater from HLW Stored in Copper Canisters. 6th Int. Symposium on Scientific Basis for Nuclear Waste Management. Boston, Mass., USA, 1-4 November.

J.W. Hansen, Radiation Effectiveness D~rived From the ~rack Structure of Heavy Charged Particles. Risø, 28 October.

J. Holcman, The Reaction of N,N-dimethylaniline Radical Cation in Strongly Alkaline Solution. 5th Tihany Symposium on Radiation Chemistry. Siofok, Hungary, 18-27 September.

U.K. Kläning and K. Sehested, Fotokemi og Strålingskemi af Uorganiske Oxyanioner (Photo Chemistry and Radiation Chemistry of Inorganic Oxyanions). Aarhus University, 10 December.

W.L. McLaughlin, A. Miller and R.M. Uribe, Radiation Dosimetry for Quality Control of Food Preservation and Disinfestation. 4th International Meeting on Radiation Processing. Dubrovnik, Yugoslavia, 4-10 October.

W.L. McLaughlin, R.M. Uribe and A. Miller, Megagray Dosimetry (or Monitoring of very Large Radiation Doses). 4th International Meeting on Radiation Processing. Dubrovnik, Yugoslavia, 4-10 October.

A. Miller, K.H. Chadwick and J.W. Nam, Dose Assurance in Radiation Processing Plants. 4th International Meeting on Radiation Processing. Dubrovnik, Yugoslavia, 4-10 October.

A. Miller, Fødevarebestråling (Food Irradiation), (for students at Suhr's Seminarium). Risø, 27 October.

A. Miller, Acceleratorbestråling (Accelerator Irradiation). "Energi, Sikkerhed, Miljø 82", Bella Center. Energiministeriet og Forsøgsanlæg Risø, 11 December.

K.J. Olsen and J.W. Hansen, High-LET Dose Response Characteristics of the Dye Film Dosimeter in the Context of Track Structure Theory. 8th Symposium on Microdosimetry. Jülich, W. Germany, 27 September - 1 October.

A. Vivian (Thames Polytechnic, London), The Genetics of Acinetobacter and Plant Pathogenic Pseudomonads. Risø, 11 November.

Lectures at IAEA Seminar on High-Dose Dosimetry in Industrial Radiation Processing, Risø, 20 September - 1 October:

J.H. Barrett, Calibration (II).

J.H. Barrett, Traceability and Intercomparison.

J.H. Barrett, Dosimetry Methods (I): Perspex, Ceric-Cereus, Potassium Dichromate.

C.L. Carmona, Dose Distribution Measurement.

P. Christensen, Dosimetry Methods (V), TLD.

J.W. Hansen, Interaction of Radiation with Matter and Absorption of Energy.

P. Hedemann, Health Physics Aspects.

I. Janovský, Dosimetry at Small Linacs.

A. Johansson, Operational Experience (Gamma).

W.L. McLaughlin, Fundamentals of Dosimetry.

W.L. McLaughlin, Dosimetry Methods (III), Film Systems.

W.L. McLaughlin, Plant Commissioning (I).

A. Miller, Risø Radiation Sources, Measuring Instruments and other Practical Matters.

A. Miller, Properties of Matter and Radiation.

A. Miller, Factors Affecting Dose Meter Accuracy.

A. Miller, Dosimetry Methods (IV), Lyoluminescence, ESR.

A. Miller, Plant Design (Electron).

J.W. Nam, IAEA High-Dose Assurance Service.

W. Oosterheert, Plant Design (Gamma)

W. Oosterheert, Plant Commissioning (II).

P.P. Panta, Light Guide Dosimetry.

T.A. Du Plessis, Quality Control at Industrial Irradiation Facility.

M. Schneider, Dose Realization in FRG.

K. Sehested, Calibration (I), Fricke Dosimetry and Modified Fricke Dosimeters.

V. Stenger, Dosimetry Methods (III), Ethanol Chlorobenzene.

E. Svendsen, Operational Experience (Electron).

K. Ulbak, Regulatory Control of Facility Safety.

Exercises

Potassium dichromate	(J.H. Barret)
The Ceric-cerous dose meter	(E. Bjergbakke)
Perspex temperature dependence	(W.L. McLaughlin)

Thin films   (W.L. McLaughlin)

Dose distribution   (A. Miller)

Lyoluminescence   (A. Miller)

Fricke dose meters   (K. Sehested)

Ethanol-chlorobenzene   (V. Stenger)

E. Bjergbakke acted as an IAEA-expert at the Department of Nuclear Engineer-ing, King Abdulazis University, Jeddah, Saudi Arabia. The purpose was to assist in formulating a work program for gamma processing studies, to deliver lectures to undergraduate students, and seminars to faculty members. Four lectures were given and three seminars were əld: 1) Risø National Labora-tory. Research of the Accelerator Department, 2) Radiation Chemistry of Water, and 3) Radiation Chemistry of Chloride Solutions with Reference to HLW-Storage.

K. Sehested acted as officially appointed examiner at the public defense by Nis Bjerre of his dissertation entitled "Oxygen Defects in Crystalline Halates and Perhalates". Aarhus University, 5 October.

6.2 Publications

Accelerator Department. Annual Progress Report (1982). 1 January - 31 December 1981. Risø-M-2348.

D. Berenstein (1982), Weigle Reactivation in Acinetobacter Calcoaceticus. Photochem. & Photobiol. 35, 579-581.

E. Bjergbakke, H. Christensen, J. Grynblat and E. Söderman (1982), Radiolys Och Rekombination Av Vatten Efter Haveri I BWR-Anlaggningar. Slutrapport. Rapport 139 063 01/ESO/ILR. Studsvik/Rejlers Ingenjörsbyrå AB.

E.A. Christensen, H. Kristensen and K. Sehested (1982), Radiation Sterili-sation. I: Principles and Practice of Disinfection, Preservation and Steri-lisation. Edited by A.D. Russell, W.B. Hugo, and G.A.J. Ayliffe. Blackwell, Oxford, 513-533.

E. Bugge Christensen and A. Miller (1982), A Program in BASIC for Calculation of Cavity Theory Corrections. Risø-M-2345.

H. Christensen and E. Bjergbakke (1982), Radiolysis of Groundwater from HLW Stored in Copper Canisters. Studsvik/NW-82/188.

H. Christensen och E. Bjergbakke, Radiolysis i Oskarshamns- och Barsebäck-reaktorn. Supplerande beräkningar. Studsvik/NW-82/251.

H. Christensen and E. Bjergbakke (1982), Radiolysis of Groundwater from HLW Stored in Intact Copper Canisters. Studsvik/NW-82/266.

H. Christensen and E. Bjergbakke (1982), Radiolysis of Groundwater from HLW Stored in Copper Canisters. Studsvik/NW-82/273.

H. Christensen och E. Bjergbakke (1982), K12. Radiolyseberägningar i O2 och TVOII. Studsvik/NW-82/321.

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6.3 Test-irradiations

Test-irradiations were carried out for:

    Alupa, Bruxelles

    Asea Kabel, Stockholm

    Ateliers des Charmilles S.A., Geneve

    Danmarks Nationalbank, København

    Danmarks tekniske Højskole, Lyngby

    Den kgl. Veterinær- og Landbohøjskole, København

    Fibiger-Laboratoriet, København

    Fiskars AB, Ekenäs

    Harald V. Lassen, Valby

    Løvens Kemiske Fabrik, Ballerup

    Meda A/S, Herlev

    Microtronic, Roskilde

    Mölnlycke A/S, Espergærde

    A/S Nunc, Roskilde

    Planteværnscenter, Slagelse

    Proteinlaboratoriet, København

    Radiflex ApS, Hedehusene

    Sankt Hans Hospital, Roskilde

    Sch nning & Arvé, Horsens

    Siemens AG, München

    Statens Seruminstitut, København

    Surgimed A/S, Ølstykke

    Teknologisk Institut, Tåstrup

6.4 Visiting scientists

N. Bjerre, Kemisk Institut, Aarhus Universitet, Aarhus.

H. Christensen, Studsvik Energiteknik AB, Nyköping, Sweden.

D.C. Dorado, Consejo de Segurcidad Nuclear, Madrid, Spain.

C. Emborg, Danmarks tekniske Højskole, Lyngby.

N. Getoff, Institut für Strahlenchemie, Vienna, Austria.

E.J. Hart, Port Angeles, WA., USA.

C. Herskind, Radiofysisk Laboratorium, Aarhus Kommunehospital, Aarhus.

B. Hickel, Saclay, Gif-sur-Yvette, France.

J.C. Humphreys, National Bureau of Standards, Washington, D.C., USA.

U. Kläning, Kemisk Institut, Aarhus Universitet, Aarhus.

W.L. McLaughlin, National Bureau of Standards, Washington, D.C., USA.

J.R. Meshram, Laxminarayan Institute of Technology, Nagpur University of India, Nagpur, India.

M. Sorabpour, Nuclear Research Center, Tehran, Iran.

S. and W. Solar, Institut für Strahlenchemie, Vienna, Austria.

A. Vivian, Thames Polytechnic, London, England.

Q.M. Youssouf, Bangladesh Atomic Energy Commission, Dacca, Bangladesh.

7. IRRADIATION FACILITIES AT THE ACCELERATOR DEPARTMENT

Electron Accelerators

1. **Linear Electron Accelerator, Haimson Research Corp.**
   Model HRC-712
   Specifications:

   Electron energy .... 10 MeV

   Average electron current .... 1 mA

   Peak electron current at 10 MeV .... 1100 mA

   Pulse length .... 0.01 - 4 μs

   Pulse repetition rates .... single pulses and
   12.5, 25, 37.5, 50, 100, 150, and 200 pps

   Accelerator room beam facilities:
   1. A bent beam with scan width of 40 cm in connection with a conveyor system provides a process irradiation capacity of 700 Mrd kg/hour.
   2. .... horizontal beam ports, full average beam peak power, for electru and X-ray irradiation.
   3. One horizontal beam port, reduced average beam power (12.5 pps) in connection with a ± 0.5% beam slit.

   Target room beam facilities:
   1. Three horizontal beam ports, reduced average beam power (12.5 pps).

2. <u>Field Emission Electron Accelerator, Febetron Model 705B</u>

Specifications:

Electron energy .... 1.5 - 2.0 MeV

Peak electron current .... 4000 A

Pulse length (electron mode) .... 50 ns

3. <u>Low-Energy Electron Accelerator, High Voltage Eng. Corp.</u>
<u>Model EPS 400-IND</u>

Specifications:

Electron energy .... 400 keV

Electron current .... 50 mA

Scan width .... 120 cm

The accelerator is provided with conveyors

to permit pilot-plant irradiation.

<u>^{60}Co-Facilities</u>

<u>10,000 Ci ^{60}Co-facility</u> (built at Risø 1957)

Designed for very homogeneous irradiation of samples with a maximum 180, 100, or 60 mm. The corresponding maximum dose rates (7,300 Ci, 1 January 1983) are 4.4×10^5 rd/h, 1.2×10^6 rd/h, and 2.9×10^6 rd/h, respectively.

<u>5,000 Ci ^{60}Co-facility</u> (built at Risø 1971)

Designed for laboratory use and fitted with a 123 mm$^{\emptyset} \times$150 mm irradiation chamber. The dose rate in the center of the chamber (4,400 Ci, 1 January 1983) is 3.8×10^5 rd/h. The cell is located at the Control Department, Statens Seruminstitut, Copenhagen.

<u>3,000 Ci ^{60}Co-cell</u> (built at Risø 1968)

Designed for laboratory use and fitted with a 120 mm$^{\emptyset} \times$200 mm irradiation chamber. The dose rate in the center of the chamber (2,700 Ci, 1 January 1983) is 2.7×10^5 rd/h.

8. STAFF OF THE ACCELERATOR DEPARTMENT

Head   : Knud Sehested
Office Staff: Ebba Haugaard and Ruth Madsen

Scientific Staff

Dvora Berenstein

Erling Bjergbakke

Jørgen Fenger

Johnny W. Hansen

Mogens Trier Hansen (leave of absence from April)

Jerzy Holcman

Bent Lynggård

Arne Miller

Technical Staff

Margit Elm Andersen

Karen Boysen

Hanne Corfitzen

Ina Hansen

Jørgen Erik Hansen

Inge Høegh (leave of absence from August)

Torben Johansen

Erik Engholm Larsen

Fritz Larsen

Inge Merete Larsen

Lauritz Nielsen

Gert Hagen Olsen

Kresten Pejtersen

Mads Wille

Consultants

Dr. E.A. Christensen, Chief Physician, Control Department, Statens Serum-
institut, Copenhagen.

Dr. E.J. Hart, Port Angeles, WA., U.S.A.

W.L. McLaughlin, Physicist, Center for Radiation Research, National Bureau
of Standards, Washington, D.C., U.S.A.

Risø - M - 2389

Title and author(s)

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Department or group

Accelerator

Group's own registration number(s)

Abstract

A description is given of work in the fields of
radiation chemistry, physical dosimetry, radia-
tion physics and technological application of
radiation, radiation bacteriology research and
irradiation technology, as well as of the opera-
tion of various irradiation facilities.

Copies to