Report

Monitoring External Irradiation
FI4P CT96 0049
Final Project Overview

Christian Schmitzer
Hannes Stadtmann
Wolfgang Wahl
Marek Wielunski
Andor Andrasi
Joe Palfalvi

August 1999

OEFZS-G--0005

AUSTRIAN RESEARCH CENTERS
Science sets signs.

ÖSTERREICHISCHES FORSCHUNGSZENTRUM SEIBERSDORF GES.M.B.H.
A-2444 Seibersdorf, Tel. ++43/2254/780-0, Fax ++43/2254/740 60, City Office: A-1010 Wien, Kramergasse 1, Tel. ++43/1/533 96 28, Fax ++43/1/533 96 28-11
Server http://www.arcs.ac.at, e-mail: seibersdorf@arcs.ac.at

AT0200531

OEFZS--G-0005

August 1999

Monitoring External Irradiation
FI4P CT96 0049
Final Project Overview

Christian Schmitzer *)
Hannes Stadtmann *)
Wolfgang Wahl **)
Marek Wielunski **)
Andor Andrasi ***)
Joe Palfalvi ***)

*) Österreichisches Forschungszentrum Seibersdorf
Bereich Gesundheit
Strahlenschutz

**) GSF Forschungszentrum für Umwelt und Gesundheit

***) KFKI Budapest

Title: Monitoring External Irradiation **Contract No: FI4P – CT96 – 0049**

Development and modelling of an individual, energy dependent semiconductor detector and suitable phantoms for the study of external irradiation

Coordinator: Dr. Chris Schmitzer (Austrian Research Centers Seibersdorf, Austria)

Partners:

Dr. Hannes Stadtmann (Austrian Research Centers Seibersdorf, Austria), Dr. Wolfgang Wahl, Dr. Marek Wielunski (GSF - Gesellschaft für Umwelt und Gesundheit, Munich, Germany), Dr. Andor Andrasi, Dr. Joe Palfalvi (KFKI Atomic Energy Research institute, Budapest, Hungary; subcontractor)

Executive Summary

Introduction

This project is devoted to the innovative development of more sensitive and more specific methods for the monitoring of external radiation, as described in the 4th Framework Programme *Nuclear Fission Safety* Executive Work Program item D.2.5. The general topic („Evaluation of Radiation Risk") defines the area of radiation protection where this research effort is located. Hence, the rationale behind such a project is the extension of knowledge about the risk of human exposure by improving the detection methodology. This may be achieved by enhancing the sensitivity of the detection element, by exploiting more detailed information on the type and energy of radiation, and by in depth understanding of the photon and neutron interaction in order to aid the interpretation of acquired data.

Abstract

Objectives

The radiation may be characterised *per se*, i.e. free in air, however, more relevant for practical purposes are the interaction processes with matter. Since this interaction of radiation with neighbouring bodies - or the material composition of the measuring element itself - must not be neglected, the involvement of phantoms both in the modelling process and the experimental verification was proposed. The overall objective of this project, therefore, is the modelling and the development of an innovative semiconductor sensor and suitable phantoms for the application in mixed photon and neutron fields.

The chosen approach relies heavily on numerical modelling and experimental verification of the detector design, taking into account the back-scatter effects represented by the specific phantoms involved. Based on commercially available silicon pin diodes, new detectors are being developed, simulated and experimentally verified as a joint effort amongst the project partners. The partnership constellation consists of two project partners and a Hungarian subcontractor fully integrated in the line of work.

Results

Neutron modelling

For neutron detection the converter or radiator technology was adopted. The detection process is therefore divided into two main steps, i.e. the production of secondary charged particles due to interaction mostly in the converter material, and the registration of these charged particles in suitable semiconductor detectors. For these irradiations, a model was introduced to allow better understanding of the measured pulse height distributions characteristic of the energy deposited in the active part of the detector. A comparison of measured and computed pulse height distributions shows excellent agreement, thus supporting a more reliable determination of the detection efficiency of incident neutrons. Within the energy range from 200 keV up to 8 MeV all observed structures can be explained and identified with the help of the computer model, see Figure 1. As a further step, research concentrated on the interaction of neutrons up to 20 MeV by modelling further interaction processes into the simulations (e.g. inelastic and elastic high energy neutron scattering).

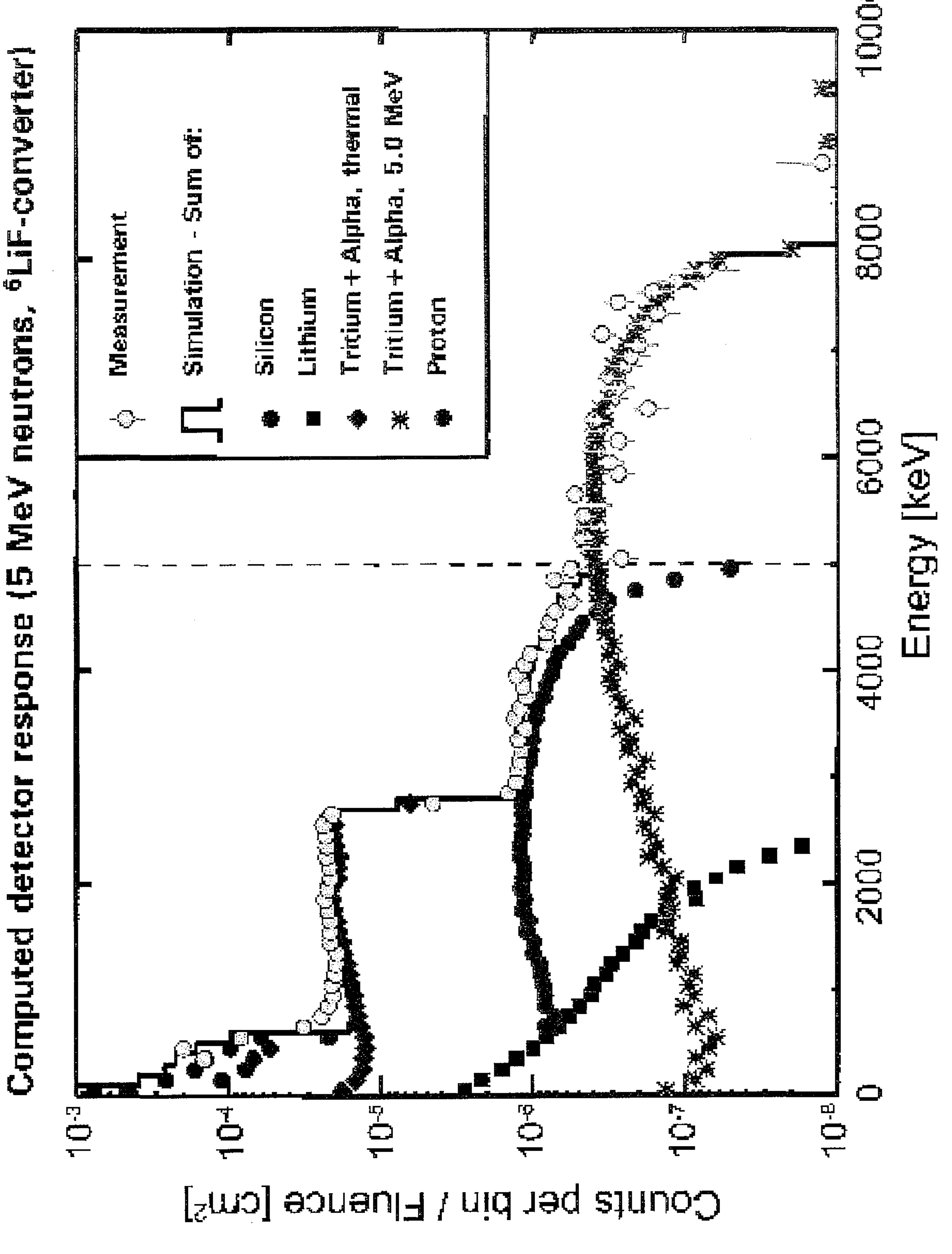

Figure 1 Deconvolution of experimental data of 5 MeV incident neutrons into specific contributions, modeled both quantitatively and qualitatively

Photon modelling

Similarly, computer models have been applied for photon irradiations of the detector. Only very low energy photons can be registered within the active layer of the detector itself due to escape of higher energy quanta out of the active layer. Hence, the thickest possible pin diodes are used and specific filters have been analysed. As a major effort, expertise and know-how regarding model calculations for photons by the EGS4 computer code was transferred from one project partner to another to aid in the interpretation of photon irradiations. Based on this knowhow-transfer, photon interaction was simulated for various detector designs and irradiation conditions. Results of irradiation experiments show good agreement between experimental data and model calculations for narrow spectra roentgen irradiations and standard radionuclides. The important interaction regimes (Photo effect and Compton scattering) are interpreted correctly and the characteristic features of the detector response may be understood by means of the modelling process as intrinsic features of the interaction process. As a further topic, the interaction processes of low energy photons and specifically the interaction with tissue equivalent materials have been studied.

Detector design

Regarding the design of the detector itself, a first generation detector system was available shortly after start-up of the project to verify initial models and assumptions. Enhancements have been sought and implemented in the areas of optimised converter material and geometry, influence of detector thickness, enhancements to the charge readout and associated electronics, and studies of possible improvements for the signal to noise ratio. Based on the model calculations and simulations for neutron and photon interaction, further calculations have been made to aid the development of a custom detector with optimised characteristics. Among these were investigations on the influence of the thickness of the active layer on photon efficiency and the analysis of various converter materials for the efficient detection of fast neutrons. Fundamental calculations and experimental results support ^{6}LiF as optimal converter material for thermal neutrons and Polyethylene for fast neutrons. Various detector generations have thus been designed, manufactured, and tested. The first versions were adaptations of commercially available pin diodes. The latest detector versions became available beginning of 1999 - modelled and designed within the project – resulting from an iterative refinement process. They have been subjected to numerous photon and neutron irradiations in pre-determined irradiation setups, testing realistic detector geometries, converters, and filters. The last version is a demonstrator multi-element sensor.

Irradiation phantoms

Since the usage of phantoms in conjunction with the detector is of major concern in this project, an inventory of phantoms was undertaken and their applicability analysed. Based on the predominantly two-dimensional geometry of the detector, a simple sliced slab phantom was designed and constructed. It was used in the first irradiation experiments. The specifications for irradiation conditions with more complex phantoms have been derived and the irradiation program itself has been executed for both photon and neutron irradiation experiments in various geometries. More complex phantoms have been employed and the possibilities for measurements and corresponding model calculations have been explored for more realistic setups. As a consequence, simple geometry bone slab phantoms were introduced as a type of pseudo- anthropomorphic phantom. This had been cautiously indicated as an option in the early project reports, depending on overall work progress and applicability and success of the models employed at that time. The basic assumptions for the models chosen have turned out to be successful, allowing the project team to pursue the option of pseudo-anthropomorphic phantoms both for a further step in the modelling / simulation process as well as for irradiation experiments involving primarily neutrons. The final step in phantom development has been another pseudo-anthropomorphic phantom representing the layered structure of a part of the skull (bone, soft tissue and skin). Designed and developed within the project, this phantom has also been employed as an option implemented towards the end of the project to verify the model calculations by corresponding irradiation experiments.

Thus the irradiation program and the phantoms involved have concentrated to establish the experimental verification for the model design calculations governing the variants of detector/converter or detector/filter designs for neutron and photon irradiations, respectively.

Mixed field irradiations

Another object of interest were mixed field irradiations, which have been employed to check the cross-sensitivity of the detector design and obtain valuable information for a combined sensor arrangement. So far, the detector designs used in the modelling process and the experimental verification have been dedicated elements for neutron and photon interaction, respectively. This was based on different physical interaction processes and, consequently, different approaches for improvement, employing appropriate combinations of detector thickness, converter, and filter materials. This activity formed the basis of a possible subsequent work effort towards an integrated detector array, capable of processing neutron and photon signatures in various energy regimes simultaneously. The multi-element detector would then consist of individual elements devised and optimised under the research effort established in the current project. A demonstrator of this development has been realised. Hence, the sensitivity of these individual detection elements for radiation not within the design limits (other type and/or energy of radiation) had to be analysed.

Achievements

The achievements of the current research project may be described closely in line with the anticipated work program. Semiconductor detectors of improved design have been developed throughout this project, resulting in detailed understanding of the interaction processes for neutron and photon irradiation impinging on the detector in the presence of complex, pseudo-anthropomorphic phantoms simulating realistic irradiation setups.

A wide array of influence factors originating from detector makeup, incident spectrum, and phantom characteristics have been inspected and analysed, leading to iterative refinements of the initial design. A major success was the excellent agreement found between simulation results based on the modelling process and experimental data. Many effects like energy response, angular response, signal to noise ratio, or converter material interaction processes influencing detector efficiency have been incorporated in the overall assessment. A final step was the elimination of free parameters in the model calculations, replacing them by quanta derived from the description of primary and secondary effects, resulting basically in a calibration function of the detector under investigation expressed in physical units (e.g. air kerma).

Regarding phantoms, the work program could be extended into previously as optional described areas, specifically pseudo-anthropomorphic phantoms. Bone slab models and partial skull phantoms resembling the layered structure of bone, soft tissue and skin were used in irradiation experiments both for neutrons and photons.

In line with efforts of the Commission to increase interaction among related projects by clustering, interesting contacts could be established and discussed during a cluster meeting convened at Seibersdorf, late in 1997. Specifically, access to the neutron irradiation facilities at the PTB have aided in the extension of the neutron energy range (up to 20 MeV).

Thus the overall goals of the research effort as a practical contribution towards the evaluation of radiation risk, as reflected in the objectives of the work program, could be realised and even surpassed.

Implications

Exploitation

The ultimate goal of the project is the laboratory prototype of a microsensor device, capable of exploiting information as to type and energy of incident radiation. A vast variety of active and passive sensing technology is already available but not necessarily applicable in certain situations due to economic, temporal or physical restrictions. A small sensing element will find many applications in the general field of radiation protection and will aid in the evaluation and control of radiation risk. The finished development may well have also an economic impact upon exploitation by the partner institutions.

Specifically, the project aimed at the development of two micro-sensor systems operating at room temperatures for external irradiation at phantoms as a novel approach to enhance the detection sensitivity, to make use of the energy information and to understand in detail the photon and neutron interaction. This development focuses on the detection of low-energy photons with a small emission probability and/or a small activity. In addition, the neutron interaction with and without a phantom was studied to improve the knowledge of the risk of human exposure. Technical solutions using elaborate germanium detectors for photons or He-3 or other detectors for neutrons, are in many cases economically not affordable, are not easy to handle, or may be impossible to realise. Possible exploitations and economic benefits are foreseen in the field of detection technology by providing a low-cost spectrometric detector without the necessity of cooling refrigerants. Technically, modelling not only the detector, but also the sensor-radiation-phantom interaction and thus arriving at a more profound understanding of fundamental interactions processes, might lead to optimised designs.

Economic impact of such a development is not available on short term. The long range implementation of cheap sensing elements which allow energy resolved determination of photon and neutron fields relevant to radiation protection purposes, will be a significant and commercially attractive option. This may lead to distinct advantages compared to equipment currently available. Further exploitation might be investigated in the direction of personal dosimetry or whole body counter applications.

Outlook

With the work packages completed, semiconductor sensor prototypes and a multi-element demonstrator are available which have been verified in practical irradiation experiments to provide the necessary information to discriminate between type and energy of incident radiation. The resultant design is available for integration as multi-element sensor to establish an array detector, providing necessary or desired spectroscopic information from many differently "tuned" sensing elements simultaneously. Such a development constitutes an interesting option for continuation of work, specifically in view of possible applications in monitoring of personal exposure or monitoring of working environment conditions. Applications ranging from nuclear industry to space may be foreseen. The application of a small, economically attractive and energy resolving detector for such monitoring purposes addresses the explicit goals of the 5th Framework Program of the European Commission – research as a problem solving approach, e.g. radiation monitoring at workplaces – and may thus be eligible for further funding. As a short term commitment, the vast number of irradiation experiments undertaken throughout this project (more than 1000 individual setups with photon and neutron sources, X-ray equipment, accelerators, research reactor channels, etc) will be analysed in greater detail than time would have allowed for the completion of this report. Subsequent publications and conference contributions are planned, a few have already been initiated and are quoted in the Final Report to his project.

Conclusion

This project deals with innovative approaches for the evaluation of radiation risk. The chosen approach relies heavily on numerical modeling and experimental verification of realistic irradiation situations, where suitably developed semiconductor detectors and appropriate phantoms are exposed to neutron and photon fields.

Scientifically, the proposed work program has been completed and options perceived throughout the project have been incorporated. This has led to iterative refinement cycles in detector design and to a special development of pseudo-anthropomorphic phantoms employed in the irradiation experiments. The overall findings demonstrate good agreement between model calculations (using numerical transport code) and experimental irradiation results. This serves as evidence that sufficient understanding of the detailed interaction processes employed throughout the models has been established to achieve accurate representation of actual measurements. This effectively constitutes an absolute calibration of the device.

The partnership structure was based on past excellence demonstrated in the field. However, the project has also served to disseminate actual working knowledge between the project partners instead of just application of that knowledge by the original experts. Hence we believe the European dimension was well justified not only by the results of the project but also by the enrichment of each partners methods and capabilities.

Commercially, the exploitation of the results is not a short term goal. The development of the novel detector - which is available as a number of laboratory prototypes – carries significance for the original program area, the evaluation of radiation risk, but it also holds promises for applications not considered feasible before due to economical or technological constraints. The report offers reflections on a possible follow-up project, aiming at optimised multi-element prototypes for energy resolved mixed field applications for radiation monitoring. Such an application is well in line with the focus of the 5th Framework Program's "problem solving" approach to ensure radiation protection for workers and the public.

Summary of Results

Monitoring of external neutron irradiation

Modelling and simulation

Pulse height distributions and the response to neutrons were calculated for ^{6}LiF converter silicon detectors and compared with measurements. It is possible to identify the components of the ^{6}Li(n,t)α reaction in the distributions of energy deposition. The detection efficiency can also be calculated for neutron energies in the range from 10 MeV to 20 MeV. The comparisons between calculations and measurements for four neutron energies show a rather good agreement in the range of about 10 % for the front geometry. The difference of about 50 % for the back geometry is due to neutrons which were scattered in the measuring hall and, therefore, caused additional signals in the measurement. It can be stated that MCNP in combination with TRIM is a useful tool for the computation of the response of ^{6}LiF converter type silicon detectors.

Figure 2 exhibits good agreement between simulated response modeling (solid lines) and experimental verification (dots), measured with the third generation of sensor.

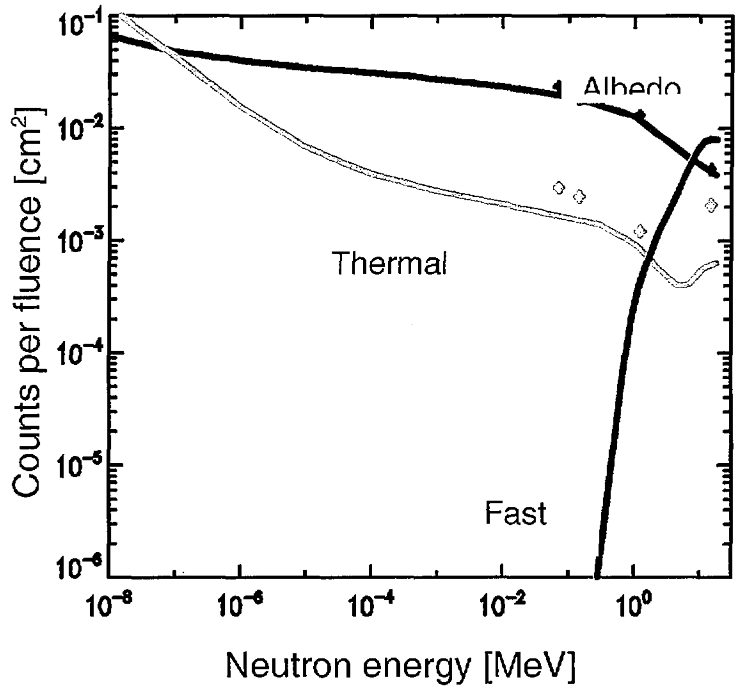

Figure 2 Theoretical modeling and experimental response for three types of sensors: two with ^{6}LiF converter (front and back) for thermal neutrons and one with polyethylene converter (front) for fast neutrons

Measurements with the integrated detector (Demonstrator)

The third generation detectors have been subject to various measurements, both in neutron and photon fields to test and verify the design assumptions. The first integrated detector was provided for first irradiation in October 98. The second version with epitaxial detector technology was ready in February 99. The majority of measurements have been derived from these detectors.

Currently we are in good agreement between measurements and modelling as well as between the different sensor generations. The studies with the integrated detector technology are very promising. The results allow to have quantitative and qualitative information about the neutron irradiation fields and, as a consequence, allow ultimately the calculation of dose (see Figure 3).

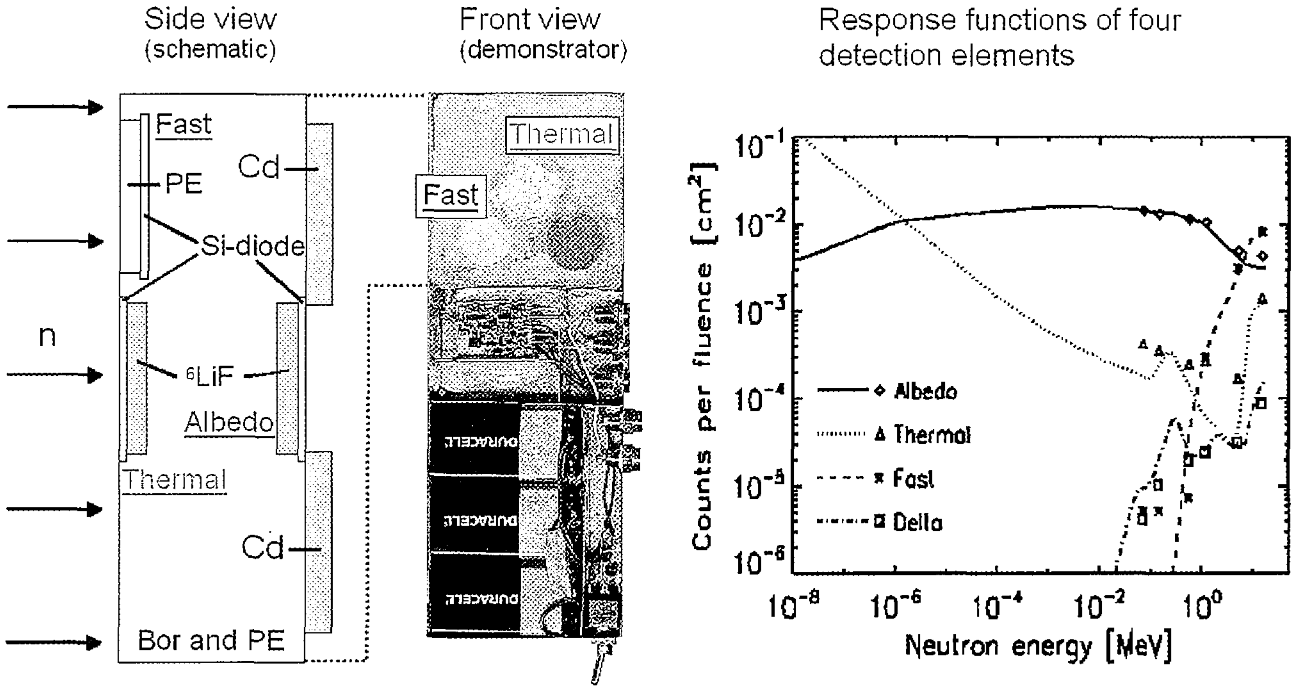

Figure 3 Integrated detector, schematically, photo and response function for three detectors: albedo fast and thermal

Dosimetric data of integrated detector (Demonstrator):

Sensitivity (CL=90%) : approx. 10 nSv for thermal detector and thermal neutrons
approx. 0.2 μSv for albedo detector and thermal neutrons
approx. 0.1 μSv for albedo detector from 10 eV up to 10 keV
approx. 10 μSv for fast detector and 5 MeV neutrons

Energy range: thermal up to 20 MeV

Energy dependence:

Detector Energy	Counts per neutrons/cm² [cm²]		
	Thermal	Albedo	Fast
Thermal	1.33E-1	5.17E-3	2.76E-5
71 keV	4.44E-4	1.46E-2	6.72E-6
144 keV	3.71E-4	1.36E-2	2.62E-6
570 keV	2.60E-4	1.19E-2	1.15E-6
1.2 MeV	2.82E-4	1.09E-2	3.28E-4
5.0 MeV	1.83E-4	1.04E-2	3.22E-3
14.8 MeV	1.72E-3	4.72E-3	8.99E-3

Table 1 Total response in counts per fluence above the threshold of 500 keV for irradiation of the integrated detector for thermal, albedo and fast sensors and for 6 energies.

Technical data of integrated detector (Demonstrator):

Detector:	Three sensors system (Si-diodes with converter)
Electronic:	Hybrid Preamplifier
Dimension:	65 x 185 x 19 mm^3.
Weight:	approx. 200 g (with batteries)
Power consumption:	+18 V 35 mA, -9 V 10 mA
Battery Life:	approx. 10 hours (with three standard 9 V batteries)

Monitoring of external photon irradiation

Approach

Verification of simulated results for photons versus experimental data is a necessary step in the development process, checking on the in-depth understanding of the appropriate interaction mechanisms. The simulation process was described in detail in the Final Report. Photon irradiation and associated setups were used to verify modeling assumptions and interpret the response curve of the individual detector arrangements.

For the analysis of the detector response for photons, irradiations in well defined photon fields have been applied at the laboratories of the Austrian Research Center. Both the radiation quality and the applied dose needs to be well known. To study the influence of a phantom and different filters, irradiations free in air and irradiations on phantoms have been performed.

Achievements

The aim of the experiments was too verify the model of the Monte Carlo simulation. The experimental pulse height distributions were transformed into the unit count/Mev/incident photon to be comparable to the simulation results presented in the Final Report. For this transformation the following parameters of the irradiations were necessary:

- Dose (or doserate and irradiation time) in terms of air kerma
- Detector thickness (250 µm)
- Detector area (200 mm^2)
- Mass energy transfer coefficient (depending of the incident radiation quality)

The comparison between simulated results and experimental data shows good agreement in the photopeak and in the Compton region for energies up to 300 keV. Figure 4 shows such a comparison between experimental data and simulation.

Si diode 250 µm: Simulation and experimental data (irradiation without phantom)

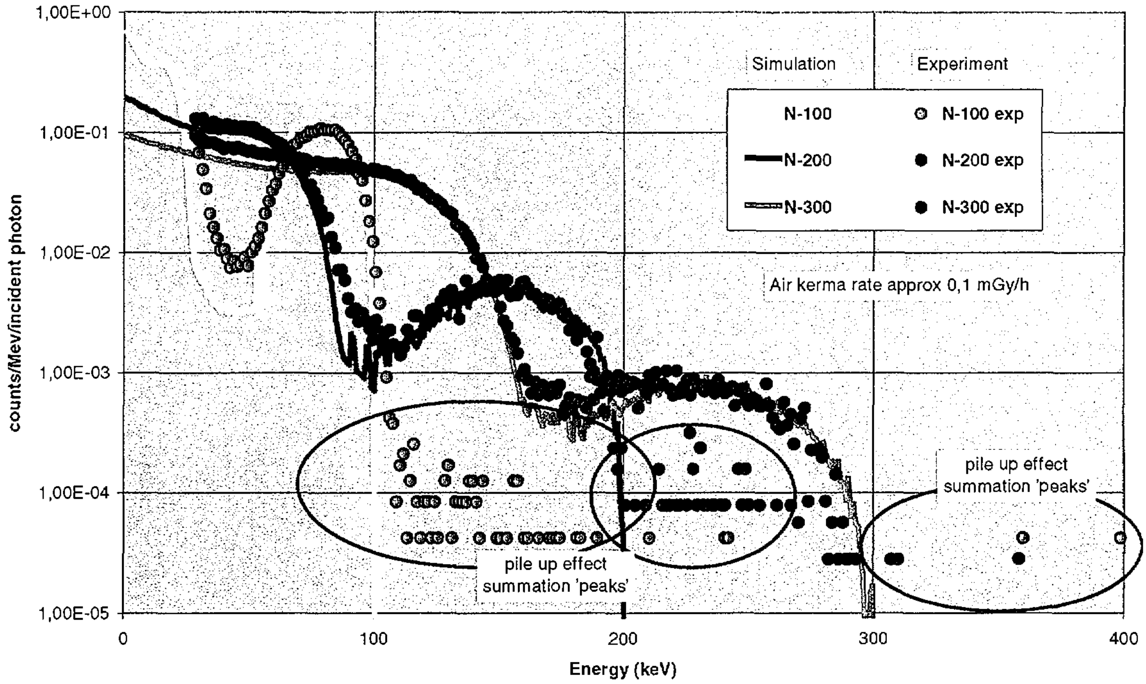

Figure 4 Comparison between Simulation and experiment for a 250 µm Si diode without a Phantom. Good agreement in the photo peak region and in the compton region.

In the transition region the agreement is not so good due to the detector system dependent energy resolution and pile up effects. The simulated values are somewhat smaller than the experimental data. Nevertheless it is not intended to change the simulation model for further investigations to achieve – in this respect - more realistic results since the energy resolution and the pile up effect is not a detector property but is caused mainly by the readout circuitry and other electronic reasons. On the other side, good agreement in the shape of the Compton edge was found.

For Al, Cu and Sn filters the agreement between simulation and experiment is acceptable (for the spectrum shape as well as for the intensities). For Pb filters the behaviour especially in the transition region is not satisfying. The exact reason is not known at the moment but might lie in the physical model of the used EGS4 version. Some improvements in the simulation set up needs to be done to achieve more realistic results.

Particularly, the following results were drawn from the described experiments:

- Phantoms:
  The influence of the phantoms increases the Compton part of the spectrum by a factor of 2 and more. The transition region between Compton and photopeak region is increased by a factor of 10 and more.
  The influence of the PMMA-Phantom is slightly higher than from the water phantom.
- Angular response
  No pronounced angular response was found for the photopeak efficiency.
  The intensity of the spectrum is increased only at the low energy (Compton) part for 60° direction of incidence.

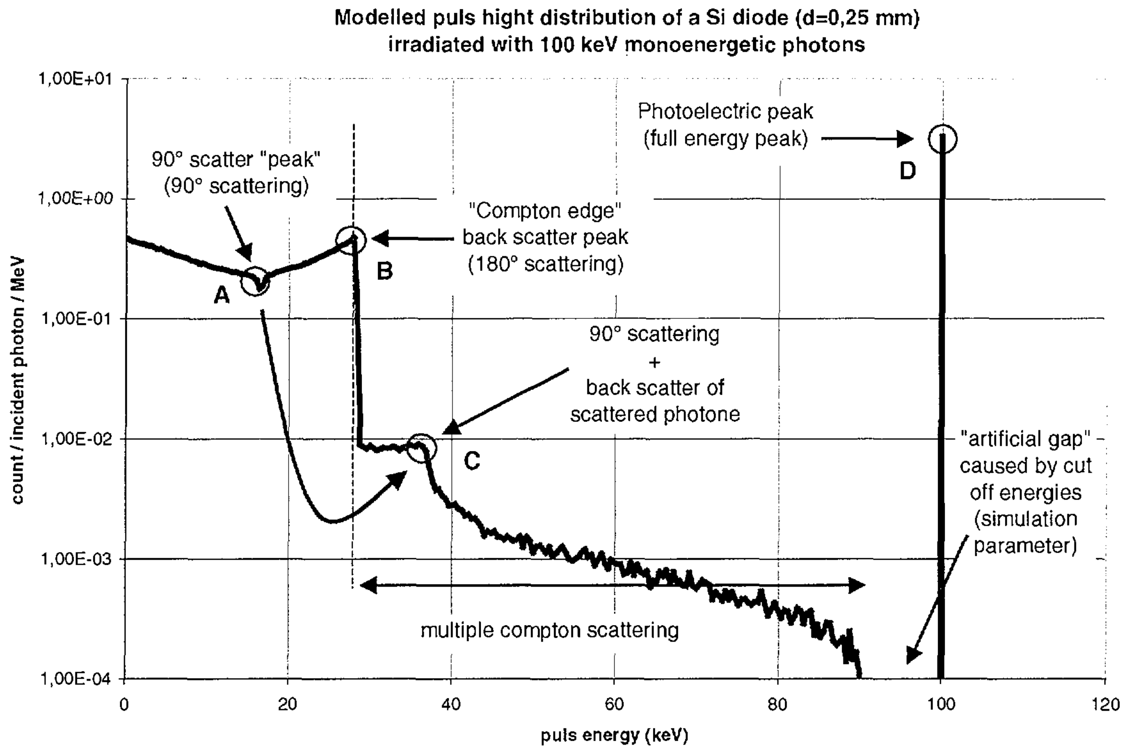

Figure 5 Simulated pulse height distribution in a 250μm thick Si diode. All peaks and edges are commented according their origin

Detailed results have been presented in the Final Report. These results have been implemented in a refinement process in the development of subsequent detector generations. A major success has been the application and verification of the specific Monte Carlo code for simulation of realistic irradiation situations. Figure 5 shall serve as representative illustration of the simulation-based explanation of the characteristic properties of a 100 keV photon irradiation.

In addition to the comparison of simulated and experimental pulse height distributions the total count response was compared between simulated and experimental response. The lower cut-off energy used in simulations and experiment was set to 30 keV in line with the experimental setup. This absolute calibration shows good agreement between modelling and experiment. At the Compton edge - were cut-off influences are most heavily noticed – the most severe discrepancies are noted in the range of 20% and more, see Figure 6. The excellent agreement at low energies and the mismatch at higher energies may be explained by the underestimation of the Compton contribution at the modelled results. However, the photon modelling has proven successful in explaining the detailed interaction mechanisms.

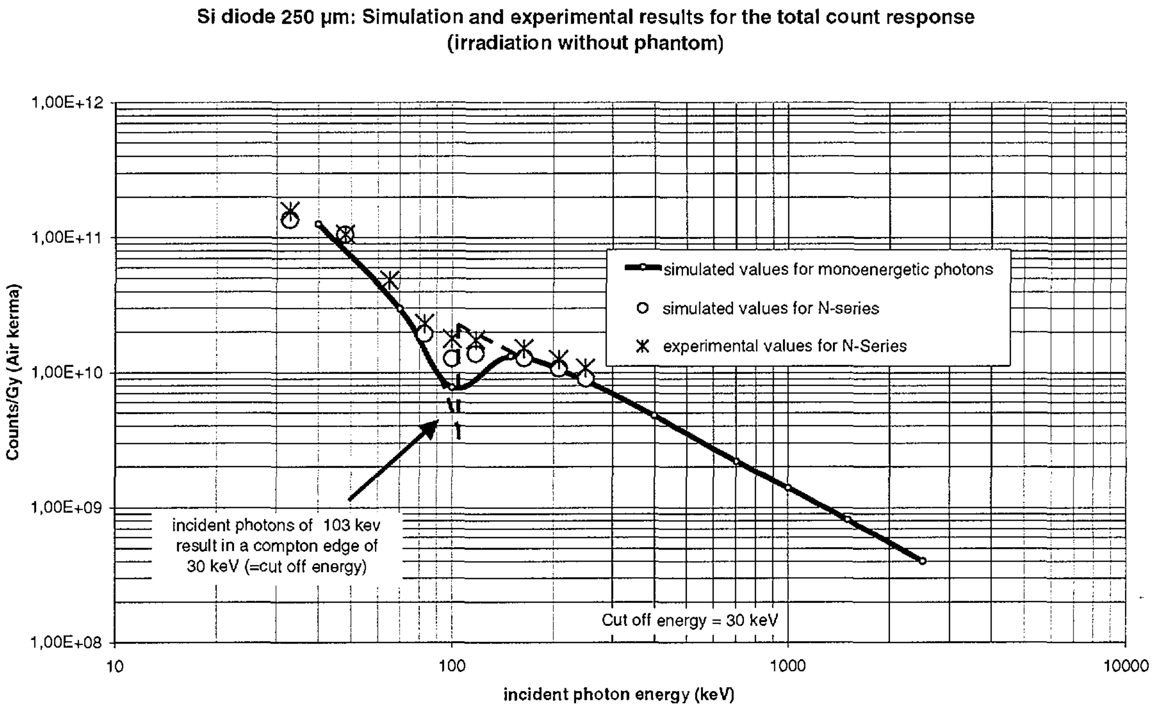

Figure 6 Comparison between simulation and experiment for a 250 µm Si diode without a phantom for the total count response. Good agreement for low energy photons. At photon energies higher than 70 keV the experiments show higher values by a factor of 1,2

Discussion of results

Introduction

The project goals specified in the proposal submitted to the Commission have been accomplished by means of the cooperative effort of all participants, both quantitatively as well as regarding quality of work. Referring to modelling, simulation, sensor development, irradiation program, as well as selection/generation of suitable phantoms, all work done under this contract and all results established are in full compliance with anticipated achievements. Hence, the work program has been completed and in most instances extended beyond the initial scope of the project. In the following discussion, the proposed aims (described in the submitted proposal) are compared with the achieved aims (described in the preceding chapters of the Final Report):

Modelling of the sensor response

Proposed aims - for low energy range:

Feasibility study, computer simulation and modelling for photon and neutron detector, respectively.

Achieved aims - for low, medium and high energy range:

- *neutrons:* simulation and modelling from thermal up to 20 MeV with and without phantom
- *photons :* simulation and modelling from 10 keV up to 2.2 MeV with and without phantom

Development of the micro-sensor system

Proposed aims - for low energy range:
Development of appropriate sensor filter elements and readout electronics for photons and neutrons, respectively.

Achieved aims - for low, medium and high energy range:

- *Neutron detection system:* Demonstrator from thermal up to 20 MeV with optimised converter
- *Photon detection system:* Laboratory device from 17 keV up to 1.3 MeV with optimised filter
- *Readout electronics:* Preamplifier and shaping amplifier (hybrid technology) are integrated in the detection system

Development of suitable phantoms

Proposed aims:
Feasibility study, specification, design and construction of optimised phantoms for energy resolved photon and neutron irradiation.

Achieved aims - for photon and neutron irradiation:

- Design and preparation as well as modelling of a variable PMMA slice slab phantom
- Development and preparation of a pseudo-anthropomorphic bone slab phantom
- Development and preparation of a pseudo-anthropomorphic head phantom

External irradiation of sensor and phatoms

Proposed aims:

Definition and specification of irradiation conditions; administering of photon and neutron irradiations in selected energy regimes to prototype sensor devices

Comparison of experimental results with simulation and modelling of sensor prototype with initial readout electronics and appropriate filtering.

Achieved aims - neutrons:

Work done at ARCS, GSF, KFKI, and PTB

- Irradiation with nearly realistic field parameters using the research reactor at KFKI Budapest
- Irradiation with monoenergetic neutron field parameters using the GSF accelerator and the source facility
- Irradiation with various targets and ion beams with different monoenergetic neutron energies using the PTB accelerator
- Irradiation with calibrated neutron sources at the PTB
- Irradiation in nearly pure thermal neutron field at the research reactor at FZS

Achieved aims - photons:

Work done primarily at ARCS

- Irradiation free in Air
- Irradiation on the ISO PMMA slab-phantom
- Irradiation on the ISO water phantom
- Irradiation free in air using different filter materials in front of the detector
- Irradiation at an angle of incidence of 60° to study the angular response of the detector

Achieved aims – neutrons/photons:

Cross-sensitivity irradiation with neutrons and photons using the neutron and photon detector (KFKI)

Networking

The successful completion of the project was mainly attributable to the high degree of cooperation and networking amongst the project partners. This is also reflected in the high number of more than 20 project meetings and work visits. Individual expertise was pulled into the project from the participating centers of excellence in the various subject fields and moulded into a joint effort. Samewise the project partners consented to extended visits of partner scientists at their institutions to pick up special expertise. The voluntary sharing of knowledge and the strong collaboration has improved both the range of know-how and the quality of solutions of all participants.

Specifically, modelling and simulation served as an important tool not only in sensor development but also in cross checking on the features of the experimental response curve and for the understanding of the detailed interaction mechanisms. Based on initial expertise at GSF and KFKI, simulation with various program codes for the specific sensor and phantom systems was implemented / enhanced at all project partners. Sensor development as an activity was subdivided into development of the detection element, the readout electronics, and appropriate converter and filter elements. This tasks were tackled by sub-networks dynamically established and even extended beyond the scope of the project by minor sub-contracting efforts. Phantoms were inventarised as a joint effort, further developments were accomplished in partial networks.

The irradiation program would not have been completed without the active support of other project groups within the cluster of radiation protection research. Specifically the sister project at PTB (Active Neutron Dosimetry) under the coordination of W. Alberts and their support shall be gratefully acknowledged. The principal idea of "clustering" of similar projects - as proposed by the Commission - has thus found positive resonance and must be recommended for further work.

It must be noted that an important element of success was the small and carefully selected partnership structure based on scientific excellence as well as the determination to cooperate not only formally but very practically. Another element of success was the implementation of a central information hub, an FTP server set up at the coordinators organisation to facilitate exchange of organisational data (e.g. meeting protocols), scientific results (e.g. simulation data, experiment results, pictures of irradiation setups), and material for preparation and distribution of mandatory reports.

Highlights

For brevity's sake the highlights of this project shall be enumerated shortly. Detailed discussions of the individual components have been made in the preceding sections focussing on the different activities.

- The installation of the communications center was a definite advantage and has helped both organisationally and regarding shortcut of scientific findings.
- The development of a self-made neutron interaction code has shed light on the detailed interaction mechanisms with neutron irradiations.
- Installation of the physical codes for various interaction regimes (neutron, photon, charged particles) and the first comparisons with real experimental data showed enough agreement to prove the methods successful.
- Perfection of interpretation allowed detailed understanding and agreement between simulation and experiment for 5 MeV neutron irradiation; samewise, initial photon irradiations confirmed the approach chosen.
- The application of phantoms demonstrated the influence of back-scatter and the anticipated Albedo effect and enhanced the know-how about realistic interaction processes. Depth dose measurements in phantoms allowed the study of exposure as a function of tissue or bone layers.
- The multi-element demonstrator for neutron exposure provided enhanced sensitivity and spectral information.
- Quantitative (i.e. calibration) and qualitative (i.e. spectral) information could be retrieved for both neutron and photon fields, with additional inputs on mixed-field behaviour.

The European Dimension:
Radiation Protection Research Goals in the Executive Work Program

Proposed aims:

In order to extend knowledge of the risk of human exposure in the field of radiation protection, it is of potential importance

- to enhance the detection sensitivity,
- to make use of the energy information, and
- to understand in detail the photon and neutron interaction

while employing sensing technology. This proposal describes an approach to increase the quality and applicability of the methods for assessment of low levels of external irradiation.
The overall objective of this project is the modelling and ultimately the development of an innovative semiconductor sensor and suitable phantoms for mixed photon and neutron fields. Contrary to already available technology, the intended design could result in an economic solution for the low energy regime of photons and neutrons. Specific to the design process, the concept will be verified by accompanying phantom simulations and irradiation.

For the evaluation of the feasibility of active dosimetry and the assessment of the suitability of existing methods and further developments, it is necessary to model the response of the sensor and parts of the phantom by applying appropriate simulation codes. Using numerical modelling and simulation as a starting point, new insights will be gained into the response function of semiconductor detectors. The resulting design will be checked in conjunction with suitable phantoms, employing low-energy neutron and photon irradiation.

Achieved aims - enhancements for evaluation of radiation risk

The general goals of radiation protection monitoring developments in this project might best be demonstrated by a matching of properties and specifications of commercially available dosemeters against similar properties of the sensing elements - and specifically the demonstrator - achieved under this project.

Achieved aims - for neutron dosemeters:

Commercially available dosemeters

The official dosemeters for neutron-exposure are mostly based on passive materials for individual dosimetry:

- Albedo dosemeter using TLD-detectors
- track edge type dosemeters using film (CR39)
- Macrofol techniques

The actual lower limit of detection (the best at present) is about 100 µSv (50 µSv for laboratory calibration measurements) and the neutron response must be well-known (separate calibration factors for different applications), whereby the sensitive energy range is always restricted. Therefore, using these dosemeters, e.g. for the actual transports of spent fuel elements (e.g with Castor containers, where the neutron response depends on the specific loading) the response must be known!

Developed demonstrator within this project

The neutron demonstrator developed within this project has the following enhanced characteristics:

- A non-restricted energy range
- The sensitivity for thermal neutrons has been enhanced by more than a factor 100, for fast neutron by a factor 10
- The system is energy resolving and – by means of a multi-element detector – may yield additional spectral information
- It is a real time device for timely detection of sources of danger thus preventing increased exposure as well as detecting the origins of unforeseen exposure

Achieved aims - for photon dosemeters:

Commercially available dosemeters

The official dosemeters for photon exposure are mostly based on passive materials for individual dosimetry:

- whole (and partial) body TLD- and film detectors
- lately also OSL materials

Available electronic dosemeters are mostly offered as additional alarm dosemeters for tactical purposes. The actual lower limit of detection (the best at present) is about 1 µSv (mostly 2 to 5 µSv). The measured energy range (the best at present) is about 20 keV (but mostly 50 to 70 keV) up to 3 MeV (but mostly 1.3 to 2 MeV). The detection of the type of radiation and the determination of the particle energy in not possible.

Results from single sensors within this project

The photon sensors developed within this project have the following enhanced characteristics:

- An energy range from 30 keV (lowest 10 keV) up to a non-restricted upper limit
- The sensitivity is more than a factor 10 better
- The system is energy resolving and – by means of a multi-element detector – may yield additional spectral information
- It is a real time device for timely detection of sources of danger thus preventing increased exposure as well as detecting the origins of unforeseen exposure

Conclusion and Outlook

The results of this work might well serve as the basis for a new generation of monitoring systems for radiation protection.

As described in this report, the knowledge acquired in this project might be employed for a better physical and radiological protection by measuring individual dose with real time dosemeters. Therefore, this applies to

- an improved overall measuring uncertainty of the individual dose;
- enhanced properties for safe handling and reliable evaluation of personal dosemeter data;
- availability of additional information on exposure conditions.

Further applications of the results of this project could be seen as "basics" for

- enhancements for environmental and workplace monitoring;
- contamination monitoring, e.g. to replace traditional wipe-test methods by modern electronic devices;
- particle selective systems, e.g. for beta-exposure (and X-ray) surface and environmental measurements.

OEFZS-Berichte

Herausgeber, Verleger, Redaktion, Hersteller:
Österreichisches Forschungszentrum Seibersdorf
Ges.m.b.H.

A-2444 Seibersdorf, Austria
Telefon 02254-780-0, Fax 02254-74060
Email seibersdorf@arcs.ac.at
Server http://www.arcs.ac.at/