UPPSALA
UNIVERSITET

UU-NF 07#08

(June 2007)

UPPSALA UNIVERSITY NEUTRON PHYSICS REPORT

ISSN 1401-6269

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DIPLOMA THESIS

UPPSALA UNIVERSITY

DEPARTMENT OF NEUTRON RESEARCH

PROGRAM OF APPLIED NUCLEAR PHYSICS

UPPSALA, SWEDEN

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Editor: J Källne

ALTERNATIVE MEASURING APPROACHES IN GAMMA SCANNING ON SPENT NUCLEAR FUEL

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Abstract

In the future, the demand for energy is predicted to grow and more countries plan to utilize nuclear energy as their source of electric energy. This gives rise to many important issues connected to nuclear energy, such as finding methods that can verify that the spent nuclear fuel has been handled safely and used in ordinary power producing cycles as stated by the operators. Gamma ray spectroscopy is one method used for identification and verification of spent nuclear fuel. In the specific gamma ray spectroscopy method called gamma scanning the gamma radiation from the fission products Cs-137, Cs-134 and Eu-154 are measured in a spent fuel assembly. From the results, conclusions can be drawn about the fuels characteristics.

This degree project examines the possibilities of using alternative measuring approaches when using the gamma scanning method. The focus is on examining how to increase the quality of the measured data. How to decrease the measuring time as compared with the present measuring strategy, has also been investigated. The main part of the study comprises computer simulations of gamma scanning measurements. The simulations have been validated with actual measurements on spent nuclear fuel at the central interim storage, Clab.

The results show that concerning the quality of the measuring data the conventional strategy is preferable, but with other starting positions and with a more optimized equipment. When focusing on the time aspect, the helical measuring strategy can be an option, but this needs further investigation.

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Svensk sammanfattning

Behovet av energi ökar i världen och i det här sammanhanget har kärnkraften fått en förnyad viktig roll. Detta bland annat på grund av att dess koldioxidutsläpp är förhållandevis låga och att de förnybara energikällornas frammarsch inte har den takt som krävs för att motsvara behovsökningen. Genom effekthöjning på många befintliga kärnkraftverk i världen har den totala kärnkraftsproduktionen redan ökat, men även bygganden av nya kärnkraftverk är igång och många är också på planeringsstadiet.

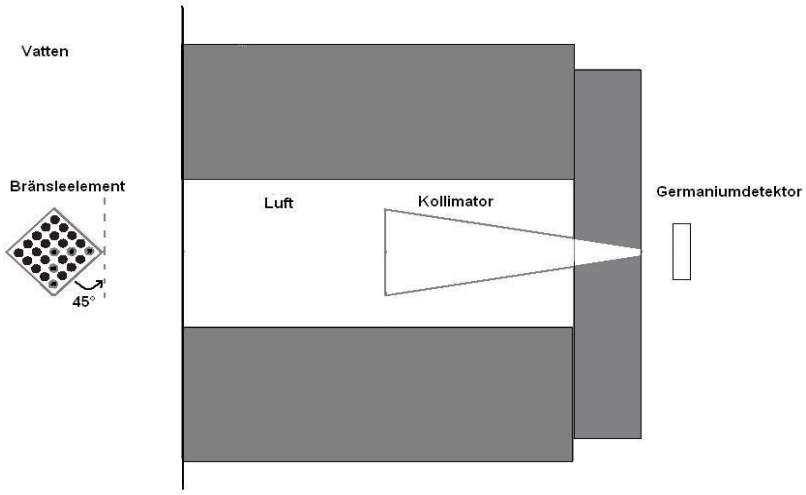
Kärnkraften, som den används idag, bygger på fissionsprocessen där en väldigt stor energimängd frigörs då tunga kärnor klyvs i mindre bitar. Reaktionen i kärnkraftreaktorerna sker genom att neutroner träffar urankärnor i bränslet, varvid urankärnorna klyvs, energi frigörs och nya neutroner utstrålas. Dessa utstrålade neutroner upprätthåller fissionsprocessen och är anledningen till att processen i kärnkraftverken är självunderhållande. De så kallade fissionsfragmenten som fås då urankärnorna klyvs är i regel radioaktiva och sönderfaller, vanligtvis genom utsändning av alfa- och/eller betapartiklar. Som regel utsänds även en viss mängd gammastrålning.

Kärnbränslet som används i svenska lättvattenreaktorer består av anrikat uran. Det anrikade uranet omvandlas till urandioxidpulver som därefter pressas till bränslekutsar. Kutsarna packas i bränslestavar som i sin tur monteras ihop till kvadratiska bränsleelement av olika storlekar beroende på vilken typ av reaktor de ska användas i. Varje element används för elproduktion i ungefär 4-6 år innan det tas ut ur härden och lagras i väntan på djupförvar. Lagringen sker först i bassänger vid kärnkraftverket i ungefär ett år, sedan i bassänger vid Centralt mellanlager för använt kärnbränsle, Clab, i 30-40 år i väntan på djupförvar.

Kärnkraften är inte en helt ofarlig energikälla, bland annat skulle olika tekniker i hela kedjan från gruva till slutförvar kunna användas vid kärnvapentillverkning. För att förhindra detta och för att sprida den civila kärnteknologin finns det en del avtal som reglerar de ansvar som hör ihop med kärnkraftsanvändandet. Det viktigaste avtalet är det så kallade Icke-spridningsavtalet, ”Treaty on the Non-Proliferation of Nuclear weapons”, NPT, där de stater som skrivit under avtalet åtar sig att tillåta kärnämneskontroll, även kallat safeguards, av all sin verksamhet rörande kärnkrafttekniker och material. Att Icke-spridningsavtalet efterföljs kontrolleras såväl på internationell som nationell nivå.

Många olika tekniker och instrument används för att uppnå målen satta för safeguards. En metod för att kontrollera att kärnmaterialet finns där det ska, och att det har använts så som deklarerat, är gammaskanning. Genom att mäta gammastrålningen som utstrålas från vissa fissionsfragment i ett använt kärnbränsle kan man få fram information om det specifika bränslets egenskaper. Mätningen går till på så sätt att ett bränsleelement placeras i en fixtur monterad vid väggen av den hanteringsbassäng där bränslet förvaras, sedan förs hela bränslets vertikallängd förbi en kollimatoröppning i bassängväggen som riktar gammastrålningen mot en detektor på andra sidan väggen. Detektorn mäter gammastrålningen från de utvalda isotoperna ^{137}Cs, ^{134}Cs och ^{154}Eu i bränsleelementet. Från den uppmätta gammastrålningen kan sedan information om det mätta bränsleelementet tas fram. I nuläget görs mätningarna genom att alla fyra hörnen av ett bränsleelement skannas och informationen läggs ihop för att få ut den totala

strålningsintensiteten för elementet, se Figur 1 där den nuvarande positioneringen av ett bränsleelement visas uppifrån.



Figur 1 *En schematisk bild uppifrån av den nuvarande positioneringen av bränsleelementet vid gammaskanning.*

I detta examensarbete har alternativa mätstrategier för gammaskanning av använt kärnbränsle analyserats. Arbetet bygger på simuleringar av mätningar på 8x8- och 17x17-bränsleelement och har verifierats genom faktiska mätningar på Clab. Målet har varit att finna en strategi som ger en totalintensitet som i görligaste mån representerar hela det mätta bränsleelementet och inte bara de bränslestavar som är närmast detektorn. Positioneringen av bränsleelementet i den konventionella strategin har gjort att vissa bränslestavar blockerar gammastrålningen från andra stavar att nå fram till detektorn. Även tidsaspekten har funnits med som en viktig parameter att ta hänsyn till.

De utvärderade mätstrategierna har i arbetet benämnts som fyrpunktsstrategin och rotationsstrategin. Fyrpunktsstrategin är den strategi som används för närvarande med en startvinkel av 45 grader, då ett hörn är placerat mot detektorn, se Figur 1. Analyserna av fyrpunktsstrategin gjordes med olika startvinklar, där bränslet skannades fyra gånger per bränsleelement, med 90 graders mellanrum. Startvinklarna som utvärderades var, med en grads mellanrum, vinklar från 1 grad till 90 grader. Rotationsstrategin som utvärderades var att utföra gammaskanningen medan bränsleelementet roterades runt sin egen vertikala axel. Simuleringarna gjordes 360 grader runt bränslet med mätningar i steg om 1.8 grader, alltså 200 simuleringar på varje element.

Resultatet visar att för fyrpunktsmätningar på ett 8x8-bränsle och ett 17x17-bränsle är de optimala startvinklarna 8 respektive 3 grader. Då fås jämnast möjliga intensitetsbidrag från de olika bränslestavarna i elementen. Nackdelen med att använda dessa startvinklar är att de kräver en hög positionsnoggrannheten för att få en tillförlitlig totalintensitet. Detta kan dock finnas med som en parameter att ta hänsyn till vid konstruktion av utrustning optimerad för gammaskanning. Rotationsstrategin ger ett något sämre resultat än den redan använda mätstrategin gällande intensitetsbidrag från de olika stavarna i bränslet. Dock har rotationsmätningarna inget problem med positionsnoggrannheten och kan också möjligtvis ge kortare mättid.

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1 Introduction

Presently, around 17% of the world's electricity is produced from the about 440 nuclear power reactors now existing [1]. In the future the demand for energy will grow and the production of electricity has to increase. Taking into account the slow increase of renewable energy production, nuclear power seems to enhance its importance This development is partly due to the fact that the emissions of carbon dioxide are very small and partly due to the very large energy density of the nuclear fuel [2]. Hence, there is an increasing interest to expand the use of nuclear power by building new reactors and improving the ones already operating. Research is also done on new reactor types, so called generation four reactors. The research is based on high demands such as, higher security, better fuel utilization, smaller risk of proliferation of material to nuclear weapons, smaller amounts of long-lived radioactive fuel waste and also to be economically competitive [3, 4].

In Sweden there are presently ten operating nuclear power reactors of which seven are Boiling Water Reactors (BWR) and three are Pressurised Water Reactors (PWR) [4]. These belong to the generation two reactors, which most of the reactors today do.

1.1 The fission process

When an unstable heavy nucleus is split into smaller parts, a great amount of energy is released. This process, called a *fission reaction*, forms the basis of nuclear energy. In nuclear power reactors neutrons interacting with the fissile nuclei in the fuel cause fission chain reactions and each fission gives rise to approximately 200 MeV of energy, two or sometimes three *fission fragments* and two or three neutrons [5]. The fission chain reaction is predominantly started by the absorption of slow neutrons in ^{235}U in the fuel. It is then self-sustaining since the released neutrons make the fission process continue by splitting the heavy nuclei in the surroundings [5, 6]. An example of a fission reaction is that of ^{235}U:

$$^{235}U + {}^{1}n \rightarrow {}^{140}Xe + {}^{94}Sr + 2\,{}^{1}n + 200\ \text{MeV}$$

The neutrons from the fission are either released directly when the reaction occurs or shortly after, and are called *prompt* and *delayed* neutrons, respectively. The share of the delayed neutrons is only in the order of a few percent, but they are in spite of this fact crucially important for the control of the fission chain reaction. If all neutrons were prompt the chain reaction would proceed exponentially in a very short time and become impossible to control. [5]

When the neutrons are released they have a relatively high energy, above 100 keV, and have to be slowed down. Slow neutrons, with energies below 1 eV have a considerably larger inclination to create a fission reaction with a ^{235}U nucleus than fast neutrons. The probability for a reaction to occur is described as the *cross section* and is measured in the

unit *barn [b]*. The slowing down of the fast neutrons is taken care of by letting the neutrons collide with particles of approximately the same mass as themselves in the surrounding material. Consequently, they will loose energy. The material used for this purpose is called the *moderator* and in the reactor types in Sweden the moderator comprises of light water and hence the name light water reactors or LWR: s. [5]

The fission fragments that possess an excess of neutrons are unstable and therefore start decaying immediately, which eventually leads to various stable nuclei. The fragments are radioactive and decay by emitting particles and/or electromagnetic radiation [7]. Hence, the content of the fuel in a nuclear power reactor changes while the reactor is still operating. The contribution to the fission rate changes from being mainly from ^{235}U in the beginning to depend primarily on new fissile nuclides like ^{239}Pu at the end of the fuel assembly's lifetime. When the fuel has been used to its maximum and is taken out of the core the decay of the fission fragments continues and radiation is still emitted [8].

1.2 Nuclear decay

The fission process, as well as other nuclear reactions occurring in the reactors, gives rise to a vast amount of different nuclides in the nuclear fuel. A lot of these nuclides are unstable, and thus decay in various ways. Accordingly, the properties of spent nuclear fuel depend to a large extent on such nuclides.

When unstable nuclides decay into different nuclides they generally emit alpha or beta particles, depending on if they are alpha or beta instable. In addition, most nuclear decays also involve the emission of gamma radiation

An *alpha decay* emits an alpha particle, which is a particle consisting of two protons and two neutrons bound together as a ^{4}He nucleus. Alpha emission is a special reaction occurring with some heavy nuclei that are too large to be stable. An example of decay by alpha emission is:

$$^{226}Ra \rightarrow {}^{222}Rn + {}^{4}He$$

When a nucleus emits an alpha particle it moves closer to a stable configuration. Alpha particles have a very limited range and can only travel a very short distance in both air and solids before they are stopped by electromagnetic interaction. [7]

There are three different types of decay that involve electrons: beta-minus, beta-plus and electron capture. Beta radiation has a larger range than the alpha radiation, but can still only travel in the order of 10 meters in air. In a beta-minus decay a neutron is transformed into a proton, a beta-minus particle and an anti-neutrino. The beta-minus particle is an electron and the anti-neutrino is a particle that carries the energy and momentum needed to conserve these quantities in the decay. The decay of a typical beta-minus emitter is: [9]

$$^{198}Au \rightarrow {}^{198}Hg + \beta^{-} + \bar{\nu}_e$$

In the beta-plus decay a proton in the nucleus changes into a neutron, a positron and an

electron neutrino. Here the electron neutrino carries the extra energy and momentum needed, e.g.: [7]

$$^{198}N \rightarrow {}^{198}C + \beta^{+} + \nu_e$$

The third type of beta decay is electron capture, were a proton inside the nucleus captures an atomic electron and forms a neutron and a neutrino, e.g.:

$$^{51}Cr \rightarrow {}^{51}V + \nu_e$$

In both alpha and beta decay the nucleus of one element (the parent nucleus) becomes the nucleus of a different element (the daughter nucleus). Often the new element is in an excited state and gamma radiation is also emitted when the nucleus decays to a lower energy level. [7]

A typical nucleus has a set of allowed energy levels with typical spacing of 0.1-1 MeV. These levels include a *ground state*, which is the state of the lowest energy, i.e. the stable state, and several *excited states*. When a nucleus in an excited state decays to a lower state of the same isotope, it can happen in one step or in several steps via other excited states. In this de-excitation, one or several photons called *gamma rays* can be emitted. This is called *gamma decay*. Gamma radiation has a very long range and therefore a much larger ability for penetration of different materials than alpha and beta radiation. It takes a couple of meters of water or several decimetres of concrete to reduce the gamma radiation from a typical spent nuclear fuel assembly to a level that is acceptable from a radiation protection point of view. [10]

By measuring the intensities of the emitted gamma rays from a fuel assembly that has been taken out of the core, the content of radioactive isotopes in that specific fuel assembly can in principle be determined by using high-resolution gamma ray spectroscopy. This since the energies of the gamma rays are well defined and well known for all radioactive nuclei, and therefore the radioactive isotopes can be traced in the spent fuel. [8]

1.3 Nuclear fuel

The nuclei ^{233}U, ^{235}U and ^{239}Pu are called fissile nuclei since they easily fission when hit by a neutron with a relative small kinetic energy. ^{239}Pu is produced in nuclear reactors while ^{233}U and ^{235}U exist in nature but with small abundances. The latter two are derived from the in nature existing uranium ores and can be used as fuel in nuclear power reactors. [5, 11]

Natural uranium consists to 99.3 % of ^{238}U. Before the uranium can be used as fuel in the Swedish types of light water reactors, it has to be enriched, i.e. the fraction of the fissile isotope ^{235}U must be increased to typically 3-5 %. After the enrichment, the uranium is converted to uranium dioxide powder, which is then sintered into small cylindrical pellets with a length and diameter of about one centimetre, respectively. The uranium dioxide has the qualities desirable for nuclear fuel, namely a high melting point, insensitivity to

radiation damage and it is chemical inert. The pellets are stacked into about 4 meter long tubes made out of zircaloy, making up a fuel rod. Zircaloy has good corrosion durability, endures high temperatures well and has a small neutron capture cross section, making it suitable for use in nuclear reactors. The rods are filled with a chemically inert gas and sealed in both ends. Finally, the fuel rods are arranged in quadratic matrices called fuel assemblies of different sizes depending on the type of reactor they are to be used in, see Figure 1.1. [12]

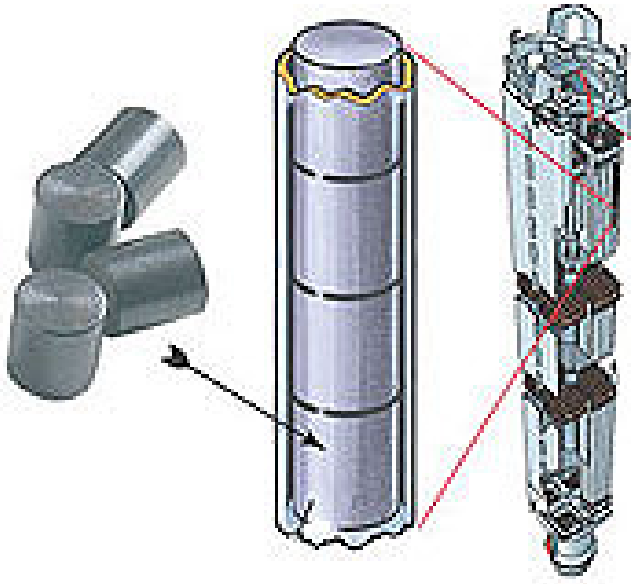


Figure 1.1 *The uranium dioxide pellets are stacked in fuel rods that in turn are arranged in quadratic fuel assemblies [13].*

In a BWR fuel assembly, a fuel channel surrounds the rods to make the flow of the water-steam mixture better. There are about 400-700 assemblies in one reactor with in all up to 70 000 rods. Older types of fuel assemblies contain 8x8 fuel rods with a central position empty for improved hydrodynamics see Figure 1.2, while modern types contain 81, 96 or 100 rods. These types also contain water channels in the centre of the assembly in order to obtain more moderation in the centre of the fuel assembly [5].

In the Swedish PWR:s there are approximately 160 fuel assemblies with, in total, about 35 000-42 000 rods, since each fuel assembly contains 17x17 or 15x15 rods. The rods in a PWR fuel assembly are more closely packed than in a BWR fuel assembly. Another difference as compared to the BWR fuel is that the PWR fuel contains internal control rods. These are moving in 24 guide tubes. In addition there is an instrumentation tube in the centre of the assembly, see Figure 1.3. [5]

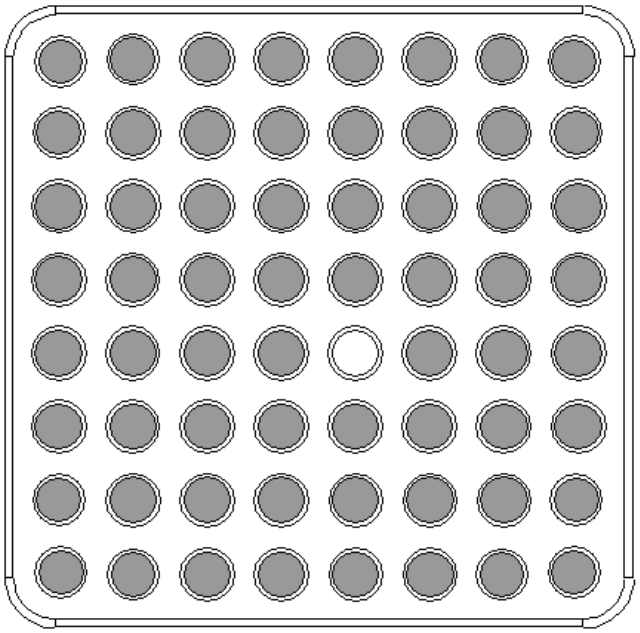


Figure 1.2 *A BWR 8x8-fuel assembly with 63 fuel rods and a central water rod for improved neutron moderation. The rods are surrounded by a fuel channel to make the flow of the water-steam mixture better [14].*

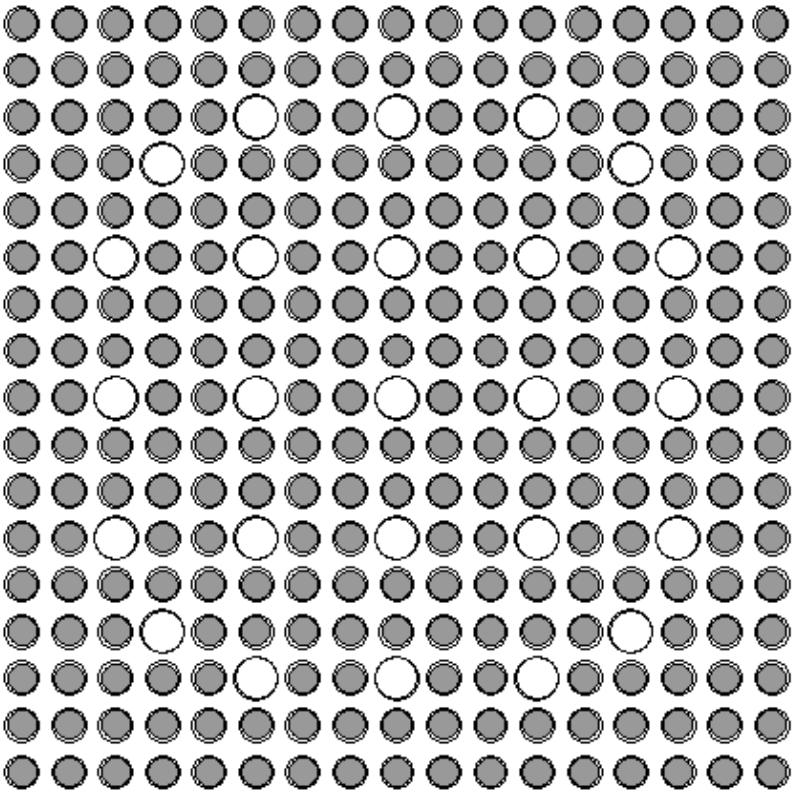


Figure 1.3 *A 17x17 PWR fuel assembly with 264 fuel rods, 24 tubes for internal control rods and one instrumentation tube [14].*

Normally in Sweden, the period of operation, or power cycle, for a nuclear power reactor is about one year before it is shut down a couple of weeks for maintenance and fuel rearrangements, where about 20 % of the assemblies are removed from the core. Each fuel assembly is used for power production in about 4-6 power cycles before the fuel is considered used to its maximum. When the fuel is removed from the core, it is stored in a pool at the power plant for typically one year and then transported to the central interim storage Clab in Oskarshamn. There the fuel assemblies are stored in 30-40 years prior the final disposal in a deep geological repository. [8,15]

1.4 Fuel diagnostics and safeguards

With the choice of using nuclear power come responsibilities. The most important agreement regulating the responsibilities concerning nuclear power is the "Treaty on the Non-Proliferation of Nuclear weapons" or NPT from 1968 [16]. The states signing the NPT are committed to use nuclear power only for peaceful purposes and to implement *safeguards*, i.e. controlling and supervising, all aspects dealing with the nuclear power and the nuclear fuel trough the whole fuel cycle. Safeguarding is performed to prevent the diversion of nuclear material from a civil nuclear fuel cycle to nuclear weapons. On an international level, the International Atomic Energy Agency, IAEA, which reports directly to the Security Council of the UN, is responsible for safeguarding the civil nuclear technology and promoting peaceful use of the nuclear power in all countries, except for the nuclear power states that perform their own safeguards. The nuclear power states have however agreed to voluntary safeguards of some of their facilities [16,17]. In Europe, the European Union through Euratom supervises that the European countries follow the commitments of the EU concerning nuclear material [17]. These commitments are strongly linked to the NPT [18]. Most countries also have their own supervisory authority on a national level, concerning nuclear issues. In Sweden, it is the Swedish Nuclear Inspectorate, SKI, that is responsible of safeguarding the nuclear power [17]. All these authorities on various levels have parallel activities but also cooperate extensively.

Techniques and instruments used for achieving the goals set for safeguards are many. A common methodology for safeguards measurements is Non-destructive assay or NDA. In the safeguarding of spent nuclear fuel, NDA gives possibilities to gain knowledge about the isotopic content of a fuel, without destroying the fuel and with minimal interference of the regular activities at the facilities. Within NDA there are several techniques employed and among these the so-called gamma scanning has experienced increased interest. [16]

When safeguarding spent nuclear fuel, it is important to verify the operator declarations that a nuclear fuel assembly has been handled in accordance to regulations and used in ordinary power cycles. The final purpose of these verifications is to decide whether the fissile content, or other materials of relevance, is missing or not. [16]

At the backend of the fuel cycle it is also of great operational importance that the fuel parameters of the spent nuclear fuel assemblies encapsulated, correspond with the declared values. A main parameter in this context is the decay heat, see Section 2.1 for an explanation, which governs the encapsulation strategy.

1.5 The purpose of this study

As mentioned, different methods are used in the safeguards of spent nuclear fuel. Gamma scanning, which will be explained in section 2, is one of them. The measuring strategy used in gamma scanning today is, in some aspects, not optimal, and the aim of this study has therefore been to investigate the effects of using alternative measuring approaches. The focus was put on improving the quality of the measured data and on decreasing the measuring time.

1.6 Method

The main part of this study consists of computer simulations of gamma scanning measurements on spent nuclear fuel using a software developed at the Department of Neutron Research at Uppsala University. The analysis of the simulated data has been done in Microsoft Excel®. Actual measurements on spent nuclear fuel located at the Swedish interim storage Clab, have been performed as a complement to the simulations. The simulations are explained in section 3 and the analysis and results can be found in section 4. In section 5 the experimental validation is explained.

2 Gamma scanning

One non-destructive technique used for verification and identification of spent nuclear fuel is based on high-resolution gamma ray spectroscopy and is called gamma scanning. This method is based on the measurement of the intensity of the gamma radiation emitted from fission products in the spent nuclear fuel and it can therefore be used to determine the isotopic content of the fuel assembly.

2.1 Fuel parameters of importance

The amount of the fission products in a spent nuclear fuel depend on many different fuel parameters, that in turn are depending on the physical conditions during reactor operation. Since the concentration of the fission products is strongly linked to some of the parameters characterising a specific fuel assembly, the results from gamma scanning can be used as a basis for fuel diagnostics and safeguard verifications. The fuel parameters of importance in gamma scanning measurements are: [19, 20]

- **Burnup**. Total amount of energy produced in nuclear fuel, measured in the unit GWd/tU, which is gigawatt days of thermal energy produced per tonne uranium initially present in the fuel.
- **Cooling time.** Time passed since the fuel was taken out of the core.
- **Initial enrichment.** The amount of ^{235}U initially present in the fuel, i.e. prior to irradiation.
- **Irradiation history.** Information of how the total burnup is distributed in time. It is of great importance that the irradiation history can be verified to correspond with expected irradiation history for a power-producing reactor. For example, short fuel cycles with low neutron flux produce more plutonium suited for weapon production.
- **Decay heat.** The power generated by decaying nuclei in a spent nuclear fuel assembly. [8]

The gamma scanning method can be used in safeguard purposes for calculations of burnup and cooling time and also verification of irradiation history and initial enrichment.

A large number of gamma radiating fission products are produced in the fuel in a nuclear power reactor, but not all of them are suitable for the gamma scanning method. The ones chosen for the measurements are ^{137}Cs, ^{134}Cs and ^{154}Eu. The measured gamma ray energies from these isotopes and their half lives can be seen in Table 2.1. Their relatively long half-lives ensure that they are measurable also at cooling times exceeding 10 years [20]. In addition, the gamma ray energies are well separated, which facilitates the evaluation of the energy spectrum, and the gamma radiation possesses high enough energies for achieving reasonable penetration of a fuel assembly. [8]

Table 2.1 *The isotopes used for the measurements with their respective gamma ray energies and half lives.*

Isotope	Gamma ray energy [keV]	Half life [years]
^{154}Eu	1275	8.6
^{134}Cs	796 and 1365	2.1
^{137}Cs	662	30.1

The detector used in the experimental part of this work is a germanium detector that provides the energy resolution necessary to separate the closely lying gamma ray energies emitted from different radioactive nuclei in the fuel. When the detector is hit by photons, the germanium reacts by exciting electrons from the valence band to the conduction band. Under the influence of an applied electric field, this causes the charges to move and creates voltage pulses. These pulses possess amplitudes proportional to the gamma energy detected and they can be counted and presented according to amplitude in a gamma energy spectrum, which then provides information about the fuel measured. In Figure 2.1 a gamma energy spectrum from the gamma scanning of a PWR fuel assembly with burnup of 47 GWd/tU and cooling time of 12 years is shown. [20]

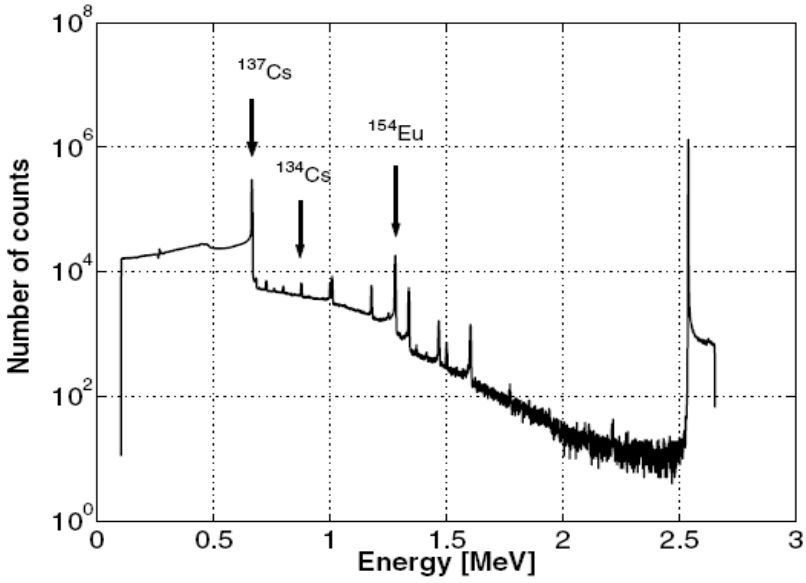


Figure 2.1 *An energy spectrum from a spent PWR nuclear fuel assembly with a burnup of 47 GWd/tU and a cooling time of 12 years. [20]*

In the figure the peaks from the isotopes studied in this work are marked with their respective names. The large peak on the right hand side is an artificial peak used for determination of the dead-time correction of the experimental data. [20]

Because of the small band gap of germanium of about 0.7 eV, the detector has to be cooled during operation, otherwise the thermal energy at room temperature can excite a too large amount of electrons to the conduction band, creating a severe leakage current [6]. Normally liquid nitrogen at 77 K serves as a cooling agent [8].

In addition to the measurements for safeguard purposes, the gamma scanning method may also be used for determination of decay heat in the spent nuclear fuel. This type of measurements are of significance in the future final storage of the fuel in a deep geological repository. For more information see ref. [21].

2.2 The production of the isotopes used in this work

2.2.1 ^{137}Cs

The production of ^{137}Cs in the fuel is quite simple since it is an isotope that is created as a direct consequence of the fission process. Figure 2.2 shows that ^{137}C is produced when the fission fragments in mass chain 137 decay in a series of beta decays. Some amount of ^{137}Cs is also produced from the neutron capture in ^{136}Xe, but about the same amount is lost from neutron capture in ^{137}Cs. [8]

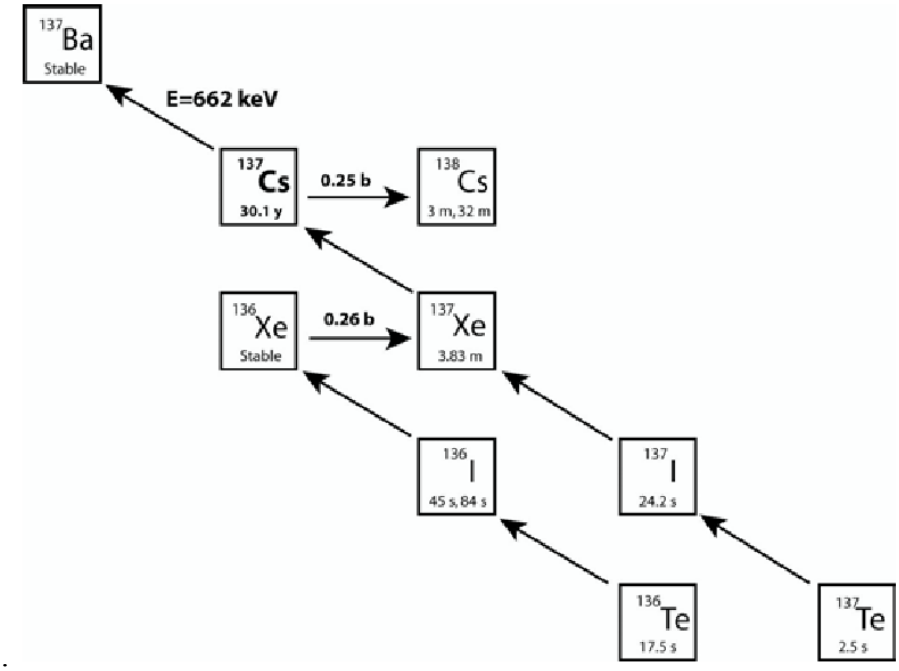


Figure 2.2 *The production path and decay of ^{137}Cs, where the beta decay and the neutron caption are shown by diagonal arrows and horizontal arrows, respectively. The half-lives of all isotopes are presented as are the cross sections for ^{136}Xe and ^{137}Cs. The gamma ray energy of ^{137}Cs is also shown. [8]*

The fission yields of ^{137}Cs for the fissile isotopes of uranium and plutonium are about the same. Together with the long half-life this makes the amount produced relatively insensitive to the irradiation history and initial enrichment. This makes ^{137}Cs usable as a reference and makes the concentration of ^{137}Cs in spent nuclear fuel depend almost linearly on burnup. This has been verified in previous simulations and the result can be seen in Figure 2.3 [20]. The long half-life makes ^{137}Cs suitable for gamma scanning measurements on fuels with cooling times of many decades. [8]

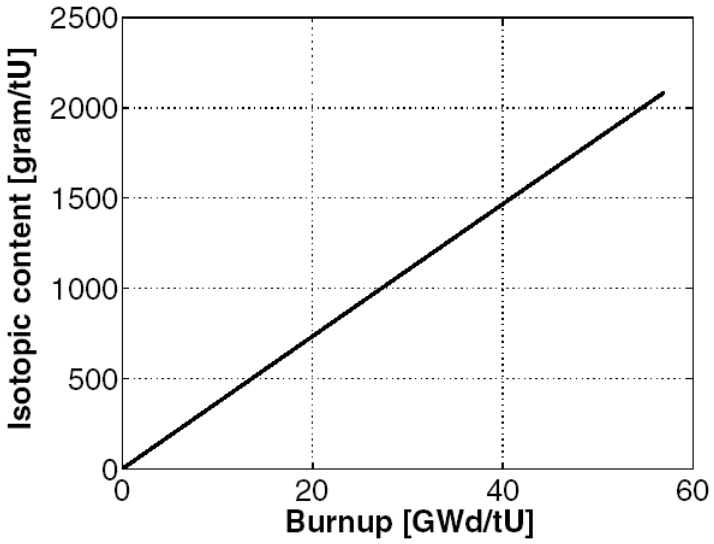


Figure 2.3 *Results from previous simulations show that ^{137}Cs depend almost linearly on burnup. A 17x17 PWR fuel assembly was simulated with an initial enrichment of 3 percent. The deviation from linearity was 0.2 percent. [20]*

2.2.2 ^{134}Cs

The production of ^{134}Cs is a bit more complicated, as Figure 2.4 shows. ^{134}Cs is principally formed by neutron capture in ^{133}Cs, which in turn is produced from beta decay of ^{133}Xe. Since the fission yield to mass chain 133 is about the same from the fissile uranium and plutonium isotopes the yield of ^{134}Cs is about the same from these isotopes as well. The production path of ^{134}Cs makes its concentration depend approximately quadratically on the burnup, see Figure 2.5. This has been verified in previous studies [20]. The build-up of ^{134}Cs is affected by the enrichment in the way that a lower enrichment causes a larger production of ^{134}Cs. This can possibly be used to verify the initial enrichment. Even though the half-life is only 2.1 years it is anticipated that ^{134}Cs can be utilized at cooling times up to 50 years, by using dedicated equipment. [20]

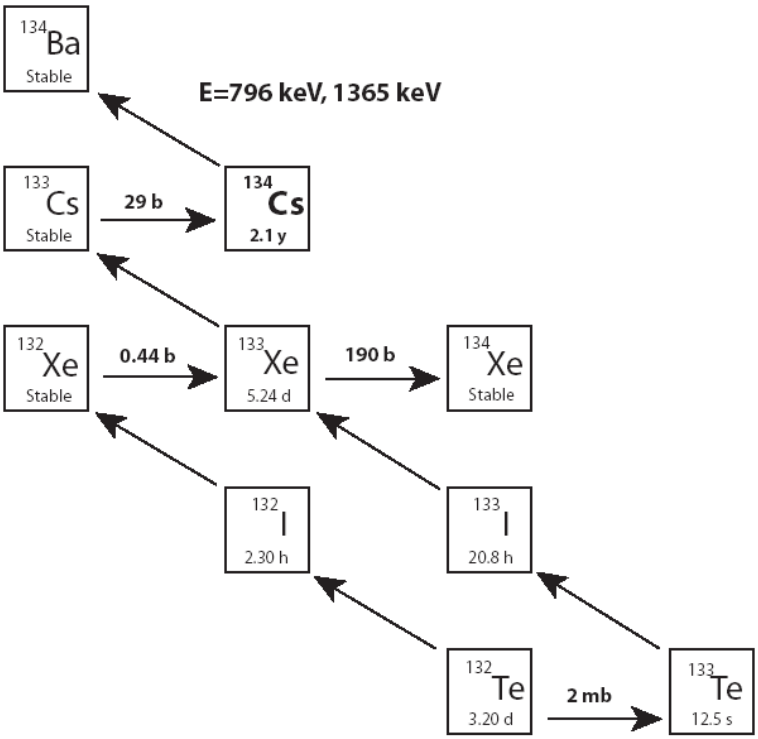


Figure 2.4 *The production path and decay of ^{134}C, where the beta decay and the neutron caption are shown by diagonal arrows and horizontal arrows, respectively. The half-lives of all isotopes are presented as are some cross sections and also the two most dominant gamma ray energies of ^{134}Cs. [8]*

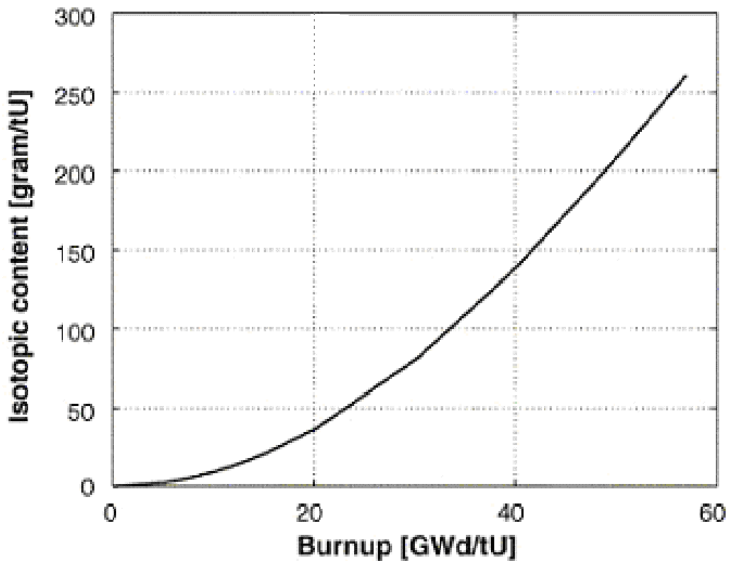


Figure 2.5 *Results from simulations show that the production of ^{134}Cs depends almost quadratically on burnup. A 17x17 PWR fuel assembly was simulated with an initial enrichment of 3 percent. [20]*

2.2.3 ^{154}Eu

By far, the production of ^{154}Eu is the most complicated of the three isotopes used here. It is produced via many different reaction chains and only to a small extent directly from fission. The production of ^{154}Eu is affected by the enrichment and also depends on whether it is derived from fission in plutonium or uranium. For a burnup up to about 30 GWd/tU, the concentration of ^{154}Eu can be described as quadratically dependent on the burnup. Above that, the dependency tends to be more linear, see Figure 2.6. [20] In addition, the production of ^{154}Eu in a BWR is dependent on the amount of steam in the cooling water, the so-called void, which makes it quite sensitive to the irradiation history.

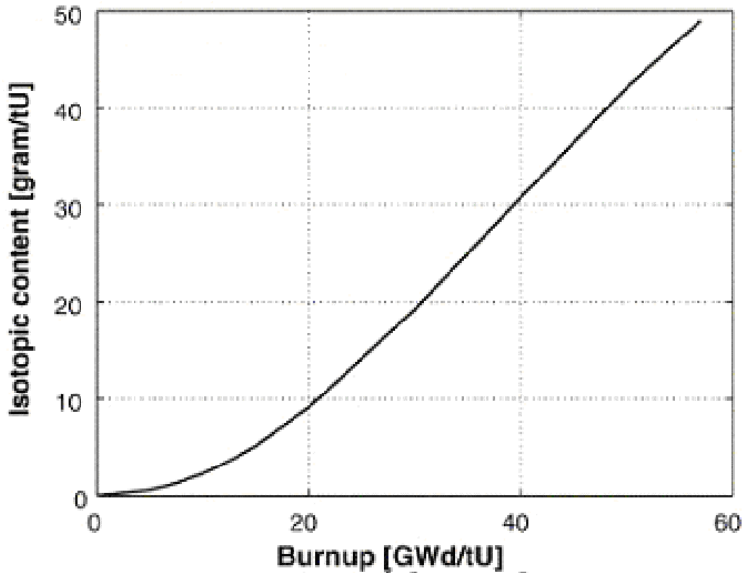


Figure 2.6 *Results from simulations show that the production of ^{154}Eu depends almost quadratically on burnup. A 17x17 PWR fuel assembly was simulated with an initial enrichment of 3 percent. [20]*

2.3 Experimental equipment

At Clab and at all Swedish BWR reactors, installations that can be used for gamma scanning measurements are available. The equipment is not optimized for the gamma scanning method but is used so far since it is easily available. At Westinghouse in Västerås there is also a measuring system consisting of a transportable detector with a collimator, called LOKET that can be used for measurements at any location. [15,19]

At the stationary installation a fixture for the fuel assembly is mounted on the pool wall, see Figure 2.7. The fixture can be moved vertically by an elevator and rotated around its own axis in a large amount of small steps by a stepper motor. From a position near the pool, it is possible for the operator to change both the vertical speed and the rotational speed and decide at which position the fixture should be at the beginning of a measurement. Inside the pool wall, a collimator is placed and on the other side of the

wall, the germanium detector is mounted. The collimator is 120 cm long and wide enough to cover the diagonal width of a fuel assembly, see also Figure 2.8. The distance from the centre of the fuel to the end of the collimator it is about 250 cm. At the back end of the collimator, a lead filter and a copper plate are placed to filter away low-energy gamma rays that otherwise would download the data acquisition system. [8]

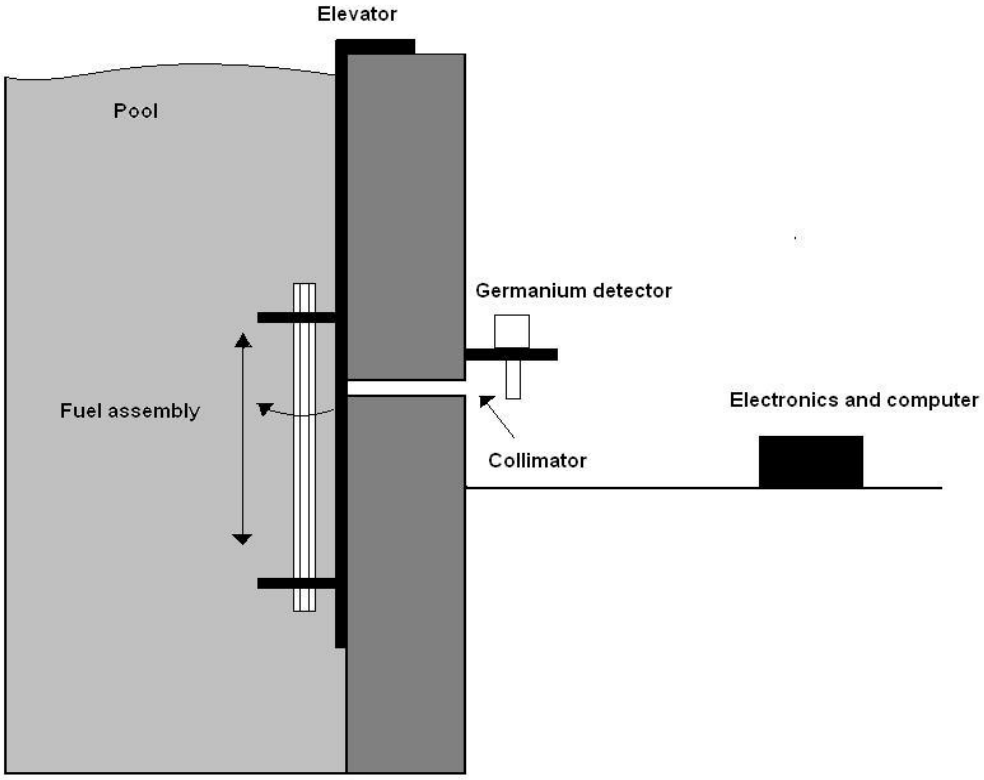


Figure 2.7 *A schematic illustration of the gamma scanning equipment. The fixture for the fuel assembly is mounted in the pool. Built into the pool wall is a collimator and behind the wall the gamma ray detector is placed.*

When a fuel assembly is about to be measured it is placed in the fixture, which is at its starting position a bit below the collimator slit. The fixture is then placed in the desired angular starting position and the measurement can start. By moving the fixture upwards in front of the horizontal collimator slit, the whole length of the fuel is scanned.

2.4 The present measuring strategy

The measuring strategy used at present begins with one corner of the fuel assembly facing the detector and the fixture in its starting position, see Figure 2.8. The assembly is then moved vertically upwards and the gamma radiation of the whole length of the assembly is recorded. When the scanning of one corner is finished, the assembly is rotated 90° and the next corner is scanned while the fixture is moving downwards. This is

repeated for all four corners and summing up the results gives the total intensity of the fuel assembly and a total energy spectrum that can be analysed. Using the present equipment, the data for the corners scanned upwards are collected in 190 sub spectra and the data for the corners scanned downwards are collected in 150 sub spectra. For each sub spectrum the measuring time is about 1 to 1,5 seconds, so a whole fuel assembly is scanned in a total of 680 sub spectra and the total scanning time is approximately 15 minutes. [22]

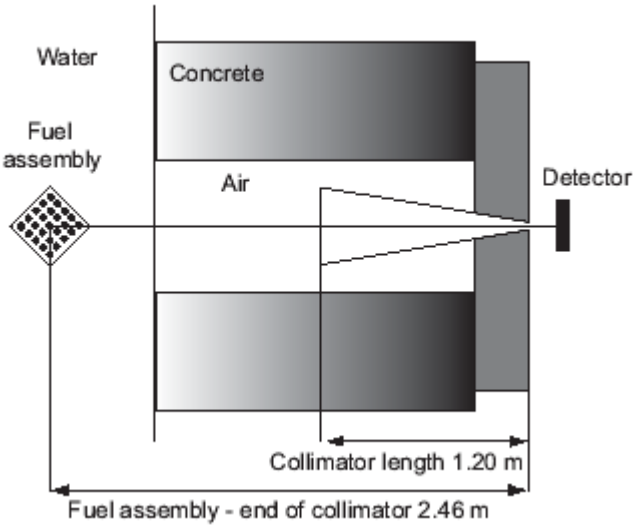


Figure 2.8 *A schematic picture of the measuring equipment used in this work from above. The fuel assembly is in its starting position with one corner facing the detector. [8]*

3 Simulations of new measuring strategies

The strategies examined in this work were four-point measurements and rotational measurements. The four-point measurement strategy is the one used at present with one corner facing the detector, i.e. with a starting angle of 45 degrees, see Section 2.4.

The conventional measuring approach is used because it is an easy way to perform the gamma scanning measurements with the equipment now accessible. The starting position for each scan is confirmed by the operator's eye from above the fuel assembly, and therefore measurements at the corners where the positioning is uncomplicated have been chosen. In the future when equipment optimized for the measurements will be available, the starting positions can be adjusted more precisely. Consequently, the uncertainty in positioning will not be a great problem and new measuring strategies could be of interest. Therefore it is important to know which starting position is the optimal to use and also to define what an optimal measuring strategy in fact means.

3.1 Evaluation criteria of the simulations

The most important aspect to include in the discussion of a successful measuring approach is the quality of the output data from the scan. The aim should be that, as much gamma radiation as possible from all of the fuel rods in the assembly should reach the detector, so that the data obtained represents the whole fuel. In the present strategy it can be concluded, from just looking at the placements of the rods in relation to the detector, that the strategy is not most favourable regarding this aspect. This since the positioning of the fuel is such that some rods block the gamma radiation from other rods. It would also be a good improvement for the gamma scanning measurements if the measuring time could be decreased. Especially considering that the method in the future is supposed to be applied to a large amount of assemblies, and time will then be precious.

3.2 Simulation procedure

The computer simulations of this work have been performed using software developed for an ongoing tomography project at the Department of Neutron Research at Uppsala University, for more details see Ref. [14]. The software involves calculations of the gamma ray transmission through nuclear fuel. The output from the program is coefficients ω_n for each fuel rod, n, in the assembly chosen. Each coefficient gives the average probability for a gamma quantum from the rod to reach the detector. By multiplying the coefficients with values of the activities A_n from the fuel rods the intensities from each rod can be received. By summing up all the intensities, for one assembly, the total intensity I for that assembly can be received:

$$I=\sum A_n\omega_n$$

In this study the following input parameters have been varied:

- the fuel type
- the starting angles
- the number of sub simulations in each scan
- the angular step.

Simulations of the present measuring strategy were performed with four sub simulations on each assembly having a starting angle of 45 degrees and an angular step of 90 degrees. See Figure 2.8 for a schematic picture of how the fuel was placed. Only one axial level has been simulated, meaning that no movements in the vertical direction have been considered in the simulations.

The fuel types simulated were a BWR 8x8-fuel assembly without fuel channel and a PWR 17x17-fuel assembly. The gamma energy simulated was 662 keV, which is from ^{137}C. This was chosen since it is dominant in the typical gamma energy spectrum, see Figure 2.1.

The simulations were validated experimentally as presented in Section 5.

3.3 Simulated four-point measurements

The basic set of simulations performed were of measurements with the conventional strategy of scanning four angles 90 degrees apart for each starting angle, however with various starting angular positions. Simulations were performed with different starting angles at one degree's interval from 1 degree to 90 degrees. For example at the starting angle of 1 degree, simulations were done at 1, 91, 181 and 271 degrees. The thought of this investigation was to see if the fuel assemblies could be measured, with the same strategy as used today but at some other starting angle than 45 degrees, and get a better quality of the output data according to the criteria stated in Section 3.1.

3.4 Simulated rotational measurements

The rotation approach looked at was performing gamma scanning by continuously rotating the assembly during the elevation. In this simulation the assembly was rotated 360 degrees around its vertical axis and simulations were done every 1.8 degrees, which means 200 sub simulations made on each assembly. The purpose of this investigation was to see if the rotation scanning gives better result concerning the data quality and whether it also makes it possible to decrease the measuring time compared to the four-point measurements.

4 Data analysis and results

All output data from the simulations was analysed in Microsoft Excel®. To agree with the goals of the study the analysis was made with focus on improving the quality of the measured data, according to the criteria stated in Section 3.1,while decreasing the measuring time.

In the analysis of the simulated data the intensity output obtained for different measurement strategies was examined. The intensity variation as a function of uncertainty in starting position was also analysed, to investigate the position accuracy needed for different angles. Furthermore and most importantly, the contributions to the total intensity from different rods was examined, to see with which measurement strategy the contribution from the different fuel rods to the total intensity is as even as possible. This is significant since the aim with the gamma scanning measurements is to get as much information of the whole fuel as achievable, not only from the fuel rods closest to the detector.

4.1 Four-point measurements

Simulations were done as described in Section 3.2 on a PWR 17x17-fuel assembly and a BWR 8x8-fuel assembly. The activities in both assemblies were presumed to be homogeneous throughout the assembly. Hence the coefficients received from the simulations were utilized as the relative intensities from each rod. To get the total intensity for each starting angle the intensities for the four sub simulations were summed up.

4.1.1 Total intensity

The simulated total intensity for all angles was plotted as a function of starting angle, see Figure 4.1 for the 8x8-fuel assembly and Figure 4.2 for the 17x17-assembly.

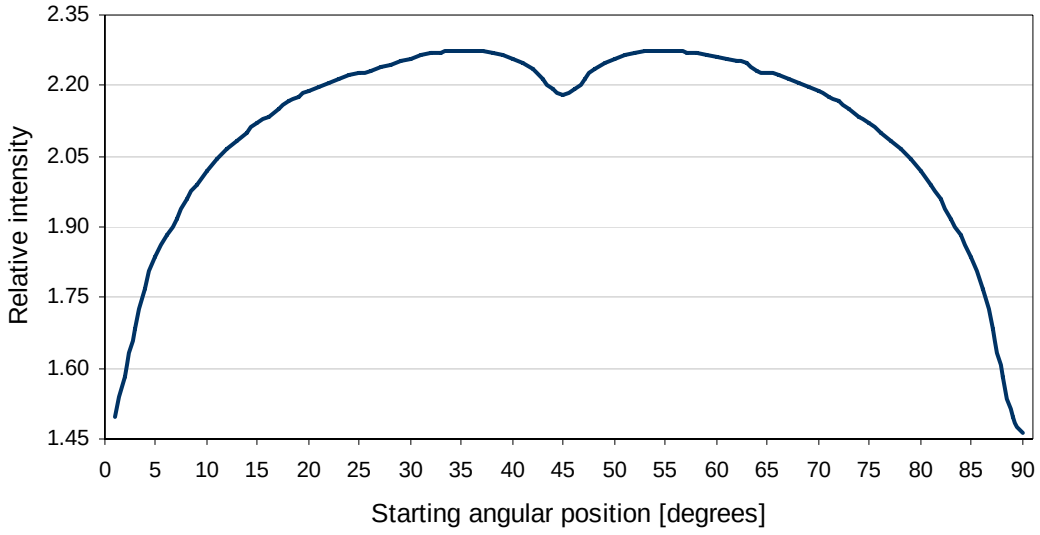


Figure 4.1 *The total intensity as a function of the starting angular position for an 8x8 BWR fuel assembly, without a fuel channel. Summing up the four intensities simulated for each angle gave the total intensity. The highest relative intensity is at 36 degrees.*

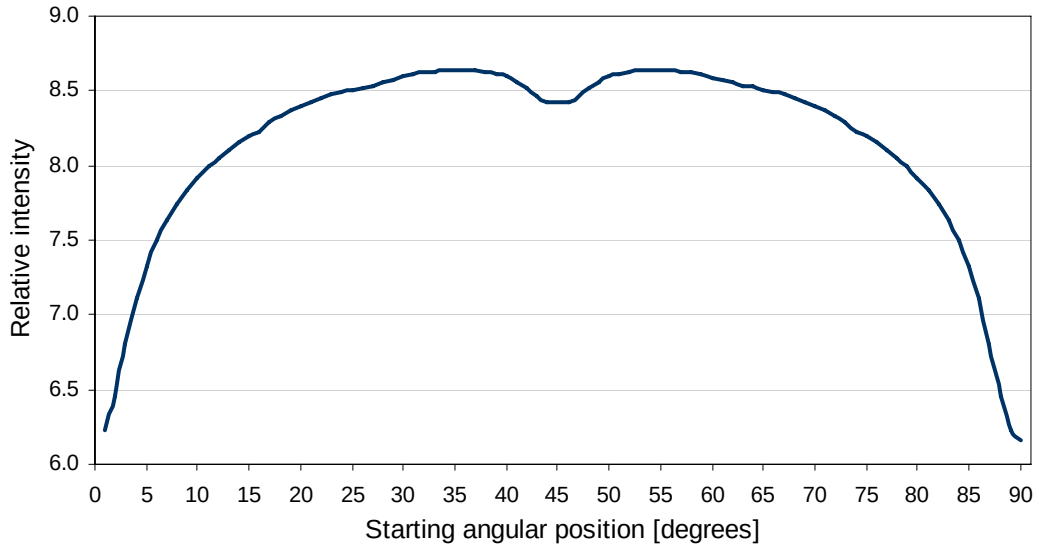


Figure 4.2 *The total intensity as a function of starting angles for a 17x17 PWR fuel assembly. Summing up the four intensities simulated for each angle gave the total intensity. The highest relative intensity is at 36 degrees.*

From Figures 4.1 and 4.2 the conclusion can be drawn that the optimal angle for measurements regarding intensity output, and intensity variation as a function of uncertainties in starting position, is not at 45 degrees. The total intensity is at its maximum at 36 degrees for both fuel assemblies. The curves are also quite flat around 36 degrees, meaning that the intensity variation as a function of uncertainties in starting

position is less here than for 45 degrees. An acceptable variation of the intensity can be set to one percent [23].

With the equipment used at present the angular positioning can only be done in steps of 1,0 degrees. So for an 8x8-fuel assembly it takes a positioning error of two degrees to get the variation of intensity to exceed one percent for the 45 degrees angle, as shown in Figure 4.3 a). For the 36 degrees starting angle it would take at least five degrees to obtain the same variation in intensity. The uncertainty due to the starting angle for a 17x17-fuel assembly is slightly smaller for both angles. As can be seen in Figure 4.3 b) it takes a three degree error in positioning to exceed a one percent intensity variation for the 45 degrees starting angle and for the 36 degrees starting angle it takes about six degrees for the same variation. Hence, measuring at a starting angle of 36 degrees would give a measurement not as sensitive to positioning error as a starting angle of at 45 degrees.

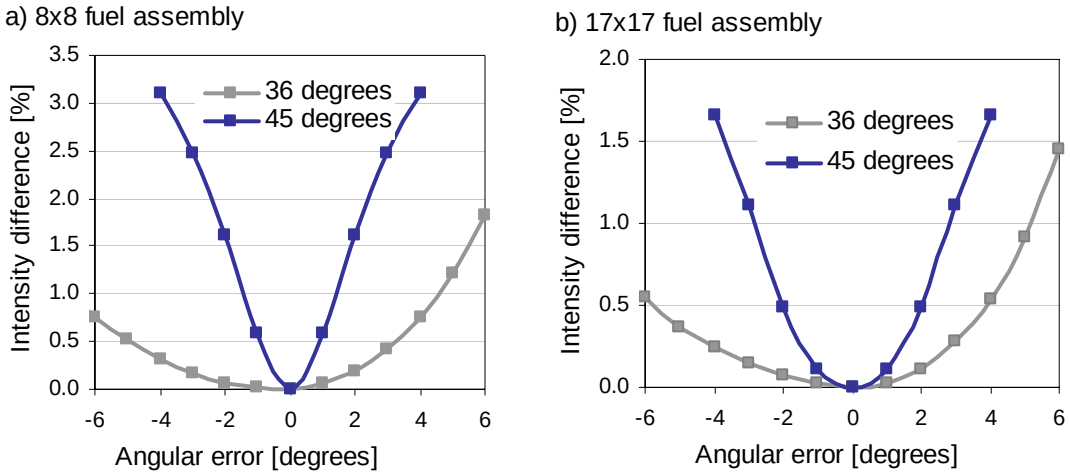
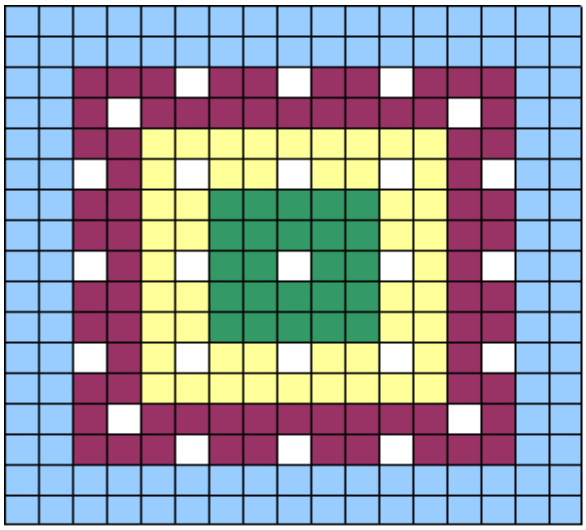


Figure 4.3 *The intensity variations as a function of angular error for the starting angles of 36 degrees and 45 degrees for a) an 8x8-fuel assembly and b) a 17x17-fuel assembly.*

The matters discussed here can however be managed by implementing some changes to the gamma scanning technique and equipment. For instance, moving the assembly closer to the detector can increase the total intensity and thereby decrease the measuring time. The intensity variation due to angular uncertainty can be managed by having equipment where a high accuracy in the angular positioning is possible. Accordingly, these issues alone should not be the foundation of a decision regarding the choice of measuring strategy.

4.1.2 Contribution from individual fuel rods

A more important aspect regarding the quality of the measured data is the contribution from different rods, in an assembly, to the total intensity. The aim of this analysis is to investigate at which starting angles the inner rods contribute as much as possible to the total intensity. Here the assemblies were divided into smaller areas to simplify the analysis, see Figure 4.4. The number for each area is used in the text.



Area Colour	Area no.
Blue	1
Red	2
Yellow	3
Green	4

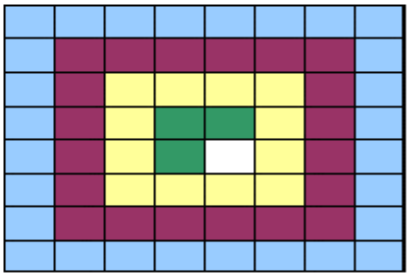


Figure 4.4 *a) A 17x17 assembly and b) an 8x8 assembly divided into areas for analyses. The water channels are marked in white. The numbers representing each area are used in the text.*

The intensity of each rod was divided with the total intensity from the assembly, this to get its contribution to the total intensity. Also the average contribution of the rods in each area was deduced. As an example, the total intensity distribution for the starting angle of 45 degrees, for an 8x8-fuel assembly, is seen in Figure 4.5.

3.6%	2.9%	2.6%	2.5%	2.5%	2.6%	2.9%	3.6%
2.9%	1.1%	0.9%	0.8%	0.8%	0.9%	1.1%	2.9%
2.6%	0.9%	0.4%	0.3%	0.3%	0.3%	0.9%	2.6%
2.5%	0.8%	0.3%	0.1%	0.1%	0.3%	0.8%	2.5%
2.5%	0.8%	0.3%	0.1%		0.3%	0.8%	2.5%
2.6%	0.9%	0.3%	0.3%	0.3%	0.4%	0.9%	2.6%
2.9%	1.1%	0.9%	0.8%	0.8%	0.9%	1.1%	2.9%
3.6%	2.9%	2.6%	2.5%	2.5%	2.6%	2.9%	3.6%

Figure 4.5 *The intensity contribution per rod for a starting angular position of 45 degrees shown in percent of total intensity.*

Table 4.1 lists the average intensity contribution from rods in each area from the analyses of the 45 degrees angle. This shows that for the starting position of 45 degrees, the rods in the outer area contribute approximately 20 times more, per rod, to the total intensity than the rods in the middle of the assembly.

Table 4.1 *Results from the analysis of the intensity contribution for the starting angular position of 45 degrees, showing the average contribution from the rods in each area to the total intensity.*

Area no.	Contribution to total intensity (%)
1	2.80
2	0.88
3	0.31
4	0.14

When a fuel assembly is scanned, the aim is to get as much information as possible from all of the fuel rods in the assembly, not just from the ones in the front row. However, at most angles the rods in area no. 1 and 2 block the inner rods so that the gamma radiation from these rods does not reach the detector. Hence, it is of importance when using the gamma scanning method to select a starting angle where the contribution to the total intensity is as even as possible from the whole assembly.

In Figure 4.6 the average contribution to the total intensity from the rods in the various areas is seen for the different starting angles for an 8x8-fuel assembly. The calculations were made as described above.

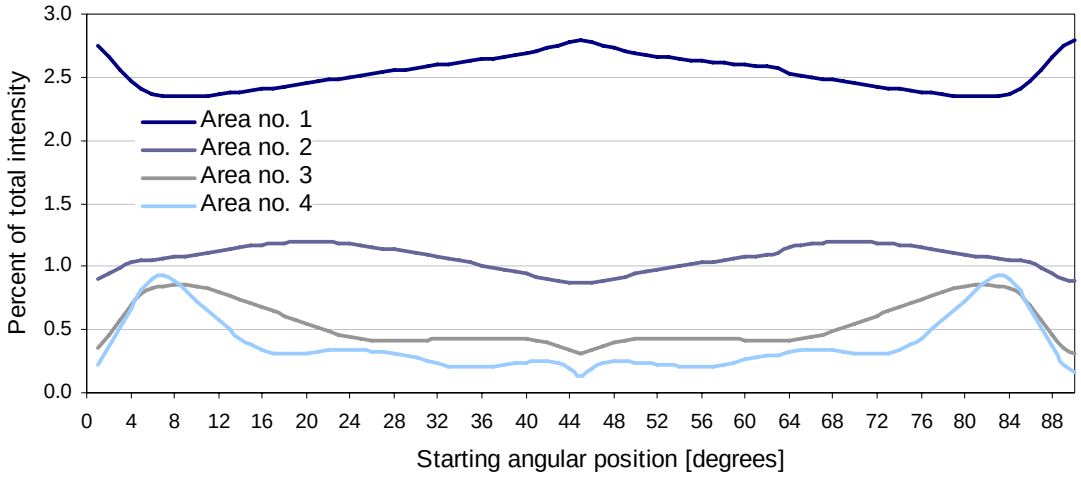


Figure 4.6 *Average rod contributions from areas no. 1- 4 to total intensity as a function of starting angle for an 8x8 BWR fuel assembly without a fuel channel.*

It is clear from Figure 4.6 that the presently used angle of 45 degrees does not give an even contribution, to the total intensity, from the different areas. At 45 degrees, the rods from area no. 1 contribute about 14 times more, per rod, to the total intensity than the rods from area no. 4. This situation can be improved by using some other starting angles and from Figure 4.6 it can also be deduced that a starting angle of about 7 degrees would be the best starting position regarding the intensity from area no. 4. In this area, each rod contributes to the total intensity with approximately 0.9 percent. This can be compared with the contribution from the same area of about 0.2 percent, at a starting angle of 45 degrees. Hence, 7 degrees would be a much better starting angle to use than the one used at present.

The aim is to develop a measuring strategy that evens out the contribution regarding all

areas in the assembly. By analysing the data shown in Figure 4.6 the solution can be drawn that 8 degrees is an even better choice of angle. This can be seen in Figure 4.7 where a comparison is done between the angles 7, 8, 36 and 45 degrees. At 8 degrees the contribution from area no. 3, which is the area with the smallest contribution in that region of starting angles, is at its highest level, meaning that a starting angle of 8 degrees evens out the contribution from all areas as good as possible.

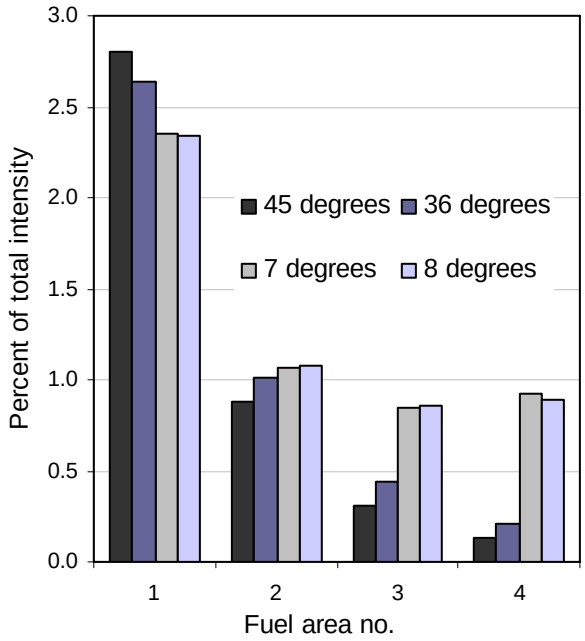


Figure 4.7 *Average rod contribution from each rod in each area to total intensity, for various starting angular positions for an 8x8 BWR fuel assembly.*

By looking at the slope of the total intensity curve at 8 degrees in Figure 4.1 it can be presumed that the intensity variation as a function of angular uncertainty is quite large for this angle. This is confirmed in Figure 4.8 where the intensity variation as a function of angular uncertainty for the 8 degrees starting angle is plotted.

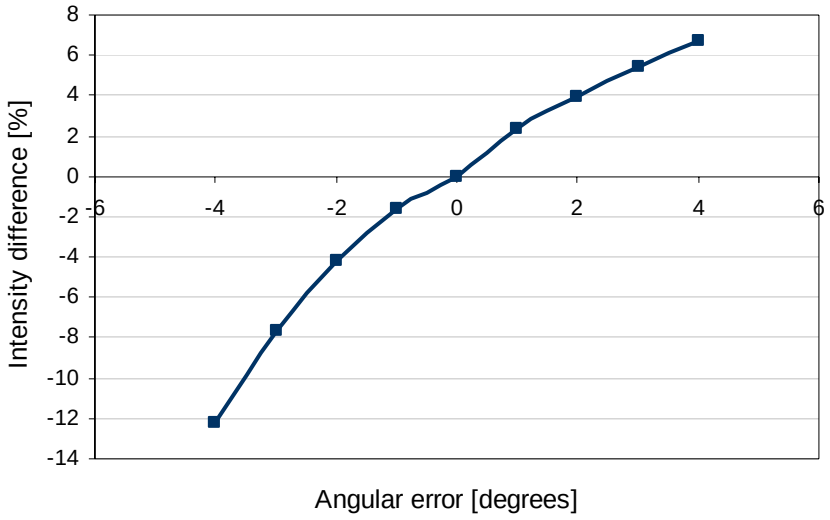


Figure 4.8 *The intensity variation as a function of angular uncertainty for the starting angle of 8 degrees for an 8x8 BWR fuel assembly.*

The figure shows that even a positioning error of less than one degree gives an intensity variation over one percent. This implies that equipment with a high positioning accuracy has to be used to be able to perform measurements using a starting position of 8 degrees.

As for the 8x8-fuel assembly, the currently used starting angular position of 45 degrees cannot be considered the optimal measuring strategy for the 17x17-fuel assembly either. This can be seen in Figures 4.9 where the average contributions to the total intensity, from the rods in the different areas, are shown for this fuel type.

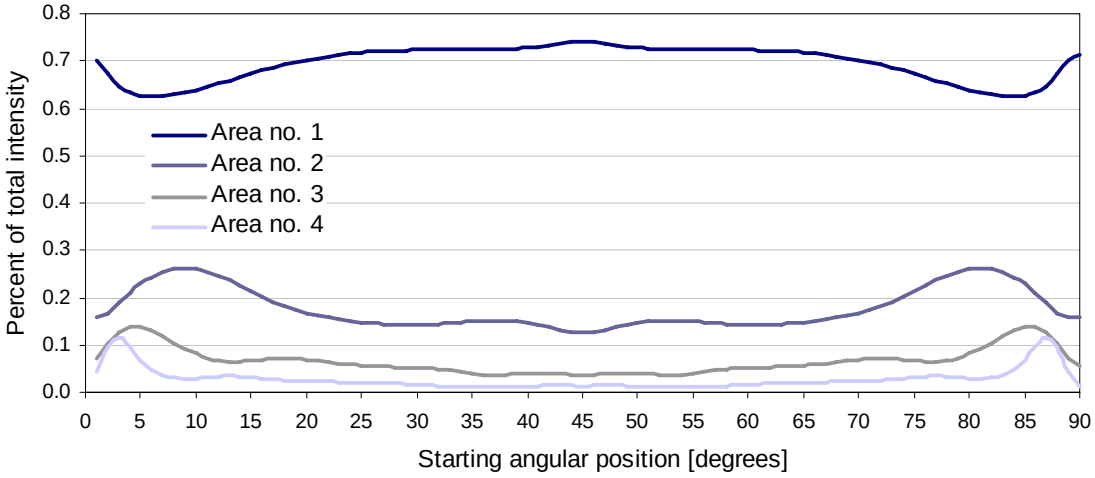


Figure 4.9 *Average rod contributions from areas no. 1-4 to total intensity as a function of the starting angle for a 17x17 PWR fuel assembly.*

Measuring at 45 degrees enhances the contribution from the outermost rods, and this gives an uneven representation of the intensity of the fuel. Looking at area no. 4 in Figure 4.9 the conclusion can be drawn that a starting angle of 3 degrees would give the highest contribution possible from this area. From a comparison with other starting angular

positions it is clear that measuring at 3 degrees gives as even as possible intensity distribution from the other areas as well. In Figure 4.10 the 3 degrees starting position is compared with the conditions at 36 and 45 degrees.

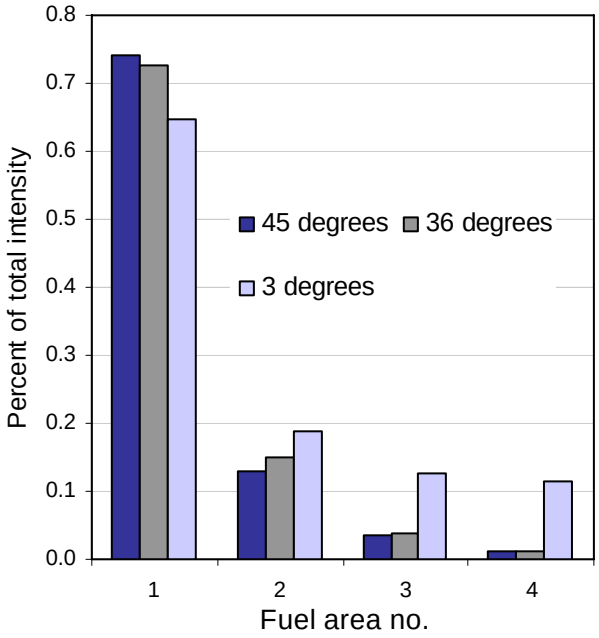


Figure 4.10 *Average rod contribution from each rod in each area to total intensity, for various starting angular positions for a 17x17 PWR fuel assembly.*

These analyses imply that 3 degrees is the best starting angular position for obtaining more even contribution for a 17x17 fuel assembly, when using the conventional measuring strategy. The problematic concerning the choice of 3 degrees as a starting angle is the sensitivity of the total intensity to possible positioning errors. In Figure 4.11 it can be seen that an angular uncertainty of one degree exceeds an intensity variation of 4 percent. This is far above the accepted level of variation, and implies that an even higher positioning accuracy has to be considered for the equipment regarding the use of a starting angle of 3 degrees for a 17x17 PWR fuel assembly, compared to the starting angle of 8 degrees for an 8x8 BWR fuel assembly. On the other hand, a positioning precision of in the order of 0,1 degrees should be possible using dedicated equipment.

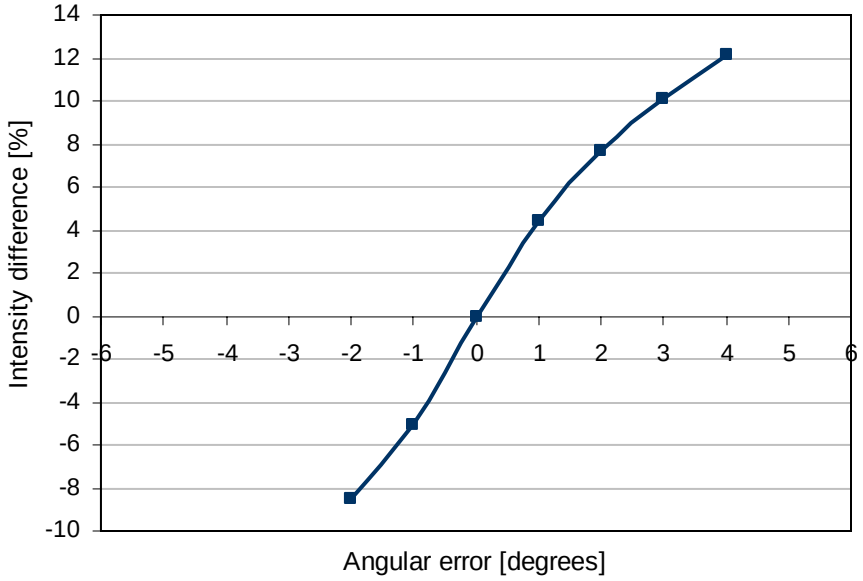


Figure 4.11 *The intensity variation as a function of angular error for the starting angle of 3 degrees for a 17x17 PWR fuel assembly.*

4.2 Rotational measurements

The rotational simulations were performed as described in Section 3.3 with measurements every 1.8 degrees around the whole assembly on both an 8x8-fuel assembly and a 17x17-fuel assembly.

4.2.1 Total intensity

The total intensity gained from a rotational measurement is more or less independent of errors in positioning. Since one scan includes many angles, 360 degrees around the fuel assembly, it does not matter at which angle the measurement starts. This is one of the advantages this strategy has compared to the four-point measurement strategy.

4.2.2 Measuring time

Another advantage is the fact that a large part of the fuel is covered in just one scan. In the four-point measurement strategy, four scans are needed to get a fair measurement of the whole fuel assembly. For the rotation strategy maybe two scans, one up and one down, is enough to get the information needed from the whole assembly. If that is the case, and the statistics is enough from the two scans, this strategy has the potential of halving the measuring time compared to the four-point strategy.

4.2.3 Contribution from individual fuel rods

The analysis of the intensity contribution at a rotation of the fuel assembly was carried out in the same way as described in Section 4.1.2 with the fuel assembly divided into the

four areas illustrated in Figure 4.4.

For the 8x8-fuel assembly the rotation simulations have been compared to the results when simulating four-point measurements with starting angles of 45 and 8 degrees. The result show that the rotation measurement gives a better result than the 45 degrees angle regarding the evenness of the intensity contribution, but not at all as good as the 8 degrees starting position, as can be seen in Figure 4.12.

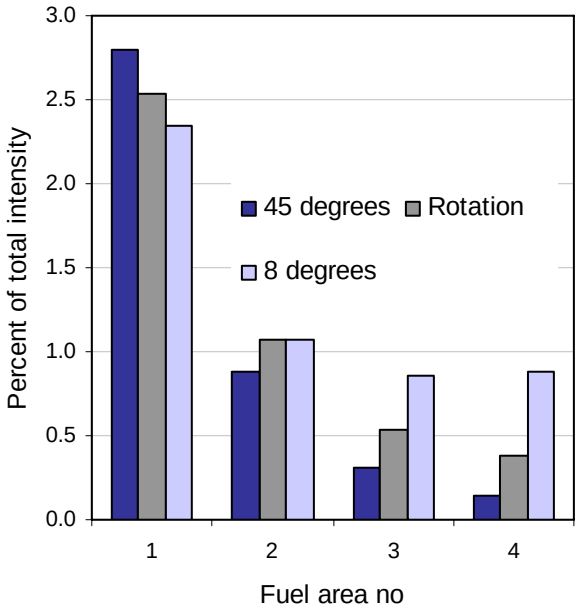


Figure 4.12 *Average contribution per rod in each area to the total intensity for an 8x8 BWR fuel assembly, for the three different measuring strategies.*

For the 17x17 fuel assembly the rotation simulation was compared to the four-point strategy with starting angles of 45 and 3 degrees. Figure 4.13 shows that also for this fuel type the rotation strategy gives a better result than the 45 degrees angle, but here the alternative starting position of 3 degrees is relatively seen even better than the 8 degrees is for the 8x8 fuel assembly.

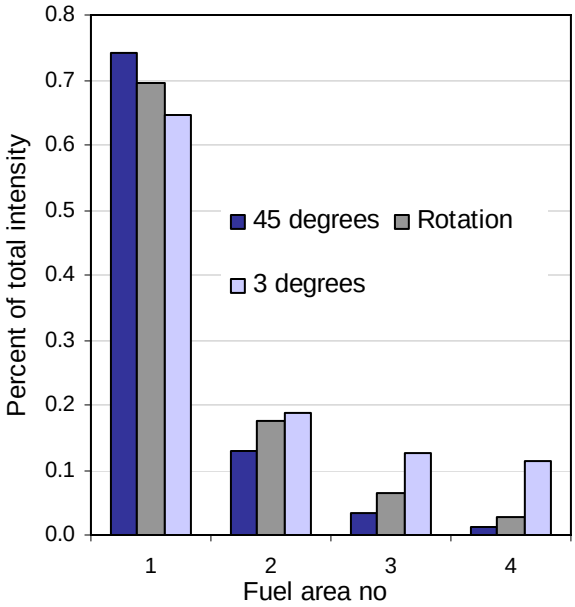


Figure 4.13 *Average contribution from each rod in each area to the total intensity for a 17x17 PWR fuel assembly for the various measuring strategies. The simulated gamma energy was 662 keV.*

Concluding this study, the rotational strategy may have benefits in terms of positioning insensitivity and measuring time, but it has a drawback in highly non-even rod contributions as compared to a well-planed four-point strategy.

4.3 The influence of different activity profiles on the results

In reality, the activities are not homogeneous throughout the fuel assembly, as was presumed in this work. This was merely a simplification made with the intention to make the analysis easier. With different activity profiles, different intensities are received and therefore the result is influenced. To take into account that the activities are inhomogeneous and to see how large influence this has on the results, an analysis was made with some alternative activity profiles. These were derived from a real activity profile from an 8x8-fuel assembly with identification no. 834. [22]

Four activity profiles where used, all with the same total activity in the assembly; one with randomly spread rod activity, one with decreasing activity towards the middle, one with increasing activity towards the middle and the last one with increasing activity towards one corner, see Figure 4.14.

a)

0.96	0.96	1.14	1.11	0.81	1.12	0.92	0.98
0.99	1.12	0.96	1.00	1.00	1.02	0.99	0.91
1.05	1.04	1.00	0.99	1.00	0.96	1.01	1.11
1.03	1.06	1.00	0.79		1.00	1.00	1.09
1.04	1.07	1.01	0.99	0.79	0.98	1.00	1.09
0.97	0.95	0.97	1.01	1.00	0.99	0.96	1.13
0.93	1.01	0.95	1.07	1.06	1.03	1.11	0.94
0.90	0.93	0.97	1.04	1.03	1.04	0.98	0.94

b)

1.05	1.14	1.11	1.11	1.01	1.00	1.04	1.03
1.03	0.96	0.99	1.00	0.99	1.00	0.98	1.12
1.04	0.99	0.93	0.95	0.96	0.92	0.98	1.02
1.12	0.97	0.90	0.79		0.93	1.00	1.06
1.04	0.99	0.96	0.81	0.79	0.94	0.99	1.03
1.06	0.96	0.97	0.95	0.91	0.94	1.00	1.00
1.07	1.00	1.00	1.00	0.98	0.97	0.96	1.04
1.01	1.09	1.09	1.01	1.11	1.13	1.01	1.07

c)

0.79	0.96	0.97	0.99	0.98	0.96	0.95	0.81
0.99	1.00	1.04	1.03	1.03	1.00	1.00	1.00
0.97	0.99	1.07	1.06	1.07	1.11	1.00	0.96
0.93	1.01	1.05	1.12		1.11	1.04	0.94
0.96	1.03	1.04	1.14	1.13	1.06	1.00	0.94
0.95	1.01	1.12	1.09	1.09	1.11	1.00	0.91
0.93	1.02	1.00	1.01	1.04	1.01	1.00	0.98
0.90	0.99	0.96	0.92	0.99	0.97	0.98	0.79

d)

0.79	0.81	0.95	0.96	0.99	1.00	1.02	1.05
0.79	0.91	0.96	0.98	0.99	1.01	1.04	1.06
0.90	0.99	0.96	0.99	1.00	1.01	1.04	1.07
0.93	0.94	0.92	1.00		1.01	1.06	1.09
0.93	0.96	0.98	0.96	1.00	1.01	1.07	1.11
0.94	0.97	0.99	1.00	1.00	1.04	1.11	1.12
0.95	0.98	1.00	1.00	1.03	1.04	1.11	1.13
0.97	0.97	1.00	1.03	1.03	1.09	1.12	1.14

Figure 4.14 *Four different activity profiles were analysed, a) one with randomly spread rod activity, b) one with decreasing activity towards the middle, c) one with increasing activity towards the middle and d) one with increasing activity towards one corner. The total activity was the same in all four cases.*

These four profiles were compared to the homogenous activity profile used previously in this work and an analysis was made of the average rod contribution in different areas as described in Section 4.1.2. Figure 4.15 shows the result with the various activity profiles for 8 degrees on an 8x8 BWR fuel assembly. The result for the 45 degrees angle on an 8x8 BWR fuel assembly is seen in Figure 4.16.

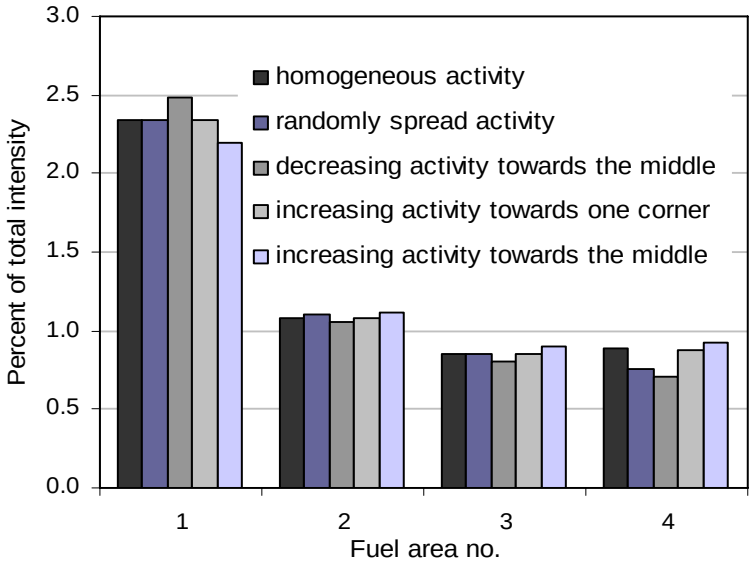


Figure 4.15 *The comparison of different activity profiles to the homogeneous activity profile used in this study, for the 8 degrees starting angular position on an 8x8 BWR fuel assembly.*

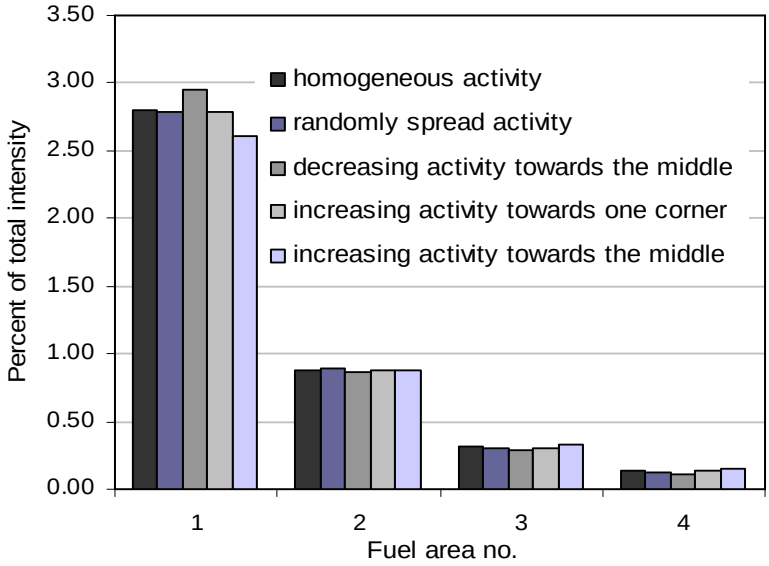


Figure 4.16 *The comparison of different activity profiles to the homogeneous activity profile used in this study, for the 45 degrees starting angular position on an 8x8 BWR fuel assembly.*

The figures demonstrate that the values for the homogeneous profile used in this study can be seen as a mean value of the alternative activity profiles, both for the 8 and 45 degrees starting angles for an 8x8 BWR fuel assembly. The conclusion can be drawn that

the results from this work can be considered representative also for fuel assemblies with realistic non-homogeneous activity distributions.

It can also be seen in the figures that the 8 degrees angle gives a much evener intensity contribution from the different areas, which is a result that emerged in Section 4.1.2. In addition, the figures show that for 8 degrees the intensity per rod in each area is more spread, when comparing the different activity profiles, than for 45 degrees. This illustrates that, when measuring at 8 degrees, the measurement gives a more accurate result concerning the activity profile of the fuel assembly.

Since no realistic activity profiles where available for the 17x17 PWR fuel assembly, the analysis could not be done on the results from the simulations on that type of fuel assembly. However, the activity distribution in PWR fuel assemblies is in general more even than in BWR fuel assemblies due to the absence of void in the reactor core.

5 Experimental validation

Actual gamma scanning measurements were performed at Clab in October 2006. In addition to the regular measurements using the present strategy as described in section 2.3, some alternative measuring approaches, linked to this study, were tried. These measurements were performed mostly on 8x8 BWR fuel assemblies with and without fuel channels, but also on two other BWR fuel types containing 64 and 100 rods. The purpose was to match the measured data with the simulated data and to validate the results from the simulations.

The data from the measurements were analysed by Otasowie Osifo at the Department of Neutron Research at Uppsala University. [24]

5.1 Four-point measurements

The first set of alternative measurements were carried out with the four-point measurement as a norm, however because the available time was short, only one scan, not four as usual, was performed for each angular position. The angular positions examined where; 37 degrees, 38 degrees, 39 degrees, 43 degrees, 44 degrees and 45 degrees. The measuring time for each angle varied between 3-5 minutes depending on if they were measured on the way up or down. The purpose was to validate the performance of the simulation code with respect to position sensitivity. However, the results from these measurements have not been analysed and have therefore not been used in this work.

5.2 Rotational measurements

A set of rotational measurements were performed where the assembly was standing still in the vertical direction at approximately the middle length of the fuel assembly while the assembly was rotating around its own axis. Calculations were made to find out where the middle of the assembly is, and measurements were done with the fuel assembly in that position. Each measurement was measured in 200 points, and one second at each point, implying that the measurement took a little more than 3 minutes.

The experimental data from this type of rotational measurements on an 8x8-fuel assembly with identification no. 0710, were compared to the simulated data for an 8x8-fuel assembly, see Figure 5.1. The comparison was performed for the gamma energy of 662 keV. By looking at the figure the simulated data seem to agree with the experimental data quite well. The higher intensity on the experimental data between approximately 270-360 degrees can be a result of an uneven activity in the fuel, with higher activity in that corner. Correspondingly, the intensities in angles between 90 and 180 degrees were lower than average.

Comparing the simulated data with the experimental data, the standard deviation was calculated to approximately 55 counts, to some extent depending on the systematic

difference described above. Since the uncertainty in the experimental data for this fuel assembly is approximately 36 counts, the standard deviation can be considered sufficiently small for the simulation to be valid within these limits. By validating the rotation simulations, the four-point measurement simulations can also be considered validated. This since the rotation measurement includes all starting angular positions investigated in the four-point measurement simulations.

Comparisons could not be performed between the simulated data and experimental data rotation for the 17x17 fuel, since no experiments were carried out on such fuel assemblies.

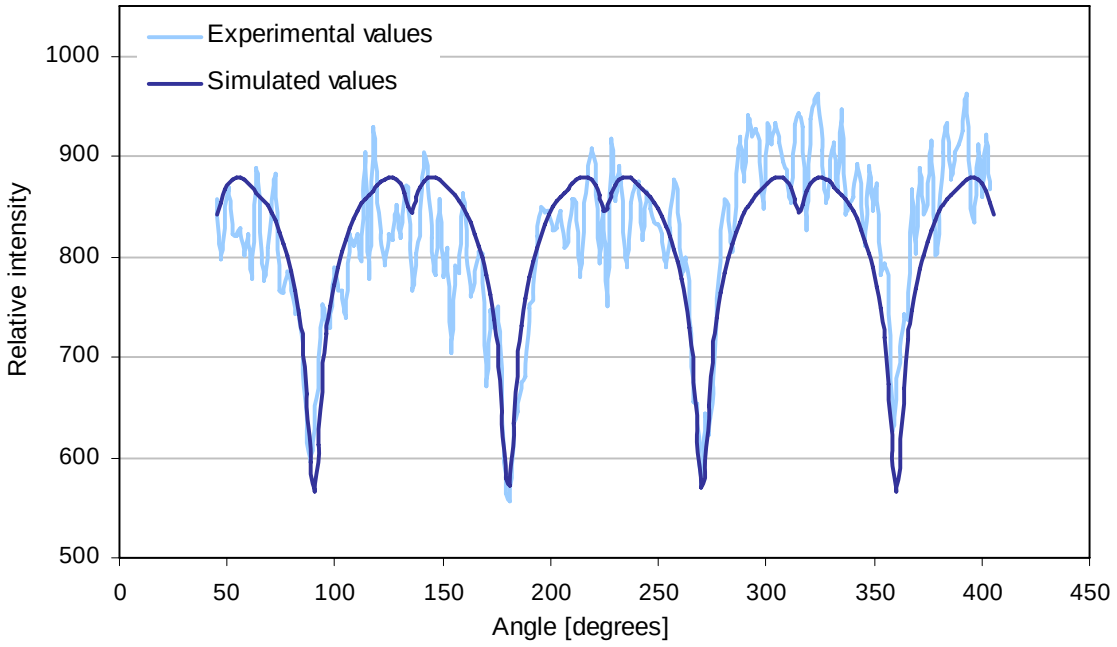


Figure 5.1 *The simulated rotation values for an 8x8 BWR fuel assembly compared to the experimental values for the 8x8 BWR fuel assembly with identification no. 0710. Both the simulated and the experimental value are for an assembly without fuel channel. The simulated and experimental gamma energies were 662 keV.*

6 Conclusions and discussion

The aim of the study was to investigate if the gamma scanning measurement could be performed in ways that would improve the quality of the output data and also decrease the measuring time. In the quality aspect the focus was on examining with which strategy the output data obtained represents the whole fuel as much as possible. Different starting angular positions for the conventional four-point strategy, and an alternative approach where the fuel assembly is rotated continuously around its own axis, were examined.

The analyses show that for the conventional strategy a new choice of starting angular position would be preferable. For an 8x8 BWR fuel assembly the best starting angular position would be 8 degrees since it gives the most even intensity contribution from the whole fuel assembly. For a 17x17 PWR fuel assembly the best choice of starting angle is 3 degrees for the same reason. The only drawbacks of choosing these starting positions are that they require very accurate angular positioning to give reliable intensity output. Constructing new equipment, optimized for the gamma scanning measurements, which can handle very accurate angular positioning, could solve this problem. The accuracy needed for measurements on an 8x8 BWR fuel assembly is 0.4 degrees, to not exceed a variation in intensity of one percent. For a 17x17 PWR fuel assembly, the corresponding accuracy needed is 0.2 degrees. In addition, it can be noted that the intensity can be adjusted to a desirable level by for example having equipment where the fuel assembly is placed further from or closer to the detector.

The rotational measurement strategy does not give the even intensity contribution hoped for and can in that aspect not compete with the four-point measurements when the optimal starting angular positions are used. The advantage with rotating the fuel while measuring is that the accuracy in positioning is not a problem. This since the total intensity includes angles around the whole fuel and therefore it does not matter at which angle the measurement starts. Regarding the time aspect, the rotational measurement can be a preferable strategy giving that a large part of the fuel is covered in just one scan. Hence, it might be enough to scan each fuel twice, ones up and the second time down, to get the information needed from the fuel assembly, and thereby the measuring time could be decreased almost by half. This presupposing that the sub spectra from two scans are enough in a statistic respect. However, this has to be investigated further.

To sum up, the conventional strategy with new optimal starting angles is the best choice concerning data quality. Regarding the measuring time, the rotational measuring strategy could be an option. The question is, which aspect is the most important to improve?

Acknowledgements

I would like to thank my supervisor Ane Håkansson for letting me do this degree project and for all the help and advice during my stay in the group. I would also like to thank everyone in the Nuclear Fuel Diagnostics and Safeguards Group for all the good ideas, help in many ways and encouragement. Last but not least I would like to thank all the people that I have spent many hours with at lunch and coffee breaks for interesting discussion about everything and nothing. You have made me feel so welcome and made me enjoyed my stay very much.

References

[1] Ringhals AB, http://www.ringhals.se, 2007-04-08

[2] Vattenfall AB, http://www. vattenfall.se, 2007-04-14

[3] Royal Swedish Academy of Engineering Sciences, http://www.iva.se, 2007-04-28

[4] Swedish Nuclear Inspectorate, http://www.ski.se, 2007-04-08

[5] *Reaktorfysik*, Kärnkraftssäkerhet och Utbildning AB, Nyköping (2004)

[6] S. Johansson, P. Kristiansson, K. Malmqvist and S. Tapper, *Introduktion till Kärnfysiken*, 5th ed., Lund, 2000

[7] H. D. Young, and R. A. Freedman, *University Physics with Modern Physics,* 10th ed*.,* Addison-Wesley Longman, 2000

[8] C. Willman, *Applications of Gamma Ray Spectroscopy of Spent Nuclear Fuel for Safeguards and Encapsulation,* PhD Theses, Department of Nuclear and Particle Physics, Uppsala University, Uppsala, 2006, ISBN 91-554-6637-0

[9] P. A. Tipler and R. A. Llewellyn, *Modern Physics*, 4th ed., W. H. Freeman and Company, New York, 2002

[10] Swedish Radiation Protection Authority, http://www.ssi.se, 2007-04-10

[11] H. Alvarez, *Energiteknik Del 2,* 2nd ed., Lund, 2003

[12] Oskarshamns Kraftgrupp AB,www.okg.se, 2007-04-08

[13] Svensk kärnbränslehantering AB, http://www.skb.se, 2007-04-08

[14] S. Jacobsson Svärd, *A Tomographic Measurement Technique for Irradiated Nuclear Fuel Assemblies*, PhD Theses, Department of Radiation Sciences, Uppsala University, Uppsala, 2004, ISBN 91-554-5944-7

[15] I. Mattsson, *Studies of Nuclear Fuel Performance Using On-site Gamma Ray Spectroscopy and In-pile Measurements*, PhD theses, Department of Nuclear and Particle Physics, Uppsala University, Uppsala, 2006, ISBN 91-554-6582-X

[16] A. Håkansson, *A Primer to Safeguards and its Instrumentation,* Department of Nuclear and Particle Physics, Uppsala University, Uppsala, 2004

[17] Nationalencyklopedin, http://www.ne.se, 2007-04-17

[18] EU-upplysningen, Sveriges riksdag, ,http://www.eu-upplysningen.se, 2007-04-13

[19] A. Håkansson and A. Bäcklin*, Non-Destructive Assay of BWR Fuel with High-Resolution Gamma ray Spectroscopy*, Department of Radiation Sciences, Uppsala University, Uppsala, 1995, ISSN 0284-2769

[20] C. Willman, A. Håkansson, O. Osifo, A. Bäcklin and S. Jacobsson Svärd, *Nondestructive assay of spent nuclear fuel with gamma ray spectroscopy,* Annals of Nuclear Energy, vol. 33, no. 9, pp 766-773, 2006, ISSN 0306-4549

[21] O. Osifo, C. Willman, A. Håkansson, S. Jacobsson Svärd, A. Bäcklin and T. Lundqvist, *Verification and determination of decay heat in spent PWR fuel by means of gamma scanning*. To be submitted to Nuclear Science and Engineering

[22] O. Osifo, private communication, 2007

[23] A. Håkansson, private communication, 2006

[24] O. Osifo, *Automatic gamma-scanning system for measurement of residual heat in spent nuclear fuel*, Licentiate Theses, Department of Neutron Research, Uppsala University, Uppsala, 2007