Postprint

On Cherenkov light production by irradiated nuclear fuel rods

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Abstract

Safeguards verification of irradiated nuclear fuel assemblies in wet storage is frequently done by measuring the Cherenkov light in the surrounding water produced due to radioactive decays of fission products in the fuel. This paper accounts for the physical processes behind the Cherenkov light production caused by a single fuel rod in wet storage, and simulations are presented that investigate to what extent various properties of the rod affect the Cherenkov light production. The results show that the fuel properties has a noticeable effect on the Cherenkov light production, and thus that the prediction models for Cherenkov light production which are used in the safeguards verifications could potentially be improved by considering these properties.

It is concluded that the dominating source of the Cherenkov light is gamma-ray interactions with electrons in the surrounding water. Electrons created from beta decay may also exit the fuel and produce Cherenkov light, and e.g. Y-90 was identified as a possible contributor to significant levels of the measurable Cherenkov light in long-cooled fuel. The results also show that the cylindrical, elongated fuel rod geometry results in a non-isotropic Cherenkov light production, and the light component parallel to the rod's axis exhibits a dependence on gamma-ray energy that differs from the total intensity, which is of importance since the typical safeguards measurement situation observes the vertical light component. It is also concluded that the radial distributions of the radiation sources in a fuel rod will affect the Cherenkov light production.

Keywords: Nuclear safeguards, Geant4, Cherenkov light, DCVD, Nuclear fuel rod

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1 Introduction

To deter from proliferation of nuclear weapons, nuclear safeguards is applied to facilities handling nuclear materials worldwide, under the framework of bilateral agreements between states and the International Atomic Energy Agency (IAEA) [1]. The safeguards measures provide credible assurances that states are honouring their international obligations, and give the authorities the ability to detect misuse of nuclear material or technology. One of the many safeguards tasks undertaken by the authorities is to verify the presence and properties of irradiated nuclear fuel assemblies by e.g. performing measurements during inspections at nuclear reactors and fuel storage sites. A multitude of instruments have been developed to assess irradiated nuclear fuel assemblies and verify them [2].

Ever since its discovery [3], Cherenkov light has become a tool useful in science ranging from physics [4] to biology [5]. Since spent nuclear fuel is frequently stored in water for radiation protection and heat removal, the radiation from the fuel will create Cherenkov light in the surrounding water. The Cherenkov light production in water due to gamma and beta emitters has been calculated [6], but the situation with a dense volume source with cladding and other structural materials that attenuates the radiation requires focused attention for the application to nuclear safeguards studied in this paper.

One instrument used by IAEA inspectors to measure the Cherenkov light intensity from fuel assemblies is the Digital Cherenkov Viewing Device (DCVD) [7]. This Cherenkov light is used to confirm the presence of a strong radioactive source in the item under study, and hence to indicate the presence of irradiated nuclear fuel. The DCVD is also used to verify the completeness of a fuel assembly, using a method based on comparing the measured intensity to an expected intensity [8]. The method currently used for predicting the intensity is based on fuel declarations [9].

The prediction model in [9] is a parametrization based on simulations of Cherenkov light production and detection in one selected fuel geometry: a simplified BWR 8x8 fuel assembly configuration. While this prediction model has performed adequately in many inspections, several simplifications are introduced in the model, such as using a single fuel configuration, and a single fuel pellet diameter and cladding thickness to represent all fuel types. This is expected to introduce systematic errors when the prediction model is applied to other fuel geometries, reducing the accuracy of the predictions. Although much work has been put into modelling the Cherenkov light emissions from a fuel [9] [10] [11], the effect of varying the fuel pellet size, cladding thickness or source distribution on the Cherenkov light production has not been studied in detail previously. Furthermore, these studies have focused on Cherenkov light production due to gamma decay of fission products, for beta decays these works have only considered the contribution due to bremsstrahlung, which was treated as gamma emissions from the fuel material.

The aim of this work is to investigate to what extent different fuel pellet diameters and cladding thicknesses affect the Cherenkov light production, and

thus to what extent the accuracy of the predictions may be enhanced by taking the fuel rod properties in each measured fuel type into account. This paper includes details on the contribution to Cherenkov light production caused by both gamma and beta decays from one single fuel rod, and investigates the effect of fuel rod dimensions on the subsequent Cherenkov light production. The knowledge gained can form a basis for future development of enhanced prediction models, which may enhance the IAEA's verification capabilities.

2 Simulating the Cherenkov light from nuclear fuels

2.1 The origin of Cherenkov light from nuclear fuels

Cherenkov light is produced when a charged particle moves faster than the speed of light in a medium [3]. When irradiated nuclear fuel is stored in water, high-speed electrons and positrons are released in the water due to the high level of ionizing radiation emitted from the fuel, and these particles in turn create Cherenkov light. The threshold kinetic energy for electrons or positrons to produce visible or UV Cherenkov light in water is around 250 keV [6].

Due to a combination of the spectral characteristics of Cherenkov light and the refractive index and light attenuation in water, the intensity of the detectable Cherenkov light peaks in the soft-UV range. For this reason, the DCVD optics contains a filter to select this light component. This also helps in reducing any background signal otherwise caused by visible light from facility lighting.

Several physical processes contribute to the production of Cherenkov light from an irradiated fuel rod in water. High-speed positrons created through pair production are typically annihilated quickly, and only give a minor contribution to the Cherenkov light production. High-speed electrons may e.g. be produced directly by beta-minus decays in the fuel rods, and such electrons may also ionize materials when passing through them, creating more free electrons. However, a majority of the Cherenkov light production originates from high-speed electrons released in the water due to interactions with gamma-rays emitted from the fuel [9]. The gamma rays are produced by gamma decays in fission products, bremsstrahlung and positron annihilation. Of these, gamma decay is the dominant source at decay energies occurring for fission products [12]. The release or production of electrons in the water occurs through Compton scattering, the photoelectric effect and pair production.

2.2 Simulated geometry

During a measurement, the DCVD is typically mounted above the fuel assemblies, which are standing in a storage pool, as illustrated in figure 1a. As a consequence, investigating the vertically directed Cherenkov light emission is of main interest in the context of DCVD measurements. In this work, Cherenkov light forming an angle less than 3 degrees to the vertical axis (along the fuel rod)

is considered representative of the measurable vertical component. The choice of 3 degrees is arbitrary, though it is narrow enough to represent the vertical light component, yet wide enough that sufficient statistics can be gathered in the simulations in reasonable time. It also allow for comparisons with earlier works, where the same angle was used [10].

The fuel rods simulated in this work are modelled as cylinders made of uranium dioxide, covered by a thin layer of Zircaloy cladding. The fuel density was modelled as $10.5\,\mathrm{g/cm^3}$, and the Zircaloy cladding simulated was composed of Zr 98.28%, Sn 1.5%, Fe 0.1%, Cr 0.07%, Ni 0.05%, with a density of $6.53\,\mathrm{g/cm^3}$. The fuel pellet diameter and cladding thickness were varied to be representative for a range of fuel designs, based on [13] [14].

In the simulations, the single simulated rod was placed in a large water volume, large enough that no radiation could escape the water. The results of the simulations include statistics on the vertically directed Cherenkov light produced in this water volume, which is of main interest, although the simulations also gathers statistics on the total Cherenkov light production in the water volume.

Due to the relatively short range of the considered radiation in water in comparison to the rod length, the Cherenkov light production will behave identically at almost all heights for a uniformly axially distributed source, with the exception near the rod ends. For this reason, this work only considers Cherenkov light production by gamma and beta emissions in a small axial region of the fuel, with a height of $1\,\mathrm{mm}$, situated mid-wise along the fuel length, and any effects of fission product decays near the rod ends are ignored. The fuel rods were modelled as being around $4\,\mathrm{m}$ in length in the simulations.

2.3   Particles simulated

The simulations of gamma decays preformed in this work, presented in section 3, have considered decay energies in discrete steps between 0.25 and $3\,\mathrm{MeV}$. This corresponds to the energy range of most fission product decays in a fuel with more than one year cooling time [9], [11]. For short-cooled fuel, additional high-energy gamma emitters may also be present. The prediction model currently used by the IAEA [9] not only includes gamma-rays produced in gamma-decays, but also includes the Cherenkov light produced due to bremsstrahlung from beta particles emitted in the decay of the abundant Sr-90 isotope and its daughter nucleus Y-90. The prediction model assumes that all beta-decay electrons are stopped in the fuel, and that no beta particles enters the surrounding water.

This work extends the previous work by also investigating Cherenkov light produced directly by beta particles that pass through the fuel and cladding, and enter the water with sufficient energy to directly produce Cherenkov light. Primarily Y-90 has been considered, due to its abundance in irradiated fuel material and the relatively high energy of beta particles. In these beta simulations, produced bremsstrahlung photons were discarded, to only investigate the direct Cherenkov light production by the beta particles. The bremsstrahlung can be treated as gamma emissions originating from the fuel rod, and are covered by

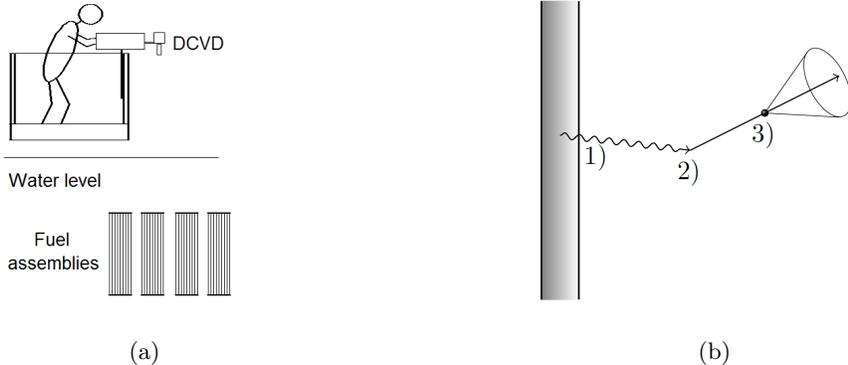(a)   (b)

Figure 1: a): The typical measurement situation when using the DCVD. b) The dominant production path of Cherenkov light from an irradiated fuel rod in wet storage: 1) a gamma ray from the fuel enters the water 2) the gamma ray Compton scatters off an electron in the water, transferring energy to the electron 3) if the electron has sufficient kinetic energy, it will emit Cherenkov light at an angle to its propagation direction. The angle depends on the electron energy and the refractive index of the water.

the gamma-ray simulations.

2.4 Description of the simulation software used in this work

The simulation toolkit used in this work is based on the Geant4 (version 4.10.00) Monte-Carlo simulation package [15], and it is a development of a previously presented simulation toolkit for estimation of Cherenkov-light production in nuclear fuel assemblies [10]. The physical processes of interest are included through a Geant4 standard physics list (`QSGP_BERT_HP`), with optical photon physics (`G4OpticalPhysics`) added to enable simulation of the Cherenkov light production. Some simulations were also done using a physics list incorporating more detailed treatment of low-energy electromagnetic interactions (`QSGP_BERT_EMZ`).

In the toolkit, several initial particles can be chosen, and in this work electrons and gamma rays have been studied. The toolkit allows for monoenergetic particle sources to be specified, or a source energy spectrum may be provided. In this work, the sources have typically been homogeneously distributed in the circular cross-section of a fuel rod, at the center height of the rod, but various radial distributions have also been simulated.

The user may save data (position, direction, energy) on all electrons and Cherenkov photons produced in a simulation for further analysis, or use built-in features to analyse the produced electrons or Cherenkov photons. The built-in features will analyse both the total Cherenkov light production in the simulations, as well as the vertically directed light produced. The energy spectrum

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of the produced Cherenkov light in the simulations include visible and soft-UV photons (300 to 600 nm wavelength).

2.5 Assumptions and limitations of this study

The Monte-Carlo simulations, which form the basis of this work, require extensive computational resources to produce data with reliable statistics. A number of assumptions and limitations have been introduced in the simulations to allow for reasonable simulations times:

- Angle of emission: In this work, it is assumed that the intensity of the produced vertically directed Cherenkov light is proportional to the intensity measurable with a DCVD. For real fuel, the fuel rods and other irradiated fuel assembly structure surfaces are typically covered by a thin layer of oxides and deposited material (CRUD), which strongly absorbs photons in the visible and near-visible range, thus mainly vertically directed light escapes a fuel assembly without being absorbed. However, further investigations are required to assess the reflectivity of actual fuel, and asses how this affects the Cherenkov light transport. Still, as long as the reflectivity is modest, the measurable Cherenkov light will be dominated by the direct vertical component.

- Considering the typical measurement situation shown in figure 1, only Cherenkov photons with an angle less than $0.3 - 0.6°$ to the vertical axis may exit the top of the fuel assembly in a direction to hit the DCVD. This angle is however so small that good simulation statistics require heavy computations. Accordingly, a larger angle of 3 degrees was used in this work, which was wider but still considered narrow enough to provide a reasonable representation of the vertical light component. This also allow comparisons with previous results [10] using the same angle.

- Photon energies: The DCVD is sensitive to photons in a narrow energy window in the soft-UV range, but using only this energy range in the simulations would result in extensive simulations with poor statistics. Similar to the emission angle, extending the energy range of the produced Cherenkov light allows for the simulations to finish in reasonable time, and an energy range from 2 to 4 eV (corresponding to a wavelength interval of 300 to 600 nm) was used. Since this work only considers Cherenkov light production, and since the refractive index of water changes little in the photon energy range considered, extending the energy range leads to additional Cherenkov light production, which is still proportional to the produced light in the soft-UV range.

- Physics modelling: Some previous works simulating Cherenkov light with Geant4 have found that the electron multiple scattering process implemented in Geant4 may introduce a bias in the Cherenkov light intensity and direction [16]. To investigate whether such bias is present in this

work, several of the simulations were performed using both the standard physics list and a physics list incorporating a highly detailed treatment of low-energy electromagnetic particle scattering (`QSGP_BERT_EMZ`). It was concluded that for the particles and energies considered in this work, the simulations agree well. Only for electrons near the Cherenkov light production threshold energy around 250 keV did the difference in the simulation results exceed 1 %, thus the standard physics list was considered sufficiently accurate for the simulations performed here.

Furthermore, these investigations are limited to gamma emission up to 3 MeV and beta emission from one isotope: Y-90. There may be other contributions to the Cherenkov light emission from nuclear fuel, but one may argue that these should be minor:

- Other beta-emitting isotopes: Of the beta-decaying fission products that are main contributors to the decay heat of an assembly [17], Sr-90 is not only among the most abundant isotopes, its daughter nuclei Y-90 beta-decays with an average beta particle energy of 0.90 MeV and a maximum energy of up to 2.28 MeV [18]. The other abundant beta-decaying isotopes rarely decays with a beta-particle energy above 700 keV. For this reason, Y-90 is expected to be the main contributor to direct beta-induced Cherenkov light, and this work focuses on the beta-decay by Y-90, in order to identify if direct beta-contribution to the Cherenkov light intensity is significant.

- Neutron emission: Neutrons produced by spontaneous fission of heavy elements present in irradiated nuclear fuel may interact with other elements, resulting in subsequent gamma or beta emissions. Using ORIGEN-ARP [19] to investigate the gamma and neutron emission of fuel assemblies with various realistic burnups and cooling times, it was concluded that the neutron emission rate is six to eight orders of magnitude lower as compared to the gamma emission rate. For this reason, neutron-induced radiation is expected to contribute negligibly to the Cherenkov light intensity.

Furthermore, one may note that the composition of the fuel will change with time, which is not taken into account in this work. The fuel rods simulated here were modelled as consisting of pure uranium dioxide, while irradiated fuel will contain additional heavier elements, mainly plutonium, as well as fission products. However, irradiated fuel still consist of typically more than 95 % of uranium dioxide, and the simplifying assumption was made that irradiated fuel material behaves as fresh fuel with respect to gamma and beta attenuation.

Finally, the refractive index of water changes with temperature, and as a result the Cherenkov light production is also affected by the water temperature. Due to the heat released by the fuel assemblies, the pools they are stored in are actively cooled, and as a result the temperature differences between different fuel assemblies is negligible. The refractive index used in the simulation corresponds to water with a temperature of 30 ° C.

3 Simulation results

3.1 General results

From the gamma-ray simulations performed, it was concluded that the dominant production path of Cherenkov light is that a gamma-ray Compton-scatters on an electron in the water, which in turn produces Cherenkov light, as illustrated in figure 1b. For low-energy gamma-rays, below 1 MeV, more than 99 % of the simulated Cherenkov light is produced in this way. At 3 MeV, more than 90 % of the Cherenkov light is produced by Compton-scattered electrons, and the rest is caused by recoil electrons released when a primary Compton electron scatters on an electron in the water. At low energies (less than 1 MeV), the Cherenkov light is almost exclusively produced by electrons which were released or produced in the water. At 3 MeV, 98 % of the Cherenkov light was produced in this way, and 2 % of the intensity was caused by electrons released or produced in the fuel or cladding, entering the water with sufficient energy to produce Cherenkov light.

Simulations were also run to investigate the relative intensities of Cherenkov light produced by gamma and beta sources of various initial energies. These investigations were made for a rod with 10 mm diameter pellet and 0.6 mm cladding thickness. In figure 2, the produced total Cherenkov light intensity as a function of initial gamma and beta energy is shown. As can be seen, the total Cherenkov light production per decay is much lower for beta-particles than for gamma-rays of the same initial energy. Thus, the beta contribution may be neglected when a relatively high-intensity or high-energy gamma source is present. Only if the gamma-ray emissions are of relatively low energy or intensity is the direct beta contribution expected to be of significance. Such a situation may occur in long-cooled fuel due to the abundance of Sr-90, and its daughter nuclei Y-90. Note also that for a Compton-scattered electron to have energy above the Cherenkov light production threshold, the energy of the initial gamma ray must be above 430 keV, explaining the bump in the gamma curve at this energy in figure 2. For energies below 430 keV, only electrons released through the photoelectric effect produces Cherenkov light.

Although an electron must have at least 250 keV of kinetic energy to produce any Cherenkov light in water, figure 2 shows that further energy is required in a beta decay for the electron to pass through the fuel and cladding with enough energy to directly produce Cherenkov light. In the simulations, beta-decays with less than 0.8 MeV of kinetic energy did not produce any direct Cherenkov light.

Furthermore, figure 2 shows that the Cherenkov light production increases strongly with initial particle energy, implying that predictions of the Cherenkov light intensity of a fuel benefit from good knowledge of the gamma and beta spectrum of the fuel. Thus, the current prediction model [9], which considers only six radioactive isotopes and standardised fuel irradiation histories, may be further enhanced by a more detailed description of the source term in the fuel.
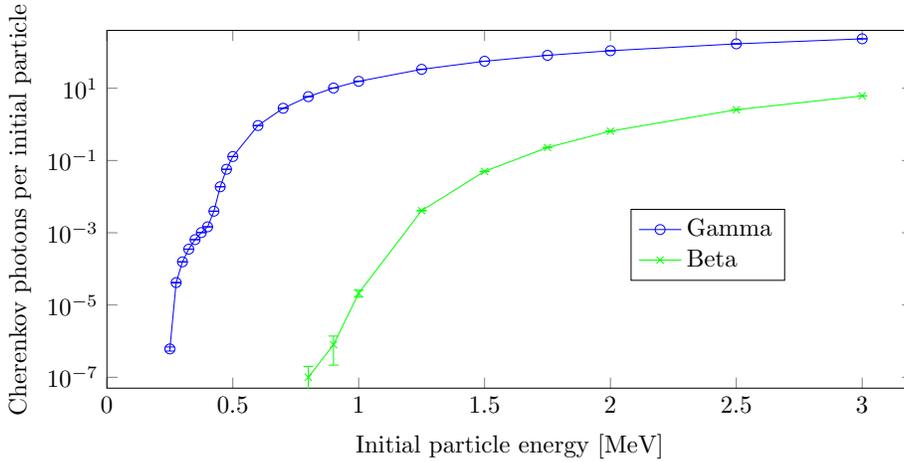
Figure 2: Total Cherenkov light intensity produced by a homogeneously distributed gamma or beta source in a single fuel rod in water as function of the energy of the initial particle.

3.2 Anisotropy of the produced Cherenkov light

Radiation produced inside a fuel rod will be attenuated more in the fuel material in the vertical direction (along the rod) than in the horizontal direction. Consequently, a nuclear fuel rod will not provide an isotropic source of radiation. It is of interest for DCVD modelling to investigate how this anisotropy affects directionality of the Cherenkov light production, since the DCVD measures the vertical component. Accordingly, simulations were executed to investigate this effect.

The results for a single rod with 10 mm diameter pellet and 0.6 mm cladding thickness are presented in figure 3 for three different gamma-ray energies and for Y-90 beta emission. The angle ϕ is the angle between the Cherenkov photon and the vertical (upwards) direction, which corresponds to $\cos(\phi) = 1$. As can be seen, lower-energy gamma rays will produce Cherenkov light that is predominately horizontally directed, whereas higher-energy gamma rays produce Cherenkov light that is closer to isotropically distributed, though still more pronounced in the horizontal direction. These results hold true for all fuel pellet radii and cladding thicknesses simulated, showing that the Cherenkov light production by a nuclear fuel rod in water is anisotropic, and that the anisotropy is affected by the energy of the initial gamma energy.

The cause of this anisotropy is that the maximum energy transfer from a gamma-ray to an electron in Compton-scattering occurs when the electron propagation direction is the same as the initial gamma-ray. The Compton-scattered electron will produce a maximum amount of Cherenkov light if it does not loose energy due to scattering. As a result of these two effects, the Cherenkov light produced has a tendency to have a similar direction to the initial

gamma-ray. Thus, the anisotropic gamma-ray emissions from the rod results in an anisotropic Cherenkov light production. This explains the features seen in figure 3, where low-energy gamma rays, which are more strongly attenuated by the fuel in the vertical direction, ends up producing less Cherenkov light in the vertical direction. For higher-energy gamma-rays, where the attenuation in the fuel material has less impact, the produced light is close to isotropic.

Additional simulations were also done for various discrete beta-emission energies, however the directionality of the produced Cherenkov light changed very little with energy, and the results were the same as for Y-90 decays, within the statistical uncertainty.

As a consequence of the identified anisotropy of the produced Cherenkov light, it is argued that the total light production systematically differs from the vertically directed light which the DCVD can measure, as further discussed in section 4. As a consequence, when using simulations of Cherenkov light intensities to predict the measured intensity, the prediction should be based on the vertically directed light, rather than using the total produced light intensity [11].

3.3 Dependencies of Cherenkov light intensity on the fuel rod geometry

3.3.1 Pellet diameter

With the multitude of fuel designs used in reactors today, the fuel pellet diameter varies with manufacturer and fuel type [13] [14], and older fuel designs tend to have larger diameters as compared to modern fuel designs. To investigate the effect of pellet diameter on the Cherenkov light production, simulations were run with the uranium fuel pellet diameter being 8-12 mm in steps of 1 mm. The Zircaloy cladding was 0.6 mm in all cases, a fairly typical thickness for several modern fuel designs. Monoenergetic gamma sources with energy between 0.5 and 3.0 MeV were simulated, while for the beta simulations the energy spectrum for Y-90 decays was used (from [18]).

In figure 4, the effect of varying the fuel pellet size on the vertically directed Cherenkov light production is presented, for three different initial gamma-ray energies and for Y-90 beta decays. As can be seen, the pellet diameter does have an effect on the intensity, and between an 8 mm and 12 mm diameter pellet the difference in intensity is around 30 % for 0.5 MeV gamma-rays, 15 % for 1.0 MeV gamma-rays and 10 % for 2.0 MeV gamma-rays. For Y-90 beta-decays the difference was around 25 %.

In conclusion, there is a strong dependence between the production of Cherenkov photons and the fuel pellet diameter, in particular for beta particles and for low-energy gammas.
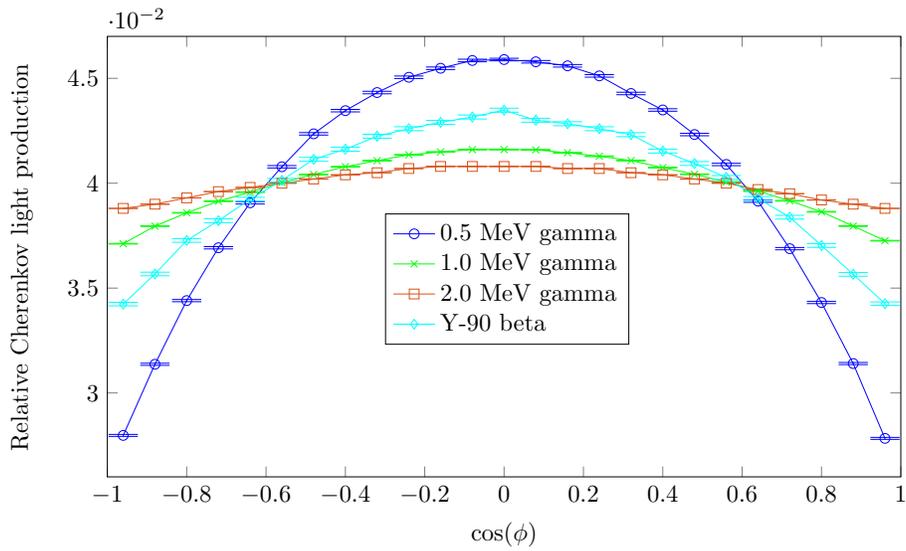
Figure 3: Relative Cherenkov light production due to a homogeneously distributed gamma source of three different energies, and an Y-90 beta source, in a single fuel rod in water as function of the cosine of the angle ϕ to the (upwards) vertical fuel axis. The intensities of each curve is scaled to a total of one, to allow comparison of the directionality of the produced Cherenkov light. For an isotropic distribution, the intensity would be flat, but here the Cherenkov light is predominately horizontally directed ($\cos(\phi) \approx 0$). In the plot, the $\cos(\phi)$ values are divided into 25 bins. In this work, photons forming an angle less than 3 degrees ($\cos(\phi) > 0.998$) to the vertical axis are considered representative of the measurable light.
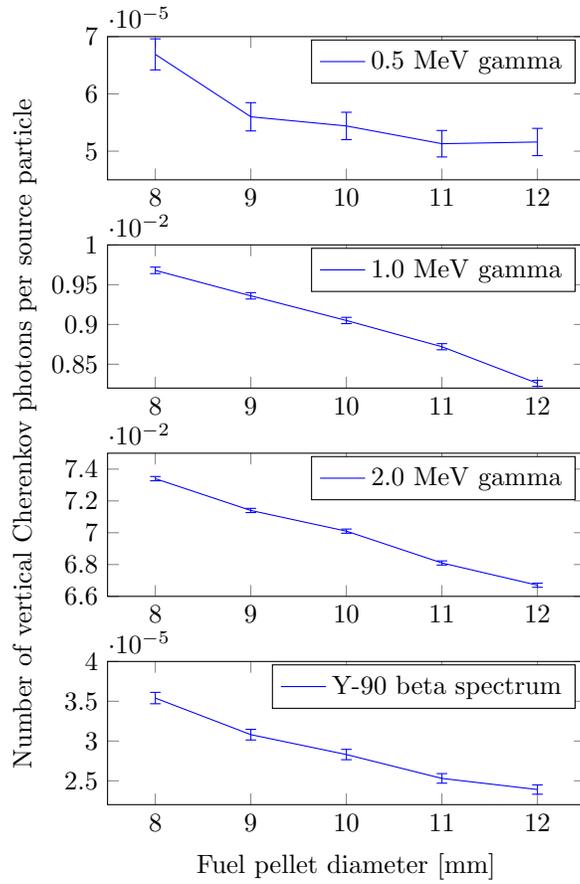
Figure 4: Number of vertically directed Cherenkov photons produced per source particle for a single rod in water for various fuel pellet diameters. Results are presented for three different initial gamma-ray energies and for an Y-90 beta spectrum. The cladding thickness was 0.6 mm.

3.3.2   Cladding thickness

Just as for the fuel pellet diameter, the fuel cladding thickness varies with manufacturer and fuel type [13], and older fuel designs tend to have thicker claddings as compared to modern fuel designs. To investigate the effect of cladding thickness on the Cherenkov light production, five simulations were run with cladding thicknesses of 0.5-1.0 mm, in steps of 0.1 mm. The fuel pellet diameter was set to 10 mm, and homogeneously distributed gamma and Y-90 sources in the fuel pellets were simulated.

In figure 5, the effect of varying the fuel rod cladding thickness on the vertically directed Cherenkov light production is presented, for three different initial gamma-ray energies and for Y-90 beta decays. As can be seen, the cladding thickness has little effect on the Cherenkov light intensity caused by gamma-decays, and comparing the intensity for 0.5 and 1.0 mm claddings, the difference is less than 4 % in all cases. However, for Y-90 decays, the difference is much greater, and an increase in vertical Cherenkov light intensity with a factor of 50 is seen as the cladding thickness is reduced from 1.0 mm to 0.5 mm. These results are expected, since the cladding is not expected to attenuate gamma-rays much, while it will strongly attenuate electrons passing through.

In conclusion, it is highly important to model the correct cladding thickness when predicting the Cherenkov light production from beta-decays, while it is of lower importance for gamma emission.

3.3.3   Radial source distribution

In an irradiated nuclear fuel rod, the burnup is generally higher (more fissions have occurred) on the rim of the rod than in its center, causing the fission product concentration to be higher there. Furthermore, high pellet center temperatures during irradiation may make certain elements, such as cesium, migrate towards the fuel rim. Cs-137 is of particular importance, since it contributes most to the Cherenkov light intensity in long-cooled (more than 10 years) fuels [9].

To investigate the effect of varying source distribution on the Cherenkov light production, simulations were run for Cs-137 gamma-decays and Y-90 beta-decays, while varying the radial position of a source distributed at a fixed distance from the fuel rod center. In both cases, the fuel rod had a 10 mm diameter pellet and 0.6 mm thick cladding.

Figure 6 shows the vertical Cherenkov light intensity as a function of radial distance. For the 662 keV gamma-rays emitted by Cs-137, a decay near the pellet rim will create on average 80 % more Cherenkov light than a decay near the center. Due to the strong attenuation in the fuel, the Cherenkov light intensity by Y-90 beta emission decreases exponentially with distance from the fuel rim. Only Y-90 beta decays on the outermost 0.5 mm of the rod created any significant amount of Cherenkov light in the simulations, and the Cherenkov light contribution was dominated by beta emissions from the fuel rim.

In conclusion, the radial source distribution has a strong effect on the Cherenkov
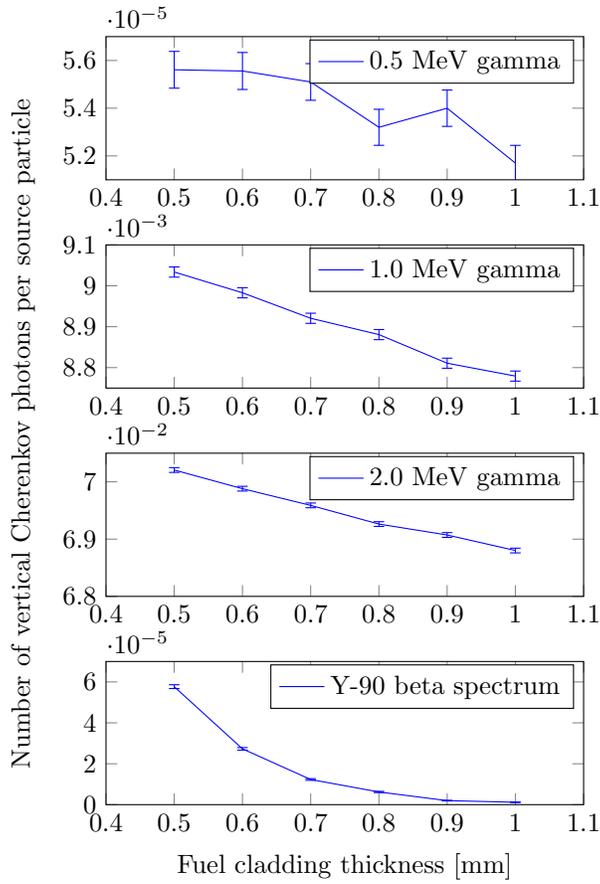
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Figure 5: Number of vertically directed Cherenkov photons produced per source particle for a nuclear fuel rod in water for various fuel cladding thicknesses. Results are presented for three different initial gamma-ray energies and for an Y-90 beta spectrum. The fuel pellet diameter was 10.0 mm.
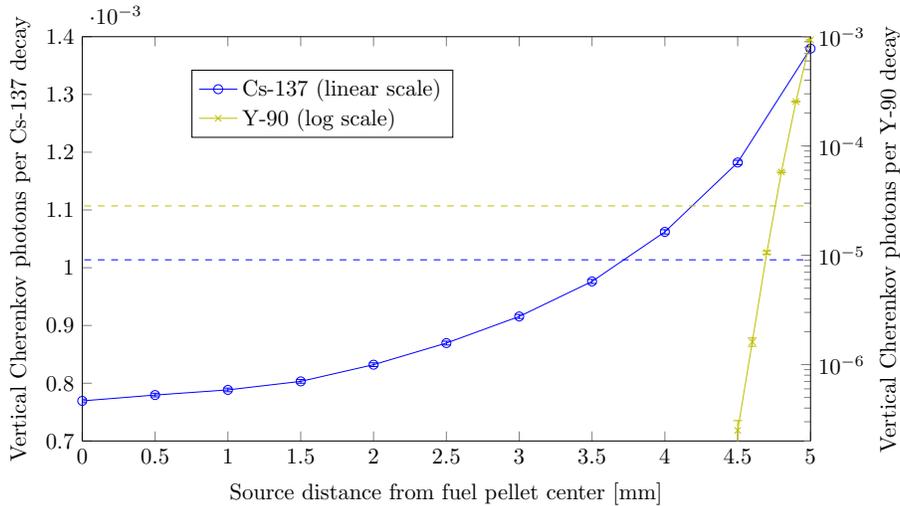
Figure 6: Vertical Cherenkov light intensity produced by a Cs-137 or Y-90 source in a single fuel rod in water as function of the source distance from the fuel rod center. The Cherenkov light intensity that would be given by a homogeneously distributed source is given by the dashed lines.

light production. Possible ways to take this into account in prediction models are discussed in section 4 below.

4   Conclusions

The purpose of this work was to investigate how various physical properties affect the produced Cherenkov light intensity from a nuclear fuel rod in water. The underlying motivation was to enable high precision when predicting the Cherenkov light intensity from irradiated nuclear fuel assemblies in wet storage, as measured by the DCVD in safeguards inspections. In this context, one should consider that the DCVD measures the vertical light, i.e. emitted in the direction along the fuel rod axis. Accordingly, the studies have given particular attention to the production of light emitted in this direction.

The following conclusions were drawn:

- For a single gamma and beta decay of the same energy, on average the interactions of the gamma ray in water will lead to a substantially higher Cherenkov light production compared to what the beta particle can produce directly;

- Electrons created in beta decays may also leave the fuel with energy high enough to produce Cherenkov light, in particular for modern fuel types with thin cladding;

- The Cherenkov light yield is anisotropic, and the angular light profile depends on the energy and the type (gamma/beta) of the decay particle;

- The fuel rod dimensions, i.e. pellet diameter and cladding thickness, has a strong influence on the intensity of the produced Cherenkov light;

- The radial source distribution also has a strong influence on the Cherenkov light production, in particular for beta emission.

One may assume that by modelling gamma as well as beta emission, taking the fuel and source geometry into account and isolating the vertical component when modelling the Cherenkov light production will allow for highly accurate prediction models for the DCVD. However, one should also acknowledge that there may be limits to how well various properties may be modelled, depending on how well the fuel may be characterized. This is further discussed below.

5 Discussion and outlook

The prediction model currently used by the IAEA for evaluating DCVD data [9] involves some limitations in that it is a parametrization of the Cherenkov light intensity as a function of fuel burnup and cooling time, which was obtained by simulating the emission of gamma rays and bremsstrahlung from one selected fuel geometry. Accordingly, the direct beta component is currently omitted, which may limit the validity of the current model. Furthermore, since the same parametrization, based on one fuel geometry is applied for any fuel geometry, this will neglect the effect of varying fuel pellet dimension, cladding thickness and rod configuration, which may also limit the validity of the current model. However, one should also acknowledge that, firstly, the Cherenkov light production is dominated by gamma emission and, secondly, the current routines for the DCVD comprise the analysis of each measured fuel type separately, implying that systematic differences between fuel geometries are taken into account by means of calibration. Consequently, one may expect also this relatively simple model to perform well, and experience proves it to be highly useful.

Still, one may identify some items which may be of importance in terms of enabling even higher predictive capabilities:

- Since the fission products present in irradiated fuel have different half-lives, the gamma spectrum of the fuel will change with time (the spectrum generally softens with time), and there is also a spectrum dependence on the fuel burnup. As shown in this work, the dependence of the Cherenkov light intensity on gamma-ray energy is different for different pellet and cladding dimensions. Accordingly, data sets comprising fuels with a wide range of burnups and cooling times may require correct modelling of fuel dimensions to enable more accurate predictions.

- Although the results of this study show that the Cherenkov light production from gamma emission dominates over that from beta emission, one

may expect that for long-cooled fuel (where Cs-137 at 662 keV is the dominant gamma emitter), the contribution from Y-90 beta emission may be significant, and its addition may enhance the precision of the predictions. In particular, this holds for fuel types with thin cladding.

- As shown in section 3.3.3, the source distributions in the fuel rods will influence the Cherenkov light production. This effect may be difficult to assess, since the radial fission product distributions are normally unknown. However, one may e.g. consider employing standard radial source distributions depending on burnup to enhance precision.

It is also reasonable to expect that the fuel rod configuration and presence of features such as guide tubes or water channels in a fuel assembly will affect the production of vertically directed Cherenkov light, in addition to the fuel rod dimensions covered in this work. Accordingly, additional studies of the Cherenkov light production in complete fuel assemblies of different designs should be performed. Such additional studies may also cover a more detailed assessment of whether there may be other important contributions from beta emitters, in addition to the here discussed Y-90. Furthermore, it may be relevant to assess the reflectivity of Cherenkov light on the surfaces of irradiated nuclear fuel rods and other fuel materials, since the reflectivity will govern how large emission angle that should be included in the analyses.

Future studies will also be conducted on investigating not only the production of Cherenkov light, but also its transport to the DCVD. This will require additional modelling of fuel assembly structures such as spacers, top nozzle and lifting handle, as well as modelling of the reflectivity of fuel surfaces and attenuation and absorption of Cherenkov light in water. The results of such simulations will also show if a prediction model based on the production of vertical light is sufficiently accurate, of if a prediction model should be based on simulations that includes transport to a detector.

Finally, one should notice that ultimately, the accuracy of available fuel data will limit the precision of prediction models for the Cherenkov light emission, and pushing the capacities of the model beyond that limit will not be relevant. Additional studies are thus required to address the predictive limits introduced by e.g. the here-mentioned radial source distributions in the fuel rods, but also those introduced by uncertainties in input data such as fuel burnup and cooling time. Furthermore, the usefulness of pushing the predictive capability beyond the attainable measurement precision may also be discussed, and it may be argued that the development of predictive and experimental capabilities should go hand in hand.

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