Modelling of the Cherenkov light emission from irradiated nuclear fuel stored in water

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Outline

• Introduction to the project
  - History and project organization
  - IAEA safeguards
  - The Digital Cherenkov Viewing Device (DCVD)
  - Earlier work at Uppsala

• Simulating the nuclear fuels and the Cherenkov light from fuels in wet storage

• Future enhancements of the DCVD.
The project was initiated in 2013, by SKC and SSM in collaboration.

The project will be fully supported by SSM after SSM’s withdrawal from the SKC collaboration.
Project organization

PhD student at Uppsala university.

Reference group with people from industry and authorities: SSM; IAEA, EURATOM, device manufacturer, image analysis specialist....

Experimental parts will be performed at CLAB and possibly at Ringhals.
IAEA safeguards

The International Atomic Energy Agency is an organization that seeks to promote the peaceful use of nuclear energy, and to inhibits its use for military purpose.

One of their main missions is safeguards: to implement safeguards to verify that nuclear energy is used for peaceful purposes.
IAEA safeguards

One safeguards task is to verify spent nuclear fuel assemblies, to ensure that no nuclear material has been diverted.

Many instruments exist to do these types of measurements. One commonly used instrument is the Digital Cherenkov Viewing Device (DCVD).
Gamma rays from the fuel interacts with the surrounding water, producing Cherenkov light.

The Cherenkov light is the most intense in the UV-range, but can be seen as a bluish glow.
By measuring the Cherenkov light generated by fuel assemblies stored in water, the fuel’s properties can be investigated non-destructively.

Images courtesy of Channel Systems
The DCVD

Image courtesy of Channel Systems
The DCVD

Why use a DCVD to verify irradiated fuel assemblies?
- Portable and quick to set up.
- Fast measurements.
- Non-destructive.
- Non-intrusive.
- Works for fuels with long cooling time/low burn-up.
- Data can be saved and reviewed later or compared with other measurements.

The aim of this project is to further enhance the capabilities of the DCVD
The DCVD

The DCVD hardware was developed by the Canadian support program to IAEA safeguards, and the software was developed by Swedish support program.

Much work has been done developing the instrument by several parties, resulting in the device used today.

Ex. Development of the device, measurements investigating the DCVD performance, simulation studies of Cherenkov light, IAEA inspector training.
The DCVD is approved by the IAEA for both gross defect verification as well as partial defect verification.

Gross defect verification: determining if an object is a fuel or a non-fuel item.

Partial defect verification: determining if part of a fuel assembly has been diverted. Current detection limit: 50% of the fuel rods in an assembly removed.
This project builds on the earlier work, and will contribute to the ongoing development of the DCVD and the analysis methodologies used.

This project was started since there was a need for a more thorough investigation for Cherenkov light creation, transport and detection.

One goal is to improve the partial defect detection capability of the DCVD.
Improving the predictions of the Cherenkov light intensity

The current partial defect verification procedures compares the measured intensity to a predicted one.

The predictions are based on operator declared values of burnup and cooling time.

By using a fuel depletion program such as ORIGEN, the gamma spectrum of fuel assemblies with varying burnups and cooling times is obtained.

Geant4 simulations show how much Cherenkov light is produced given the spectrum
Improving the predictions of the Cherenkov light intensity

The simulated Cherenkov light production as a function of burnup and cooling time is used to interpolate an estimated intensity for fuel assemblies that are to be measured.
Improving the predictions of the Cherenkov light intensity

What advantages and disadvantages exist for this model?

Advantages:
- Precalculated intensity curves allows for very quick estimation of intensity.
- The two parameters that affect the intensity the most is taken into account (burnup and cooling time).
- The data which the operator must provide is very basic (BU and CT).
- A simplified fuel assembly model (single rod in water) allows for quick simulations of the Cherenkov light production.
Improving the predictions of the Cherenkov light intensity

What advantages and disadvantages exist for this model?

Disadvantages:
- Does not take into account the irradiation history of the fuel.
- Does not take into account the geometry of the fuel assembly.
- Does not take into account Cherenkov light production due to beta decays in the fuel.

This should be taken into account in order to improve the accuracy of the predictions!
Improving the predictions of the Cherenkov light intensity

A method has been developed to do predictions taking irradiation history, fuel geometry and beta decays into account, while still allowing for quick predictions.

Similar to the current method, it is based on an extensive pre-calculation, allowing for quick predictions afterwards.

The pre-calculation in this model is extensive enough that a computer cluster should be used.
Improving the predictions of the Cherenkov light intensity

The precalculations are done by simulating the Cherenkov light production inside a complete fuel assembly.

Simulations are then done for each rod in the complete assembly geometry.

Simulations are done with the initial particles being gamma-rays or electrons of various energies.

The result is an estimate of how much Cherenkov light is produced inside the fuel assembly, for decays of various energies in each of the rods in the assembly.
Improving the predictions of the Cherenkov light intensity

For acceptable statistical uncertainty, about 100-500 CPU-hours are needed to simulate a single fuel assembly.

Fuel designs differ between manufacturers, and especially BWR geometries can differ a lot.

For best possible accuracy when predicting the Cherenkov light intensity, each geometry should be simulated separately.
Improving the predictions of the Cherenkov light intensity

Once the precalculations are done, predictions can be done quickly.

The operator must first give information about the fuel, such as during which reactor cycles it was in the reactor, and the power level during each cycle.

Using a fuel depletion program such as ORIGEN, the fuel history can be simulated, to give an accurate gamma spectrum and content of beta-decaying isotopes.
Improving the predictions of the Cherenkov light intensity

The simulated gamma spectrum and beta spectrum is the combined with the pre-calculated values of how much Cherenkov light is generated by gamma-rays and beta-particles at different energies.

The time needed to execute a fuel depletion calculation and combining the results with the precalculations is on the order of a few seconds.

Fast enough to be used in the field!
Improving the predictions of the Cherenkov light intensity

Comparison of old and new predictions:

*Comparison between old and new methods (scaled to CT=10 y)*
Improving the predictions of the Cherenkov light intensity

For short-cooled fuel, the irradiation history strongly affects the Cherenkov light production.

For measurements of such fuels, the irradiation history must be taken into account, and this method allows for that.

This may allow the DCVD to be used more frequently when verifying short cooled fuels, such as fuels stored at reactors in Sweden prior to transport to CLAB.

Today, the FORK detector would be the detector of choice for such measurements.
Improving the predictions of the Cherenkov light intensity

The new model is in need of experimental validation, which can hopefully be done at Ringhals and CLAB.

Ringhals provides an opportunity to measure short-cooled fuel, where the fuel history must be taken into account.

CLAB provides an opportunity to measure a diverse set of cooling times and burnups.
Improving the predictions of the Cherenkov light intensity

Other results from comparing the new model to the old one:

- Irradiation history matters a lot for short-cooled fuel, not so much for long-cooled fuel.

- Beta-decay electrons may exit the fuel rods and enter the water with sufficient energy to produce Cherenkov light if the cladding is thin.

- The fuel geometry does affect the Cherenkov light production.
Future work

Further enhancements may be made to the prediction model:

- Radiation from one assembly may enter a neighboring assembly, and cause Cherenkov light.

- Propagation of Cherenkov light from the fuel to a detector position may be simulated. This requires knowledge of the structural components of the fuel and its axial burnup profile.

- Image analysis may be used to extract more information from the measurements.
Summary

- Enhanced prediction models take irradiation history, fuel assembly geometry and beta decays into account.

- Significant precomputation required, but once done predictions can be made quickly.

- Verification against experimental data still required.
Thank you for your attention!

Questions?