Validation of General Purpose Mathematical Efficiency Modeling with ISOCS – 15579

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ABSTRACT

Gamma spectroscopy is a commonly used method for radioactive waste characterization and activity determination in in-situ objects. The gamma rays emitted by radionuclides in the waste container matrix are highly penetrating and can be measured using one or more gamma ray detectors, thus allowing for a passive nondestructive assay. One problem is that a source based calibration of full energy peak efficiency can be difficult or impractical because of the large size and/or an unusual shape of the sample geometry. One attractive solution is to use mathematical efficiency modeling to calculate the full energy peak efficiency.

The In-Situ Object Calibration Software (ISOCS) has successfully been used for more than a decade for mathematical efficiency modeling of template based geometries. Templates include the most common objects in waste characterization and D&D, including but not limited to: boxes, drums, and pipes with hotspots, beams, tanks and walls. Scenarios exist where these templates cannot model the desired measurement geometry. CANBERRA has developed a general purpose version of ISOCS where primitive objects can be combined into practically any geometry. The primitive objects are right circular cylinder, right elliptical cylinder, right circular cone, right elliptical cone, sphere, spheroid, ellipsoid, box (rectangular parallelepiped), torus, and beaker (any cylindrical symmetric object). Multiple primitive objects can be combined using the priority scheme and cut by planes into almost any desired shape. In addition, multiple objects can be defined in the same scene, for example cylinders next to each other or a pipe and a box. Collimators can be constructed as easily as in template based ISOCS.

The ray tracing algorithm in ISOCS has been extended to support the new primitive objects for attenuation calculation between the radioactive source and the detector end cap. The new version uses the same vacuum efficiency response, or characterization, in the energy range 10 – 7000 keV of individual detectors to be able to calculate the efficiency as accurately as possible.

MCNP has been shown to be able to calculate detection efficiencies for any geometry and the new version of ISOCS have been validated to MCNP. The vacuum efficiency is based on an MCNP model and this model was the base for constructing an identical model in MCNP as in ISOCS. The calculated efficiencies from the two codes have been compared and the agreement is within 3% except for the lowest energies for one geometry.

INTRODUCTION

In gamma spectroscopy the efficiency calibration is used to relate the number of counts in the full energy peak in the spectrum to the number of photons emitted from the measured radioactive source. The efficiency for a sample depends on the measurement geometry and the detector used. It is a crucial part of the analysis and any error or bias in the efficiency calibration will be directly reflected in the activity determination. Measuring the detector response with known radioactive sources was for a long time the dominant means of determining the efficiency. For the last couple of decades mathematical efficiency modeling have emerged as an alternative to source based efficiency calibrations. Modeling reduces source inventory needed for gamma spectroscopy and gives flexibility when measuring samples with odd shapes. For non-destructive assays (NDA) and decommissioning and deconstruction (D&D) it is common to have samples where it is either very expensive or impractical to create a source with the same geometry that the object that needs to be measured. Mathematical efficiency modeling is particularly attractive for these situations.

Photon interactions with matter are well known and tabulated data exist for the energy range of interest for gamma spectroscopy. This information can be used to calculate the efficiency of the detector geometry combination. There are three general categories for mathematical efficiency modeling: ray tracing where the path length through different parts of the geometry are calculated and used together with the linear attenuation coefficient to calculate the efficiency [1-3], Monte Carlo radiation transport where single photons are tracked through the geometry and can scatter with the materials [4] and efficiency transfer where a measured efficiency for a particular geometry is transformed to a another geometry by using the change in solid angle and linear attenuation through the materials [5]. Mathematical efficiency calculations requires detailed knowledge about detector parameters, generally to better precision than the parameters supplied from the detector manufacturing process. Monte Carlo methods can give the most information but are both labor and calculation intensive, efficiency transfer methods require a measurement with a known source of a similar energy and geometry as the one that the efficiency is needed for.

The in-situ object counting software ISOCS [1-3] has been successfully used for two decades for NDA and D&D applications. It uses a detector specific vacuum efficiency response, or characterization, together with a ray tracing algorithm to calculate the efficiency for objects located on the end cap up to 500 m from the detector. The vacuum efficiency response is generated from an MCNP model that is validated with NIST traceable sources and removes the need of user inputs of the not well enough known detector parameters. The geometries can be made from one of 21 different templates which cover a majority of the geometries for the NDA and D&D applications. However there are still situations where the desired geometry cannot be modeled using the templates and a general purpose template is needed. ISOCS have been extended with a general purpose template where virtually any geometry can be modeled as long as it is within 500 m from the detector end cap.

The geometries are made up of primitive objects, right circular cylinder, right elliptical cylinders, right circular cones, right elliptical cones, boxes, spheres, spheroids, ellipsoids, pyramids and tori. The primitive objects can be translated and rotated to any arbitrary position in space. Combining the primitive objects using the priority scheme and cutting the objects with planes can create any shape that is not represented by the primitive objects.

EFFICIENCY COMPARISON

Four geometries created with the general purpose template have been compared to MCNP and in one case with an ISOCS calculation using the complex box template. MCNP was chosen because it is impractical to create these geometries with sources with known activity. MCNP has been the industry standard for photon transport for decades and it has been verified to be able to reproduce measured efficiencies for a wide variety of geometries. It is also possible to create almost any kind of geometry with MCNP.

The energies used in all comparisons are commonly used lines from plutonium, americium, Naturally Occurring Radioactive Material (NORM), Cs-137 and Co-60; containing energies chosen so that they are covering a large energy range. Because of long calculation times for MCNP the lowest energy used was 45 keV. The energies and isotopes are shown in TABLE I.

Table 1, the energies and the isotopes that emit them that was used in the comparison between ISOCS and MCNP

Isotope	Energy (keV)	Isotope	Energy (keV)
Pu-240	45	Pa-234^{m}	766
Am-241	59.5	Pa-234^{m}	1001
Pu-239	129	Co-60	1173
Pu-238	152	Co-60	1332
Pu-241	208	Bi-214	1765
Pu-239	413	Bi-214	2204
Bi-214	609	Bi-214	2448
Pu-240	642	Tl-208	2615
Cs-137	661		

The first scenario is a 2 m wide, 1 m high and 0.5 m thick box with 1 mm thick stainless steel walls. The box is filled with dirt with 1.6 g/cm^3 with uniformly distributed radioactivity except for one hot spot located 25 cm from the left wall, 80 cm from the bottom and 10 cm from the front wall. The hot spot is 3 cm wide, 5 cm high and 2 cm thick. The hot spot contains the same amount of activity as the rest of the dirt. The detector is centered 1 m from the front surface of the box. The geometry is shown in Figure 1.

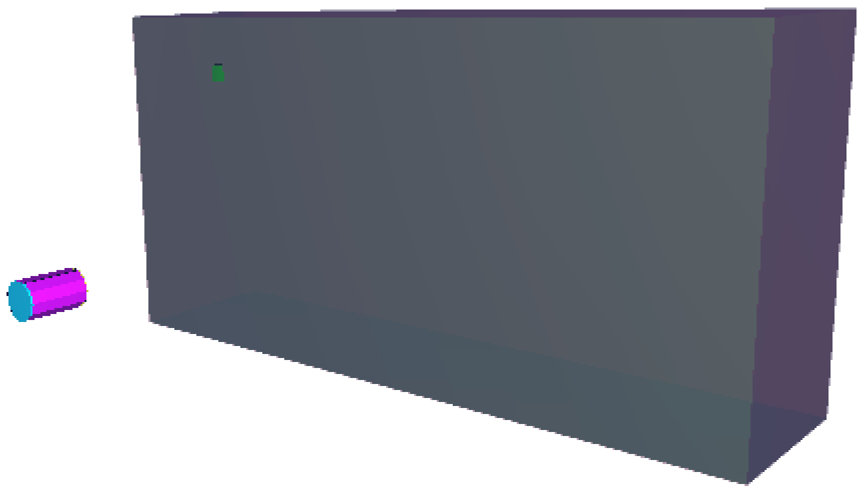

Figure 1, the geometry containing a box with a hotspot.

This scenario can be modeled in MCNP, the new general purpose ISOCS template and the standard ISOCS complex box template. The comparison between the three can be seen in Figure 2.

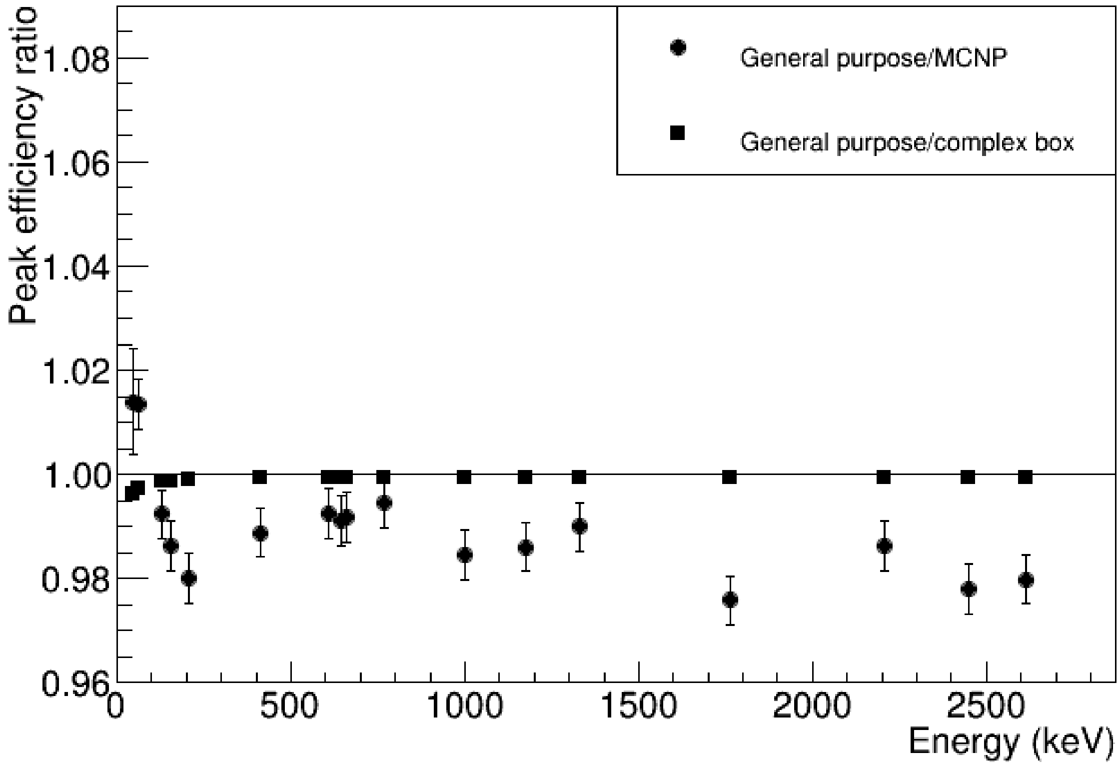

Figure 2, the comparison of peak efficiency between general purpose ISOCS, the complex box template and MCNP for a box with a hotspot.

The convergence was set to 0.1 % for the two ISOCS calculations and the uncertainty of the ratio is the same as the size of the markers. For the ratio between ISOCS and MCNP the uncertainty is the statistical uncertainty of the MCNP calculation which was 0.5 % except for the lowest energy where it was close to 1 % because of long calculation time. The agreement between the general purpose and the complex box templates are less than 0.2% for all energies and for most energies it is below 0.1% indicating that the general purpose template can reproduce the efficiencies of the other ISOCS templates to within convergence. Comparing ISOCS to MCNP shows that all energies are within 2.5% and most energies are within 1-2 %.

If a drum is added to the above geometry it is no longer possible to compare to any other ISOCS templates and the efficiencies will therefore only be compared to MCNP. The drum was 75 cm high with a radius of 25 cm, the drum wall thickness was 1 mm and the material was stainless steel. The drum matrix was the same type of dirt as in the box and the drum contained as much radioactivity as the box. The drum was placed between the box and the detector 25 cm to the right of the center of the box. Figure 3 shows the geometry.

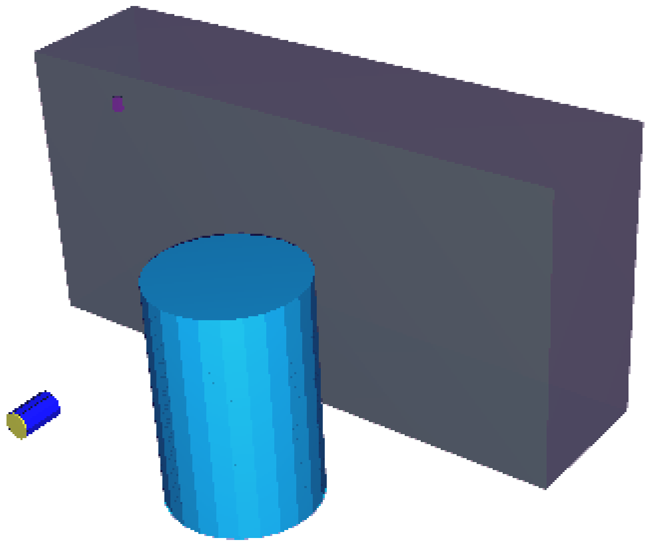

Figure 3, the geometry with a box with hotspot and a drum.

The ratio of the peak efficiency calculated by ISOCS and MCNP is shown in Figure 4. The peak efficiencies are reproduced to within 3% and most energies are within 2%. The ratio for all energies, except for 45 keV where the statistical uncertainty is about 1.5%, is between 0.97 and 0.99 which shows that the efficiency calculations are consistent over the entire energy range but have a small bias of about 2%.

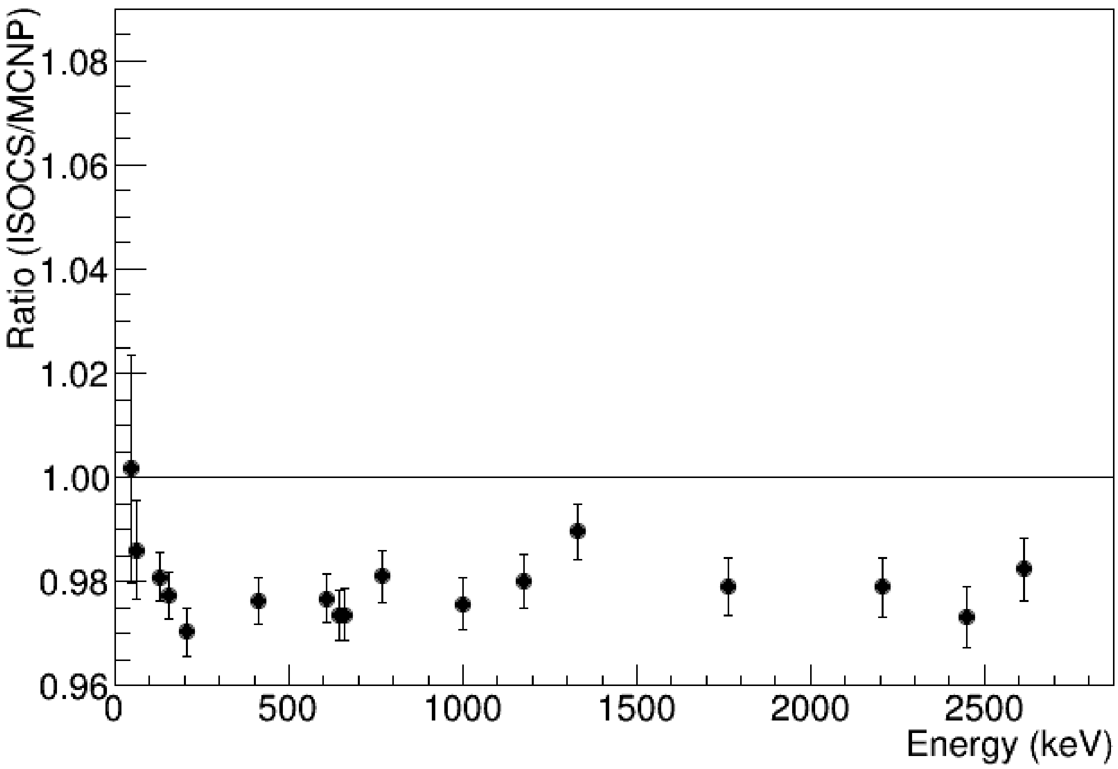

Figure 4, the ratio of efficiencies calculated by ISOCS and MCNP for a box with hot spot and a drum

A 20 cm diameter pipe containing radioactive water is mounted along the wall in a room. In the corner of the room there is a 90 degree bend of the pipe. The bend has a radius of 50 cm and the pipe extends 2 m in both directions from the bend. The detector is positioned 2 m from the bend and is aiming straight at it. The radioactivity is uniformly distributed in the water in the entire pipe, the geometry is shown in Figure 5.

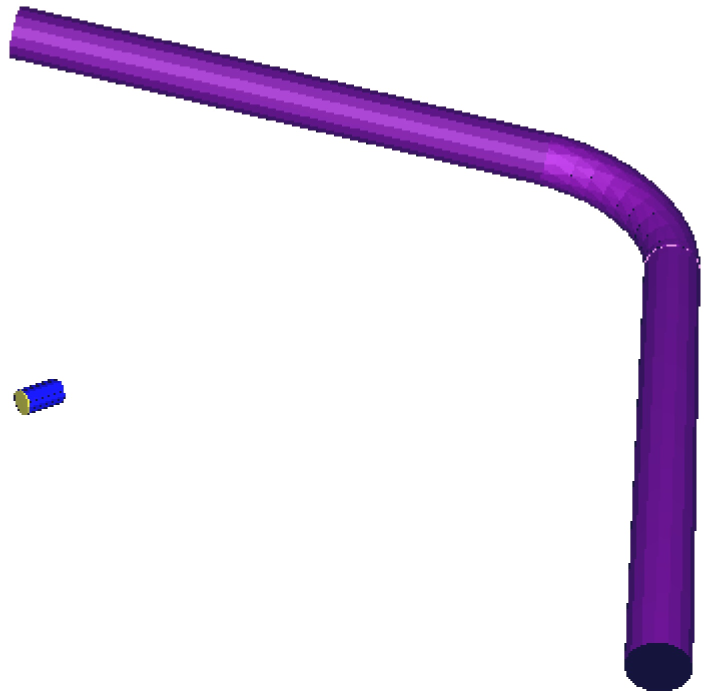

Figure 5, the geometry with a pipe containing radioactive water.

Figure 6 shows the ratio of the peak efficiency between ISOCS and MCNP. As with the previous geometries the ISOCS peak efficiencies are within 3% and a bias of about 2% lower than MCNP except for the lowest energies where ISOCS is slightly higher than MCNP.

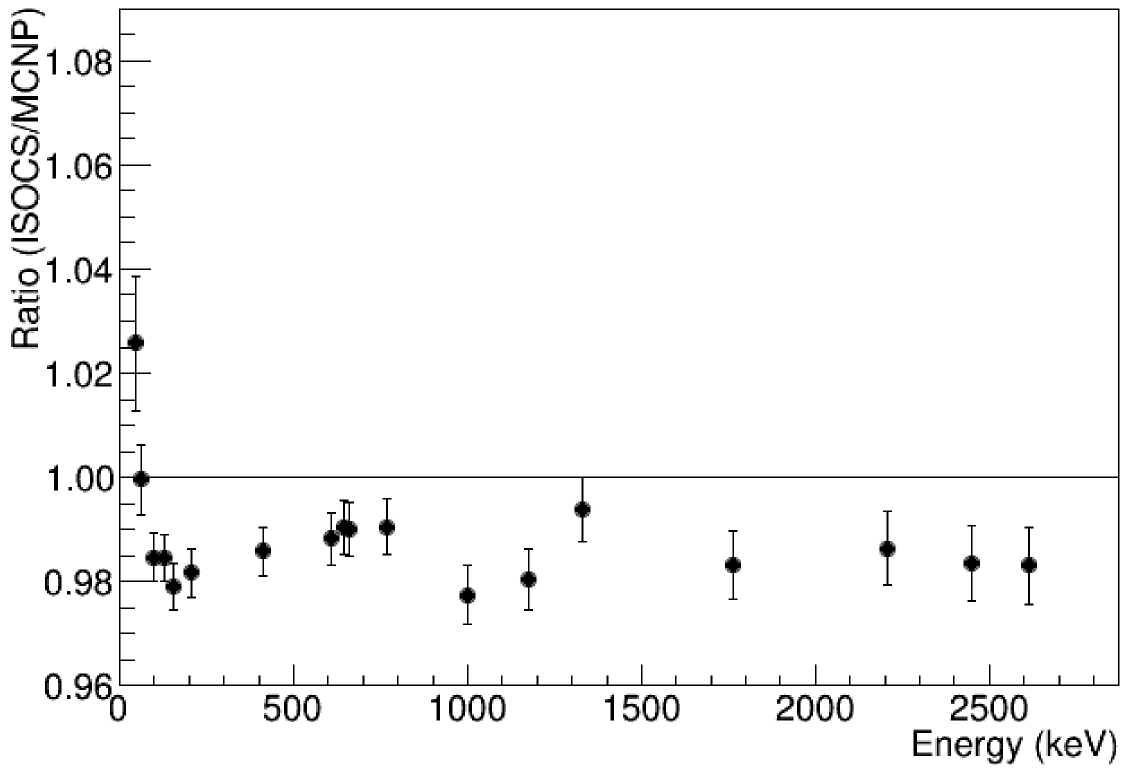

Figure 6, the ratio of the peak efficiencies calculated by ISOCS and MCNP for a pipe with a 90 degree bend.

The fourth geometry is a container loaded with 10 plastic bags containing debris which is approximated by 0.3 g/cm^3 cellulose. The container is 6 m long 2 meter high and 3 meter wide and the truck walls are made of 1 mm stainless steel. The bags are 1 m high and have a 50 cm radius. 7 bags are non-radioactive and 3 have a single hot spot in them. The hot spots were modeled as 2.5 cm radius spheres and one of them contained 50% of the activity and the other two 25% each. The detector was located 2 m from container and pointing at the center of it. The geometry is shown in Figure 7.

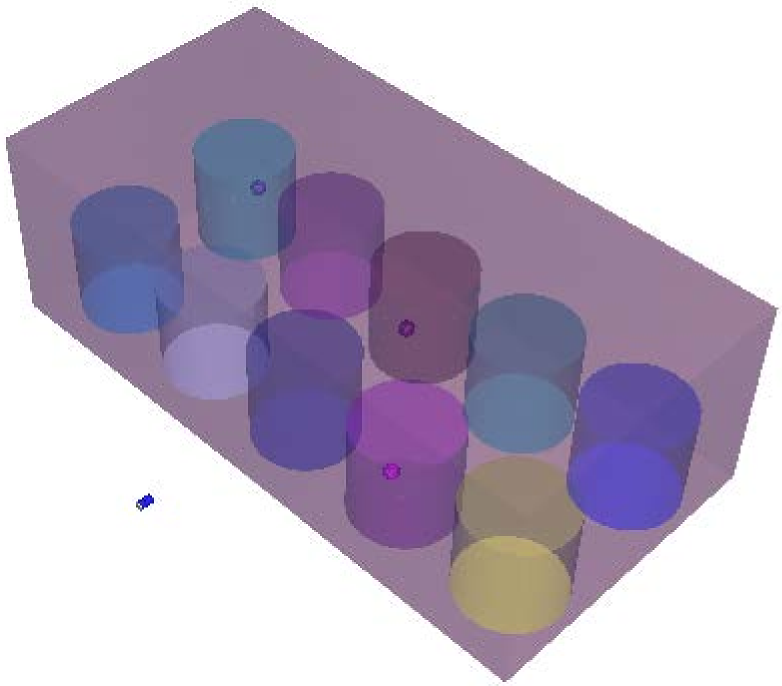

Figure 7, the geometry of the container with 10 plastic bags. The 3 hot spots are enlarged for visibility.

The peak efficiencies were calculated for ISOCS and MCNP and the ratio is shown in Figure 8. For higher energies than 100 keV the ratio of this geometry is the same as for the other geometries. The increase of the ratio for low energies is higher for this geometry than for the other three. The agreement for 45 keV is 6 % with a one sigma statistical uncertainty of 2%.

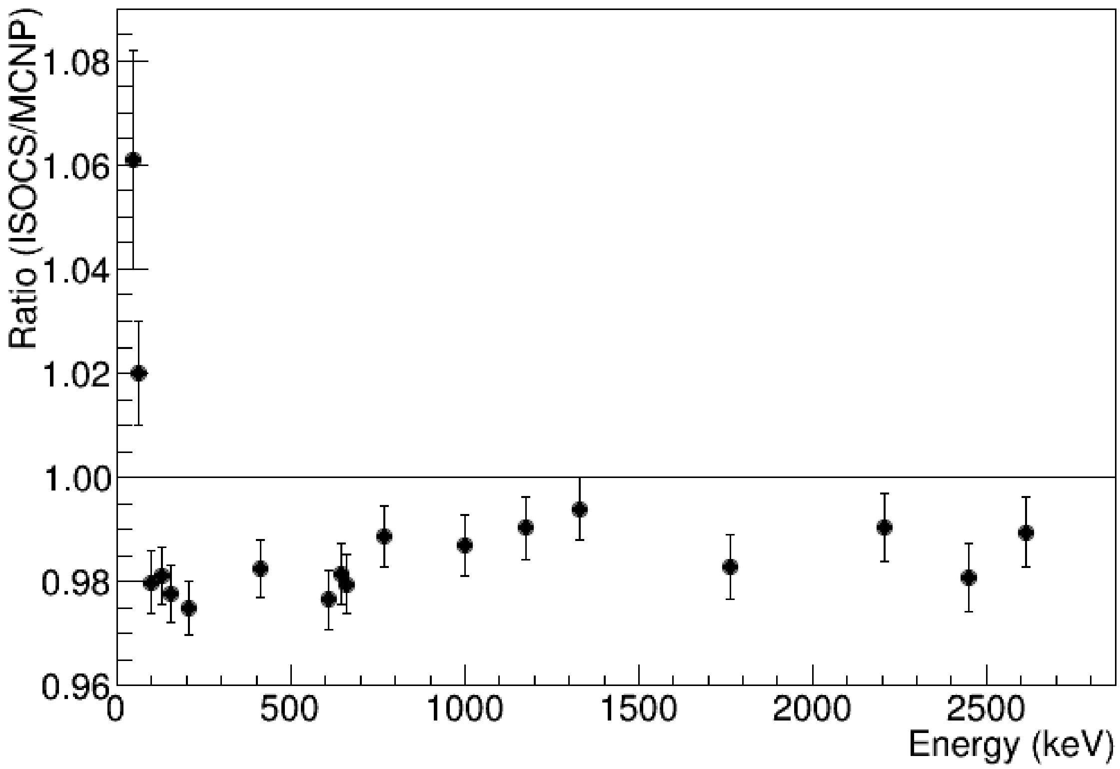

Figure 8, the ratio of peak efficiencies calculated by ISOCS and MCNP for a container with 10 bags with cellulose.

The ISOCS calculations finish in a few seconds with a convergence factor of 0.1%. The goal of the MCNP calculations was to reach 0.5% statistical uncertainty which took about 10 hours of calculation time on comparable computer as the ISOCS calculations. For the lower energies where the attenuation is high the statistical uncertainty reached was only around 1-1.5% because of the long computation times. Directional bias, where the photon emission was limited to a cone that covers the detector, was used as variance reduction in the MCNP calculations.

CONCLUSION

A general purpose template has been developed for ISOCS were geometries can be built up by one or more primitive objects. The primitive objects can be rotated, translated, combined using the priority scheme and cut by planes into virtually any kind shape. The peak efficiencies calculated by ISOCS using the new template have been compared to MCNP for 4 NDA and D&D geometries and in one case to the complex box template. The agreement with the complex beaker template is within the convergence of 0.1%. The peak efficiencies calculated by ISOCS are within 3% for all geometries and energies except for the lowest energies for one of the geometries where the agreement is about 6%. All 4 geometries show a bias of about 2% lower efficiencies than MCNP for energies above 100 keV. However it is common for these kinds of geometries to have not well known parameters and the uncertainties rising from these not well known parameters are generally much larger than the 2% bias that ISOCS have compared to MCNP. The ISOCS calculations are order of magnitudes faster than MCNP calculations.

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