LUND INSTITUTE OF TECHNOLOGY
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MASTER'S THESIS

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Validation of new fuels for storage in the dry storage facilities of the Nuclear Power Plant at Oskarshamn using MCNP

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Abstract

To prove that fresh nuclear fuel can be stored in the dry storage facilities at the nuclear power plants it is necessary to fulfill the requirements from Strålsäkerhetsmyndigheten. This can be proved in different ways. In this thesis it is done by using the Monte Carlo method based computer code MCNP version 4c2. The objective is to prove that the fuel bundle designs 'GE14 Nordic' and 'Atrium 10XM' can be stored safely in the dry storage facilities of the Oskarshamn nuclear power plant. Results from the simulations shows interesting characteristics well suited for further academic research as well as satisfactory general results which proves the possibility to store the desired designs in the dry storage facilities at the plant.

Acknowledgements

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I would also like to point out that there for this thesis have been a good collaboration between Lund Institute of Technology, Chalmers University of Technology, OKG and myself. Chalmers and LTH have both played a big part in making this thesis come true. Thanks for all the support from everyone involved.

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List of Abbreviations

The following list of abbreviations is provided for the ease of reading the following thesis report. The abbreviations are provided in chronological order as they appear in the text.

Abbreviation	Full Word
O1	Oskarshamn unit 1
O2	Oskarshman unit 2
O3	Oskarshamn unit 3
SSM	Swedish Nuclear Regulatory Commission
NPP	Nuclear Power Plant
OKG	Oskarshamn Nuclear Power Plant
GNF	Global Nuclear Fuel
NRC	U.S. Nuclear Regulatory Commission
MCNP	Monte Carlo N-Particle code
k_{eff}	Effective Neutron Multiplication Factor
BWR	Boiling Water Reactor
BA	Burnable Absorbers
pcm	percentmil ($1 \cdot 10^{-5}$)
w%	weight percent

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1 Introduction

Recently the Oskarshamn plant have switched vendors of fresh fuels for their units from Westinghouse to Global Nuclear Fuel, GNF, and Areva. This also means that the design and composition of the fresh fuel bundles stored in the facility will change. Because of this an analysis of the new bundles inside the facilities needs to be performed in order to assess the fact that unwanted criticality events will never occur inside the facility at any time.

At nuclear power plants it is important to know what is happening at all different locations of the plant where fissile material is present. This is in order to prevent any unwanted criticality accident. What this project aims for is to perform an analysis of the dry storage facilities of the Oskarshamn units O1, O2 and O3 which are all boiling water reactors, BWR. This analysis is performed using the Monte Carlo method based simulation code MCNP. The version of the code used is MCNP4c2 with the cross section library of ENDF/B-V.

The way to make sure that no unwanted criticality accidents can occur one looks at the effective neutron multiplication constant, k_{eff}. This is a number which is meaningful from zero to just above one. This number tells us, how many neutrons will be present in the system in the next generation of neutrons in the neutron cycle. if k_{eff} is < 1 there will be fewer neutrons available after the current neutron cycle and the reaction will die out over time. If k_{eff} is equal to one a critical system is obtained and there will be a constant amount of neutrons present in the system at all times. The last possibility for k_{eff} is to be > 1. When this occurs there is a rise of the amount of neutrons present in the system over time and this is called a supercritical system.

The method of determining k_{eff} in the dry storage facilities used at Oskarshamn today is with the deterministic code CASMO. This code generates an infinite lattice of identical fuel bundles and from that lattice determines the k_{eff} of the system. With this code there are assumptions made which can make the k_{eff} differ to some extent from the true value. One of the reasons for using MCNP alongside the CASMO analysis is that it uses a completely different approach to solving the problem. By using the two completely different methods to evaluate the system one may get a more complete an realistic picture of the overall behavior.

2 Theory

2.1 Reactor Physics Fundamentals

The fuel used in a nuclear power plant is uranium. The fuel before entering the reactor usually consists of two major isotopes of that element. These isotopes are ^{238}U and ^{235}U where the latter is the isotope which is used as fuel. The way energy is released is through splitting the nucleus of the ^{235}U isotope. This is done by a neutron which at low energies get absorbed by the nucleus which then by internal instability splits into two fragments and a few excess neutrons with high kinetic energy. This process generates heat which is used to boil water.[1]

The excess neutrons produced in the process can then be used to split new nuclei. This can in turn create a chain reaction where new nuclei are split with neutrons from previous fissions. These chain reactions can occur at different rates. They can proceed at an uncontrolled rate and at a controlled rate, where the latter is the most desirable. The rate of new neutrons compared to old neutrons is described by the effective neutron multiplication factor, k_{eff}.[2]

In order to get the excess neutrons to lose energy, so a fission reaction can occur in the reactor, a moderating material is used. This moderating material contains a high amount of light atoms such as hydrogen and carbon. The reason why hydrogen-rich materials are used is because neutrons lose the most amount of energy if they collide with atoms close to their own weight. The moderating material used in this project is water of varying densities. [1]

This can easily be realized after considering the two following experiments. The first one is, if a stone is thrown at a big rock. Then the stone will just bounce off the rock and not loose any energy in the collision. The second experiment is when one is looking at two billiard balls. When they collide a large part of the energy from the incident ball is transferred to the one at rest.[2]

The effective neutron multiplication factor, k_{eff}, is a measurement of how many neutrons are present in each generation of the neutron cycle. This can in turn be interpreted as how fast the chain reaction is progressing. The k_{eff} have three different distinct behaviors depending on its value. [1]

- When k_{eff} is <1 the system is called subcritical and any possible chain reaction will die out over time i.e. less neutrons are produced than needed to sustain a chain reaction.
- When k_{eff} is equal to 1 the system is called critical and the chain reaction in the system is held at a constant rate i.e. as many neutrons are produced as there are neutrons consumed.
- When k_{eff} is >1 the system is called super critical. This means that more neutrons are produced than is needed to sustain a chain reaction, hence there will be more neutrons available for fission reactions and more energy will be released in the system.

2.2 Requirements for criticality evaluations of dry storage facilities

2.2.1 Criteria and Limits

The authority giving the limitations and requirements which nuclear power plants in Sweden must obey is Strålsäkerhetsmyndigheten, SSM. In order for the NPPs to store fresh fuels in their facilities they have to comply with the guidelines SSM provides. According to [4] there are no fixed guidelines as to how the analysis is to be carried out but SSM refers to the American Nuclear Regulatory Commision documents[5] for consultation in the matter.

There are four identified types of initiating events which could occur in the dry storage facilities of the nordic designed NPPs[4]. These initiating events are classified in categories from H1 to H4 according to their expected event frequency. These four initiating events have to be given special consideration when performing the analysis if applicable to the facility in question. The four major initiating events can be seen in table 1.

Initiating Event	Description	Classification
Water flooding of the facility	Fuel is stored with the highest assumed reactivity and the fuel rack is flooded with liquid water	H2
Dropped fuel bundle 1	Fuel is stored at highest assumed reactivity at normal conditions. One fuel assembly is dropped and ends up on top of the other bundles or in-between two fuel bundles if this is possible	H3
Optimal moderation	Fuel is stored with highest assumed reactivity and the storage rack is filled with a homogenous water/air mixture which generates the optimal moderation	H3
Dropped fuel bundle 2	A fuel bundle is dropped and ends up right next to parts of the fuel bundle sticking up through the floor middle platform of the storage facilities	H4

Table 1: Major initiating events for consideration when doing a analysis of the dry storage facility of a NPP [4]

Another event which could be considered is, in the event of an earthquake

the fuel bundles would end up somewhere outside of their regular placement in the fuel racks.

According to [6] there are other configurations of moderator density which could potentially generate a higher k_{eff} than the value given at homogeneous optimal moderation. The potential event in question would be when there is a higher moderator density around some of the fuel rods and a lower moderator density in the rest of the facility. Some of the material which is used for transport exhibit these properties as working like a moderator with a higher density than its surroundings. The materials considered are materials which have a high density of hydrogen or other low-Z atoms.

SSM has for the different categories of initiating events set criteria on the effective neutron multiplication factor, k_{eff}, which can be seen in table 2

Event class	k_{eff}	Min. criticality margin
H1-H2	< 0.95	0.05 / 5.27%
H3-H4	< 0.98	0.02 / 2.04%

Table 2: SSM criteria on k_{eff} in dry storage facilities[4]

Additionally, the criticality evaluations needs to be documented and performed to an accuracy that it is possible to perform an independent review of the results and still reach the same conclusions. It is also said that the criticality evaluation is to be performed in such a way that the maximum neutron multiplication for the system is obtained, i. e. the evaluation must be conservative. Along with these requirements the methods used to perform the evaluation must be well established.[4]

The criticality evaluations must also show that the observed system is subcritical even though abnormal events occur and that the system is subcritical with sufficient margin when uncertainties and deviations of the modeling and verification experiments are considered. Along with this the calculations shall explicitly show the subcriticality of the system, depending on fissile material and construction parameters.[4]

2.2.2 Methodology for criticality evaluation

With notation according to [4] the general methodology for criticality evaluations can be described by the following reasoning.

In order for the evaluated system to be considered safe from criticality accidents the calculated multiplication factor, k_p, including uncertainties has to be below a set reference value, k_{ref},

$$k_p \leq k_{ref} \tag{1}$$

In this equation the left hand side represents the upper limit of the final calculated multiplication factor while the right hand side represents the lower tolerated limit for the calculated k_{eff} of the system.

To obtain the correct k_{ref} to be used as limit the following relation is used

$$k_{ref} = k_c - \Delta k_c - \Delta k_m \tag{2}$$

where k_c is the k_{eff} value obtained from verified calculations or criteria determined by SSM. The factor Δk_c is the absolute value of the uncertainties of the verified calculations or if a criteria from SSM is used this factor is zero. The values for the pre-determined criticality margin, Δk_m, for the dry storage facilities can be obtained from table 2.

The factor k_p from equation (1) can be defined as

$$k_p = k_{sc} + \Delta k_{sc} \tag{3}$$

Where k_{sc} is the obtained multiplication factor calculated with any chosen method and Δk_{sc} is the uncertainties in method and modeling. These uncertainties can be made up of uncertainties such as statistical uncertainties in the Monte Carlo method, dimensions of the objects, materials, relative placement, manufacturing differences and conservatism in description of these parameters. If burnable absorbers, BA, is used the uncertainties associated with them is also included in this factor.

If the uncertainties are mutually independent they may be statistically combined. On the other hand correlated and mutually dependent uncertainties must be combined by addition.

2.3 Earlier Evaluations

Earlier evaluations regarding preventing criticality accidents in the dry storage facilities at Oskarshamn have previously been done. These evaluations we red one for the fuel bundle designs Svea-64[6][7] and Svea-96 Optima2[8] manufactured by Westinghouse/ABB-Atom. The evaluations were performed using Monte Carlo based methods with either the code KENO or MCNP. Evaluations were made by Westinghouse and OKG independently of each other.

The results of the evaluations all point towards it being possible to store fresh fuel inside the facilities at a higher enrichment than is being used in the reactors at Oskarshamn today. The results then end up being the base for generic criteria on what kind of fuel is allowed to be stored inside the facilities without criticality occurring. These results will in turn be one of the limiting factors for the fuel bundles being designed at OKG.

Earlier assessments regarding storing the fuel bundle designs 'GE14 Nordic' by GNF and 'Atrium 10XM' by Areva in the dry storage facility have been made[9]. This report bases its conclusions on earlier calculations made for various fuel bundle designs. In order to validate these conclusions SSM would like to see the assessment done explicitly for the bundle designs in question in the dry storage facility where it is to be stored.

2.4 The Monte Carlo Method with MCNP

2.4.1 General Features

The Monte Carlo method in the form used in computers today was invented by John von Neumann in the 1940s.[10] It was developed for calculation of particle transport since this is too complicated to do by hand. One of the greatest benefits is that the method can be used to look at real and complicated geometries which otherwise would have to be simplified. The code MCNP, Monte Carlo N-Particle, primarily analyzes the particles neutrons, photons and electrons. The primary particles analyzed in this thesis are neutrons.

The basis of Monte Carlo simulations is that simulations are done on just one particle at a time. This means that one follows the particle through its entire lifetime until it dies. During its lifetime all the events happening to the particle along the way is tallied. What happens to the particle is decided through a number of factors such as geometry of the problem, materials used and the cross section library used. The cross section library used in the problem provide the proper statistical distribution of possible events to occur.

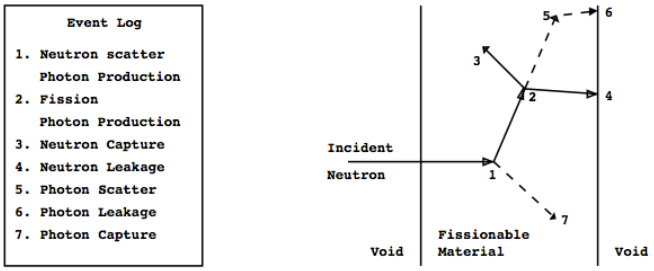


Figure 1: Schematic picture of a possible neutron "history" in a Monte Carlo simulation [3]

Figure 1 shows an example of a neutron lifetime in a Monte Carlo simulation. What happens to each particle during its lifetime is completely random, but the probability for each event to happen is determined by the cross-section libraries used for the simulation. Also one first looks at what happens to the original neutron and if additional particles are created during its lifetime the produced particle is banked and analyzed further once the original particle is dead. When all of these particles are analyzed and dead it is called one "history". All events that occur during a history are saved in a datafile, tallied, so that analysis of which events have occurred during the simulations can be done. The principle of several different reactions throughout a lifetime can also be seen in *Figure 1.* Another interesting feature which also can be seen in this figure is that the model dictates that the particle will move in a straight line between collisions without the influence of outer forces. This effect could contribute to a very small error in the calculations.

The Monte Carlo simulation method is a powerful method of analyzation but one also needs to make some assumptions in order for the theory to work. Some

of the assumptions needed to be made are that one has to neglect relativistic effects. The medium which is looked at needs to be considered static i.e. the geometries and materials will not change after or during the reaction. One also needs to make the assumption that the particles do not interact with each other and that the material properties are not changed by reactions.[3]

Generally it is preferred to use completely random numbers. However when using computers this is not possible. The way to get around this is to use a pseudo-random number generator, that is a sequence of numbers which pass any statistical test for randomness but are repeated after a large amount of numbers. These sequences are created through a uniform (0,1) distribution of numbers which are mapped into a sequence of numbers.[3]

Another important aspect to consider is the statistics of the simulations. The accuracy of the simulations all depend on the model used. The results of your simulations can not be more accurate than your model of the problem i built. The precision of the problem can be significantly improved by regulating the amount of neutron histories being used in the simulations. The easiest way of accomplishing this is to run the simulation with a large amount of particles. This is an effect of the law of large numbers which states that if a test is performed a large number of times the result will converge toward the most probable value.

All in all the Monte Carlo method has many advantages. One of the major advantages is its simplicity. Another advantage which makes it beneficial is that the method doesn't solve the transport equation directly but instead simulates the collisions. Of course not everything is good with the method, there are some drawbacks as well. The biggest one of these has to be that in order to obtain a good and precise result one needs to perform a lot of particle histories, but that on the other hand requires a large amount of computational time.

2.4.2 kcode Features

The card used in MCNP in order to determine the k_{eff} of a system is called kcode. The result of these calculations are a final k_{eff} and a standard deviation for the result. The final k_{eff} and the standard deviation are then combined into a final confidence interval for the result on three levels. The three confidence intervals produced are on the 64%-, 95%- and 99% level.

The kcode calculations are performed in cycles. One cycle is when MCNP have performed a predefined number of neutron histories. The results of this cycle is then carried over to the next cycle, where the results are used as initial values for the next computational cycle. There are active and inactive cycles. The inactive cycles are used to cancel out numerical effects and for the calculated k_{eff} value to stabilize. The active cycles are used to collect statistics towards the final result.

The information which is to be provided to the kcode card is how many neutron histories which is to be run in each cycle of the simulations, an initial guess of k_{eff}, the number of cycles to skip before k_{eff} accumulation and the total number of cycles for the simulations. The initial spatial distribution of

fission neutrons also has to be provided. This can be done in three ways: By determining x, y, z point locations of the cells, by defining points in a volume or by using a distribution from previous simulations. This source will dynamically change over time and reach a spatial equilibrium. Hence the simulations needs a few cycles initially for the neutron sources to reach an equilibrium.

One effect which is also related to using a certain amount of initial cycles before collecting k_{eff} is the initial guess of k_{eff}. A initial guess which is too poor the result can under certain conditions generate cycle results for k_{eff} which are extremely low.[3] Hence a few initial cycles before starting active k_{eff} accumulation are recommended for this effect to be cancelled.

The definition of k_{eff} in MCNP is formulated as

$$k_{eff} = \frac{\text{fission neutrons in generation } i+1}{\text{fission neutrons in generation } i}$$

In MCNP this is estimated in three different ways for the k_{eff} and the related standard deviations is also calculated. No one estimator will be the best for all problems. Hence, the result which is the best approximation of the system is a combination of all three estimations with a standard deviation for the combined results.[3]

In order for the estimators to provide a correct result at least 30 active cycles needs to be run after the initial cycles. Using fewer than 30 active cycles any trends in the k_{eff} calculations have not been fully developed and hence will not be detected by the code. In fact [3] recommends that 200-400 active cycles are to be used for the simulations. This provides large batches of k_{eff} cycles which provides good statistics for determining standard deviations for the calculations.

The criticality algorithm produces a very small negative bias in the estimated eigenvalue which has to be considered when designing the simulations. This bias depends upon 1/N, where N is is the number of source particles per generation. Because of this effect it is desirable to make N sufficiently large. According to [3] any value of N$>$200 should be sufficient to reduce the bias to a sufficiently small level.

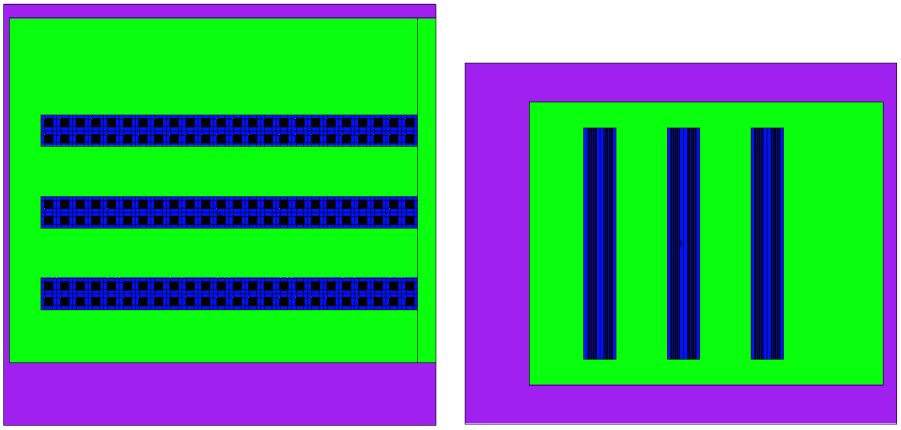
When the simulations are done, one should study and understand all the WARNING messages to determine if those in some way will influence the results. The final thing to check after the simulations are done, is the output file. It should be studied properly in order to determine that everything has turned out the way it is supposed to. What to look for in the output files are, for instance, if the problem terminated properly, enough cycles were skipped to ensure normal spatial mode for the fission sources was achieved, all cells with fissionable material was sampled, the average combined k_{eff} appears to be varying randomly about the average value for the active cycles, the combined k_{eff} does not exhibit a trend in the latter stages of the calculations and if the combined k_{eff} figure of merit is stable.[3]

3 Implementation of the Models

In this section the models of the different components of the facilities are presented as well as the approximations and simplifications made.

3.1 Oskarshamn 1

3.1.1 The Dry Storage Facility



(a) Overview in the x-y plane (b) Overview in the y-z plane

Figure 2: Plots of the dry storage facility model for O1 obtained using MCNP

The dry storage facility at Oskarshamn unit 1 is modeled in figure 44.

The facility is located inside the reactor building of the O1 unit. The walls to the storage facility is made out of concrete and each of them have a different thickness which is dependent on the location inside the plant.

In figure 45(a) the dry storage facility is viewed from above. From this figure one can see that there are three equally large blue areas. These areas is where the fuel racks and fuel bundles are located. At Oskarshamn 1 there are 138, (23x2x3), slots for fuel bundles, but it is modeled as 144 fuel bundles. This is done to save time when writing the codes and it adds more fuel inside the facility and hence adds conservatism to the final result. The fuel racks consists of a stainless steel bar along the floor where a socket for fixating the fuel bundle is located and a lattice of wielded stainless steel bars towards the top of the bundle in order to keep the bundles straight and at the right distance from each other. Stainless steel is a material which absorb neutrons. In order to have a conservative simulation the steel structures in the bottom and the top have been removed from the model and hence there will be more neutrons present in the system which will lead to a higher k_{eff}. This fact can be seen in figure 45(c) where there is an empty space from the bottom floor to the start of the fuel bundle.

The ceiling of the dry storage facility is in reality located several meters away from the top of the fuel bundles. To simplify the calculations in a conservative

way the roof has been lowered significantly to an equal level from the top of the bundles as the floor is to the bottom of the bundles. This increases the neutrons available for the fuel which contributes conservatively to the final result by raising the final k_{eff}. This approximation can be seen in figure 45(c). Another effect of this approximation is that the storage facility can be modeled symmetrically from the middle of the fuel bundle inside the storage facility.

In the physical dry storage facility there is a concrete platform close to the top of the fuel bundles which is used for inspection of the box numbers of the bundles. This concrete platform includes steel reinforcement. This entire platform would be a neutron absorber due to the reinforcement steel. To simplify the model in a conservative way this entire platform is disregarded. Disregarding this platform will increase the neutrons available for fission inside the system.

The walls and ceiling and floors of the facilities are also made out of reinforced concrete. This steel would act as a neutron absorber and in order to simplify the model in a conservative way the steel inside the concrete is disregarded.

In figure 45(a) there is a green box located to the immediate right of the fuel racks. This is a wall of water which is placed there in order to reduce the computational domain and also to add conservativeness to the calculations. In the physical storage facility the room extends several meters beyond the fuel racks to another concrete wall. The water wall which reduces the computational domain also works as a neutron reflector and keeps neutrons inside the system and available for more fission reactions. This in turn adds to the conservativeness and raises the final k_{eff} of the calculations.

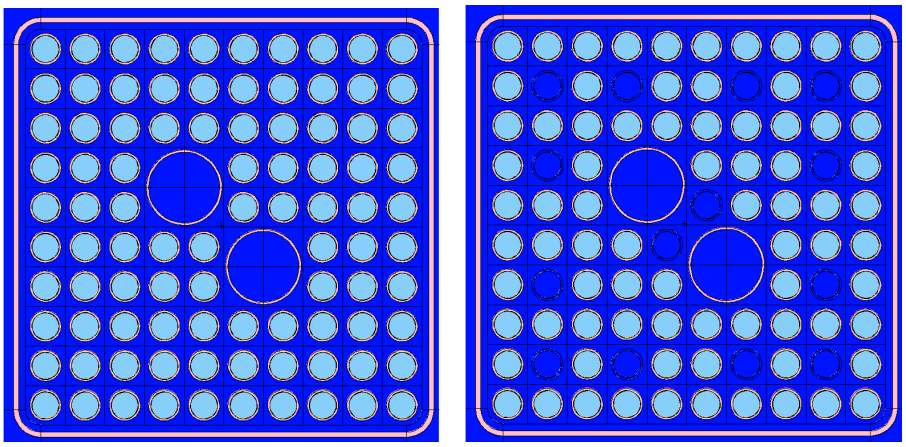
The dimensions of the storage facility have been collected from structural drawings at the Oskarshamn NPP as well as from internal reports from OKG. [6], [7] , [8]

3.1.2 GNF - GE14

The 'GE14 Nordic' fuel bundle design consists of two types of rods. One type is a full length fuel rod which stretches the entire span of the fuel bundle. The second type of rod is a rod which is only part length of the entire bundle. Cross sectional images of the 'GE14 Nordic' fuel bundle design at two different heights from the floor can be seen in figure 3

In the physical versions of the 'GE14 Nordic' fuel bundle there is a handle on top of the assembly as well as a socket on the bottom of the assembly. These are made out of stainless steel which is relatively transparent to neutrons but still does have an absorption cross section[11]. These features of the fuel bundle was removed in the model in order to remove unwanted absorption, raise the neutrons present in the system and to add conservativeness to the calculations.

Zircalloy is present as the box wall and as the walls of the water channels in the center of the bundles.



(a) Lower section (b) upper section

Figure 3: Cross section view of the 'GE14 Nordic' fuel bundle design model for O1 obtained using MCNP

In figure 3(a) a cross sectional view of the lower part of the fuel bundle can be seen. In this part of the fuel bundle both types of rods are present. The part length and full length rods both start at the same position in the bundle and the model. The two big circular channels are the water channels of the fuel bundle.

In figure 3(b) another cross sectional image of the fuel bundle is taken. From this figure can be seen that the rods which are part length are not present. They have instead been replaced by water at the same density which is present in the bulk of the dry storage facility.

The design parameters for the GE14 fuel bundle for O1 has been obtained from GNF and implemented in a correct manner.[12]

3.2 Oskarshamn 2

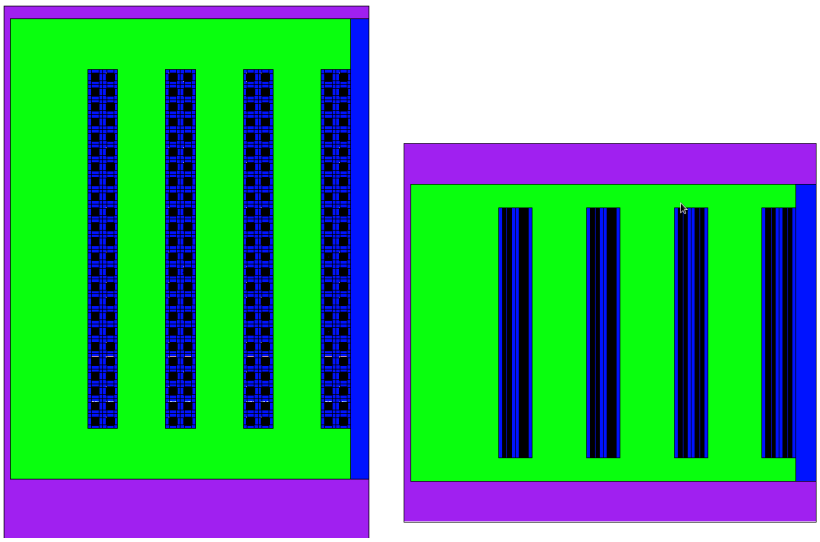
3.2.1 The Dry Storage Facility

The dry storage facility at Oskarshamn unit 2 is shown in figure 4.

The facility is located inside the reactor building of O2. The walls to the storage facility is made out of concrete and each of them have a different thickness which is dependent on the location inside the plant.

The largest difference between the storage facility of unit 2 and the storage facility of unit 1 is the orientation of the fuel racks, number of fuel racks and the location of the water wall. The dry storage facility of O2 can facilitate 192, (24x2x4) fuel bundles. These are oriented in four parallel fuel racks which can be seen in figure 4(a).

The room extends for several meters to the right of the fuel rack furthest to the right. Because of that a water wall has been placed next to that fuel rack in order to increase conservatism in the calculations.



(a) Overview in the x-y plane (b) Overview in the x-z plane

Figure 4: Plots of the dry storage facility model for O2 obtained using MCNP

It should be noted that the placement of the water wall most certainly will influence the calculations. By moving the water wall away from the rack a lower k_{eff} should be obtained, but then the conservatism of the simulations will be tampered with.

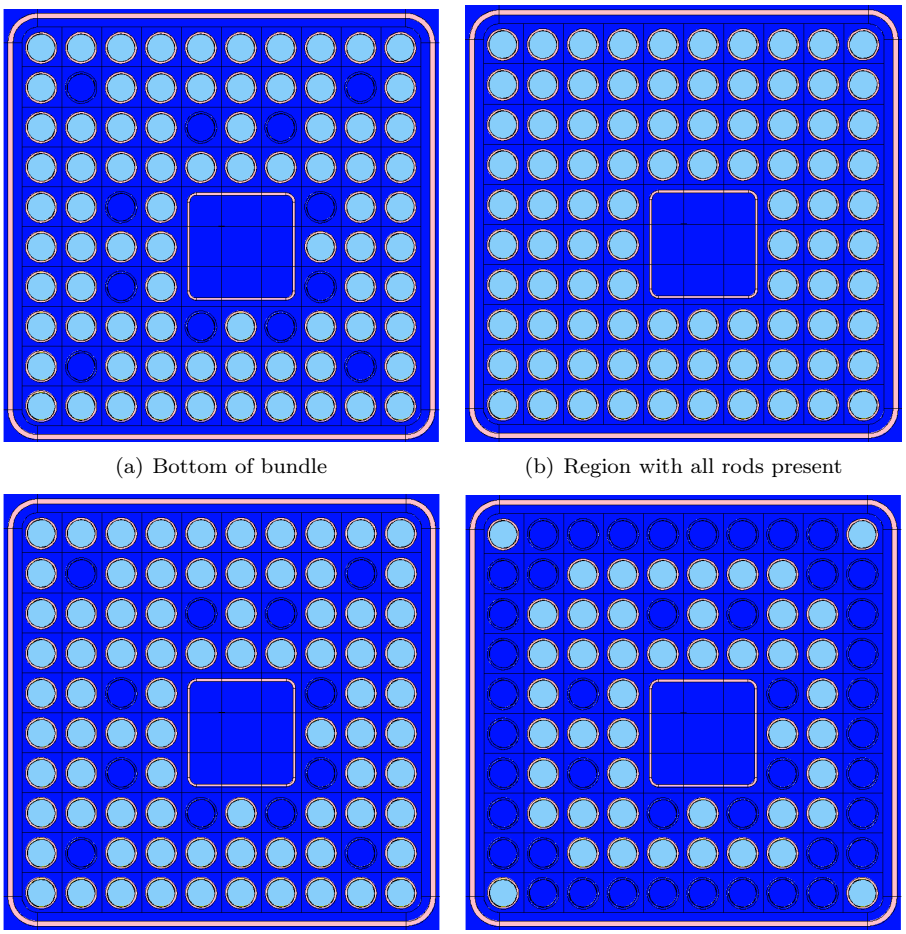
In addition to the assumptions already mentioned, the simplifications and modifications made to the model of the dry storage facility of O1 can also be applied to the model of the dry storage facility of O2.

The dimensions of the storage facility have been collected from structural drawings at the Oskarshamn NPP as well as from internal reports from OKG. [8], [7] , [6]

3.2.2 Areva - Atrium 10XM without Burnable Absorbers

The Atrium 10XM fuel bundle design consists of three types of rods. One type is a full length fuel rod which stretches the entire span of the fuel bundle. The second type of rod is a part length rod, which starts a few centimeters above the bottom of the bundle and ends a few centimeters below the middle of fuel bundle. The third kind of rods are the edge rods which are located along the edge of the fuel bundle. These rods extend from the bottom of the bundle until about 10 centimeters below the top of the fuel bundle. Cross sectional images of the Atrium 10XM fuel bundle design at four different heights from the floor can be seen in figure 5.

In the physical versions of the Atrium 10XM fuel bundle there is a handle on top of the assembly as well as a socket on the bottom of the assembly. These are made out of stainless steel which is relatively transparent to neutrons but still does have an absorption cross section.[11] These features of the fuel bundle



(a) Bottom of bundle

(b) Region with all rods present

(c) Region after the end of the part length rods

(d) Top of bundle

Figure 5: Cross section view of the 'Atrium 10XM' fuel bundle design model for O2 obtained using MCNP

was removed in the model in order to remove unwanted absorption, raise the neutrons present in the system, simplify the model and to add conservatism to the calculations.

Zircalloy is present as the box wall and as the walls of the water channel in the bundles. The water channel has in this model been simplified by being extended from the bottom of the bundle to the top, while in reality the water channel would get smaller towards the bottom and top of the bundle.

In figure 5(a) a cross sectional view of the lowest part of the fuel bundle can be seen. In this part of the fuel bundle the part length rods are not present and can therefore not be seen. The positions where the part length rods will start is filled with water at the same density as in the bulk of the storage facility. The square shaped hole off-center is the water channel.

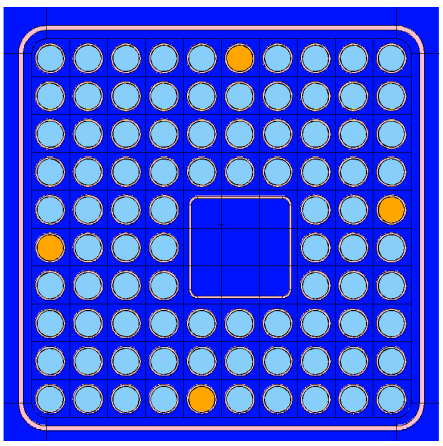
In figure 5(b) another cross sectional image of the fuel bundle is shown. From this figure one can see that all rods are present in this region of the bundle.

Figure 5(c) shows a cross section from the fuel bundle in the region where the part length rods again are no longer present. The positions where the part length rods were present is filled with water of the same density as the rest of the dry storage facility.

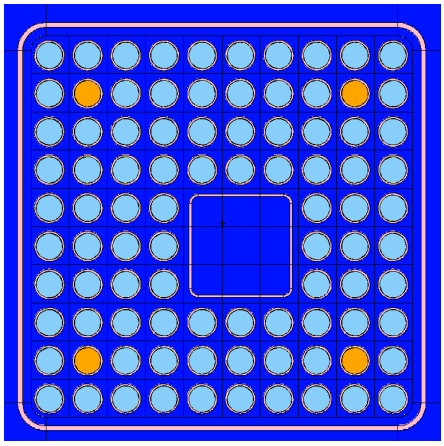
The last figure, 5(d), shows the region of the fuel bundle where only the full length fuel rods are present. The other positions are filled with water of the same density as the storage facility is filled with.

The design parameters for the Atrium10XM fuel bundle for O2 has been obtained from Areva and implemented in a correct manner.[14]

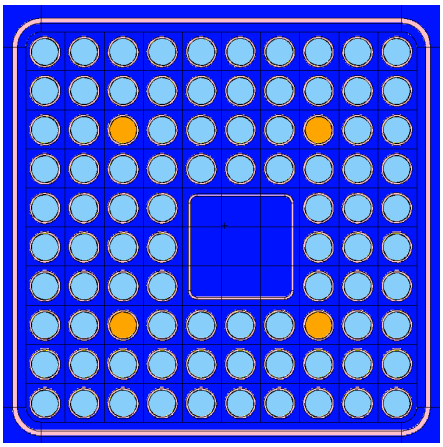
3.2.3 Areva - Atrium 10XM with Burnable Absorbers



(a) BA located in the edges



(b) BA located in part length rods



(c) BA located in optimal positon

Figure 6: Cross section view of the 'Atrium 10XM' fuel bundle design model with Burnable Absorbers in different positions for O2 obtained using MCNP

In the case of where BA is present the design of the bundle is identical as to the case when there is no BA present. All assumptions and simplifications are

also valid.

The difference is that there are four fuel rods containing BA mixed in with the fuel to a level of 2 w%. The burnable absorber used is Gd_2O_3. These rods are placed symmetrically with respect to the diagonal symmetry line of the fuel bundle because of OKG internal regulations. Usually the fuel stored in the facility have 8 or more BA rods as standard. Since a generic analysis of the facility is desired a lower amount of BA rods and a lower BA level than usually present is used for the simulations. For different cases the BA rods have been placed in different positions of the fuel bundle. The different cases can be seen in figure 6.

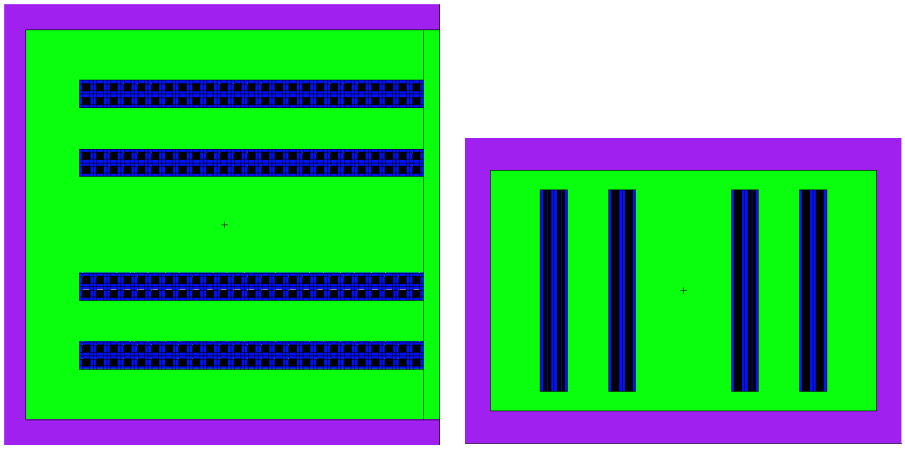
It is postulated that the placement of the BA rods shown in figure 6(a) would be the case with the least absorbing effect of the BA rods. Looking at the case in figure 6(b), the BA rods are placed in the part length fuel rods. This option has the least amount of BA present in the bundle because of the rod length. The most optimal position of the three cases is assumed to occur in figure 6(c). In this case the BA rods are full length and placed in close proximity to other full length rods which theoretically would enable them to absorb more neutrons and hence decrease the k_{eff} the most.

All BA rods have two BA free regions, one in the bottom and one at the top of the rod. The top zone is usually 30 cm long and the bottom zone is 15 cm long.

The data for for this bundle is consistent with the case without BA except in the rods containing the BA. In these rods the density will be different and lower compared with the fuel rods not containing BA. The density of these rods can be calculated using equation (**??**).

3.3 Oskarshamn 3

3.3.1 The Dry Storage Facility



(a) Overview in the x-y plane (b) Overview in the y-z plane

Figure 7: Plots of the dry storage facility model for O3 obtained using MCNP

The dry storage facility at O3 is modeled in figure 7.

The walls of the storage facility is made of concrete and each of them have a different thickness which is dependent on the location inside the plant.

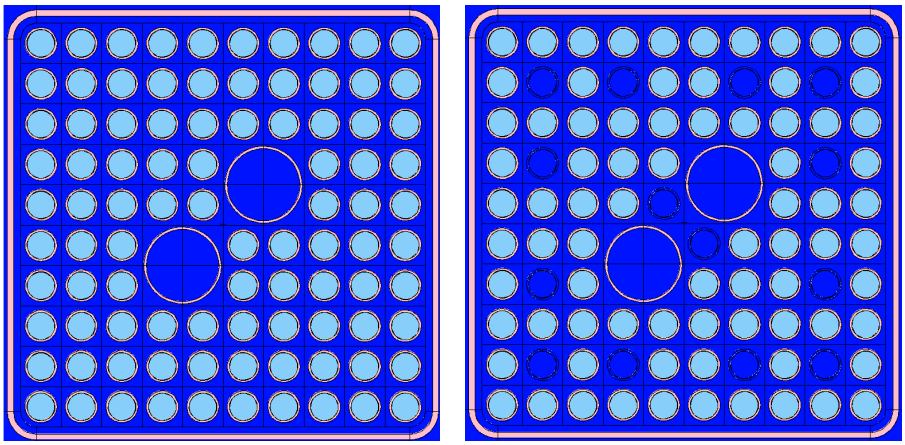
The assumptions made to the models of the facilities at O1 and O2 also applies to the facility at O3. The difference in this facility is that there are four fuel storage racks which are not placed with an equal distance from each other. There is a larger distance between the two middle fuel racks than in the previous facilities. The distance is about twice as large compared to the distance between the two racks which are located closer to each other.

Another difference is that the fuel racks are slightly bigger than in the other two facilities and can in total facilitate 200, (25x2x4), fresh fuel bundles.

The physical facility stretches another several meters to the right after the end of the fuel racks. A water wall is again put in that position to minimize the computational domain and to keep more neutrons in the system as well as adding conservatism to the calculations.

The dimensions of the storage facility have been collected from structural drawings at the Oskarshamn NPP as well as from internal reports from OKG. [8], [7] , [6]

3.3.2 GNF - GE14



(a) Lower section (b) upper section

Figure 8: Cross section view of the 'GE14 Nordic' fuel bundle design model for O3 obtained using MCNP

The design of the fuel bundles which are to be stored at the facility at O3 is almost identical to the previous described design of 'GE14 Nordic'. The main difference is the box thickness. The key design parameters can as earlier be obtained from GNF.[12]

4 Method and Calculations

4.1 Optimal Moderation

The method used to determine the maximum k_{eff} for the system is called the "optimal moderation" technique. This technique is built on the fact that the quality of moderation of neutrons is dependent on the amount of moderator material present in the system. Hence the system is put through a series of simulations where the moderator density is varied. This results in a graph showing the k_{eff} of the system as a function of moderator density present in the system.

The graph provides relevant information towards the facility's resistance to criticality events from normal storage of fuels to the unlikely event of the facility being flooded by liquid water.

The moderator material used for these simulations is a homogeneous water/air mixture, where the primary moderating atoms is the hydrogen present in the water molecules. This moderating mixture is used because it is the most probable moderating material to be present in the dry storage facility.

The initial simulations for the different densities were run with 40 kcode cycles where 10 are inactive and 30 are active cycles. This was done in order to get a statistically acceptable initial guess of which density maximum moderation would occur.

Once the spectrum is obtained the optimal density of the moderator/air mixture is determined. This density and the surrounding densities were then simulated again but with 200 cycles. This was done in order to reduce the standard deviation which in turn narrows the confidence interval of the simulations at those points and then produces a more precise result of k_{eff} around the maximum values.

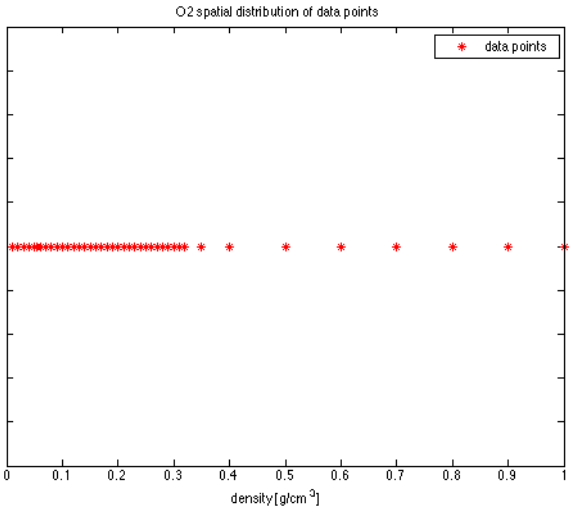


Figure 9: The different densities of the simulations

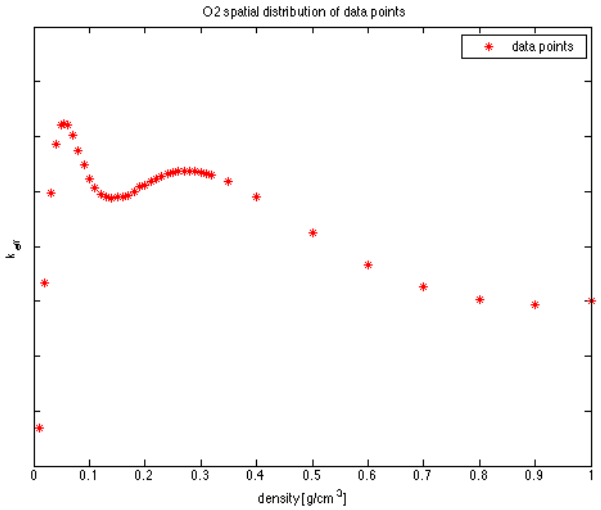


Figure 10: Datapoints of the simulations

The data points used for the simulations to obtain the k_{eff} spectrum is evenly distributed with a distance of 0.01 g/cm^3 from 0.01 g/cm^3 to 0.32 g/cm^3, then followed by 0.35 g/cm^3 which in turn is to be followed by 0.40 g/cm^3 and from then on one data point every 0.1 g/cm^3 until liquid water at 1 g/cm^3 is reached. This distribution of data points was chosen in order to get sufficient resolution of the variations in k_{eff} for different densities inside the facility and from there being able to determine where the optimal moderation will occur. The distribution of data points for the simulations can be seen in figure 9 and figure 10 as the data points located around optimal moderation.

There is one exception to this distribution, for the simulations run on O2 there is an extra data point added at 0.053 g/cm^3 due to the fact that this is where the optimal moderation occurs in that specific facility, and the small margins resent in that facility.

4.2 Enrichments

Earlier evaluations have been made on 4.0 w% enrichment of ^{235}U for Svea-64[7] and 4.3 w% enrichment of ^{235}U for Svea-96 Optima 2[8]. The goal is to generate a generic limit on what is allowed to be stored in the dry storage facilities. The initial guess towards which enrichment was to be used was set to 5 w%. In order to assess whether this level of flat enrichment in the fuel bundle was reasonable, studies had to be performed. Different enrichments were tried with simulations at a few densities around optimum moderation. Since earlier calculations had been done at 4.3 w% this set a lower limit of flat enrichment in the fuel bundles.

The simulations were run at 40 cycles with 30 active in order to get a rough estimate of how much the enrichment would influence the calculations and where to put the level of enrichments in the simulations. These simulations were performed for a few data point around optimal moderation for each facility.

The different enrichments tried in these simulations can be seen in table 3

Facility	Enrichments [w%]
O1	4.3, 4.5, 5.0
O2	4.1, 4.2, 4.3, 4.5
O3	4.3, 4.5, 5.0

Table 3: A breakdown of different enrichments tried

4.3 BA positions

As mentioned in section 3.2.3 a study with BA present in the fuel was performed for the O2 facility. The BA rods were placed in three different positions in the bundle in order to evaluate where they would have the least effect and still making the optimal moderation simulations pass the set limits. The position of these rods in the bundle can be seen in figure 6 where the yellow rods are the BA rods.

The simulations were run at 40 cycles with 30 active in order to get a rough estimate of how much the BA rod position would influence the calculations and from there decide which BA rod positions to investigate further. These simulations were performed for a few data points around optimal moderation for O2.

4.4 Uncertainties

4.4.1 Method Uncertainty

In order to obtain a statistical indication on how accurate the MCNP calculations are for the dry storage facility the method proposed in [15] was used in the same manner as in [8].

However there was a problem obtaining experiment files which could be used and be run in MCNP4c2 hence the results obtained with MCNP5 had to be used with a conservative approximation of the error. The reason for the conservative approximation is due to the fact that there is a difference in cross sections used in MCNP4c2 and MCNP5. For MCNP4c2 the library ENDF/B-V is used while in MCNP5 the library ENDF/B-VI is used. This difference in cross section library would generate a difference in the obtained k_{eff} for each experiment used for the method.

A conservative estimation of $\Delta k = 0.03291$ was found in [8] using the 12 experiments which most resemble the conditions in the dry storage facility from table 21 in [15]. The value of 1000 pcm was added as reasonable conservatism because of the difference in cross sections and because the conditions in the experiments consider differ from the conditions in the dry storage facility. So the final uncertainty which is to be added on after conservative rounding up is $\sigma_{\text{method}} = 0.04300$.

4.4.2 Other Uncertainties

Other uncertainties which were being studied were the mutually independent uncertainties which according to [4][16] were allowed to be combined statistically.

These statistically combined uncertainties are then to be added to the final result as a part of the Δk_{sc} as mentioned in section 2.2.2.

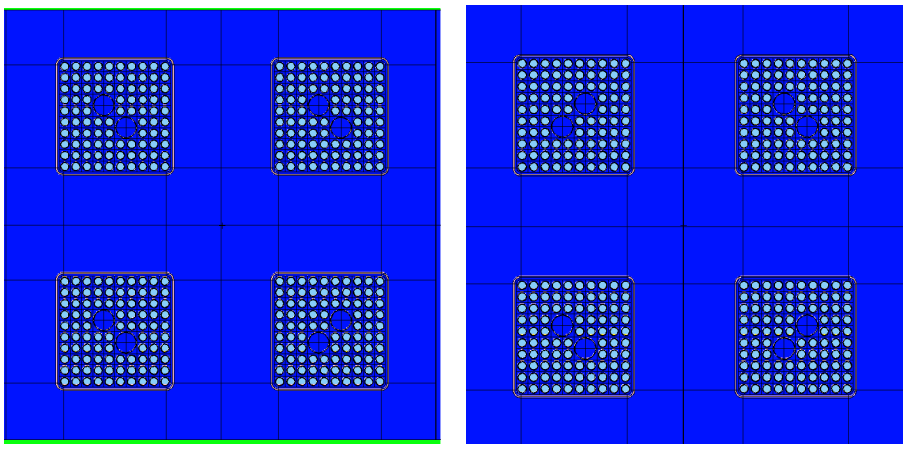
The uncertainties which have been studied and taken into account are uncertainties in enrichment, pellet density, BA w%, BA pellet density as well as manufacturing uncertainties affecting the final k_{eff}. In addition to these uncertainties, studies have been made towards how one or two rotated fuel bundles will effect the k_{eff} of the system.

These mentioned effects have been evaluated conservatively. If the studied effect had a negative contribution to the final k_{eff}, this contribution was set to zero. The if the studied effect had a positive contribution to the final k_{eff}, the effect was conservatively rounded upwards to the closest 50 pcm level. The highest obtained value for the effect studied was taken and applied conservatively to all facilities. If the confidence intervals of the simulations overlap too much, the uncertainties are estimated by the largest upper width of the confidence intervals.

The MCNP simulations were run at 200 cycles with 150 active in order to obtain a small enough standard deviation for the confidence intervals to remain reasonably small. The evaluations were performed around optimal moderation for each of the facilities.

According to results obtained in [16] and discussions with the author, the manufacturing uncertainties contribute at a very low level towards the final k_{eff}. Hence this contribution, σ_{man}, was conservatively put to 100 pcm.

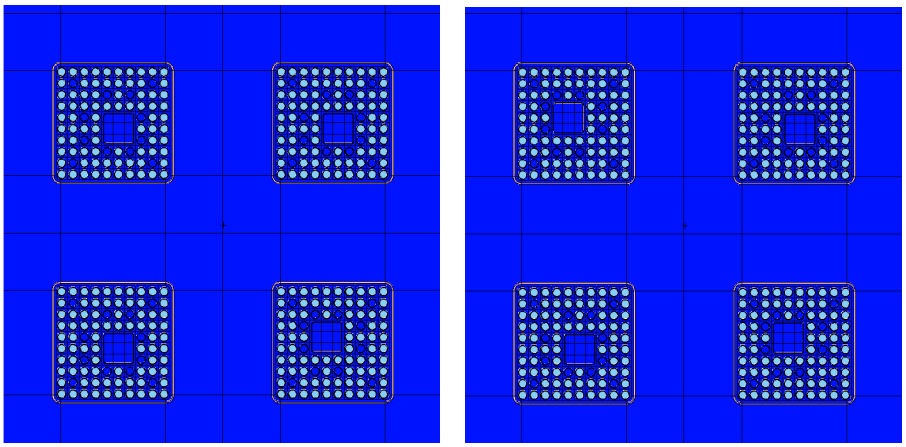
4.5 Rotated fuel bundles



(a) One rotated bundle (b) Two rotated bundles

Figure 11: Plots of the rotated fuel bundles inside O1/O3 dry storage facility

When performing the simulations for the rotated fuel bundles the aim was to rotate the bundles in such a way that as much fissile material as possible was directed against each other. The rotated bundles for O1 and O3 can be seen in



(a) One rotated bundle (b) Two rotated bundles

Figure 12: Plots of the rotated fuel bundles inside O2 dry storage facility

figure 11 and for O2 in figure 12. These rotated bundles have been placed as much towards the middle of the facility as possible.

The simulations were run at 200 cycles with 150 active cycles.

4.6 Assumptions

When considering which cases to run for the simulations the physical reality of the dry storage facility was considered. The cases presented in section 2.2.1 are not all applicable to the physical reality of the dry storage facilities of the Oskarshamn units.

The case of Dropped fuel bundle 1, where one fuel assembly is dropped and ends up on top of or in-between two fuel bundles is not applicable because there is an iron casing lined with a thin sheet of plexi glass protecting anything from entering in the wrong position. The fuel bundle cannot be dropped in-between two bundles because of the geometry.

The case of Dropped fuel bundle 2 when a fuel bundle is dropped and ends up right next to parts of the fuel bundle sticking up through the floor middle platform of the storage facility is not applicable either. This is because of the iron casing protecting the already present fuel bundles.

The case of an earthquake occurring and thus making the fuel bundles ending up closer to the other fuel bundles is not plausible. This assessment is done due to the fact of the geometry of the dry storage facility. If an earthquake should occur the geometry by the platform and the wielded iron bars keeping them i place will act as a pinch an thus keep them in place. The bundles might be a bit bent but the only possible direction for the bundle to be bent is in the direction away from the storage rack. Hence this evaluation is not done.

The case of having a denser moderator around some fuel rods have been studied in order to evaluate the hypothesis presented in [6]. The moderator density

around the full length fuel rods have been varied while keeping the moderator density around the part length and edge rods constant. The moderator density inside the facility have been kept constant at the same density as around the edge and part length rods.

5 Results

In order to present the results in a reasonable way it is in sections 5.1, 5.2 and 5.3 assumed that the density at where optimal moderation occurs is known. This can be said because the rough simulations in reality were performed before other simulations were made. These assumptions will be presented as results in section 5.4 and onwards.

The effects studied are all performed around optimal moderation for each of the facilities since this is where the effect will have the most impact towards the final result.

5.1 Enrichments

Initially the goal was to use 5 w% ^{235}U in all facilities. The obtained results from simulations with different levels of enrichments of ^{235}U in the dry storage facilities are shown in figures 13 through 15. The results of these simulations provide a base for the continuing simulations and uncertainties.

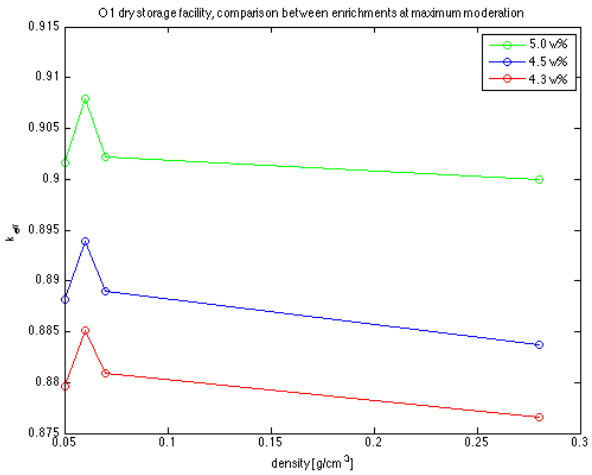


Figure 13: Results from simulations around optimal moderation for O1 with different enrichment levels

With the results from the simulations the initial guess of flat enrichment 5 w% proved to be too bold. Instead the simulations proceeded with an enrichment of 4.5 w% in O1 and O3. In the storage facility of O2 even the case of 4.5 w% was too bold so the simulations proceeded with an enrichment of 4.3 w%.

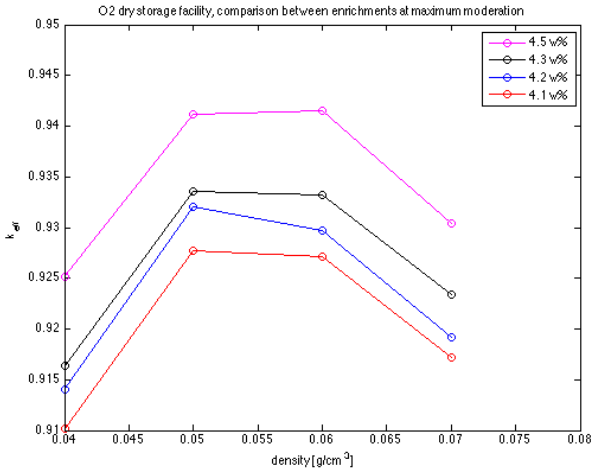


Figure 14: Results from simulations around optimal moderation for O2 with different enrichment levels

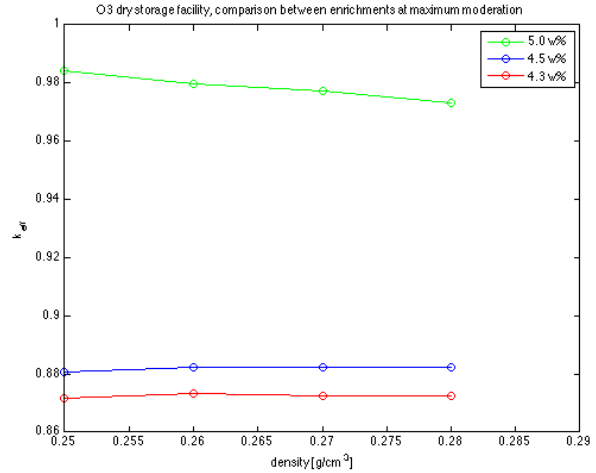


Figure 15: Results from simulations around optimal moderation for O3 with different enrichment levels

5.2 Rotated Fuel Bundles

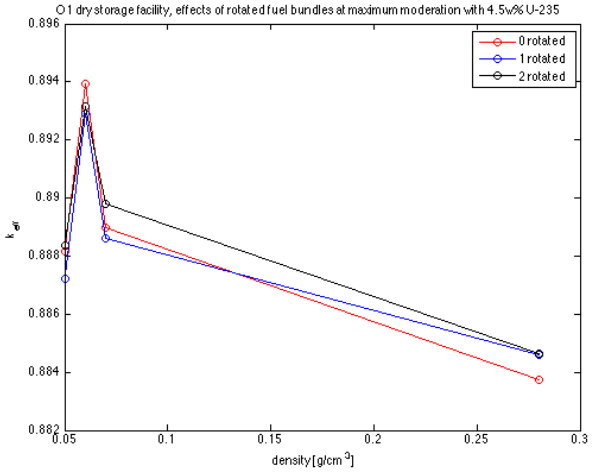


Figure 16: Results from simulations around optimal moderation for O1 with rotated fuel bundles

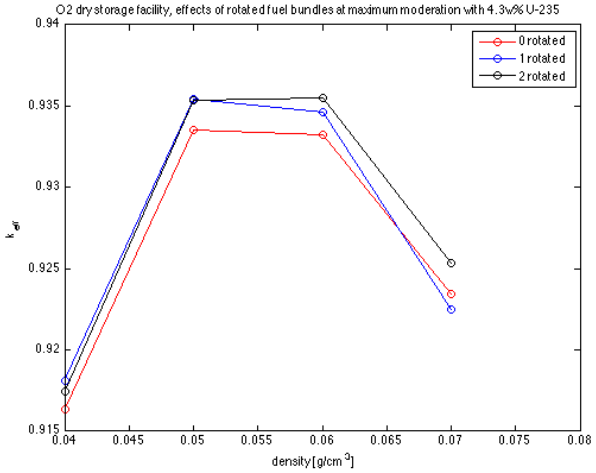


Figure 17: Results from simulations around optimal moderation for O2 with rotated fuel bundles

The results from the surveys on how the rotated fuel bundles affect the final k_{eff} can be seen in figures 16 through 18. As mentioned in section 4.4.2 the maximal positive contribution in all facilities was looked for. This difference in reactivity conservatively rounded up would be the final reactivity change contribution for the rotated fuel bundle for all facilities.

As one can see in figure 18 the effect of rotated fuel bundles have a negative effect on the final result of k_{eff} in the O3 facility. Hence the maximal reactivity

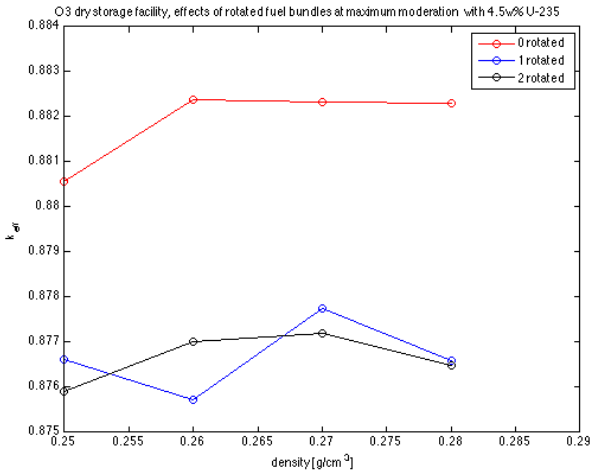


Figure 18: Results from simulations around optimal moderation for O3 with rotated fuel bundles

contribution which can be obtained from O3 is zero.

Looking at the O1 facility, figure 16, one can see that there is a clear positive effect of the rotated bundles at the density 0.07 g/cm^3. This effect has a maximum value of 83 pcm at this density. If the top peak around 0.05 g/cm^3 is studied more closely it is found that the reactivity contribution is actually negative. Hence, the maximum reactivity contribution from O1 would be 83 pcm.

From figure 17 it can clearly be seen that it is in the storage facility of O2 that the rotation of fuel bundles have the highest effect on the final k_{eff} result. This occurs at 0.06 g/cm^3 for two rotated bundles and the reactivity contribution 223 pcm. This value is then conservatively rounded upwards to 250 pcm.

From these results it can be deducted that the maximum conservative contribution of rotated fuel bundles, σ_{rot}, is 250 pcm.

5.3 Uncertainties

The studies and results presented in this section are aimed towards conservatively evaluating the magnitude of the components of uncertainties which could affect the final result.

5.3.1 Uncertainties in fuel without BA

The uncertainties studied in this section are uncertainty in enrichment and uncertainty in pellet density. The uncertainties in enrichment can be seen in figures 19 through 21.

From figures 19 through 21 one can see an overall trend that a higher enrichment gives a higher resulting k_{eff}. This is according to theory.

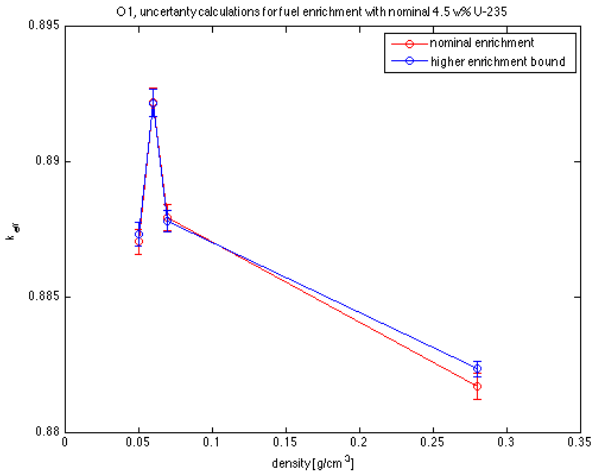


Figure 19: Results from simulations around optimal moderation for O1 with vendor supplied uncertainty in enrichment level

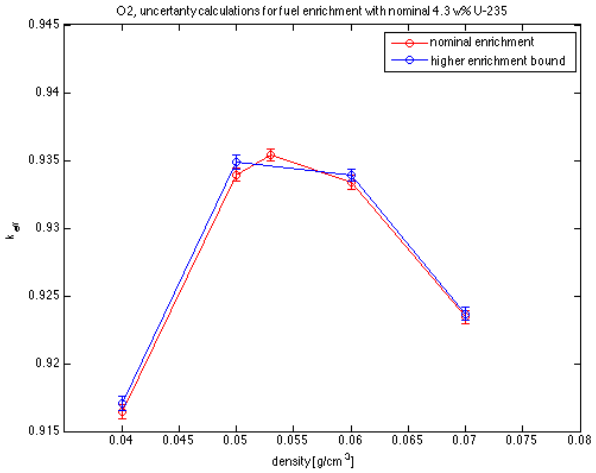


Figure 20: Results from simulations around optimal moderation for O2 with vendor supplied uncertainty in enrichment level

When looking at figure 19 one can see that there is not much difference around optimal moderation. Instead the biggest difference without the confidence intervals is noticed around 0.28 g/cm^3.

In figure 20 the trend is absolutely clear and it shows that there is an overall raise in reactivity with a raise in enrichment. However, this trend is not statistically confirmed.

An interesting effect arises in figure 21 with the peak shifting from 0.26 g/cm^3 to 0.27 g/cm^3. However the expected trend that there would be a rise in reactivity is present.

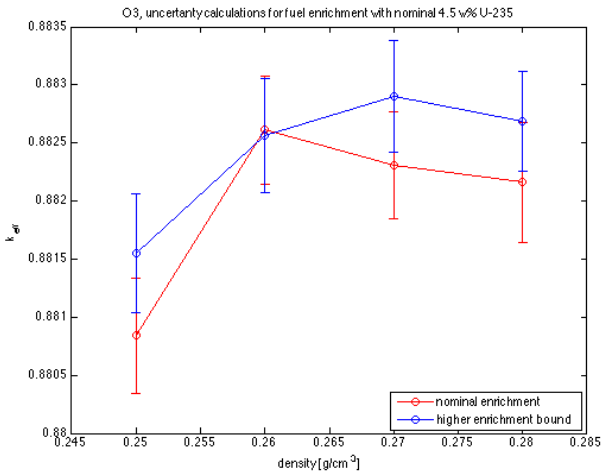


Figure 21: Results from simulations around optimal moderation for O3 with vendor supplied uncertainty in enrichment level

When looking at figures 19 through 21 it is seen that the confidence intervals of each simulation are overlapping. Since the 99% confidence intervals obtained from the simulations overlap to a large extent it is not possible to distinguish a definite trend. Hence the estimated uncertainty will be the upper limit of the obtained confidence intervals. The highest value is obtained from the O2 facility which is 54 pcm. Conservatively rounded upwards to the nearest 50 pcm gives, σ_{enr} to be 100 pcm.

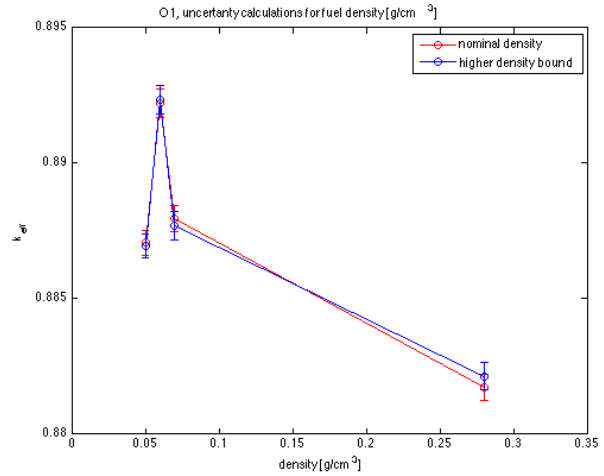


Figure 22: Results from simulations around optimal moderation for O1 with vendor supplied uncertainty in pellet density

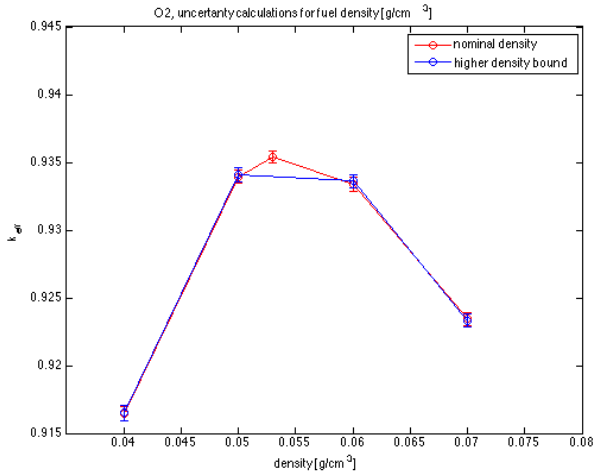


Figure 23: Results from simulations around optimal moderation for O2 with vendor supplied uncertainty in pellet density

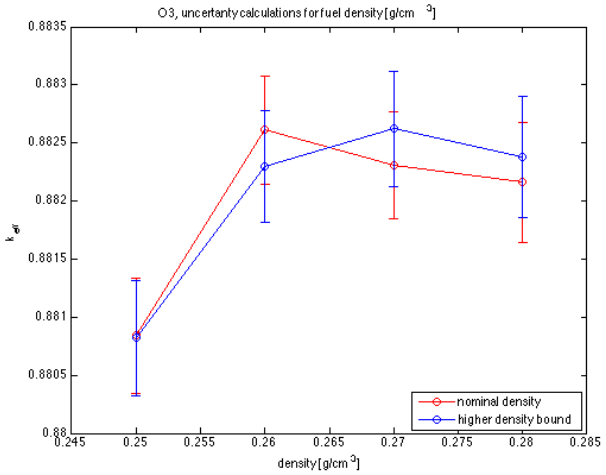


Figure 24: Results from simulations around optimal moderation for O3 with vendor supplied uncertainty in pellet density

When studying the second uncertainty, which is the pellet density, in figures 22 through 24, no obvious trend can be found. Also, the change in reactivity is very small.

For O1 the largest change in reactivity occurs at 0.28 g/cm^3 as can be seen in figure 22.

For the O2 facility, figure 23, there is a raise in reactivity for almost all of the data points.

In the O3 facility, figure 24, the same effect as when studying enrichment uncertainty occurred. The max peak shifted positions. No real trend can be

distinguished from these data points, but the maximum reactivity change is 35 pcm which occurs at 0.27 g/cm^3.

However none of these trends are statistically confirmed.

When looking at figures 22 through 24 it is seen that the confidence intervals of each simulation are overlapping. Since the 99% confidence intervals obtained from the simulations overlap to a large extent it is not possible to distinguish a definite trend. Hence the estimated uncertainty will be the upper limit of the obtained confidence intervals. The highest value is obtained from the O2 facility which is 55 pcm. Conservatively rounded upwards to the nearest 50 pcm gives, σ_{dens}, to be 100 pcm.

5.3.2 Uncertainties in fuel with BA

This section only applies to the O2 facility since it is the only facility with BA present in the fuel in the calculations. This will be explained in section 5.5

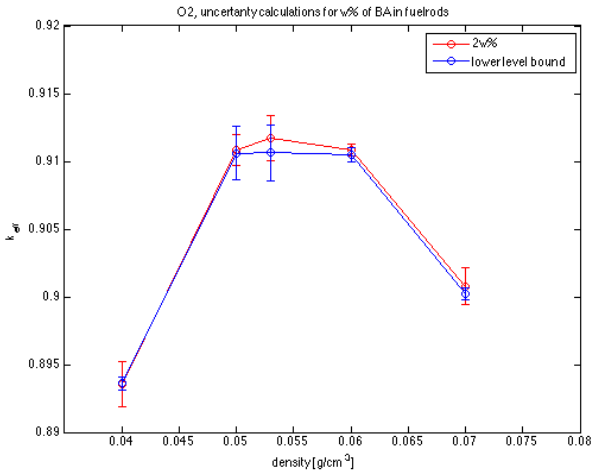


Figure 25: Results from simulations around optimal moderation for O2 with vendor supplied uncertainty in BA level present in pellet

As can be seen in figure 25 the results from studying a case with a lower level of BA present in the fuel does not really comply with theory. One can also determine that the confidence intervals are largely overlapping and hence the result cannot be statistically confirmed and hence this uncertainty is approximated with the width of the 99% confidence interval. The result obtained for σ_{BA} is then 200 pcm.

Figure 26 shows the result of the simulations for uncertainties in BA pellet density. Simulations have been done for both a higher density and a lower density. This plot shows mixed and inconsistent results and they are also no statistically confirmed. The maximum obtained value is 72 pcm. In order to

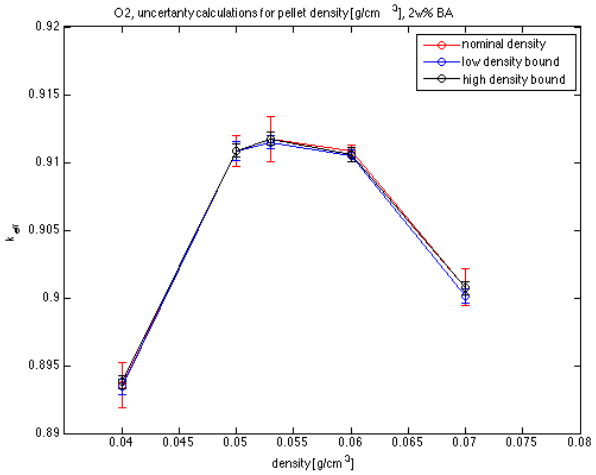


Figure 26: Results from simulations around optimal moderation for O2 with vendor supplied uncertainty in BA pellet density

preserve conservativeness the uncertainty for BA pellet density, σ_{BAdens}, is set to be 100 pcm.

5.3.3 Total Uncertainties

Previous sections have described how the uncertainties used in this section is obtained. These obtained uncertainties will now be used to calculate the total uncertainty.

Even though the maximum reactivity change might not occur at maximum moderation it will still be considered that the change is independent of density. Hence the calculated total uncertainty will be applied to all data points of the calculation. In table 4 the earlier obtained uncertainties are collected.

Uncertainty	Notation	Magnitude [pcm]
Method uncertainty	σ_{method}	4300
Rotated fuel bundles	σ_{rot}	250
Enrichment	σ_{enr}	100
Manufacturing	σ_{man}	100
Pellet density	σ_{dens}	100
w% BA	σ_{BA}	200
BA pellet density	σ_{BAdens}	100

Table 4: Summary of obtained uncertainties

Since the latter presented uncertainties are mutually independent, they are allowed to be combined statistically to a total uncertainty. This is done by the following equation

$$\sigma_{\text{tot}} = \sqrt{\sigma_{\text{rot}}^2 + \sigma_{\text{enr}}^2 + \sigma_{\text{dens}}^2 + \sigma_{\text{man}}^2} = 304\text{pcm} \approx 320\text{pcm} \tag{4}$$

or if BA is present in the bundle it is calculated by

$$\sigma_{\text{tot}} = \sqrt{\sigma_{\text{rot}}^2 + \sigma_{\text{enr}}^2 + \sigma_{\text{dens}}^2 + \sigma_{\text{man}}^2 + \sigma_{\text{BA}}^2 + \sigma_{\text{BAdens}}^2} = 377\text{pcm} \approx 400\text{pcm} \quad (5)$$

According to section 2.2.2 and equation (3) the total uncertainty has to be added to the final obtained simulated result. The factor Δk_{sc} from equation (3) can be written as

$$\Delta k_{sc} = \sigma_{\text{method}} + \sigma_{\text{tot}} \quad (6)$$

Where σ_{method} is obtained from section 4.4.1.

5.4 O1

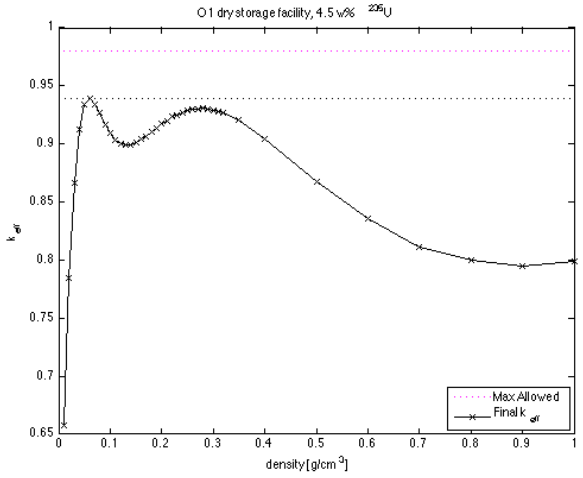


Figure 27: Final result of simulations of the O1 facility

Figure 27 shows the final result from the simulations of the O1 facility. The black line in the figure represents k_p of equation (3). As can be seen the final result has a comfortable margin to the maximum allowed value. A breakdown of how the final result is obtained can be seen in figure 28

To start of with, the red line shows the output values obtained from the MCNP simulations. The spatial distribution of these data points can be seen in figure 9. This makes up the k_s-part of equation (3).

The blue line, which is the next line above the red line in the graph, is the upper limit of the 99% confidence interval produced by the MCNP calculations. The green line is the value of σ_{method} added on to the values of the blue line according to the arguments presented in section 2.2.2. Finally the black fully drawn line is where the value of σ_{tot} was added on to the values of the green line. These parts makes up the Δk_{sc} of equation (3) and hence also the final result of the evaluation of the O1 facility.

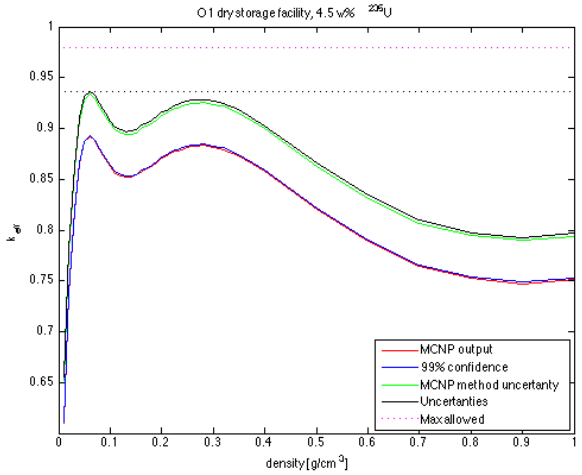


Figure 28: Breakdown of final result from simulations of the O1 facility

The magenta dotted line in figure 28 is the maximum value set by SSM for H3 events, i. e. for optimal moderation. The black dotted line is the final obtained value for the evaluation of the facility extended for easier overview. Also it can be said that the magenta dotted line equates to k_{ref} and the black dotted line equates to k_p from equation (1).

The final value to determine is the H2 event of when the whole facility is flooded with liquid water. The value for this evaluation can easily be obtained from figure 28 by looking to the far right of the graph and collect the value of k_{eff} at the density 1 g/cm^3

The values obtained from the simulations are presented in table 5

Max k_{eff}	0.9387
Density	0.060 g/cm^3
H1/H2 margin	15 110 pcm / 15.9%
H3/H4 margin	4 130 pcm / 4.2%

Table 5: The results from simulations of the O1 facility

The percentage margin is calculated by the following relation

$$\sigma_{\text{margin,H3/H4}} = (0.98 - k_p)/0.98 \tag{7}$$

for H3/H4 events and for H1/2 events the margin is given by

$$\sigma_{\text{margin,H1/H2}} = (0.95 - k_{\text{eff, 1g/cm}^3})/0.95 \tag{8}$$

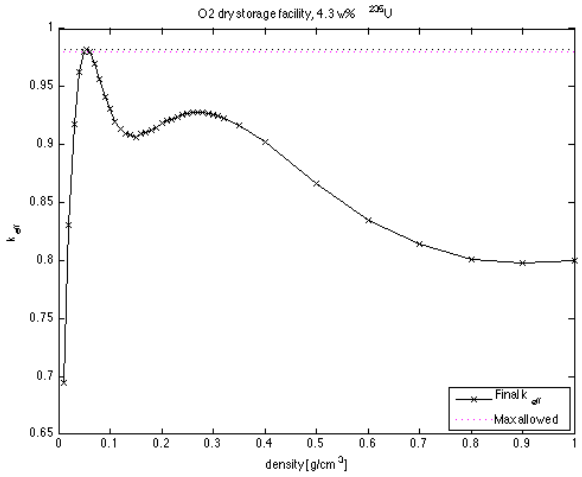


Figure 29: Final result of simulations of the O2 facility without BA present

5.5 O2

5.5.1 Without BA

The obtained result from the simulations performed on O2 can be seen in figure 29 and a breakdown in figure 30.

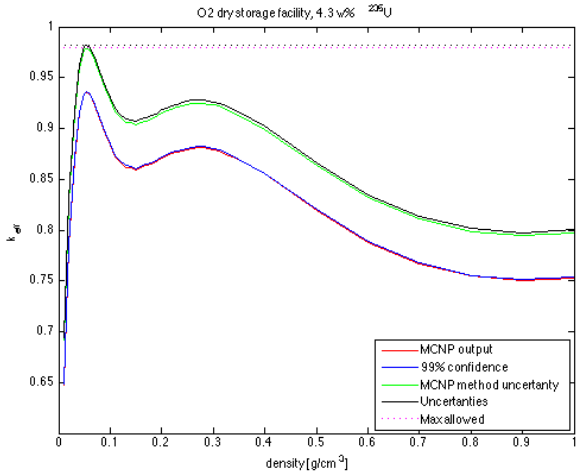


Figure 30: Breakdown of final result from simulations of the O2 facility without BA present

By following the same procedure as in section 5.4 the breakdown for the facility at O2 can be explained. From figures 29 and 30 it can be seen that the final obtained value is very close to the magenta dotted SSM limit line. In order

to more closely determine if the values are below the SSM limit figure 31 shows an enlargement of the optimal moderation area of figure 30.

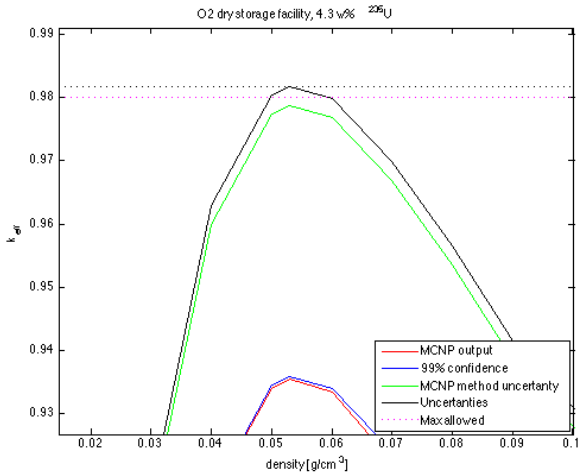


Figure 31: Zoom around optimal moderation on breakdown of final result from simulations of the O2 facility without BA present

From this figure it can be determined that the obtained result overshoots the SSM limit by a small margin. Hence, the final results for the O2 facility without BA present in the fuel do not satisfy the SSM limits at a satisfactory level for the H3 event of optimal moderation. In table 6 the results for this evaluation is presented.

Max k_{eff}	0.9818
Density	0.053 g/cm^3
H1/H2 margin	14 980 pcm / 15.8%
H3/H4 margin	-180 pcm / -0.21%

Table 6: The results from simulations of the O2 facility

The H1/H2 and H3/H4 margins have been calculated using equations (7) and (8).

5.5.2 With BA

Because of the results in section 5.5.1 something had to be done in order to reduce reactivity inside the facility. Lowering the level of enrichment of the fuel was to be a last resort since earlier calculations with the enrichment of 4.3 w% and some BA rods have been shown to pass the criteria for other fuel designs. The solution to the problem was that BA rods were added to the bundle. In order to determine where the BA rods should be placed in the simulations three cases were postulated. The cases can be graphically be seen in figure 6.

The results from the simulations run on the different BA rod positions can be seen in figure 32. From this graph one can see that placing the BA rods

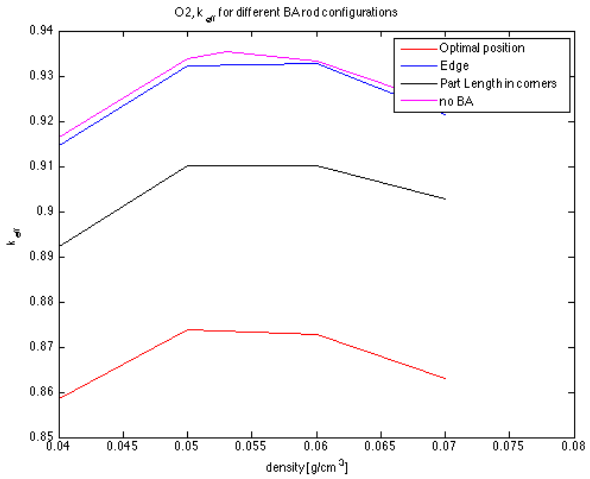


Figure 32: Results from the simulations of BA rod positioning

towards the edge of the bundle will not generate that much on an effect towards reactivity reduction. The placement of the BA rods in the most central positions was the most effective position of the rods. This reduced the k_{eff} of the system significantly. The placement of BA rods which produced a small enough reduction in the total k_{eff} but did not put any stringent conditions on the configuration of the bundle was the placement of the BA in the part length rods.

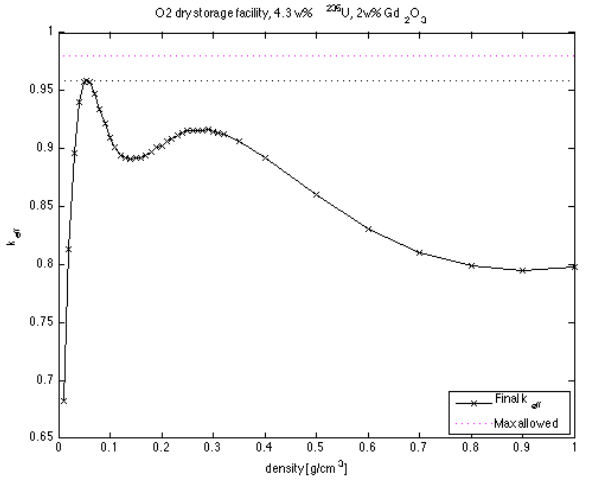


Figure 33: Final result of simulations of the O2 facility with BA present

The final result for the evaluation of having BA in the part length rods is shown in figure 33 and a breakdown is shown in figure 34. The graph is obtained in the same manner as described in section 5.4. From this figure it can be seen

that the facility can handle these bundles with a satisfactory margin if there are BA rods present at certain conditions. The results obtained are presented in table 7.

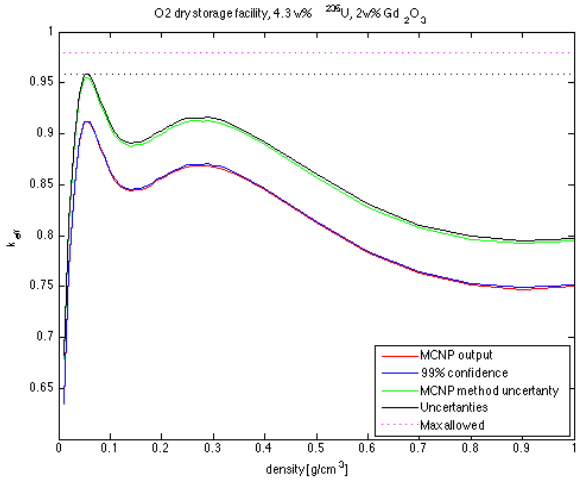


Figure 34: Breakdown of final result from simulations of the O2 facility with BA present

Max k_{eff}	0.9583
Density	0.053 g/cm^3
H1/H2 margin	15 260 pcm / 16%
H3/H4 margin	2 080 pcm / 2.12%

Table 7: The results from simulations of the O2 facility containing BA rods

The H1/H2 and H3/H4 margins in table 7 have been calculated using equations (7) and (8).

5.6 O3

The final results from the simulations are shown in figure 35. The properties of this graph shows that optimal moderation occurs at the second bump instead of the first which is the case in the O1 and O2 facilities. It can also be seen that there is a comfortable margin to the maximum limit set by SSM. The breakdown of the result is shown in figure 36 and this follows the method presented in section 5.4

The final results are presented in table 8, where The H1/H2 and H3/H4 margins have been calculated using equations (7) and (8).

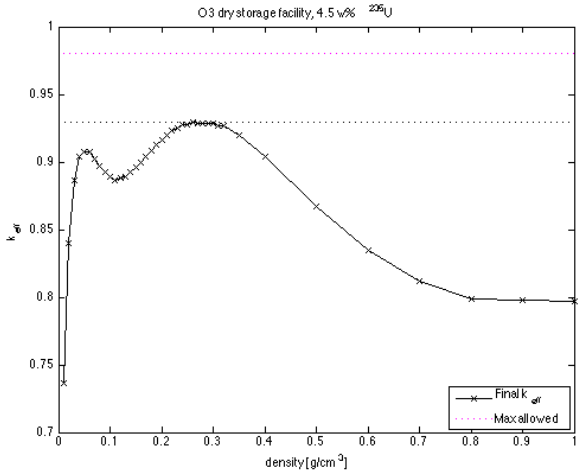


Figure 35: Final result of simulations of the O3 facility

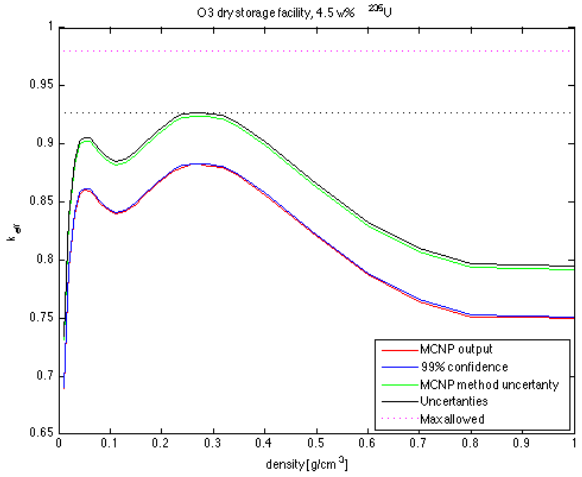


Figure 36: Breakdown of final result from simulations of the O3 facility

"Storhet"	value
Max k_{eff}	0.9291
Density	0.260 g/cm^3
H1/H2 margin	15 340 pcm / 16.1%
H3/H4 margin	5 090 pcm / 5.2%

Table 8: The results from simulations of the O3 facility

5.7 Statistics

In order to assess the validity of the results the statistics of the simulations have to be studied.

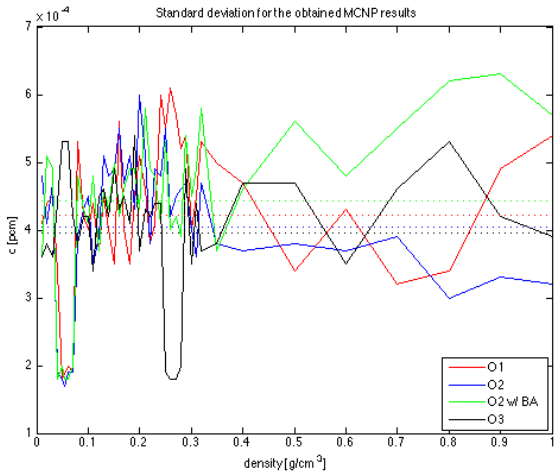


Figure 37: Standard deviation of k_{eff} for each facility as a function of moderator density

Figure 37 shows the standard deviation for all data points of the MCNP simulations. The dotted lines are the average standard deviation for the respective simulations according to color. It can be seen that the standard deviations consistently have a value fairly close to the average value. The exception to this is the large dips which occurs from 0.04 g/cm^3 to 0.07 g/cm^3 for the O1 and O2 facilities and 0.25 g/cm^3 to 0.28 g/cm^3 for the O3 facility. These dips correspond to the fact that the simulations around optimal moderation have been performed with a larger amount of cycles than the others. This was done in order to obtain a more precise result around optimal moderation. From this graph the conclusion can be drawn that there is a higher precision in the results obtained around optimal moderation for each of the facilities, because of the higher amount of cycles run in the simulations at those points.

In order to check wether the 99% confidence interval produced by MCNP was consistent with the standard deviations, the obtained MCNP value was subtracted from the upper limit of the 99% confidence interval from the MCNP simulations. This can be seen in figures 38 and 39. Figure 38 shows the calculation in absolute pcm values and figure 39 shows the same thing but as % deviation from the mean value of the different facilities.

It can be seen that these values are consistent with the obtained standard deviations and hence the conclusion that the simulations are consistent and valid can be drawn

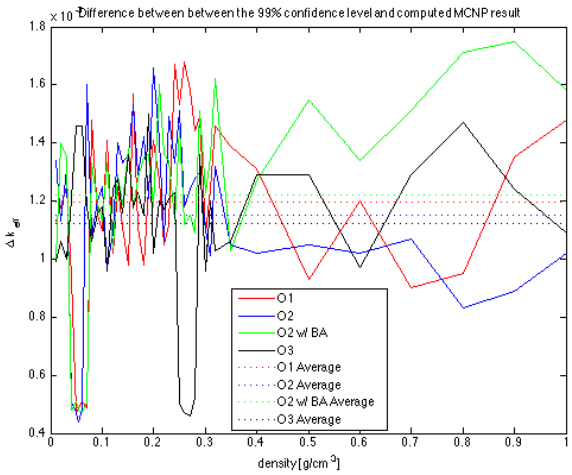


Figure 38: Obtained result subtracted from the 99% confidence interval value for each density of the simulations

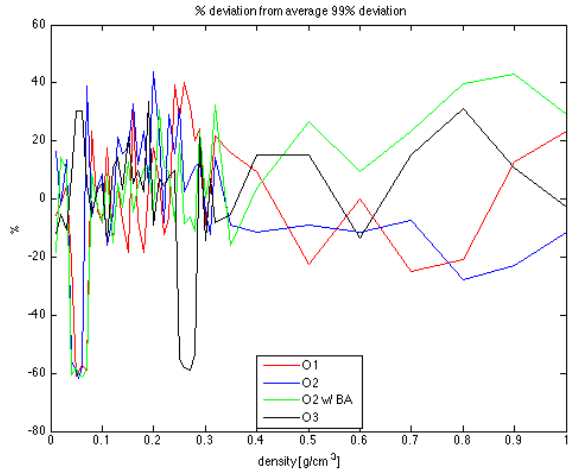


Figure 39: Obtained result subtracted from the 99% confidence interval value for each density of the simulations presented as % deviation from the mean value for the facility

5.8 Other conditions

For the results shown in figure 40 the moderator density around the full length fuel rods have been varied while keeping the density at 0.24 g/cm^3 in all other positions. The intention is to simulate materials used during transport still being left within the assembly during storage in the facility at O2. The facility at O2 has presented itself to be the most sensitive facility, with the smallest margins.

The result of these simulations can be seen in figure 40. The red line is

the values obtained for the O2 facility for the regular simulations without the 99% confidence values. The blue line is the values obtained when simulating transport materials being left with the fuel bundles after transport. The data points have been marked in the figure.

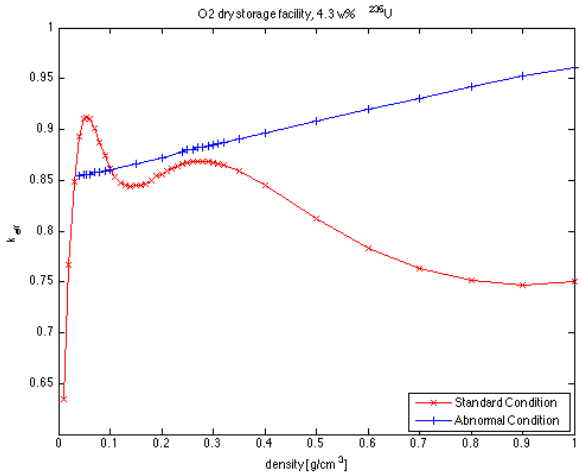


Figure 40: Example of a special case where the k_{eff} can obtain a higher value than allowed

It can be seen that the hypothesis postulated, in [6], is true and the maximum value is obtained when there is liquid water surrounding the full length fuel rods. This value is higher than the optimal moderation value which is completely in line with the predictions in [6]. It has to be noted that in order to obtain these values the same thing has been applied to all fuel bundles inside the facility. There has been material left around all full length rods in all bundles in the facility. This will in practice never happen due to the rigorous ocular inspections being made to the fuel before being stored inside the facility.

However one conclusion which can be drawn from this experiment is that it is important to get rid of all the material used to prevent fuel damage during transport. This has to be done thoroughly before the fuel can be stored inside the facility in order to prevent anything like the situation above from happening.

5.9 Comparison to older results

In order to determine whether the results obtained are reasonable a comparison between the obtained results and older results has been done. The bundle design which have been chosen for comparison is the 'SVEA-64' bundle design. This was chosen due to the availability of earlier MCNP results. The results can be seen in figures 41 through 43.

As can be seen in the figures the general shape of the obtained curves coincide well with the older results. The maximum values for the optimal moderation

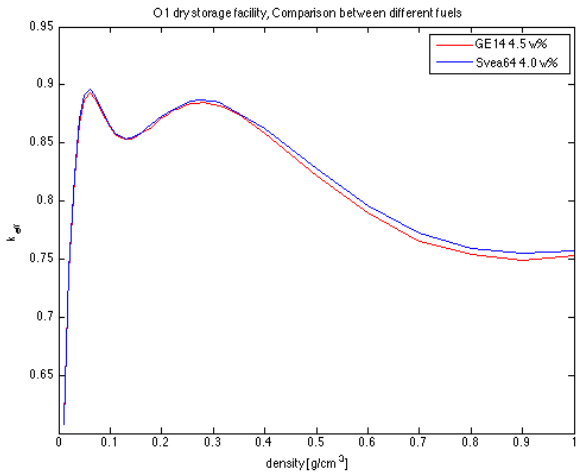


Figure 41: Comparison between 'Svea-64' and 'GE-14 Nordic' for the facility O1

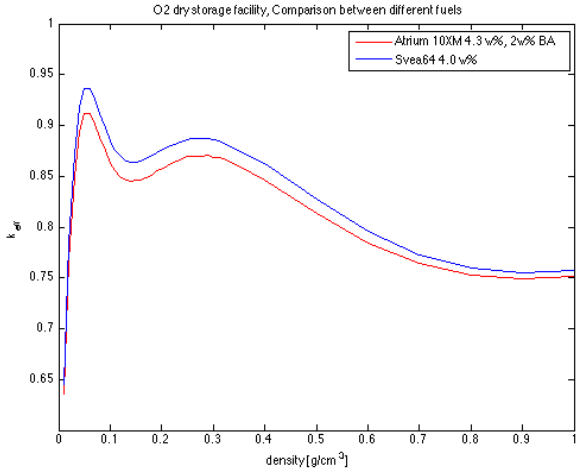


Figure 42: Comparison between 'Svea-64' and 'Atrium 10XM' for the facility O1

simulations occur at the same place in the different facilities. This fact points towards the results of the simulations being reasonable and valid.

The fact that the values obtained from the new simulations are slightly lower in magnitude than the earlier obtained values can be explained by the design of the fuel bundles. The 'SVEA-64' fuel bundles have all full length rods and a enrichment of 4.0 w% ^{235}U while the bundles studied have part length rods in the design. This breaks the homogenicity of the bundle and could create an overall lowering effect of the total k_{eff}. It can also be noted that the 'SVEA-64' design is a 8x8 fuel pin design which uses thicker fuel rods. The fuel bundle designs 'GE14 Nordic' and 'Atrium 10XM' are designed with 10x10 rods. In

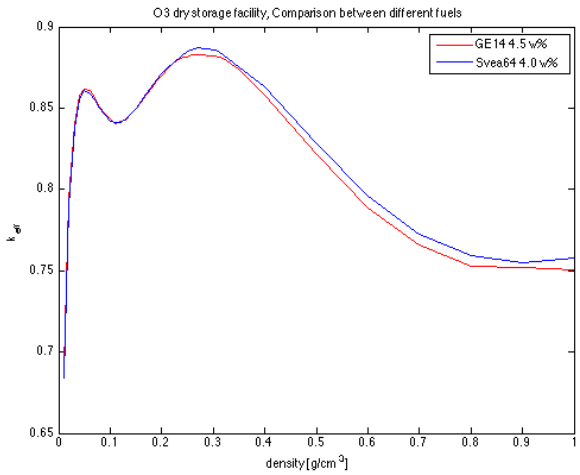


Figure 43: Comparison between 'Svea-64' and 'GE-14 Nordic' for the facility O3

order to facilitate that amount of rods inside the assembly of roughly the same size as 'SVEA-64' the rods in the new designs need to have thinner dimensions.

The fact that the maximal k_{eff} in the simulations does not occur when liquid water is present, can be explained by the fact that the system is heavily overmoderated in that configuration. Hence, this effect will reduce the k_{eff} of the system. As to where the maximum points occur and why there are two bumps in the graphs the most probable explanation is that it is due to geometry reasons of- and inside the facility. At the present time further statements regarding this matter cannot be done since it would require a completely different methodology in order to assess and explain from where these bumps in the result arise. Variables that could be studied in order to determine this more closely are the spacing between the racks, spacing between the bundles and the number of bundles inside the facility.

5.10 Summary and Conclusions

To sum things up the results obtained from these simulations prove that the fuel bundle designs 'GE14 Nordic' and 'Atrium 10XM' can be stored in the respective facilities. The final results are condensed into table 9. The limits to compare the results with are found in section 2.2.1 and presented in table 9.

Facility	Max k_{eff}	Density [g/cm^3]	Margin H1-H2 [%]	Margin H3-H4 [%]
O1	0.9387	0.060	15.9	4.2
O2	0.9818	0.053	15.8	-0.18
O2 (BA)	0.9583	0.053	16.1	2.12
O3	0.9291	0.260	16.1	5.2

Table 9: Summary

The O1 facility passes the limits with flying colors as it has a H3/H4 margin of 4.2% and a H1/H2 margin of 15.9%. The H3/H4 margin is well below the 2.04% margin required to pass the criteria.

From this the generic conditions to the 'GE14 Nordic' fuel bundle design is that the flat enrichment cannot be above 4.5 w% ^{235}U. No BA rods inside the bundles are required in order to store the fuel in the facility.

The O2 facility is the facility with the most stringent conditions on the design of 'Atrium 10XM' which is allowed to be placed inside the facility. The bundle has a H3/H4 margin of 2.2% which is not far away from the SSM limit of 2.04%, but it does satisfy the criteria. However the H1/H2 margin is with a value of 16.1% well away from the required 5.27% limit.

The bundle cannot have a higher flat enrichment than 4.3 w% ^{235}U and it is required to have at least 4 BA rods which are placed symmetrically along the diagonal symmetry line of the bundle where two have to be on the symmetry line. The BA can be placed in a full length rod which will reduce the final k_{eff} which has been proved in earlier simulations, but it can also be placed in the part length rods which are located one step in on the diagonal in the bundle. There is also allowed to be a 30 cm BA-free zone in the top of the part length bundle and a 15 cm BA-free zone in the bottom of the fuel bundle when the BA is placed in the part length rods. The lowest allowed level of BA present in the fresh fuel is 2w%.

Usually the fuel being placed inside the facility has 8 or more BA rods present in the fuel bundle, so in reality this condition in not very stringent.

The O3 facility also passes the limits with flying colors as it has a H3/H4 margin of 5.2% and a H1/H2 margin of 16.1%.

The generic conditions for the 'GE14 Nordic' fuel bundle design to be stored inside the facility is that the bundle cannot have a flat enrichment of ^{235}U higher than 4.5 w%. No BA rods are required for the bundle design to be stored inside the O3 facility.

Another condition which has to be pointed out is that all fuel bundles have to be inspected thoroughly in order to remove any material used during transport before being stored inside the facility. This has to be done in order for the event described in section 5.8 not to occur.

6 Discussion

The results from the simulations of the 'GE14 Nordic' and 'Atrium 10XM' fuel bundle designs coincide to a large extent with earlier results from simulations and studies on other fuel bundle designs. An example for the bundle design 'SVEA-64' can be seen in figures 41 through 43 which have been obtained from [7]. From the text by W. Lipiec[8] the results for the bundle design 'SVEA-96' have been studied. These results also coincide very well with the results obtained for the 'Atrium 10XM' design. The density at where optimal moderation occurs coincide with the results from this thesis. The maximum k_{eff} obtained for 'SVEA-96' do not differ significantly from the value obtained in the simulations for 'Atrium 10XM'.

Since the design of the bundles studied in this thesis differ from most other bundles studied earlier there should be some discrepancy between the results. The densities at where optimal moderation occurs are still the same for the different facilities, this shows that the model exhibit the same characteristics as earlier simulations. Since the results coincide with older experiments which have been approved by SSM, it can be concluded that the model and the results from the simulations are generally reliable and correct.

The calculations can be further refined by increasing the number of runs and decrease the statistical uncertainty. At the densities where optimal moderation occurs the statistics were the best because of the number of cycles performed around those densities. The upper width of the confidence intervals produced by MCNP around those densities were no larger than 50 pcm. The 50 pcm wide confidence interval could be made better but that would require too much unnecessary computer time since the result would be the same in the end. Hence the statistics for the simulations are sufficient for the purpose.

It can also be noted that the simulations passed all the statistics tests which are built in into the MCNP code. Because of this it can be noted that the statistics of the simulations are reliable and correct for the geometry present in the model.

Because the method uncertainty addition to the MCNP result is used to provide a higher k_{eff} means that the result should be looked at more as a possible outcome than a fact. This result must not be used as a buffer for making unstudied decisions, meaning that one can not use this result and say that it applies to other cases unless the effects of the changes are considered. In order to make this completely valid one needs to consider the cross section libraries used in the simulations and how they impact the final result. In certain cases new simulations should be made to confirm the conclusions drawn.

One other feature of the study which needs to be addressed is the other uncertainty calculations. These simulations have been performed around where optimal moderation occurs for each of the facilities, since this is where the uncertainties will have the most impact on the final results. The results obtained from these simulations have deviated so little from the results obtained by the standard simulations that their error bars have overlapped to a large extent. This means that there cannot be a statistically distinguished difference between

the results of the two different simulations. Hence the approximation with the upper width of the confidence interval as the uncertainty is very conservative. In order to fully resolve the differences one needs to run the codes for a sufficiently larger amount of time. The results obtained from those simulations would not have contributed to a more precise result of the uncertainty simulations.

One last interesting topic which could be the subject for academic research is how the geometry of the facilities affect the final result of the simulations. Since it can be seen that O2 facility is the most limiting facility and the maximum peak of the simulations are quite large, one could argue that there might be some limiting factors in that storage facilities which have to be considered when designing future plants.

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A Popular Science Article

Theory

The fuel used in a nuclear power plant is uranium. The fuel before entering the reactor usually consists of two major isotopes of that element. These isotopes are ^{238}U and ^{235}U where the latter is the isotope which is used as fuel. The way energy is released is through splitting the core of the ^{235}U isotope. This is done by a neutron which at low energies get absorbed by the nucleus which then by internal instability splits into two fragments and a few excess neutrons with high kinetic energy. These excess neutrons can then be used to split new nuclei. This can in turn create a chain reaction where nuclei are split at an uncontrollable rate. The rate of new neutrons compared to old neutrons is described by the effective neutron multiplication factor, k_{eff}.

In order to get these excess neutrons to loose energy, a moderating material is used. This moderating material contains a high amount of hydrogen atoms. The reason why hydrogen rich materials are used is because neutrons loose the most amount of energy if they collide with atoms close to their own weight. The moderating material used in this project is water of varying densities.

Before the fuel is inserted and used in the reactor, it needs to be stored somewhere. This is done in facilities at the nuclear power plants. In order to make sure that no uncontrolled chain reactions can occur inside that facility, different types of analyses are performed. One way these analyses can be performed is through the code MCNP which a computer code based on the Monte Carlo simulations principle.

The Monte Carlo simulations principle is completely based on statistics. The experiment in question is performed multiple times with different initial conditions. Out of the statistics provided by these experiments one can then determine properties of the system studied. Since all events are saved and counted almost anything can be determined from the experiments. The major thing which can be decided for this application is the multiplication constant of the system i. e. the k_{eff}.

Background

Recently the Oskarshamn plant have switched vendors of fresh fuels for their three boiling water reactor units. This also means that the design and composition of the fresh fuel bundles stored in the facility will change. Because of this an analysis of the new bundles inside the facilities needs to be performed in order to assess the fact that unwanted criticality events will never occur inside the facility at any time.

The way to make sure that no unwanted criticality accidents can occur one looks at the effective neutron multiplication constant, k_{eff}. If k_{eff} is equal to one a critical system is obtained and there will be a constant amount of neutrons present in the system at all times, it also implies that there is a self sustaining controlled chain reaction.

Method

The way the result is determined is through the following equation.

$$k_p \leq k_{ref}$$

In this equation the left hand side represents the upper limit of the final calculated multiplication factor while the right hand side represents the lower tolerated limit for the calculated k_{eff} of the system. In order to obtain the k_p one needs to consider the method used and the uncertainties associated with the method and the model used.

In the physical storage facility the fuel is arranged in storage racks, the walls are made of reinforced concrete and the facility is reasonably large. When producing the models used for the simulations, certain simplifications to the true geometry had to be made. The steel used to reinforce the concrete was removed, the dimensions of the room was changed so the model had smaller dimensions than the true facility. Also in order to decrease the model in a conservative fashion a fictitious wall made of water had to be inserted.

All of these simplifications needed to be done in order to reduce computational time and to add conservative values to the calculated results. The reason why conservative values are wanted is that if the simulations pass the requirements with the simplifications made the true system will be sufficiently safe.

What has been done in these simulations is that the whole facility has been filled with a water/air mixture of different densities ranging from 0.01 g/cm^3 to 1 g/cm^3. This provides graph of k_{eff} for the system as a function of moderator density.

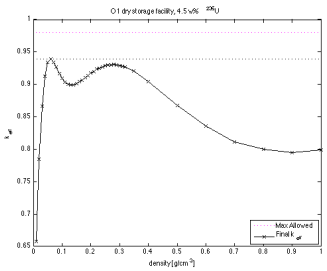
Results

Results of the MCNP simulations can be seen in figures 44 and 45. They have been presented in different ways hence the different appearances of the figures. The black lines in both figures 44 and 45 of the graphs are identical. In figure 45 the graphs show how the results in figure 44 was obtained through addition of the different uncertainties.

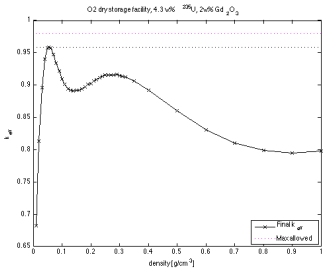
The plots of the results in figure 45 show at the top a magenta dotted line. This is the maximum value the results of the simulations are allowed to reach. The simulated result with a simulation uncertainty are the red/blue lines of figure 45. The green line are the results when systematic uncertainties are added and the black line is the results when all production uncertainties are considered. The final result is the black line. The margin of the results is the difference between the magenta and the black dotted lines, as can be seen the margin of the results are good.

The maximum k_{eff} value obtained occurs for the O2 facility and has a value of 0.9583. The maximum value which is allowed is 0.98 hence a margin of 0.0217 is obtained. This is a satisfactory margin considering that the SSM margin limit it 0.02. The general conclusion of the work is that the new fuel designs are allowed to be stored in the facilities before use in the reactor.

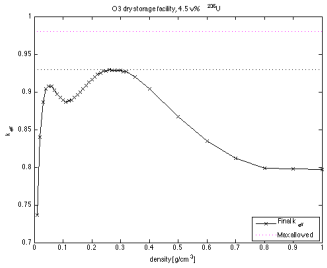
One of the reasons why the results differ from each other inside the facilities are because of geometry differences between the facilities. They each contain different amounts of fuel elements as well as the alignments of the relative to the facility walls are different.



(a) Results from the O1 unit

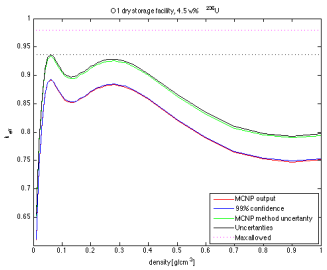


(b) Results from the O2 unit

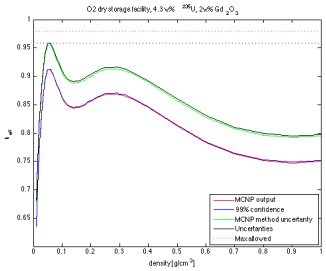


(c) Results from the O3 unit

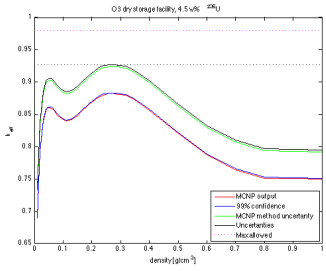
Figure 44: Simulated value of k_{eff} as a function of moderator density, final results.



(a) Results from the O1 unit



(b) Results from the O2 unit



(c) Results from the O3 unit

Figure 45: Simulated value of k_{eff} as a function of moderator density, breakdown of final results with uncertainties included