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ENRICHMENT DETERMINATION FOR PEBBLE BED REACTOR SYSTEMS

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ENRICHMENT DETERMINATION FOR PEBBLE BED REACTOR SYSTEMS

URČENÍ OBOHACENÍ U REAKTORŮ S KULOVÝM LOŽEM

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1 GENERAL BACKGROUND INFORMATION

The PBMR is a helium-cooled, graphite-moderated high temperature nuclear power reactor. A unique feature of this reactor is its fuel cycle in which fuel spheres are randomly loaded and continuously circulated through the core until they reach their prescribed end-of-life burn-up limit. As spheres of different burn-ups are mixed within the reactor and the spheres in different parts of the reactor move through it at different speeds, it is not possible to depend on computational or procedural methods to manage the fuel as is the case in more conventional reactors.

When the reactor is started up for the first time, the lower-enriched start-up fuel is used, mixed with graphite spheres, to bring the core to criticality. As the core criticality is established and the start-up fuel is burned-in, the graphite spheres are progressively removed and replaced with more start-up fuel. Once it becomes necessary for maintaining power output, the higher enriched equilibrium fuel is introduced to the reactor and the start-up fuel is removed to the spent fuel tank. Since it is expected that at a certain point, the burn-up of the start-up fuel could exceed the qualification limit for that fuel, it is important that all the start up fuel is removed before that a certain burn-up limit is reached.

When the equilibrium fuel nears the bottom of the reactor, it is important to discriminate between the irradiated start-up fuel and the irradiated equilibrium fuel to ensure that only the equilibrium fuel is returned to the reactor. A particularly challenging aspect of the discrimination requirement is that there is no physical difference between the two types of fuel spheres except their enrichment.

There is therefore a need for an on-line enrichment discrimination device that can discriminate between irradiated start-up fuel spheres and irradiated equilibrium fuel spheres. The device must also not be confused by the presence of any remaining graphite spheres. Due to its on-line nature the device must accomplish the discrimination within tight time limits.

A secondary consideration is that during the commissioning of the reactor, the reactor core could be loaded with a mixture of start-up fuel spheres and graphite spheres and then, before going critical, could be required to unload the fuel again due to some unanticipated problem. In this case the unirradiated fuel and graphite spheres need to be separated with a high degree of confidence. Since the neutron-based discrimination techniques being considered in this project have the potential to perform this function, this scenario will also be considered.

1.1 PROBLEM DEFINITION

During enrichment discrimination (when the start-up fuel spheres (SUFS) are being removed), the burn-up of the SUFS changes. The equivalent burn-up of the equilibrium fuel (EFS) is required for the enrichment discrimination therefore PBMR supplied the preliminary burn-up for the EFS for each pass as well as the equivalent SUFS burn-up values.

Spheres are removed and re-inserted to the reactor in a way that a similar burn-up can occur both for SUFS and EFS as seen in Tables 1 and 2.
A broader technical scope of the problem of separating EFS from SUFS after exiting the reactor was given by the set of the following conditions:

1.2 PERFORMANCE REQUIREMENTS

a. The discrimination error probability shall be less than 1e-3.
b. b. The instruments shall discriminate between irradiated start-up fuel spheres (burn-up between 12.1 GWd/tU and 69.2 GWd/tU) and irradiated equilibrium fuel spheres (burn-up between 13.4 GWd/tU and 25 GWd/tU). The instrument should discriminate between fresh (un-irradiated) start-up fuel spheres and graphite spheres.

Table 1 Burn-up of the both fuel pebble types after each pass of the 9.6% enriched fuel through the core at different times during the running in phase I

	Channel 1		Channel 2		Channel 3		Channel 4		Channel 5	
Initial Fuel enrichment	Number of Pebbles	Burnup (MWd/t)	Number of Pebbles	Burnup (MWd/t)	Number of Pebbles	Burnup (MWd/t)	Number of Pebbles	Burnup (MWd/t)	Number of Pebbles	Burnup (MWd/t)
9.6%	383	31686	1435	15760	997	14139	1923	13934	634	26374
4.2%	366	22690	1511	14696	1050	13963	2026	13805	606	20029
4.2%	366	22690	1511	14696	1050	13963	2026	13805	606	20029
4.2%	366	22690	1511	14696	1050	13963	2026	13805	606	20029
4.2%	227	23126	1435	16459	997	15747	1923	15589	376	20469
4.2%	227	23126	1435	16459	997	15747	1923	15589	376	20469
Reloading time for the 31965 pebbles is 6 days, which gives a reloading rate of 5328 pebbles/day										
9.6%	300	26773	1160	14539	806	12816	1555	12923	497	21783
9.6%	325	40623	1160	27203	806	25648	1555	25730	538	36309
4.2%	337	27232	1673	36793	1162	35608	2242	35639	557	24945
4.2%	337	27232	1620	27151	1125	26429	2170	26399	557	24945
4.2%	337	27232	1620	27151	1125	26429	2170	26399	557	24945
4.2%	300	28271	1607	27639	1116	26923	2154	26892	497	26024
Reloading time for the 31965 pebbles is 9 days, which gives a reloading rate of 3552 pebbles/day										
9.6%	344	32514	1563	19492	1085	17099	2094	17201	569	26787
9.6%	261	44466	1302	35144	904	33047	1745	33105	433	39395
9.6%	265	54408	1302	47481	904	45643	1745	45663	440	49896

Table 2 Burn-up of the both fuel pebble types after each pass of the 9.6% enriched fuel through the core at different times during the running in phase II

	Channel 1		Channel 2		Channel 3		Channel 4		Channel 5	
Initial Fuel enrichment	Number of Pebbles	Burnup (MWd/t)	Number of Pebbles	Burnup (MWd/t)	Number of Pebbles	Burnup (MWd/t)	Number of Pebbles	Burnup (MWd/t)	Number of Pebbles	Burnup (MWd/t)
4.2%	361	54111	1545	57553	1073	56007	2071	55988	598	50630
4.2%	352	40209	1564	38595	1086	37654	2096	37551	582	37688
4.2%	352	40209	1564	38595	1086	37654	2096	37551	582	37688
Reloading time for the 31965 pebbles is 10 days, which gives a reloading rate of 3196 pebbles/day										
9.6%	344	33399	1593	20884	1106	18230	2134	18372	569	27398
9.6%	342	48923	1592	38859	1106	36568	2134	36649	567	43754
9.6%	281	60546	1494	53527	1037	51557	2002	51586	466	56000
9.6%	282	69852	1230	63867	854	62128	1648	62122	467	65794
4.2%	342	75075	1308	72237	908	70698	1752	70664	566	71593
4.2%	344	51403	1624	62673	1128	61478	2177	61390	569	48899
Reloading time for the 31965 pebbles is 12 days, which gives a reloading rate of 2664 pebbles/day										
9.6%	354	33310	1582	19169	1099	16719	2120	16809	586	27155
9.6%	348	49960	1578	37826	1096	35699	2115	35741	576	44681
9.6%	348	63817	1578	53729	1096	51906	2115	51905	575	59261
9.6%	320	75031	1548	66763	1075	65182	2074	65150	529	71025
9.6%	271	83196	1267	76409	879	75001	1697	74948	449	79591
4.2%	295	89156	1287	84220	894	82950	1725	82882	489	85910
Reloading time for the 31965 pebbles is 10 days, which gives a reloading rate of 3196 pebbles/day										

c. The discrimination performance shall be attained with a post-irradiation decay times between 175 h and 150 days.

d. The measurement and processing time should be 29s or less. If this cannot be achieved, then after consultation with the PBMR, the time shall be less than 36s.

e. The enrichment levels differ by approximately 5%, the exact values are 4.2% and 9.6%.

f. Spheres are made from graphite with several thousand coated fuel kernels in a central region. Outer diameter: 60 mm, Fuel kernel region diameter: 50 mm. Currently there is no physical difference between EFS and SUFS except the enrichment. The parameters were used to model the spheres directly in MCNP, the exact values from literature for carbon and kernel coating was used.

g. The spheres are in a pipe with helium gas pressurized to 9 MPa. The wall of the pipe is typically 10mm thick steel.

h. The enrichment discrimination function is only required for a limited period in the life of the plant – when it is run-in with SUFS. The EFS is gradually introduced once the plant is running with SUFS being removed concurrently. The total application time for the instrument is expected to be approximately two years. These impact the cost that will be accepted for this instrument.

i. The temperatures will be approximately 300◦C close to the fuel channel, but external cooling for the instrumentation could be considered.

j. This is negotiable but the instrument detector should not be larger than 400mm x 400mm.

1.3 POSSIBLE DND SCENARIOS FOR PBMR PROJECT

A neutron source with a corresponding relatively high neutron flux (e.g. Cf252 source) can be used to irradiate the spheres [1]. The spheres, after irradiating by neutrons, will be emanating delayed neutrons. The measured rate of those neutrons can be used to discriminate SUFS and EFS. Two scenarios of DND system are possible in principle for PBMR project (both scenarios are sketched in Figure 1):

1/ The irradiation position of the spheres is the same as the measurement position. This concept is based on the set-up requiring minimal impact on the DPP fuel handling system design. The sphere is irradiated by the neutron source, which is removed after irradiating, and the delayed neutrons detection is started immediately after that. The time for the sphere irradiation and delayed neutrons detecting is limited to 30 s (i.e. $T_{irr} + t_1 + t_2 \leq 30\ s$).

2/ The irradiation position and the measurement position of the spheres are not same. DND system consists of two units: irradiation unit (IU) and measurement unit (MU). The sphere is irradiated in irradiation unit by the neutron source and the sphere is removed to the measurement unit immediately after the irradiation. The irradiation time is limited to the 30 s and measurement time is limited to the 30 s as well, transfer time for movement the sphere into the MU is approximately 4 s (i.e. $T_{irr} \leq 30\ s$, $t_1 \leq 4\ s$ and $t_2 \leq 30\ s$).

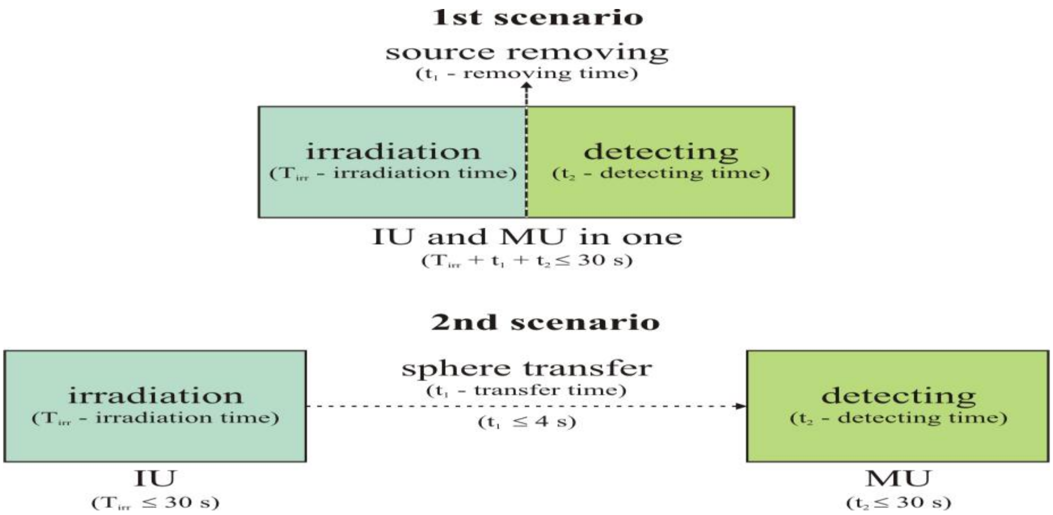

Figure 1 Possible 2 scenarios for DND system.

The calculations focused on deriving the number of delayed neutrons emitted by the spheres (SUFS and EFS) after their irradiation by the neutron source. The analysis in this section performed only for the first scenario because this scenario requires minimal impact on the DPP fuel handling system design. The second scenario is analyzed within the reports [2] and [3] and expanded in following sections. The current set up of the Measurement Valve Block (MVB) is shown at Figure 2, Figure 3 and changes proposed in the two scenarios are depicted in the following figures Figure 4, Figure 5.

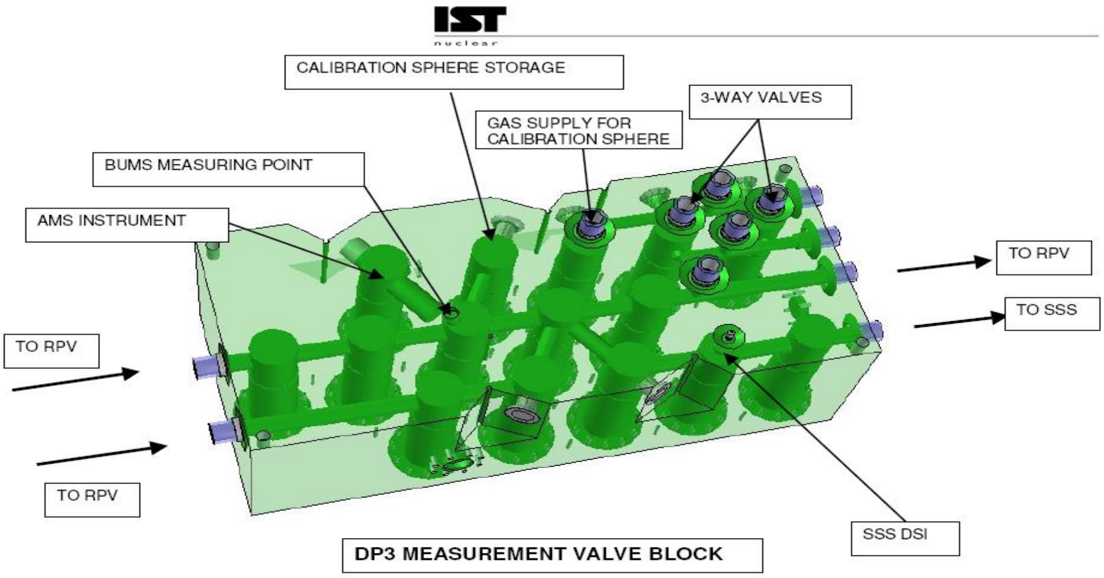

Figure 2 Measurement Valve Block.

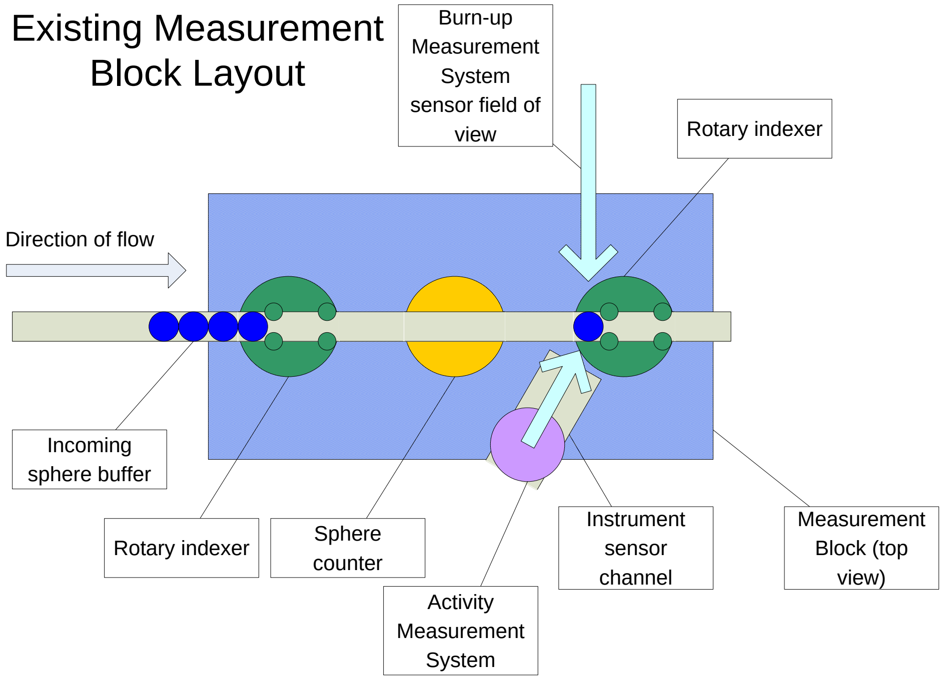

Figure 3 Layout of measurement valve block.

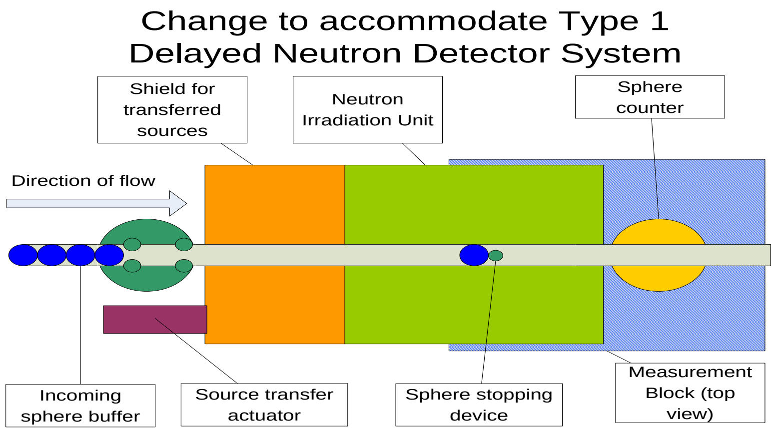

Figure 4 Layout of measurement valve block with DND scenario 1.

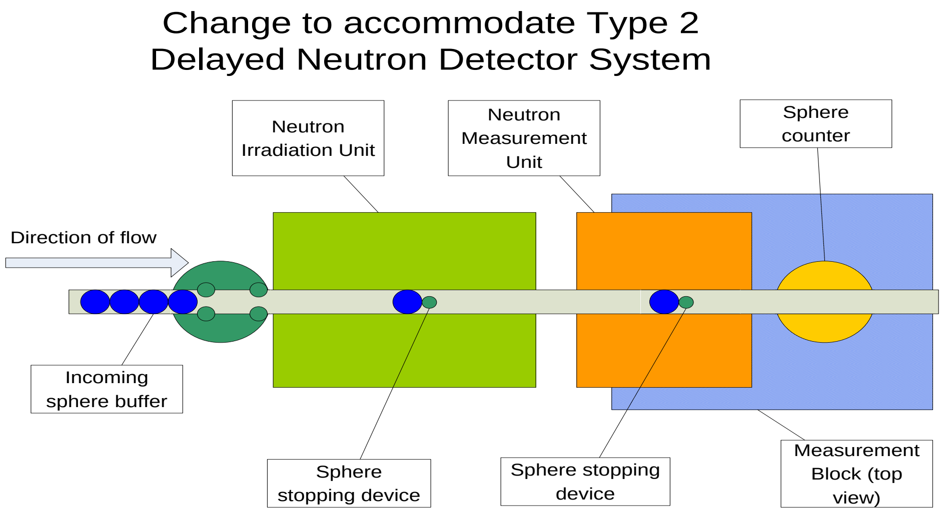

Figure 5 Layout of measurement valve block with DND scenario 2.

1.4 MONTE CARLO SIMULATIONS

MCNP [4] calculations provided the number of fissions (*F*) occurring in the fuel pebble. Then the number of delayed neutrons can be estimated analytically. For the analyses it is important to know the irradiation time (T_{irr}), time of start of delayed neutron counting after irradiation (t_1), time of delayed neutron counting (t_2), and basic parameters ($\square_i$, a_i, $\square_d$) of delayed neutrons for the heavy nuclei fission products.

The following geometrical simplifications were used in the MCNP model:

- channel for calibration sphere is filled by steel,
- rotary indexer is not shaped,
- right part of the channel for the fuel spheres is filled by steel.

The full MCNP model of the fuel pebble was implemented in the DPP fuel handling geometry. The fuel part in this model consists of coated particles embedded in a graphite matrix. The material composition of the fuel sphere corresponds to the fresh fuel. Concentrations of constituent isotopes were determined on the basis of the data from the PBMR. The Cf source was modeled as a cylindrical isotropic source with neutron energy distribution corresponding to the Watt fission spectrum of the Cf252 source.

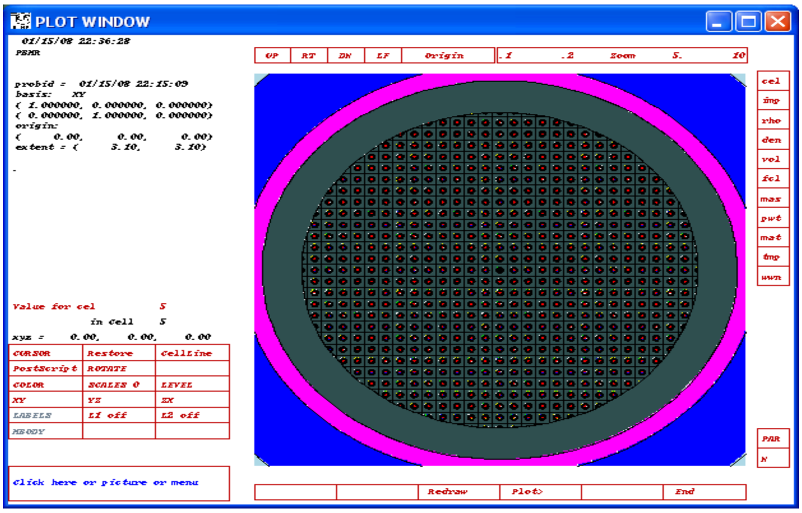

Figure 6 MCNP graphical output – coated particles embedded in a graphite matrix

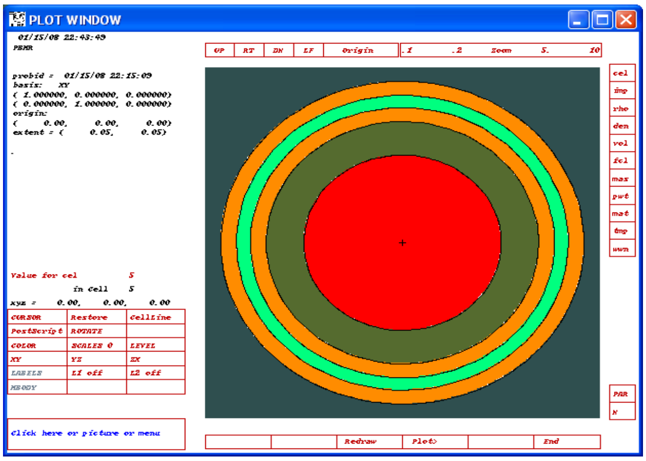

Figure 7 MCNP graphical output – detail of the coated particle with following layers: Fuel Kernel (red), Porous Carbon Buffer (dark green), Inner Pyrolytic Carbon (orange), Silicon Carbide (light green), Outer Pyrolytic Carbon (orange)

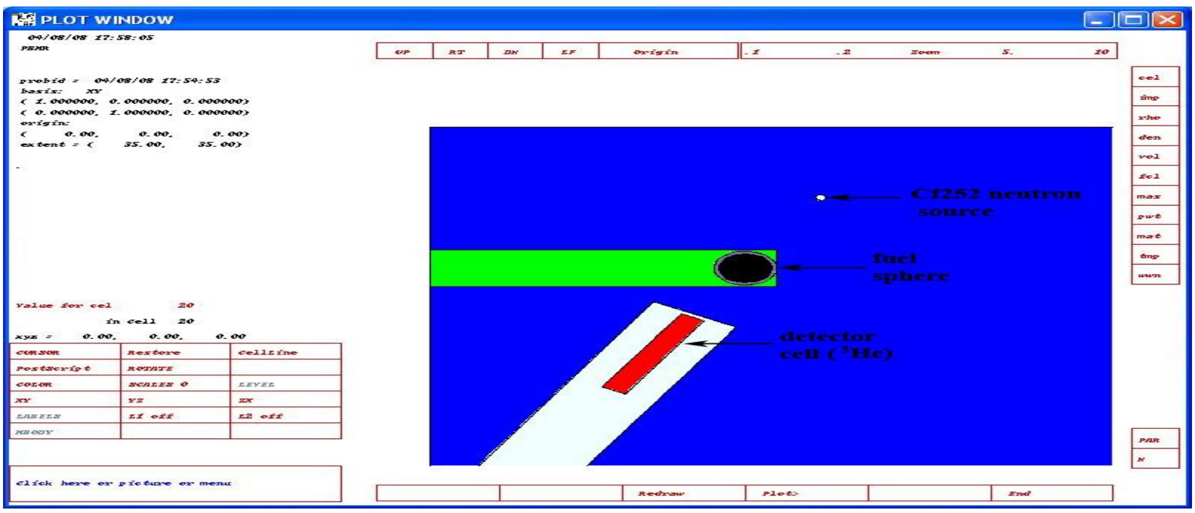

Figure 8 MCNP graphical output of the modeled geometry

The results from the simulations for models with SUFS and EFS are given in Table 3.

Table 3 Results from MCNP simulations

	fresh SUFS	fresh EFS
number of fissions in fuel sphere[1]	6.395E-06	1.306E-05

The resulting total number of delayed neutrons is given in Table 4 for the following time specification: the irradiation time T_{irr} = 15 s, the time of source removing t_1 = 1 s, detection time t_2 = 14 s.

Table 4 Number of delayed neutrons emitted by irradiated fuel sphere per 14s

	fresh SUFS	fresh EFS
total number of delayed neutrons	2.957E-07	6.038E-07

Table 5 contains the numbers of detected delayed neutrons within the detecting time t_2 = 14. The values in the table were calculated using above mentioned detector efficiency and values from Table 3.

Table 5 Number of detected delayed neutrons emitted by fuel sphere (detecting time: 14 s)

	fresh SUFS	fresh EFS
total number of delayed neutrons	1.479E-10	3.019E-10

The values are normalized per one source neutron emitted by Cf252 (i.e. the source emissivity *S* is equal 1 n/s). In the extreme case of the commercially most expensive Cf source, i.e. if the spheres are irradiated by Cf252 with emissivity $S = 1.10^{12}$ n/s, we can detect only 150 delayed neutrons from SUFS and 300 delayed neutrons from EFS for detecting time 14 s. It is clear that the unacceptably strong neutron source is necessary for such a set up.

1.5 DND DETECTORS

The amount of delayed neutrons is, under current geometrical constrains for the DND, low and that would even further complicate the background suppression and extraction of the delayed neutron signal. Next reduction of the delayed neutrons in the detection area is caused by distance between fuel pebble and detector and by influence of the materials (thick layer of steel) between fuel pebble and detector. Detection of delayed neutrons in one direction only is not ideal and the 2π or 4π geometry is usually used for such a measurement type. Detailed study of a detection system and measurement cycle appropriate for DND is done within reports [5] and [3].

1.6 DND FEASIBILITY CONCLUSION

In theory, the described DND method can lead to solving the depicted problem when detecting delayed neutrons shortly after the spheres irradiation by high neutron flux: i.e. the method will separate SUFS and EFS.
From the above-mentioned analysis it is clear that the DND is not likely to work in the proposed current PBMR measurement set-up. The high neutron absorption in steel, unfit moderation properties and detection efficiency are the reasons for that.

Hence a set-up with two devices positioned closed to each other is here proposed. The first irradiation device with a properly moderated neutron source (e.g. Cf252 in H_2O or D_2O) is described in the report [5]. Another device, moderating and measuring delayed neutrons will be coupled after the irradiation device. This second device, with its moderator, reflector and detectors is studied in the reports [2] and [3].

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[1] results are normalized per source neutron, i.e. it is divided by total number of neutrons, which MCNP generated inside the sources.

2 DND SOLUTION AND ITS PRACTICAL VARIANTS

Calculations within the feasibility study show how the DND method in a proper set-up with two units – irradiation unit (IU) and measurement unit (MU)- can be implemented to fulfill PBMR requirements to separate fuel spheres. Here we propose 3 versions of set-ups with different IUs, the first two versions of IU are same as for the PND (Prompt Neutrons Detector) approach, and hence both methods can be used in parallel. The third version of IU is unique for the DND solution. MU is identical for all three versions, designed in a way that it can use commercially available parts.

The ISO-DND IU has the best characteristics from the three IU options shown. The method will separate SUFS, EFS and pure graphite spheres with high accuracy and required speed, all within the conditions given, providing correct detectors are used and the Cf252 neutron source of given parameters is economical.

2.1 DND IMPLEMENTATION BACKGROUND

Expanding on the information stated above for fulfilling the task it is essential to:

- Have a neutron source in IU with a corresponding relatively high neutron flux that can be used to irradiate the spheres. The spheres, when removed from the flux, will be emanating delayed neutrons. The measured rate of those neutrons can be used to determine the spheres.
- The ideal irradiation time (T_{irr}) depends on the half-lives of delayed neutrons. Ideal time is about 400s[2] but the real conditions, especially when DND is to be performed together with PND and only one sphere can be irradiated at the time, lead to lower values. Sufficient T_{irr} leads to saturated activity of irradiated sample. Saturated activity is maximal possible activity of a radionuclide formed in some irradiated sample. It is for infinite irradiation time theoretically, but the saturated activity is achieved if the irradiation time corresponds to ten half-lives. The maximal number of delayed neutron emitters is arising for saturated activity. It is clear that the shorter the time the worse the delayed neutron rate is. The dependence of delayed neutron emission rate on various irradiation times is explained in [6].
- The detection system in MU uses a moderator to thermalize the delayed neutron spectrum. The average energy of the delayed neutrons is smaller (300 - 600 keV) than that of the prompt neutrons (2 MeV in average).

Three important aspects in delayed neutrons detection as for PBMR fuel are summarized here:

1/ Neutron background resulting from minor actinides' spontaneous fissions and (alpha, n) reaction within the fuel will be decreasing accuracy of the device. As the number of delayed neutrons is roughly 2 orders of magnitude smaller than the number of prompt neutrons, relatively high neutron flux within the irradiation assembly is essential.

2/ Half-lives of delayed neutrons are different for different mother fissionable elements and the measurement must reflect this fact. Namely, the half-life and fraction of delayed neutrons is higher for U235 than for Pu239.

3/ The shorter the interval of moving the spheres from IU to MU, the better the overall statistics of the number of the detected delayed neutrons is. The same aspect improves the detection abilities for the groups of delayed neutrons with shorter half-lives.

Realization of DND depends on a simple chain of conditions: the neutron source in IU must be strong enough and well moderated to provide a neutron flux with good properties for enough time to generate enough fission within SUFS/EFS. Then the transport time between IU and MU must be as short as possible with the constraint of shielding the IU neutron sources from MU detectors. In the end the MU must have good efficiency to measure delayed neutrons within the measurement time frame given. And the background from the minor actinides' drives the properties of the used solution.

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[2] CTU experience with delayed neutrons detecting at VR-1 reactor: the optimal T_{irr} is 400 s.

2.2 DERIVING THE SHAPE AND MATERIALS OF DND

As a result, and in cooperation with PND, the following three DND IU shapes were tested by MCNP [4] calculation:

- Neutron channels DND (NC-DND).

This set-up uses neutron channels IU with 2 neutron sources (same as for PND and used together with PND)

- Back irradiation DND (BI-DND).

This set-up uses back irradiation IU with several neutron sources (same as for PND and used together with PND).

- Isotropic DND (ISO-DND).

This set-up uses isotropic IU (unique for DND, cannot be used for PND).

The first part of MCNP calculation focused on material and dimension optimization of IUs, i.e. to find the appropriate dimension and material composition of IUs in order to maximize the number of fissions inside the fuel sphere. As a start the thermal and total neutron fluxes inside fuel cells were calculated for various dimension and material composition of IUs. The core part of the MCNP model was the fuel sphere located inside the 10 mm thick steel tube with interior diameter of 65 mm. The space between the fuel sphere and the steel tube is filled with helium. The neutron fluxes were calculated inside the fuel cell, which was filled by vacuum for this purpose. The F4 tally card (flux averaged over a cell [particles/cm^2]) was used for the neutron flux calculations. Based on the MCNP results the appropriate dimension and material composition were selected for each IU.

2.3 DELAYED NEUTRON DETECTION DEVICE (DNDD)

Czech Technical University proposes a Delayed Neutron Detector set-up with two units – irradiation unit (IU) and measurement unit (MU) that can be implemented to fulfill PBMR requirements. We considered 3 versions of set-ups with different IUs. However, MU is identical for all three versions, designed in a way that it can use commercially available parts. The main part of MU is DNDD, which is described in this chapter.

DNDD will be operating in a mixed field of gamma, delayed neutron and background neutron radiation. As the discriminating signal comes from delayed neutrons only, the other sources of radiation need to be suppressed. The detailed analysis of detector and its properties is part of this chapter. As an example one can assume B10 boron corona chambers or He3 detectors deployed in 2π geometry around the sample to detect thermal neutrons. Experiments at the VR1 nuclear reactor showed that the measurement with commercially available detectors is possible, but next experiments focused on gamma issue are required.

2.4 DNDD BACKGROUND

The detection system in MU uses a moderator to thermalize the delayed neutron spectrum. The average energy of the delayed neutrons is smaller (300 - 600 keV) than that of the prompt neutrons (2 MeV in average). The background resulting from minor actinides' spontaneous fissions within the fuel may affect fuel discrimination precision of the device.

Gamma radiation is present in the mixed field and its signal needs to be suppressed in the measurement.

2.5 DETECTOR REQUIREMENTS AND CONSTRAINTS

The detector system (DNDD) has to consider conditions rising from the MU DND setup. However, the detector system has also influence on the final design of MU DND. In other words, it is not possible to completely split the task of finding the best geometry and design of DND to achieve the highest flux of delayed neutrons at the detector without taking into account detector parameters. Solution of this problem represents multidimensional problem where each part affects the rest of system.

Therefore, the process of finding optimal DND parameters was done in two steps. The first step was described in previous chapters. The aim then was to find optimal parameters of DND from the point of view of an efficient irradiation of fuel spheres. This report adds to these results parameters of detectors and provides a feedback to the design of DND geometry, namely the DNDD.

The main issues the detector system has to cope with are:

1. measurement of low neutron flux,
2. limited time available for one measurement,
3. high gamma background.

The first two points obviously require detectors with as high detection efficiency as possible. Energies of delayed neutrons are somehow lower than energies of prompt neutrons from fission. This gives a good opportunity to moderate delayed neutrons and thus shift their energies to higher cross section values for materials "converting" uncharged neutrons into radiation detectable in the detector. This means focus can be put in the case of DND on thermal neutron detectors.

The detector must have on the other hand low sensitivity on gammas to deal effectively with the point 3. Pulse height discrimination of gamma background can be used. This, however, assumes that single pulses of neutron and gamma signal are distinguishable in time. Substantial pile-ups can prevent pulse height discrimination of the gamma background.

As reference detectors for this study the Canberra ^{3}He detectors were selected. They can offer a better detection efficiency compared to BF_3 as the high neutron detection efficiency is the key factor for DNDD. There is a selection of different lengths and diameters as well as gas filling pressures of these detectors. These detectors can be filled up to 6 bars of ^{3}He gas.

Basic detector parameters for the MCNP model:

Diameter	2.5 cm
Length	15 cm
Wall material	stainless steel
Wall thickness	0.5 mm
^{3}He pressure	6 bar

2.6 OVERALL NEUTRON DETECTION EFFICIENCY AND NUMBER OF DETECTED DELAYED NEUTRONS

The MU DND unit proposed in the report [5] was supplemented with detectors described above. Based on the analysis in previous report, four of these ^{3}He detectors were placed to positions where the highest flux of thermal neutrons is expected. The layout of DNDD is show in Figure 9.

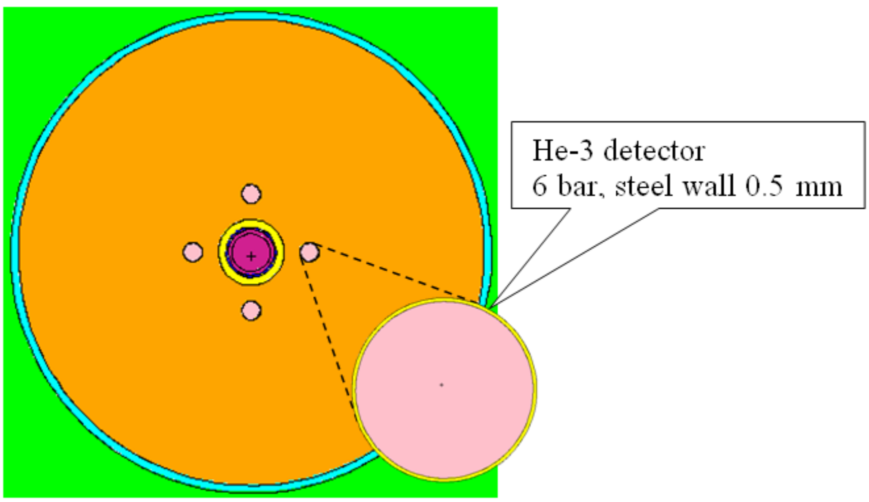


Figure 9 MCNP input of DNDD with implemented 3He detectors inside MU DND

2.7 OVERALL NUMBER OF DETECTED NEUTRONS

Numbers of detected neutrons for the different combinations of SUFS and EFS burn-up are summarized in Table 6. The data in table were calculated for measurement time of 30s and californium source emission of 1.50E+09 n/s.

Table 6 Total number of neutrons detected in DNDD per 30 s for various burn-up scenarios of fuel pebble

Cycle	SUFS	EFS	
1	5852	12435	2.12
2	5418	11595	2.14
3	7097	10808	1.52
4	9795	11906	1.22
5	14799	15923	1.08

The statistical error of counted neutrons is given by Poissonian distribution. I.e. it is a square root of the number of counts. The discrimination of the fuel spheres is then based on simple comparison of the measured number of counts with some chosen threshold. I.e. if the measured number of neutron counts is higher than the threshold, the examined sphere is EFS. If it is lower than threshold, the sphere is SUFS. However, because of the statistical nature of the measurement, there is a non-zero probability that the EFS will show number of counts lower than the set threshold and vice-versa for the SUFS. This determines the statistical precision of the selection. I.e. the relative number of fuel spheres where measured count will fall on the "wrong side" of the threshold is the relative precision of the device. It is obvious that the two distributions must be as distant as possible. This can be achieved by increasing the detected number of neutrons: e.g. by increasing the Cf source emission.[3]

It is clear that a reasonable Cf source emission has to be found to achieve the requested discrimination precision, which was set to be wrong decisions in 1E-3 cases. Figure 10 shows dependency of fuel discrimination error on Cf source emission. This result indicates that the optimal Cf source emission to achieve precision of fuel discrimination of 1E-3 is at least ~1.50E+09 n/s.

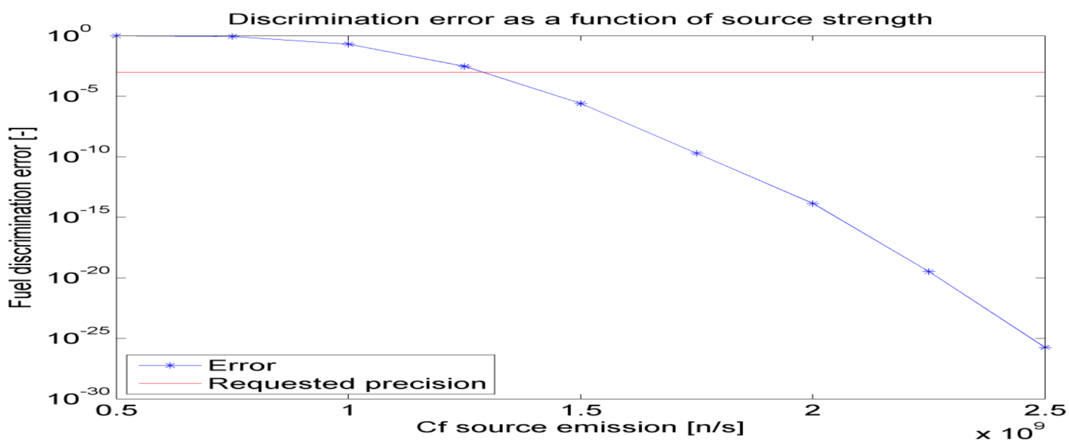


Figure 10 Error of EFS and SUFS discrimination as a function of Cf source emission. The lowest Cf source emission to achieve the discrimination error less than 1E-3 is of ~1.50E+09 n/s.

[3] Another way is that the generated neutron flux and thus number of fission will increase – this was however already done in finding the best geometry and detector.

The detailed analysis of discrimination error has also shown that it is not possible to use only one value of threshold for all different burn-ups of the fuel. I.e. if the threshold will be set for fresh fuel only then this value of threshold will generate high discrimination error when the fuel will reach higher burn-up. Similarly, it is not possible to optimize the threshold value for higher fuel burn-up because then the discrimination with such threshold will fail for the fresh fuel. This means that the position of the discrimination threshold has to be adjusted in time as the fuel is gaining higher levels of burn-up (Figure 11). The threshold adjustment can be done using measurement of fuel burn-up of each measured fuel sphere within DND or just adjusted in time when switching from lower scenarios to higher ones when it is known the low burn up fuel can not pass through the reactor. This approach may require additional studies. Another possibility would be to set the threshold according to "an average burn-up" in the core measured by the independent burn-up measurement device or simulated.

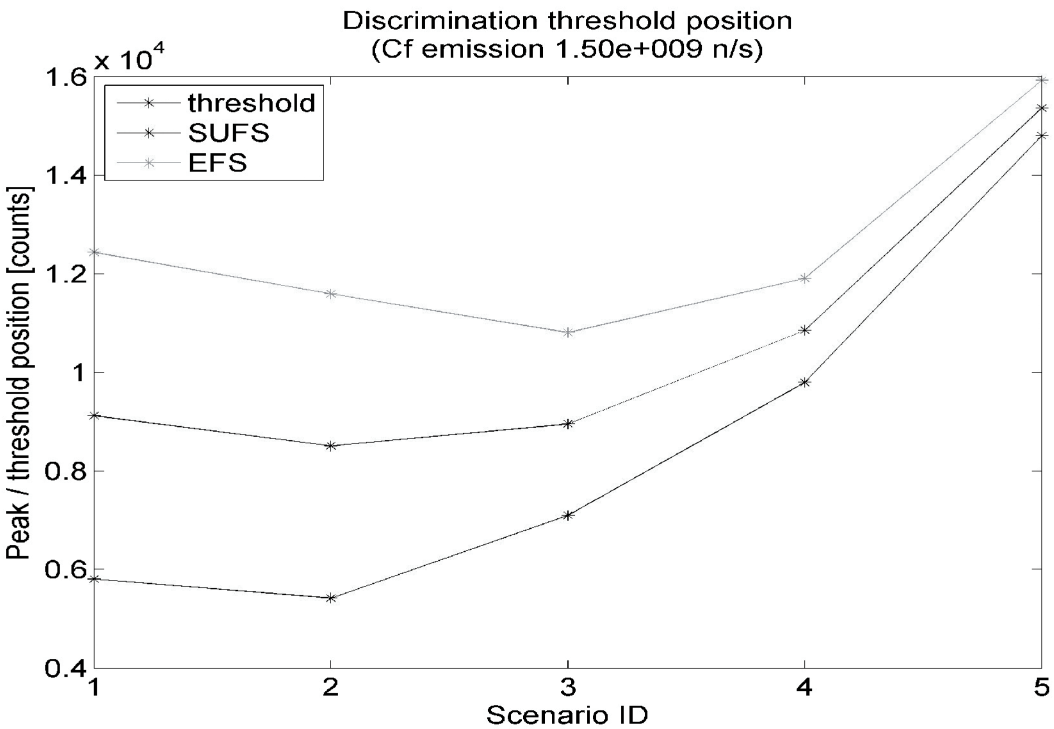


Figure 11 Mean number of neutron counts and necessary threshold position for each scenario of SUFS and EFS burn-ups.

The following figures (Figure 12) show detected number of counts in form of Poissonian distributions for worse SUFS and EFS burn-up combination scenarios.

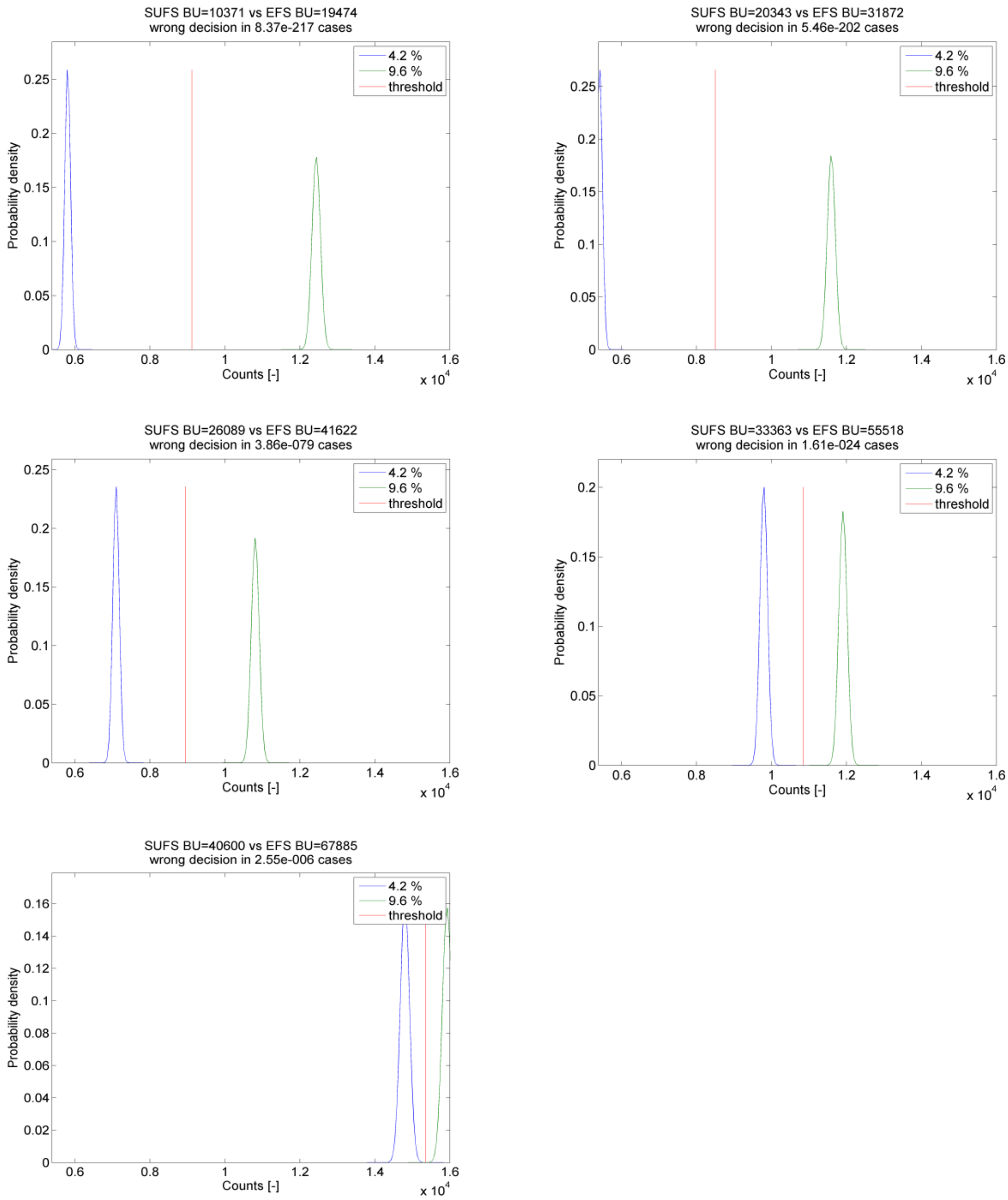


Figure 12 Detected number of counts in form of Poissonian distributions for worse-case SUFS and EFS burn-up combination scenarios (Cf source emission = 1.5 E9 n/s)

2.9 DND CONCLUSION

Various detectors are available to be used in the measurement unit of the delayed neutron detector. The choice of the best detector is driven by the signal, which are delayed neutrons, and the background, which are gammas and background neutrons. The simulations proved that the number of detected neutrons in DNDD can be high enough to allow fuel enrichment discrimination with error better than 1E-3. In order to achieve this, a Cf source of neutrons with emission of ~1.5E9 n/s is needed. Because the gamma doses from irradiated fuel are so high, additional modifications to the measurement unit were proposed using Pb shielding. The simulations show that the shield leads to the sufficient decreasing of gamma dose rate without erasing the neutron signal, but it is necessary to verify this assumption by appropriate experiments for higher doses.

The experiment at the VR-1 reactor shows that CTU has sufficient measurement capabilities (analyzers and various detectors) to prepare the experimental setup, which can verify the influence of gamma background to the detection system. Considering that the gamma doses permitted at the VR-1 site are relatively low (3mSv/h) when compared to the PBMR conditions, this kind of experiment is not possible to done at VR-1 reactor.

If other studies are to be conducted, CTU is capable of preparing experiments leading to verify the influence of gamma background to the detection system. This kind of experiment can be done in close cooperation with Czech Metrology Institute. This institute has sufficient strong gamma (gamma dose rates of 10 Gy/h) and neutron sources (emissivity up to 10^9) available.

3 PROMPT NEUTRON DEVICE (PND)

Experimental and theoretical results within this section indicate that the prompt neutron device (PND) is capable of distinguishing between the start-up and equilibrium fuel spheres of the PBMR reactor within the conditions given. Furthermore the method can clearly mark the pure graphite spheres and enable their recognition if fresh fuel is to be removed from the PBMR reactor.

But in the current PBMR measurement block geometry, we do **not** believe that the separation of spheres with different enrichment can be performed using PND. Changes of the PBMR current set-up are needed. The report expands on the reasons and indicates a possible solution. This section defines the scope of research required for studying the concept for neutron-based fuel enrichment discrimination: measuring the neutron emission of a fuel sphere that is being irradiated by a moderated neutron source, referred in the document as PND.

3.1 PERFORMANCE REQUIREMENTS

A broader technical scope of the PND problem of separating EFS from SUFS after exiting the reactor is similar as for the DND problem. It follows, yet again, the conditions:

a. The discrimination error probability shall be less than 1e-3.

b. The instruments shall discriminate between irradiated start-up fuel spheres (burn-up between 12.1 GWd/tU and 69.2 GWd/tU) and irradiated equilibrium fuel spheres (burn-up between 13.4 GWd/tU and 25 GWd/tU). The instrument should discriminate between fresh (un-irradiated) start-up fuel spheres and graphite spheres.

c. The discrimination performance shall be attained with a post-irradiation decay times between 175 h and 150 days.

d. The measurement and processing time should be 29s or less. If this cannot be achieved, then after consultation with PBMR, the time shall be less than 36s.

e. The enrichment levels were specified to be 4.2% and 9.6% respectively.

f. Spheres are made from graphite with several thousand coated fuel kernels in a central region. Outer diameter: 60 mm, Fuel kernel region diameter: 50 mm. Currently, there is no physical difference between EFS and SUFS except the enrichment. The parameters were used to model the spheres directly in MCNP, the exact values from literature for carbon and kernel coating was used.

g. The spheres are in a pipe with helium gas pressurized to 9 MPa. The wall of the pipe is typically 10 mm thick steel.

h. The enrichment discrimination function is only required for a limited period in the life of the plant – when it is run-in with SUFS. The EFS is gradually introduced once it is running with SUFS being removed concurrently. The total application time for the instrument is expected to be approximately two years. These impact the cost that will be accepted for this instrument.

i. The temperatures will be approximately 300°C close to the fuel channel, but external cooling for the instrumentation could be considered.

j. This is negotiable, but the instrument detector should not be larger than 400mm x 400mm.

Table 7 Results from MCNP simulations

	neutron fluxes[4] [1/cm²]			
	detector cell		fuel cell	
energy bin [MeV]	$\Phi_{4.2\%}$	$\Phi_{9.6\%}$	$\Phi_{4.2\%}$	$\Phi_{9.6\%}$
0.00E+00 - 2.50E-08	-	-	4.6730E-09	4.5668E-09
2.50E-08 - 1.00E-06	7.0093E-07	7.1047E-07	2.0705E-06	2.0449E-06
1.00E-06 - 5.00E-01	5.4167E-04	5.4169E-04	1.5675E-03	1.5674E-03
5.00E-01 - 1.00E+00	7.6449E-05	7.6451E-05	3.4598E-04	3.4613E-04
1.00E+00 - 2.00E+00	1.9857E-05	1.9859E-05	1.6376E-04	1.6401E-04
2.00E+00 - 2.50E+00	2.0110E-06	2.0121E-06	2.5590E-05	2.5690E-05
2.50E+00 - 4.00E+00	1.8734E-06	1.8749E-06	2.5972E-05	2.6095E-05
total	6.4256E-04	6.4260E-04	2.1308E-03	2.1313E-03
	ratio of the neutron fluxes			
	detector cell		fuel cell	
energy bin [MeV]	$\Phi_{9.6\%}/\Phi_{4.2\%}$		$\Phi_{9.6\%}/\Phi_{4.2\%}$	
0.00E+00 - 2.50E-08	-		9.7726E-01	
2.50E-08 - 1.00E-06	1.0136E+00		9.8760E-01	
1.00E-06 - 5.00E-01	1.0000E+00		9.9994E-01	
5.00E-01 - 1.00E+00	1.0000E+00		1.0004E+00	
1.00E+00 - 2.00E+00	1.0001E+00		1.0015E+00	
2.00E+00 - 2.50E+00	1.0006E+00		1.0039E+00	
2.50E+00 - 4.00E+00	1.0008E+00		1.0047E+00	
total	1.0001E+00		1.0002E+00	

The fuel sphere irradiation by neutrons from Cf252 source was simulated in MCNP. The F4 tally card, which is a standard tool for flux calculation in MCNP (flux averaged over a cell [particles/cm²]), was used for the neutron flux calculations. The neutron fluxes were calculated in the detector cell and fuel cell for 7 neutron energy bins. The results from MCNP simulations for the model with the fuel enrichment of 4.2% and 9.6% are summarized in Figures 13-16, and Table 7.

The resulting neutron fluxes for all energies are similar for both enrichments. Thus, it is obvious that the enrichment discrimination is not possible in the original PBMR geometry.

Contributions of the neutrons from the Cf252 source decrease ability to discriminate neutrons from various enriched fuel pebbles. The results of the MCNP simulations, focused on the determination of neutron flux distributions in the PBMR geometry, are given in these figures. The MCNP MESH TALLY cards were used for the calculations. The simulation was made in the square lattice with steps of 1x1 cm.

[4] The neutron fluxes are shown in MCNP standard format, i.e. normalized per source particle. The MCNP does not take into account real time and therefore is the neutron flux in units of 1/cm² and not 1/cm²/s as usual.

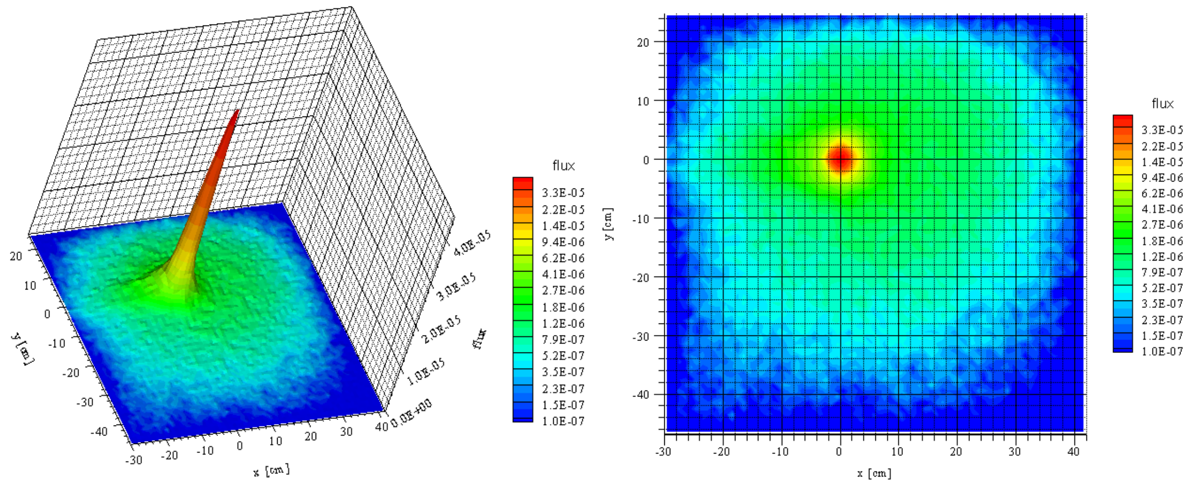


Figure 13 Neutron flux distribution for energy interval 0.025 eV – 1 eV and SUFS.

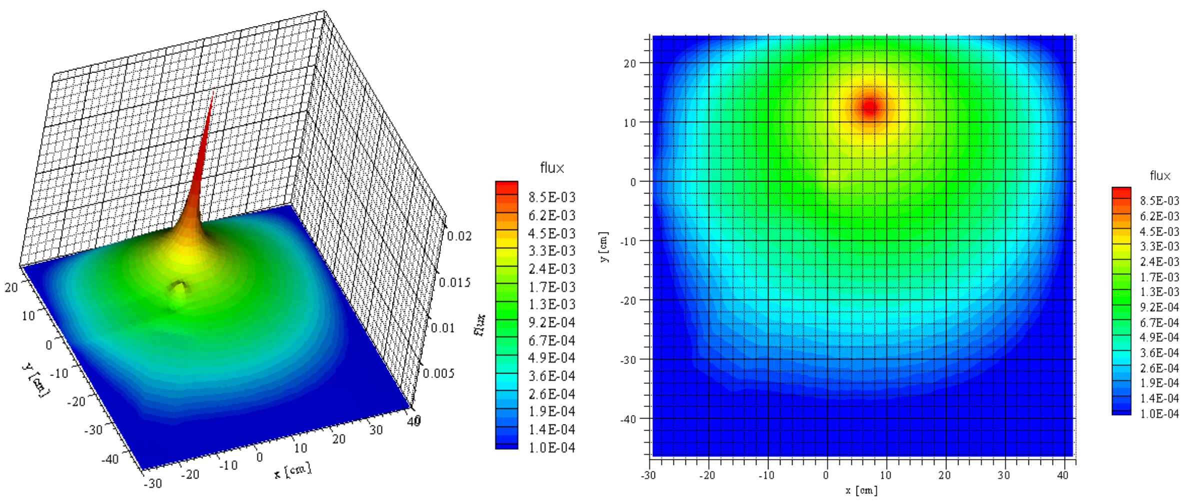


Figure 14 Neutron flux distribution for energy interval 1 eV – 2.5 MeV and SUFS.

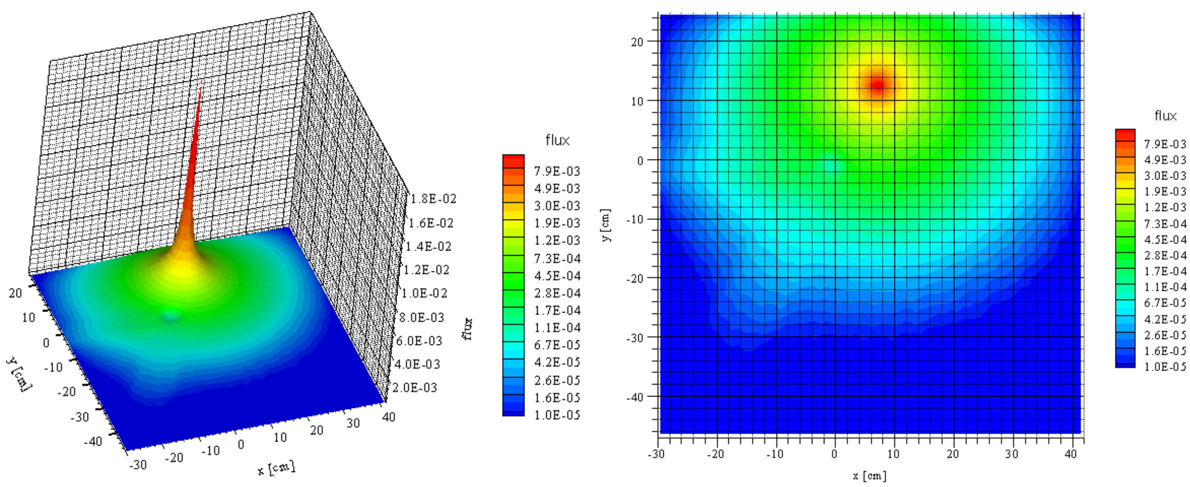


Figure 15 Neutron flux distribution for energy interval 0.5 MeV – 1 MeV and EFS.

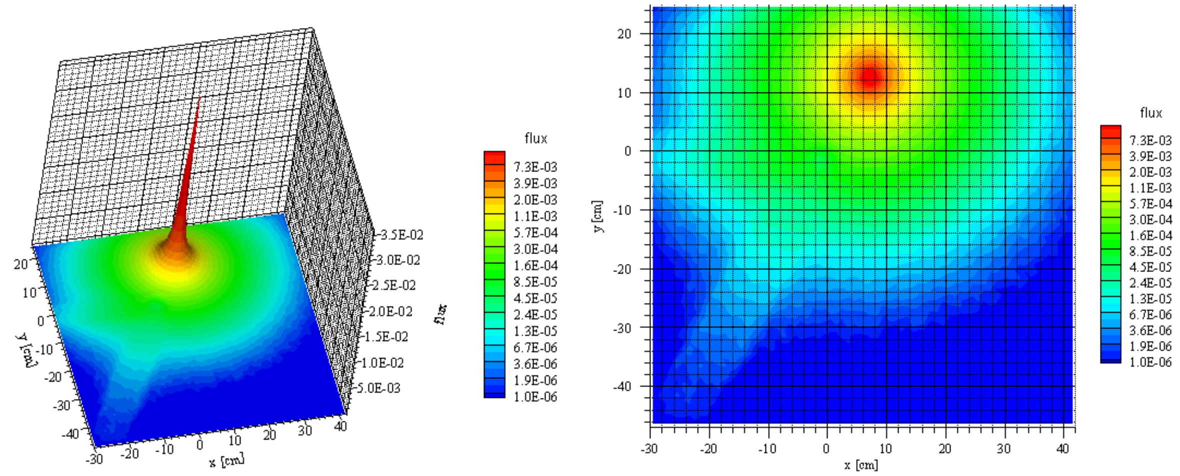


Figure 16 Neutron flux distribution for energy interval 1 MeV – 2.5 MeV and EFS.

The thick layer of steel, distance of the source, the fuel sphere, and the detector, or the energy spectrum of irradiating neutrons have to be changed in order to allow separation of the fuel spheres. Several options are possible: a) moderating the spectra of the neutron source, b) using a beam of thermal neutrons, or c) minimizing the amount of neutron absorbers. The next MCNP model and simulations was be conducted to support these assumptions. The simulations were focused on the selection of a suitable neutron source moderation and determination of the best position of the neutron source, fuel pebble, and the detector.

3.2 ESTIMATING THE NUMBER OF DETECTED FAST NEUTRONS

The detection of fast neutrons in BI-PND relies on the directional properties of the proposed fast neutron detector. Here silicon detectors (thickness of 0.3 □m and size 5 x 5 cm^2), combined with 1 mm thick polyethylene fast neutron converters, were considered.

3.3 DERIVING THE NEUTRON SOURCE USED IN PND

The requirements on neutron source parameters for application in PND are similar as for DND. Therefore, all comments and notes given for DND are valid also for selection of a suitable neutron source for PND. As in the case of DND, californium sources are considered to be the best option for the PND.

3.4 SUGGESTING THE WAY TO DERIVE OPTIMAL DIMENSIONS OF PND

Reliable performance of the PND device relies on good statistics of counted prompt neutrons from the fission. Therefore, maximization of the number of fission neutrons by maximizing flux of neutrons in the fuel sphere from the external source is essential. This can be done by optimizing the shape and dimensions of the moderator and reflector within the PND unit.

The number of detected neutrons can be increased by extension of the measurement time. This is, however, limited by external constrains of the PBMR design. Effects of neutron and gamma background on the detector response have to be considered in the final design as well. The above mentioned parameters and effects can be tested experimentally.

The PND method described in this report can lead to discrimination between SUFS and EFS. The discrimination process can be done in one device, which combines the irradiation and measurement together. The fuel discrimination is based on detection of prompt fast neutrons from the fission induced by moderated (combination of D_2O moderator and Be reflector) Cf252 source. The two geometrical set-ups were proposed: the Back Irradiation PND method, and the Neutron Channel PND method. The highest fission rates can be obtained from the unit design of the type BI-PND where the neutron sources are placed close behind detector units and the fuel sphere. Therefore, the BI-PND was emphasized in this report compared to NC-PND, which provides lower neutron flux in the fuel sphere and thus generates a lower fission rate.
The prompt fast neutrons from the fuel can be detected in a detector array consisting of semiconductor detectors. The detectors are based on a combination of polyethylene (i.e. hydrogen rich) neutron-to-proton converter and semiconductor diodes. Such a neutron detector array exhibits strong angular sensitivity. Neutrons are detected only from the front side (with the polyethylene).
A constraint of the PND method is that it can only irradiate and measure one fuel sphere at a time. Other spheres in the vicinity of the measured one would increase the neutron and gamma background.
The estimates of number of detected fast neutrons indicate that a sufficient amount of fast prompt fission neutrons can be detected to discriminate between fresh SUFS and EFS, and also pure graphite spheres. A study which will take into account also gamma and neutron background as well as numbers of neutrons originating from the neutron source and recoiled on heavy elements in front of the detector and thus increasing background will be performed as a part of the detector report. Estimation of the precision of fuel discrimination and final judgment, if the PND device can provide fuel sphere discrimination, is concluded there.

Prompt Neutron Detector (PND), was studied in two different set-ups in [7]. The Back Irradiation (BI) and the Neutron Channel (NC) options were considered. Both PND solutions are suggested to be placed in one physical unit – the so called irradiation unit (IU) – and requirements for a neutron detector itself are similar in both cases.

A special, new type of fast neutron detecting device (FNDD) is suggested inside the IU, which uses polyethylene as a conversion layer and detects recoiled protons in a semiconductor. It is shown that such a device has characteristics very suitable for the PND problem:

1. The FNDD is less sensitive to thermal neutrons, which are used to irradiate the spheres.
2. Contribution from gamma background can be suppressed by using a smaller detector size and its distance and/or shielding.
3. Theoretical calculations showed an angular sensitivity dependence of the detector, which was confirmed by experiments. Both BI and NC set ups benefit from this fact. Monte-Carlo simulations and the experimental detector tests indicate that the PND method can discriminate the fuel spheres with different enrichment.

Within the feasibility study theoretical calculations were completed with initial experiments with positive and promising results. However, as the FNDD is in the Research & Development phase, follow-up experiments are needed to confirm parameters of both BI-PND and NC-PND solutions, and the cost of the FNDD must be estimated.

3.5 DETECTOR REQUIREMENTS AND CONSTRAINTS

As stated within before and expanding on the information stated within [8], it is essential to adhere to the following conditions:

- As a thermal neutron flux is present within IU, a careful choice of the FNDD is essential to detect a fission neutron signal distinctly from the irradiation neutron flux background, i.e. sensitivity to fast neutrons must dominate the sensitivity to thermal neutrons.
- The detection system inside IU uses shielding, reflector, and moderator to maximize the effect of irradiating neutrons from the source.

The most important aspects in prompt neutron detection are the background neutrons resulting from:

A/ minor actinides' spontaneous fissions and (alpha,n) reactions in the irradiated fuel,
B/ original Cf neutron source.

Hence the FNDD must be sensitive enough to the induced fission neutrons and insensitive to the original neutron flux in order to provide good discriminatory power. On top of all the stated conditions, the statistics of the detected fission neutrons must exceed enough the background from spontaneous fission neutrons and/or co-present gamma radiation.

The requirements on the detector system for PND are derived from the design and fuel type discrimination manner in PND. As mentioned in the previous reports, the PND device relies on the detection of prompt fast neutrons from the fission in the fuel induced by an external neutron source. The work summarized in previous reports was focused on finding optimal dimensions and positions of all parts of the PND system to maximize the amount of induced fissions and thus also fast neutrons from fission. This report contains study of conditions of the neutron detector in this setup.
A detector suitable for application in PND must provide reasonably good sensitivity to fast neutrons coming from the fission. It must also provide a way to distinguish between the neutrons from fission in the fuel and from the source, which will be generating thermal neutron flux inducing the fission. The detector must be sufficiently insensitive to gamma radiation from the neutron source as well as from the fuel.
There are many different neutron detectors, which are suitable for fast neutron detection (for example plastic scintillators, boner spheres, etc.). However, the requirements of distinguishing neutrons from the source and from fission is reducing the group of possible candidates.
The idea behind PND is to distinguish fast neutrons from the fuel from fast neutrons from the external source by utilizing the directional characteristics of a fast neutron detector, which consists of a silicon diode and a polyethylene radiator. Polyethylene is a hydrogen rich material, which is easy to obtain, handle, and machine. Therefore it is well suitable for such an application. The approach of combining polyethylene with a planar chip distinguishes such detector from the other fast neutron detectors by providing higher sensitivity to neutrons from one side of the detector only. This is the reason why such detectors were selected for the PND geometry studied in this feasibility study.
Another advantage of such a detector is that it can run in single particle counting mode. That means that the error of the measured signal is given just by Poisson distribution of the counted numbers. Thus, the error can be decreased by extension of measurement time or increase of fission rate in the investigated fuel. Such a detector provides an unlimited dynamic range.
The PND set-up uses back irradiation IU with 3 Cf neutron sources. The neutron sources are placed behind the detector. Fast neutrons are detected through the recoil of protons from a hydrogen rich material. These protons can be subsequently detected in a semiconductor detector. Such an arrangement of detector exhibits an angular dependency. Fast neutrons approaching the polyethylene from the side of semiconductor (which is nearly transparent for them) cannot directly recoil protons back into the detector.
The set-up cross-section is shown in Figure 17. The Cf sources are located close together inside the D_2O moderator to ensure that all the fast neutrons from the sources will irradiate the detector cell from the back side. Distance L_s from the center of the fuel cell is same for all sources. The moderator is surrounded by a reflector with the radial dimension R_m and 10 mm thick nickel cladding. Contrary to the DND approach, the detector cell was used in PND calculations.
The questions to be answered[5] are:
What is the signal generated by neutrons from the external source?

What is the signal by neutrons from the induced fission?

What is the signal generated by gamma background?

[5] Other questions may include: radiation hardness of the detector, gain drift with temperature, counting stability, dead time, etc. Many of these and other questions are closely related to the final selection of a concrete detector. Therefore, they are not closely addressed in this feasibility study.

Neutrons hitting the detector from the backside cannot recoil the protons back to the silicon. Therefore, no signal can be seen. However, it is necessary to evaluate number of events when the fast neutron is recoiled on a heavier element. Thus it still keeps a sufficient energy, but it gains direction of flight from which it can recoil the proton into the detector. The neutrons from the external source can be recoiled also on heavier elements in the PND setup or fuel. These interactions can also be detected and generate unwanted neutron background in the detector.

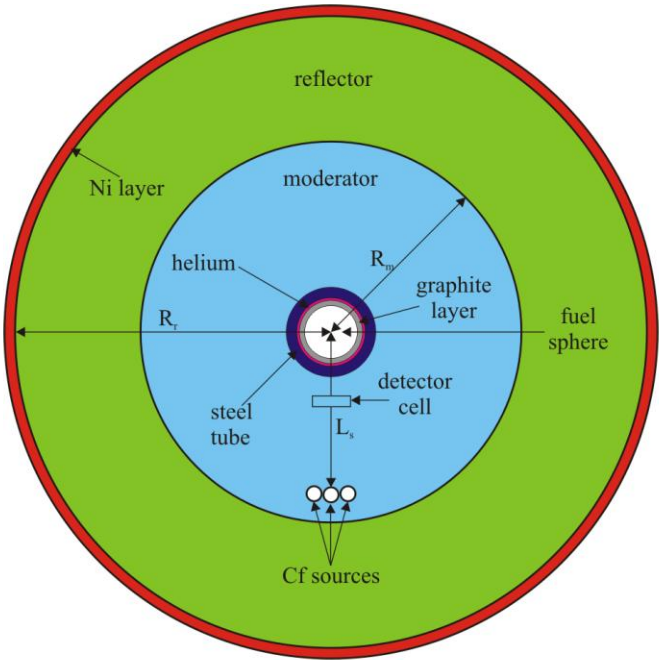


Figure 17 BI-PND set-up

3.6 OVERALL NUMBER OF DETECTED NEUTRONS

Numbers of detected neutrons for the different combinations of SUFS and EFS burn-up are summarized in Table 8. The table was calculated for measurement time of 30s and californium source emission of 5.00E+09 n/s.

Table 8 Numbers of detected neutrons from different sources. Cf neutron source emission used was 5.00E+09 n/s.

Number of detected fast neutrons [n/30s]						
	Scenario					
Fuel	**0**	**1**	**2**	**3**	**4**	**5**
SUFS	52 930	51 844	44 264	45 503	43 257	41 435
EFS	115 134	109 126	100 471	86 241	74 448	65 275
Ratio	2.18	2.10	2.27	1.90	1.72	1.58

Number of detected fast neutrons including background [n/30s]						
	Scenario					
Fuel	**0**	**1**	**2**	**3**	**4**	**5**
SUFS	12 891 107	12 890 021	12 882 440	12 883 680	12 881 434	12 879 612
EFS	12 953 311	12 947 303	12 938 648	12 924 417	12 912 625	12 903 451
Ratio	1.004825	1.004444	1.004363	1.003162	1.002421	1.001851

As mentioned above, the error of counted neutrons is given only by Poissonian distribution. I.e. it is a square root of the number of counts. If the same EFS and SUFS spheres will be measured repeatedly, the resulting measured numbers of counts will form distributions as it is shown in Figure 18.

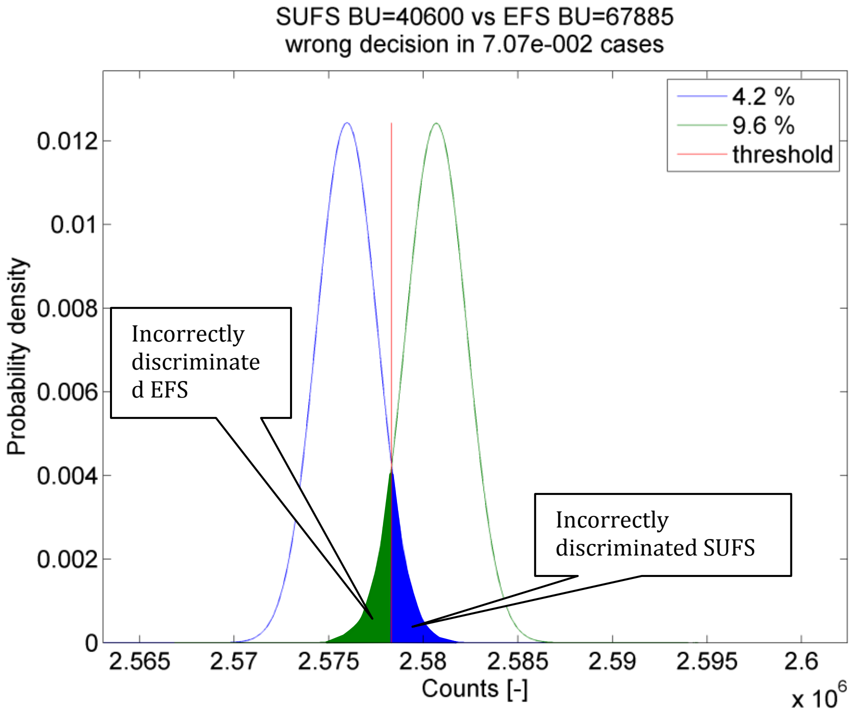


Figure 18 Poisson distributions of measured counts from EFS (enrichment 9.6%) and SUFS (enrichment 4.2%).

The discrimination of the fuel spheres is then based on simple comparison of the measured number of counts with some chosen threshold. I.e., if the measured number of neutron counts is higher than the threshold then the examined sphere is EFS. If it is lower than the threshold, the sphere is SUFS. However, because of the statistical nature of this measurement there is a non-zero probability that the EFS will show number of counts lower than the set threshold and vice-versa for the SUFS. This determines the precision of the selection. I.e. the relative number of fuel spheres where measured counts fall on the "wrong side" of the threshold is the relative precision of the device. It is obvious that the two distributions from Figure 107 must be as distant as possible. This can be achieved by increasing the detected number of neutrons by increasing the Cf source emission.[6] The effect of separation of count distribution is demonstrated in Figure 19.

[6] Another possibility is to improve detector overall detection efficiency or to improve the setup geometry so that the generated neutron flux and thus number of fission will increase – this was however already done in finding the best geometry and detector.

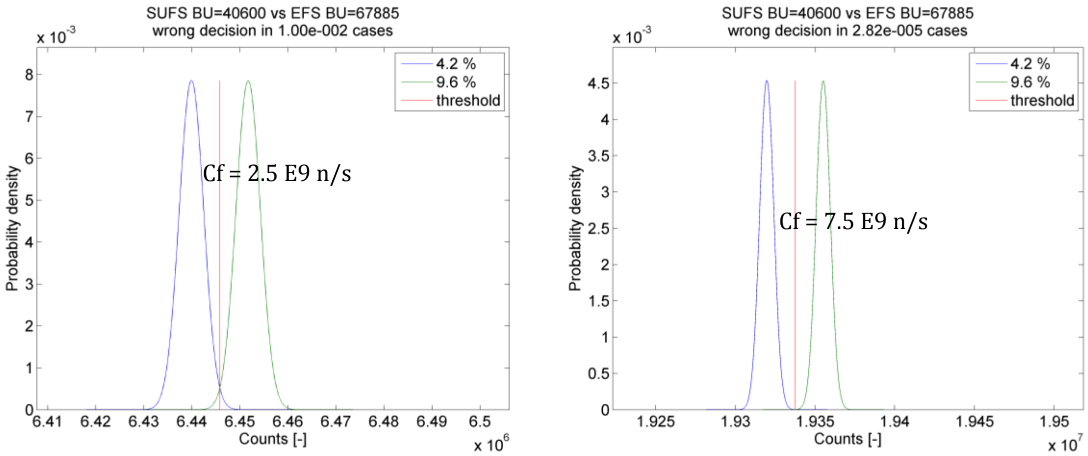


Figure 19 Separation of the count distribution by increasing the Cf source emission three times.

It is obvious that a reasonable Cf source emission has to be found to achieve the requested discrimination precision, which was set to 1E-3 wrong decisions. Figure 20 shows dependency of fuel discrimination error on Cf source emission. This result indicates that the optimal Cf source emission to achieve precision of fuel discrimination of 1E-3 is at least ~4.50E+09 n/s.

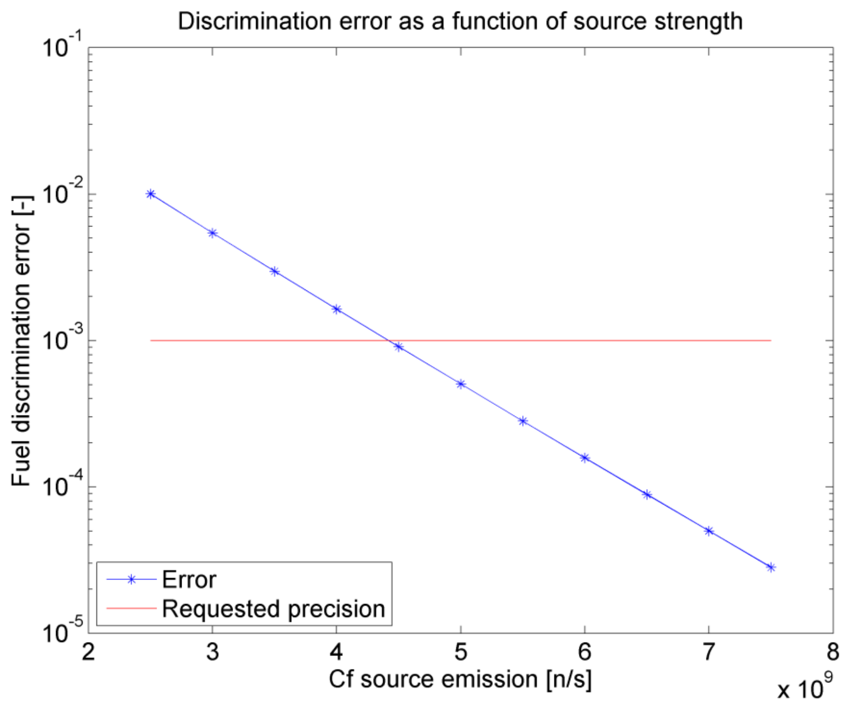


Figure 20 Error of EFS and SUFS discrimination as a function of Cf source emission. The lowest Cf source emission to achieve the discrimination error less than 1E-3 is of ~4.50E+09 n/s.

The detailed analysis of discrimination error has also shown that it is not possible to use only one value of threshold for all different burn-ups of the fuel. I.e. if the threshold will be set for fresh fuel only then this value of threshold will generate high discrimination error when the fuel will reach higher burn-up. Similarly, it is not possible to optimize the threshold value for higher fuel burn-up because then the discrimination with such threshold will fail for the fresh fuel. This means that the position of the discrimination threshold has to be adjusted in time as the fuel is gaining higher levels of burn-up (see Figure 21). The threshold adjustment can also be done using measurement of fuel burn-up of each measured fuel sphere within PND. Another possibility exists to set the threshold according to "an average burn-up" in the core measured by the independent burn-up measurement device or simulated.

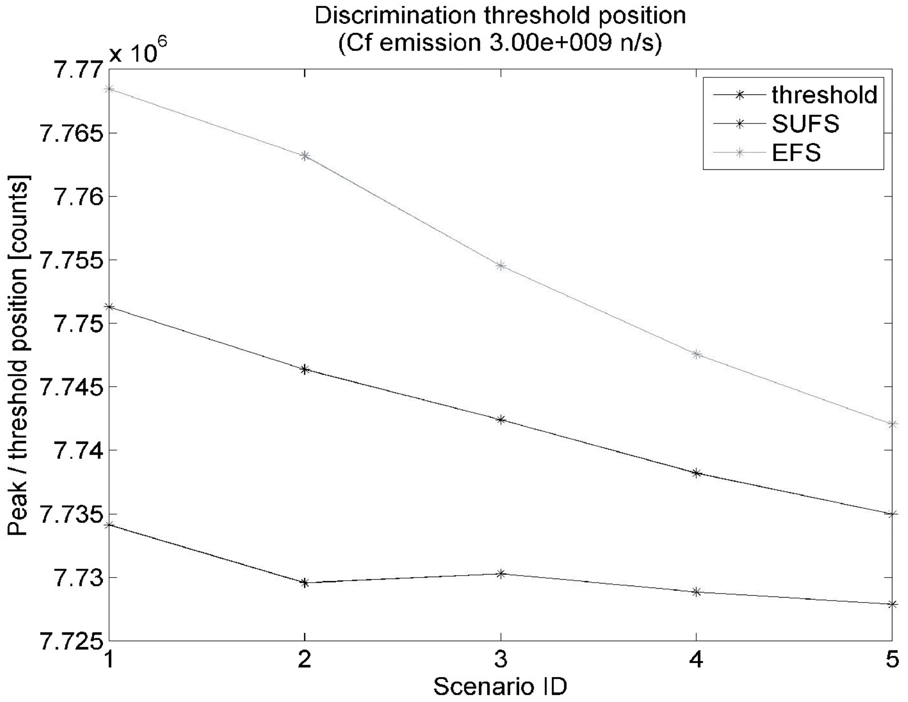


Figure 21 Mean number of neutron counts and necessary threshold position for each scenario of SUFS and EFS burn-ups.

3.7 EXPERIMENTAL EVALUATIONS OF THE PND CONCEPT

A wide range of experimental evaluations of the fast neutron detection with silicon detector was conducted using the Medipix-2 pixel detector [9]. They lead us to suggested PND design modifications.

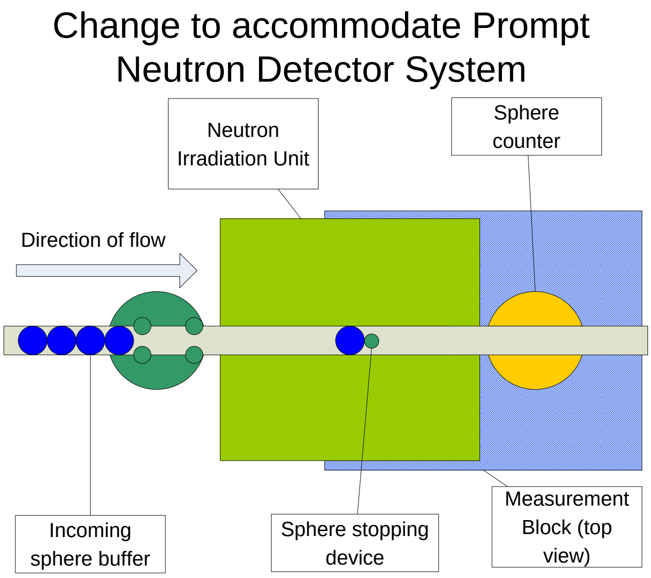


Figure 22 PND on MVB, top view.

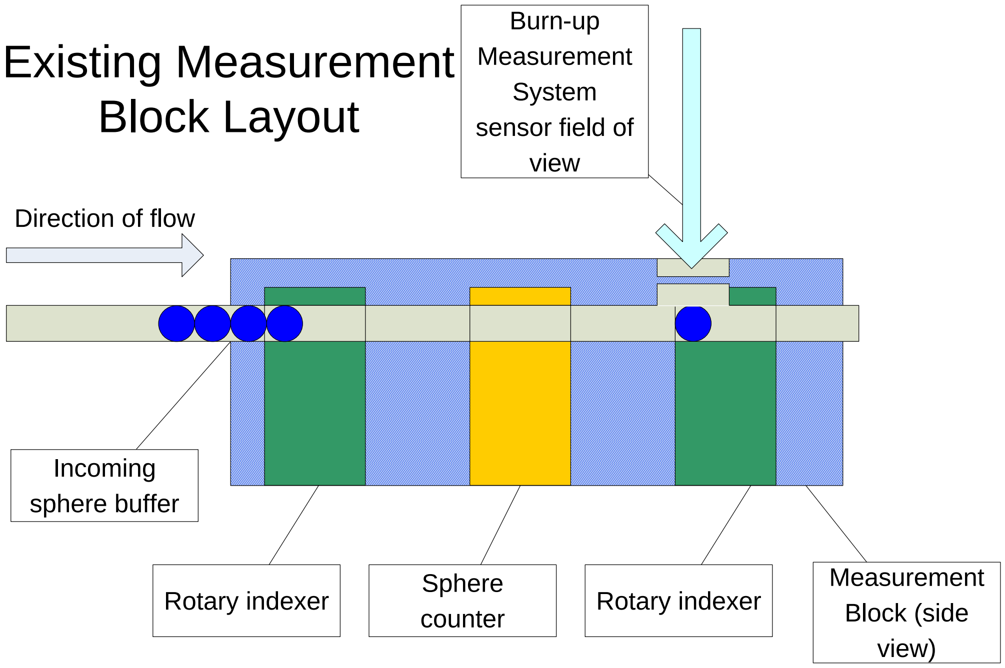


Figure 23 Current MVB, side view.

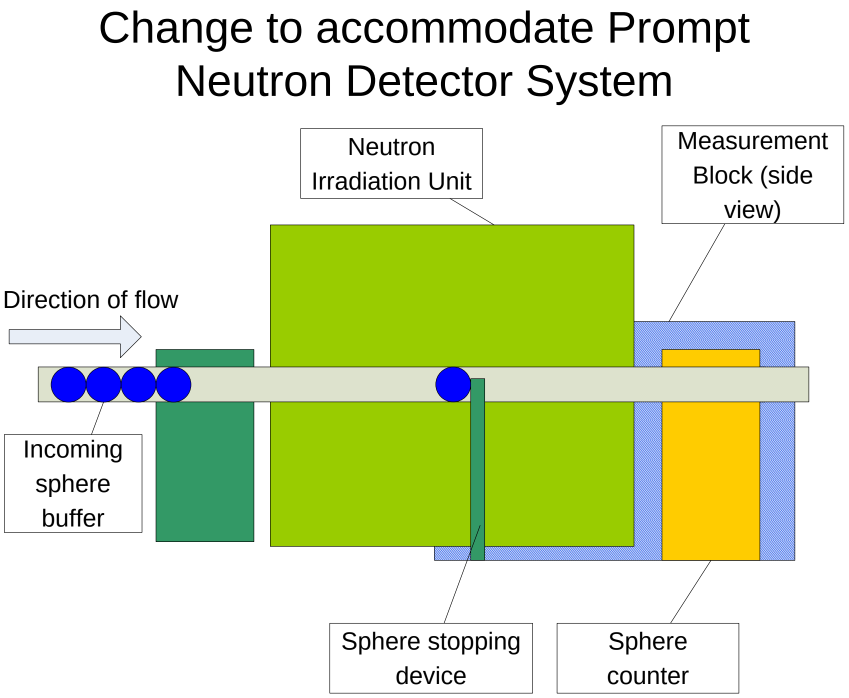


Figure 24 PND in MVB, side view.

3.8 PND SOLUTION CONCLUSION

The key part of the proposed PND setup is a fast neutron detector consisting of a polyethylene neutron converter and a silicon diode. The detector works on a principle of proton recoil from the hydrogen rich polyethylene and the subsequent detection of protons in the silicon diode. A wide range of Monte-Carlo simulations and experimental tests was done to characterize parameters of this fast neutron detector.

The simulations proved that the number of detected prompt fission neutrons which were generated in the fuel by the external source can be high enough to allow fuel enrichment discrimination with error better than 1E-3. In order to achieve this a Cf source of neutrons with emission of ~4.5E9 n/s is needed.
The rather harsh conditions caused by the activated fuel as well as by the Cf neutron source make fuel enrichment discrimination challenging, but solvable. The intensive gamma flux generates a significant background in the detector but it can be sufficiently suppressed by usage of a pixelated detector and pulse height discrimination. This leads to necessity to reduce the single detector element to size of tens of micrometers. This allows single particle detection, which is needed for a proper fast neutron counting. The small area of detector elements (pixels) reduces the probability of multiple gamma interactions in one pixel and thus reduces the pile-up of gamma pulses. Then the simple pulse height discrimination can be used. The size of one detector element at level of tens of micrometers is a realistic size as it is a typical size of pixels in imaging or particle tracking detectors used for example in high energy physics.
The ability to suppress the gamma background was demonstrated in measurement with Medipix-2 pixel detector, which was irradiated by a beam of neutrons at ILL, Grenoble. The measurement was done in a radial channel of the ILL's reactor. The beam contained a wide spectrum of neutrons from thermal up to fast neutrons. The beam was also highly contaminated by gamma radiation. The Medipix-2 detector, with its pixels of 55x55 μm^2, was able to suppress the gamma background sufficiently and was able to clearly distinguish the fast neutron signal.
The last important contribution to the detector signal is neutrons directly from the external source. It was proposed to use a Cf neutron source with emission of about 4.5E9 n/s. Source with such an emission induces sufficient fissions in the examined fuel.
The simulations showed that the detector is up to 25 times less sensitive to neutrons from the back side rather than from the front side. The simulations also indicate that fast neutrons from the Cf source do generate a high count rate in the detector even if they penetrate the detector from the back side. This signal is about three orders of magnitude higher than the signal from prompt fission neutrons. Nevertheless, the discrimination of fuel enrichment is still possible.
The neutron background can be reduced by placing the sources at longer distance behind the detector. The decrease in the detected neutron background is more significant than the decrease in the number of detected prompt fission neutrons.
An issue, which was not addressed in this analysis, yet is the radiation hardness of the detector system. This parameter strongly depends on the detector used and cannot be easily addressed without experimental knowledge of this detector parameter. The final PND setup will have to take the radiation hardness of detector into account. Also the cost element depends on the chosen detector, which is in the R&D phase, and will be estimated in later sub reports of the feasibility study.

4 COMPARISON OF DND AND PND SOLUTIONS, RECOMMENDED PATH

Delayed Neutron Detector (DND) and Prompt Neutron Detector (PND) are the two solutions on how the equilibrium (EFS) and start-up (SUFS) fuel spheres at PBMR can be discriminated. Both methods are also able to identify fuel spheres with no fissionable material. The methods can also be applied when more than two different fuel enrichments are used in the reactor in the same time or if enrichments are different from the current set-up (i.e. different from 4.2% and 9.6%).

This document focuses on physical, technical, implementation, and cost advantages of both solutions. Either DND or PND are functionally feasible and able to distinguish the spheres from each other. The pros and cons are directly linked to their different construction.

We propose the DND set-up [10] with two units – irradiation unit (IU) and measurement unit (MU) that can be implemented to fulfill PBMR requirements. Having 2 units, instead of 1 for PND, makes the DND solution larger and requires more modifications of the current PBMR setup. We considered 3 versions of set-ups with different IUs. However, the MU is identical for all three versions, designed in a way that it can use commercially available parts. The main part of the MU is the Delayed Neutron Detection Device (DNDD) and its calibration to stand high gamma flux is the main challenge of the DND solution. The main advantage of the DND is usage of commercially available parts.

PND was studied in two different set-ups [11]. The Back Irradiation (BI) and the Neutron Channel (NC) options were considered. Both PND solutions can be packaged as a single unit – the so called irradiation unit (IU) – and can meet PBMR's requirements to separate fuel spheres with smaller modifications then the DND solution. Moreover, both IUs can be used as the initial part of DND described in the report [12]. The key challenges in the practical implementation are the choice of the suitable fast neutron detector, which can be costly as it is still in the R&D phase, and deriving its correct position within IU.

PND irradiates and measures the spheres in the same time, opposed to two units of DND, hence it is smaller and consists of a single unit. However, PND's technical implementation is more advanced, due to the detector that must be used. It also brings uncertainty in the cost element. DND applies more matured technology but requires two units and as a solution it is more bulky.

We believe that the upper cost estimate of the solution should not exceed 1,500,000 USD per detector system. We also believe that using careful optimizations the cost can be radically decreased, possibly up to one order of magnitude. A very conservative cost analysis showed that a strong neutron source, required for either of the solutions, and the neutron detectors, meeting the high standards, will be driving the cost of the solution. In the feasibility study we focused on a solution that has only one target: distinguish the spheres with as small error as possible. However, in reality the size of the solution and its implementation cost must fit into the framework of PBMR. Further optimizations taking into account size, cost, and precision of the device can answer this issue.

4.1 PHYSICAL AND TECHNICAL CONSTRAINTS

Both methods are based on detecting fission neutrons from the fuel spheres. Multiplicative properties of the fuel depend on burn up as follows:

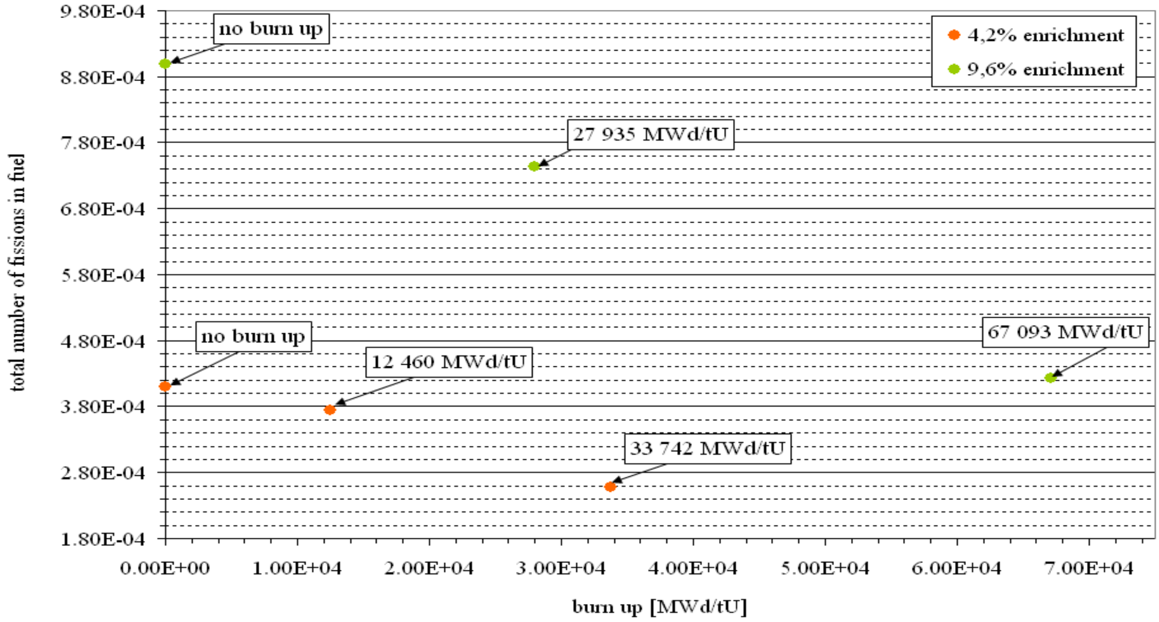


Figure 25 Number of fissions for various burn up levels of pebble fuel irradiated in ISO- IU per 1 neutron from the Cf neutron source

As EFS fuel enters the reactor after SUFS fuel, only some combination of burn up scenarios can occur in the same time. Apart from the fresh fuel, discrimination between irradiated start-up fuel spheres and irradiated equilibrium fuel spheres was studied in the worst case scenarios as shown below[7]:

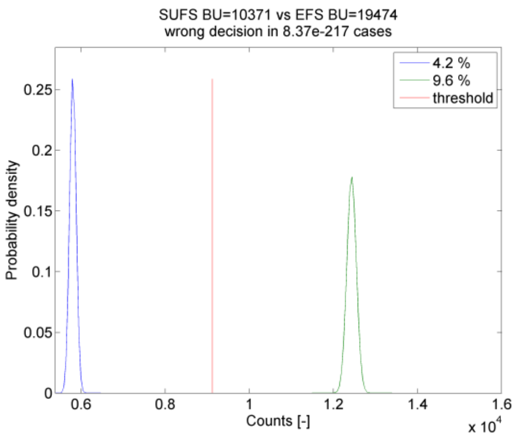
Cycle	Maximal EFS burn-up	Minimal SUFS burn-up
	MWd/tU	MWd/tU
1	19474	10371
2	31872	20343
3	41622	26089
4	55518	33363
5	67885	40600

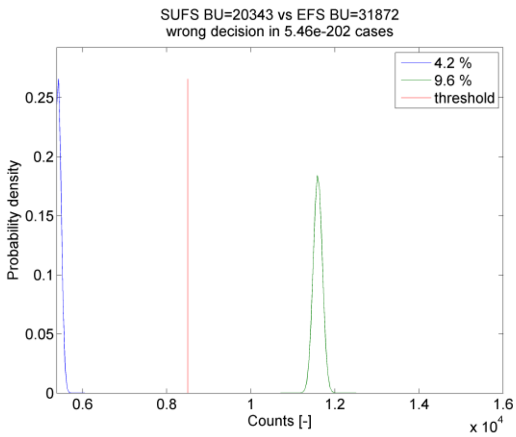
Even though the two solutions, PND and DND, are based on the same property – multiplicative properties of the fuel - they differ from each other, namely in the two following main areas: used detectors and size.

4.2 DND ADVANTAGES AND CHALLENGES

DND uses tested and commercially produced parts; it is its greatest advantage. On the other hand, the solution requires 2 units, which make it larger than PND. Also a rapid transfer with accurately measured transfer of fuel transfer time from IU to MU is required for DND and may create an additional source of uncertainty.

The following graphs summarize the discriminatory performance of the DND solution in the conditions as stated in detail in report [12].





7 SUFS of a particular cycle must be discriminated from EFS of the same cycle or less (e.g. 5th cycle SUFS must discriminated from 1 – 5 cycle EFS) Hence, there are the 5 worst case scenarios to be studied plus the case with fresh fuel.

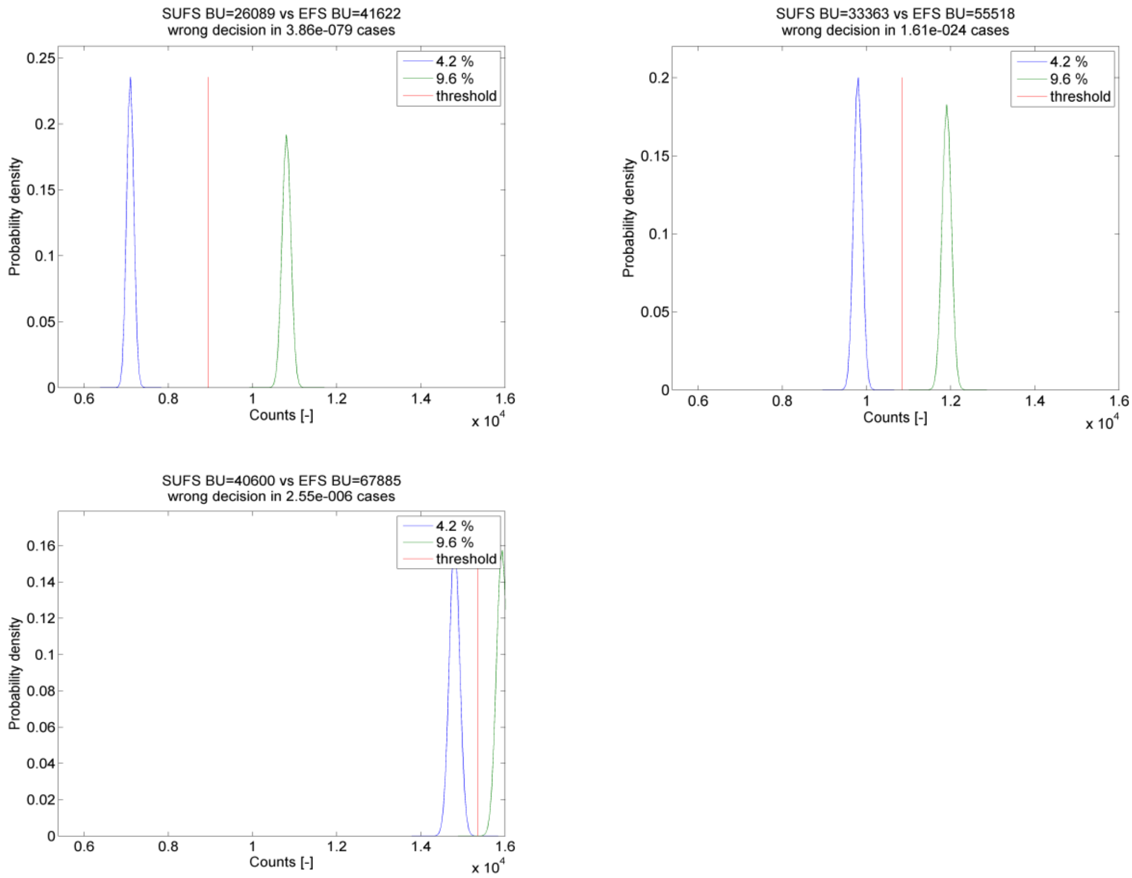


Figure 26 DND: Detected number of counts in form of Poissonian distributions for worse-case SUFS and EFS burn-up combination scenarios (Cf source emission = 1.5 E9 n/s)

All studied scenarios together provide the following discrimination characteristics for DND:

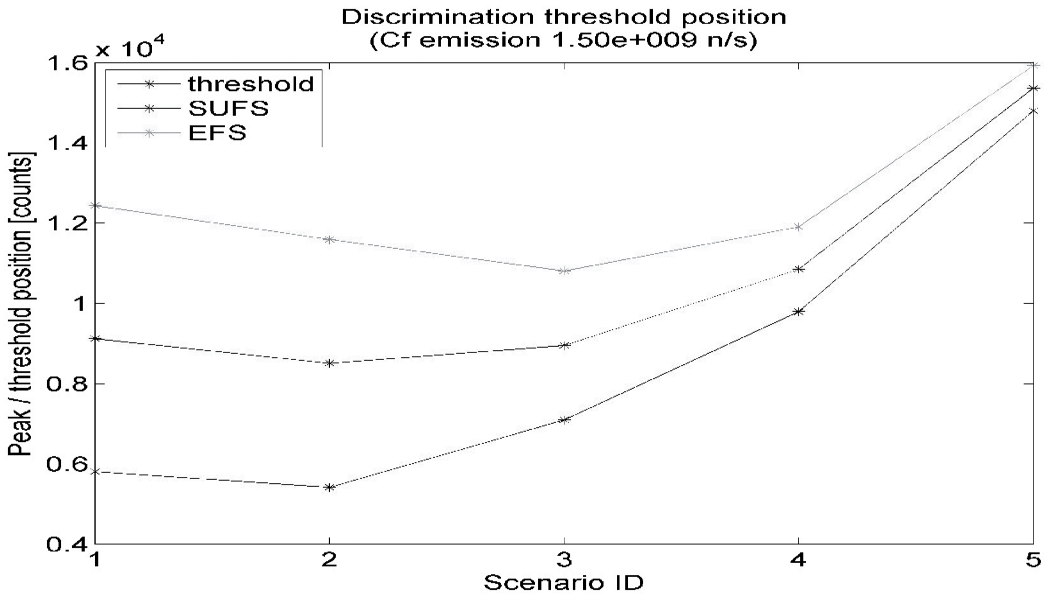


Figure 27 DND: Mean number of neutron counts and necessary threshold position for each scenario of SUFS and EFS burn-ups

The follow up work should focus mainly on the choice and testing of an optimal "off-the shelf" detector. The choice of the best detector is driven by the signal, which are delayed neutrons, and the background, which are gammas and background neutrons. The background neutrons do not pose a significant problem for all detectors. Because the gamma doses from irradiated fuel are so high, additional modifications to the measurement unit were proposed using Pb shielding.
If other studies are to be conducted, CTU has measurement capabilities, wide range of different neutron detectors, and gamma samples and can test the detectors up to gamma dose rates of 10Gy/h [8].
In terms of selecting an optimal neutron source, the DND discriminatory error dependence as a function of the used Cf neutron source is as follows:

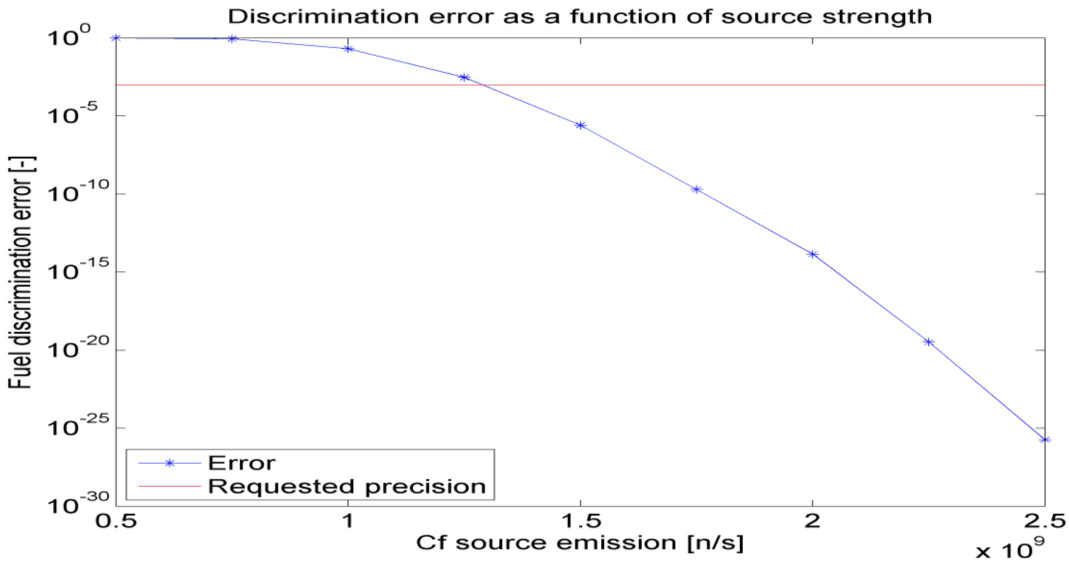


Figure 28 DND: Error of EFS and SUFS discrimination as a function of Cf source emission. The lowest Cf source emission to achieve the discrimination error less than 1E-3 is of ~1.50E+09 n/s.

4.3 SUMMARY FOR THE DND SOLUTION

- This concept should provide robust performance, using a neutron source that is intense, but not intolerably so.

- The fact that the sphere needs to be irradiated, then transferred to a separate unit for measurement means that additional volume; sensors and sphere manipulation devices (implying penetration(s) of the pressure boundary) are required for this instrument compared with the prompt neutron concept.

- Further design optimization should reduce the required source intensity and volume.

- This concept is technically feasible, but the impact on the DPP fuel handling system will be significant unless other optimization is performed

[8] Comparable to PBMR conditions.

4.4 PND ADVANTAGES AND CHALLENGES

Discrimination in the case of PND is different than in the case of DND; as the background from the Cf source is quite large and constant for both enrichments, the relative difference is not as significant as for DND. However, the absolute difference with decent statistics provide a good reason to believe PND has a good potential as demonstrated in the following graphs showing the signal for EFS and SUFS:

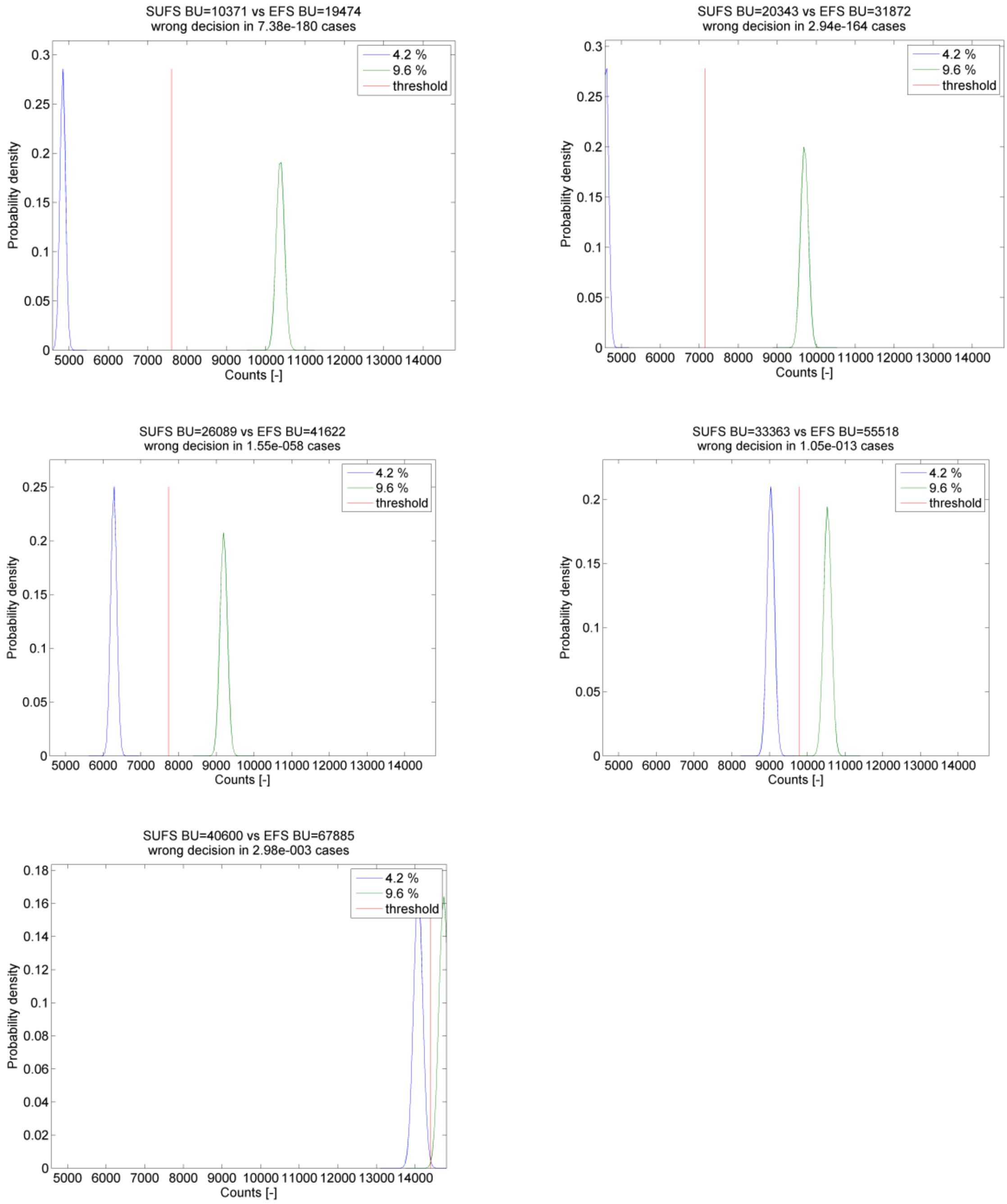


Figure 29 PND: Detected number of counts in form of Poissonian distributions for worse-case SUFS and EFS burn-up combination scenarios (Cf source emission = 1.25 E9 n/s)

In order to achieve the desired discriminative properties a stronger source for PND is required; the combined discrimination chart for Cf source emission = 3.00 E9 n/s is as follows:

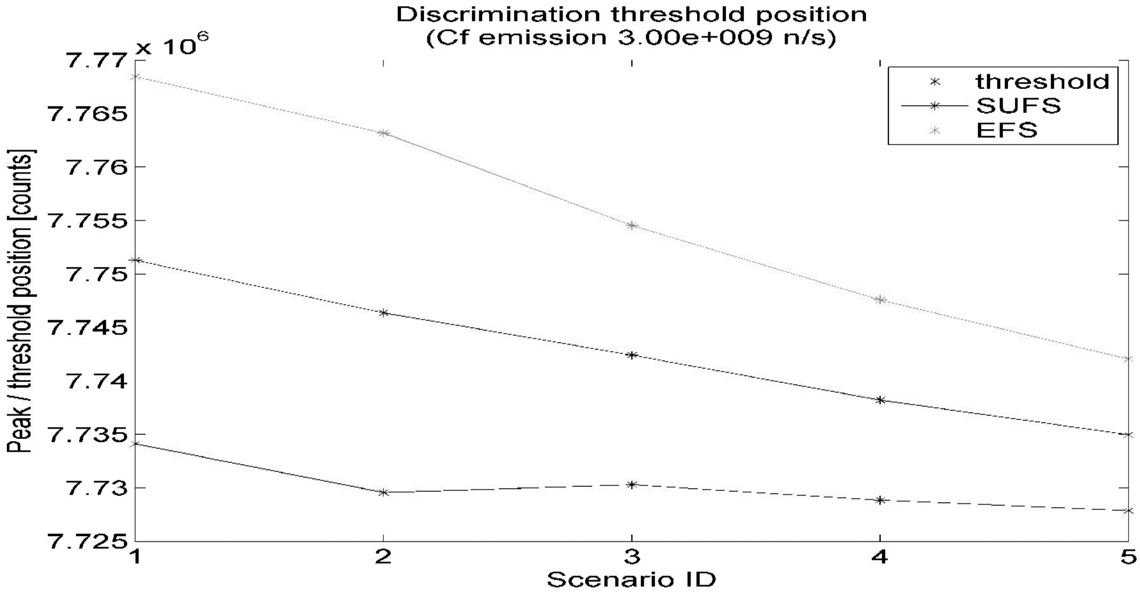


Figure 30 Mean number of neutron counts and necessary threshold position for each scenario of SUFS and EFS burn-ups.

In terms of selecting an optimal neutron source, the PND discriminatory error dependence as a function of the used Cf neutron source is shown here:

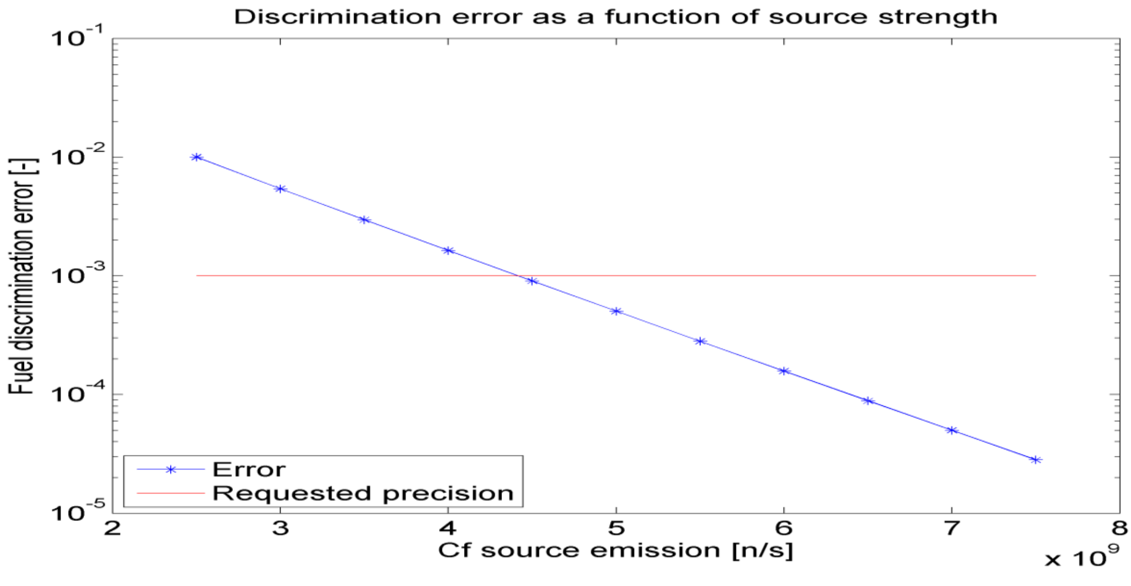


Figure 31 PND: Error of EFS and SUFS discrimination as a function of Cf source emission.

PND, using one unit only, is physically smaller than DND. The key part of the proposed PND setup is a fast neutron detector consisting of a polyethylene neutron converter and a silicon diode[9]. A wide range of Monte-Carlo simulations and experimental tests were done to predict parameters of the fast neutron detector.

[9] It is currently not available commercially in a required form and it works on a theoretically well understood principle of proton recoil from the hydrogen rich polyethylene and the subsequent detection of protons in the silicon diode.

The tough radiation conditions caused by the activated fuel as well as the Cf neutron source make the fuel enrichment discrimination challenging, but solvable. The background from the Cf neutron source neutrons is an additional source of PND measurement uncertainty that is not present in the DND solution. Therefore any PND calibration will be more demanding than a DND calibration. Placing the sources at longer distance behind the detector can reduce the PND neutron background. The decrease in the detected neutron background is then more significant than decrease in number of detected prompt fission neutrons.
The intensive gamma flux generates a significant background in the detector but it can be efficiently suppressed by usage of a pixelated detector and pulse height discrimination. In this respect PND shows better properties than DND. The size of one detector element at level of tens of micrometers is a realistic size as it is a typical size of pixels in case of imaging or particle tracking detectors used for instance in high energy physics.
An issue which was not addressed in this analysis yet is the radiation hardness of the detector system. This parameter strongly depends on the detector used and cannot be easily addressed without experimental knowledge of this detector parameter. Also the cost element depends on the chosen detector, which is in the R&D phase, and can vary.

4.5 SUMMARY FOR THE PND SOLUTION

- The PND concept works, but only with a rather intense neutron source.

- The fact that the sphere is irradiated and measured simultaneously is attractive in that the required hardware and volume is greatly reduced compared with the delayed neutron concept. This will greatly reduce the impact on the DPP fuel handling system.

- The concept is desirable in principle but the main objection is the level of background neutrons detected due to the geometry and neutron source used.

- Because this concept is novel there is still considerable scope to improve its performance through further geometric optimization and the consideration of alternative neutron sources.

- In conclusion, this concept is needs further work be done to address the design shortcomings, as there is agreement that there is still considerable scope for performance improvements.

4.6 IMPLEMENTATION AND COST CONSTRAINTS

The feasibility study primarily focused on achieving appropriate discriminatory properties with other free parameters (e.g. space, cost) being of secondary importance[10]. The first conclusion of the feasibility was that neither PND nor DND solution can be implemented without changes of the current PBMR setup, even though the required changes are not revolutionary. A logical outlook is that once a technically feasible solution is found, the cost optimization follows in the second step.

It is a large cost difference if a prototype or a series of the same product is made. In order to stay on the conservative side we assume a prototype production with all material amounts rounded up with very conservative margins. The cost covers manufacturing of the DND/PND units only; i.e. it does not cover other R&D work, changes of the current PBMR layout, certification, trips, transport, etc.

With no profit, taxes, overheads taken into account "a back of the envelope" calculation provides the following results:

For the DND solution, we estimate the cost to be EUR 815,000 per one measurement block.

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[10] Follow-up analysis should therefore focus on optimising those free parameters assuring the system still operates properly.

For the PND solution, we estimate the cost to be EUR 950,000 per one measurement block.

If the two solutions are to be used in the same time in one measurement block, we expect the cost to be EUR 1,265,000.

Clearly reducing the dimension of the units, using cheaper detectors, less intense sources and/or cheaper material can reduce the cost several times; additional analysis are required in this regard.

4.7 MECHANICAL ITEM COST

DND uses 2 units, PND uses only 1. All mechanical prices are estimated for DND, PND being scaled down accordingly.

Nickel is used for both solutions because of its desirable nuclear properties. The cost of nickel is currently $30,500 a ton and the price is quite volatile. We assume than no more than 200kg of nickel will be needed.
An conservative estimate of EUR 10,000 is taken. (5000 for PND).

Heavy water, because of its nuclear properties, was chosen; price of D_2O is roughly $500/kg, volatility being quite stable. We do not think about using more than 100kg of D_2O.
An conservative estimate of EUR 45,000 is taken. (45,000 for PND).

Beryllium can be bought roughly for USD 500/kg. We do not expect to use more than 100kg of Be.
A conservative price of EUR 50,000 is assumed. (50,000 for PND).

Manufacturing in the prototype environment we assume as 200% of the material cost, i.e. EUR 210,000 (EUR 200,000 for PND). Please be aware that some of the used technologies are not standard (e.g. nickel welding, working with poisonous Be) and need to be taken to account.

Sub-total for manufacturing: EUR 315,000 (EUR 300,000 for PND)

4.8 NEUTRON DETECTOR COST

The choice of a detector for DND can be done from several possibilities, depending on the radiation endurance. The PND detector has to be designed and fabricated from scratch. Therefore we assume EUR 300,000 for DND detectors and EUR 450,000 for PND. We feel a great potential to decrease the estimates in the future.

4.9 CF SOURCE COST

The presented data are obtained from [13]. Since PBMR may be using Cf sources for other purposes, more recent quotes may be available directly.

While source material is sold to commercial vendors at a current price of $60 μg^{-1} of Cf252, plus encapsulation, packaging, and transportation charges. Typical costs for loan and return of a <7µg source total ~$11,000. Similar costs for a source in the range of 7 µg to 3 mg (neutron intensities ranging up to 7×10^9) total ~$20,000, while sources in the 3- to 5-mg range total ~$28,000. Loan/return costs of pre-existing sources from inventory containing >5 mg total ~$32,000. Sources containing >8 mg typically require custom fabrication, but a source containing the maximum permitted Cf252 content of 50 mg (neutron intensity ~10^{11}) can be obtained for ~$51,000. None of these costs include transportation charges.

As a conservative estimate for four sources EUR 200,000 is assumed.

4.10 ADDITIONAL BENEFITS OF USING NEUTRON DISCRIMINATION

Identification of SUFS and EFS was the primary goal of the feasibility study. However, there are other potential benefits of both DND and PND solutions.

1. Graphite spheres with no fissionable material will generate no fission neutrons and can very easily be identified by both DND and/or PND.

2. PBMR, being in the first phase of implementation, can in the future use different fuel setups then currently proposed. Namely different enrichments can be used and/or more than two types of the fuel deployed. Both methods can easily be adapted to the new conditions.

3. The Cf neutron sources, used inside IU, can be sold or reused for other purposes in the PBMR reactor once the fuel discrimination in the equilibrium reactor operation mode is no more required. Since quite strong neutron sources are assumed, their activity and cost, once they are removed from IU, will still remain substantial.

4.11 CONCLUSION

Both PND and DND can separate SUFS from EFS used in the modified PBMR setup. DND uses a more matured technology, PND is smaller in size and requires smaller modifications of the PBMR setup.

Estimates of the costs per one measurement channel are as follows:
DND EUR 815,000, PND EUR 950,000, PND & DND EUR 1,265,000.
Risks and issues were identified for each concept. N.B. that many issues are common to both concepts:

Prompt Neutron Detection	**Delayed Neutron Detection**
a. Keeping moderator fluid from boiling in 250ºC - 300ºC environment.[11]	a. Keeping moderator fluid from boiling in 250ºC - 300ºC environment.
b. Implementation of burn-up measurement as part of enrichment discrimination?	b. Implementation of burn-up measurement as part of enrichment discrimination?
c. VERY intense neutron sources required.	c. Intense neutron sources required.
d. Gamma shielding concept?	d. Gamma shielding concept?
e. Calibration concept?	e. Calibration concept?
f. Calibration frequency?	f. Calibration frequency?
g. Radiation hardness of detector.	g. Measuring irradiation time of spheres in irradiation unit.
h. Detector sensitivity to environmental factors	h. Minimizing sphere transfer time from irradiation unit to measurement unit (this can be traded off against source strength).
i. Trade-off between measurement time and source intensity	i. Accuracy of measurement or control of sphere transfer time?
j. Supplier/manufacturer for detector.	j. Up to what gamma dose rate can the detectors compensate accurately?

Taking all the results into account, we proposed using PND and DND simultaneously, providing the DND solution physically fits inside PBMR. A more risky route is using DND on its own, and the most risky option is to deploy PND only with the benefit of saving space.

[11] If other moderator and/or reflector material is used, some of the issues may not be relevant.

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6 ABSTRACT/*ABSTRAKT*

A unique feature of PBMR graphite-moderated high temperature nuclear power reactors is its fuel cycle in which fuel spheres are randomly loaded and continuously circulated through the core until they reach their prescribed end-of-life burn-up limit. As spheres of different burn-ups are mixed within the reactor and the spheres in different parts of the reactor move through it at different speeds, it is not possible to depend on computational or procedural methods to manage the fuel as is the case in more conventional reactors.

When such a reactor is started up for the first time, the lower-enriched start-up fuel is used, mixed with graphite spheres, to bring the core to criticality. As the core criticality is established and the start-up fuel is burned-in, the graphite spheres are progressively removed and replaced with more start-up fuel. Once it becomes necessary for maintaining power output, the higher enriched equilibrium fuel is introduced to the reactor and the start-up fuel is removed to the spent fuel tank. Since it is expected that at a certain point, the burn-up of the start-up fuel could exceed the qualification limit for that fuel, it is important that all the start up fuel is removed before that a certain burn-up limit is reached.

There is therefore a need for an on-line enrichment discrimination device that can discriminate between irradiated start-up fuel spheres and irradiated equilibrium fuel spheres. The device must also not be confused by the presence of any remaining graphite spheres. Due to its on-line nature the device must accomplish the discrimination within tight time limits.

A secondary consideration is that during the commissioning of the reactor, the reactor core could be loaded with a mixture of start-up fuel spheres and graphite spheres and then, before going critical, could be required to unload the fuel again due to some unanticipated problem. In this case the unirradiated fuel and graphite spheres need to be separated with a high degree of confidence. Since the neutron-based discrimination techniques being considered in this project have the potential to perform this function, this scenario was also be considered.
The thesis describes two ways – one based on delayed neutrons, and one based on delayed neutrons, that solve the problem. Detailed numerical analyses and cost comparison is conducted.

Unikátním rysem PBMR grafitem moderovaných vysokoteplotních jaderných reaktorů je palivový cyklus, ve kterém jsou palivové koule náhodně vloženy a průběžně recyklovány v aktivní zóně, dokud nedosáhnou svého předepsaného limitu vyhoření. Koule různých obohacení jsou náhodně smíchány v reaktoru a v různých jeho částech se pohybují různými rychlostmi. Není tedy možné, aby šla určit jejich historie, jak je tomu v případě konvenčních reaktorů.

Je-li takový reaktor zavezen palivem poprvé, používá se nižší obohacení paliva ve směsi s grafitovými koulemi, aby se dosáhlo kritičnosti. Vzhledem k tomu, že kritičnost se mění v čase, jsou grafitové koule postupně odstraněny a nahrazeny palivem. Pokud je nutné udržet výkon reaktoru v čase, víceobohacené palivo později nahradí nížeobohacené. Vzhledem k tomu, že se očekává, že vyhoření u nížeobohaceného paliva může překročit provozní limit tohoto paliva, je důležité, aby všechno nížeobohacené palivo bylo odstraněno ze zóny před dosažením svého limitu vyhoření.

Je proto potřeba použít zařízení na určení obohacování, která může rozlišovat mezi ozářeným nížeobohaceným a víceobohaceným palivem. A tento přístroj nesmí být zmaten přítomností zbývajících grafitových koulí. Vzhledem ke svému charakteru, toto zařízení též musí provést diskriminaci v krátkém čase.

Tato práce popisuje dva způsoby - jeden založený na zpožděných neutronech, a jeden založený na okamžitých neutronech - které oba řeší uvedený problém. Podrobné numerické analýzy a srovnání nákladů jsou provedeny.

Druhým aspektem je, že při zavezení reaktoru palivem může být požadováno, aby se palivo vyložilo kvůli nějakému neočekávanému problému. V tomto případě koule paliva musejí být odděleny s vysokým stupněm spolehlivosti. Vzhledem k tomu, že metody rozlišení obohacení za použití neutronů mají potenciál k provedení této funkce, byl tento scénář rovněž zahrnut.