SIMULATION OF VANADIUM DETECTORS IN DRAGON

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ABSTRACT

The Vanadium detectors are used in CANDU-6 reactors to provide mapping data for the on-line reactor regulating system. They can also be used to adjust the diffusion theory flux required for fuel management calculations using a reactor simulation code. Because of the importance of these detectors in the flux mapping approach, it is essential that we understand how they are affected by the reactor environment.

The code DRAGON has been used to evaluate the detector self-shielding effect. Since the Vanadium detectors are located perpendicularly to the horizontal fuel channels, a 3D supercell model is first considered. We also propose approximate 2-D models which will be used to determine how the detectors are affected by the local core conditions.

I. INTRODUCTION

The burnup simulation using the flux mapping approach rely on the in-core flux Vanadium detectors.[1, 2] This technique has been implemented in the HQSIMEX reactor simulation code and used for burnup and fuel management calculation at Gentilly-2 nuclear power station.[3] Because of the importance of these detectors in the flux mapping approach, it is essential that we understand how they are affected by various reactor environment. With flux mapping technique, uncertainties in the in-core measurements lead to errors in flux distributions obtained from diffusion theory calculation which have a cumulative effect on fuel burnup history.

The lattice code DRAGON can solve the transport equation for 2-D cluster cells, as well as for 3D supercells.[4] Since the Vanadium detectors are located perpendicularly to the horizontal fuel channels in the core a 3D supercell model similar to that used for CANDU reactivity devices could be required to take into account correctly the local neutron flux depression resulting from their presence in the core. However, the Vanadium detector is much smaller than the reactivity devices and the overall effect on the cell properties of its presence in the core should be proportionally smaller. Accordingly, a 2D cell calculation may be sufficient to obtain accurate reaction rates and reactivity worths for the detector. Various 2D models of the Vanadium detector will be proposed and compared against the reference solution obtained from a 3D supercell model for the detector similar to that used for the steel adjuster rods.[5, 6]

In the first section of this paper we will briefly describe how these detectors work. Then we will discuss the DRAGON 3-D and 2-D supercell models that were used in our analysis. In the third section, which will be devoted to numerical results, we will analyze the effect of environment on the detector self-shielding parameter. Finally we will conclude.

II. DESCRIPTION OF THE VANADIUM DETECTOR

The Vanadium detector belongs to the category of self-powered neutron detectors (SPND) which can operate without an externally applied voltage.[1] As shown in Figure 1, these detectors have a coaxial configuration where the outer metallic sheath called the collector is separated by an insulator from the central conductor called the emitter which is responsible for the generation of the signal. Neutrons that pass through the collector and the insulator can be absorbed by the emitter and lead to activation products that will decay through the emission of beta particles that give rise to a current, which when measured gives an estimate of the neutron flux reaching the detector.[1, 2, 7] In the case of the Vanadium detector, the collector is made up of Inconel-600, while the emitter is composed of Vanadium. The insulator is generally a material which is nearly transparent to neutron such as MgO or Al_2O_3. The activation reaction taking place in the emitter can be represented by the following nuclear chain:

$$^{51}_{23}\mathrm{V} + ^{1}_{0}\mathrm{n} \rightarrow ^{52}_{23}\mathrm{V}^* + \gamma \rightarrow ^{52}_{24}\mathrm{Cr}^* + ^{0}_{-1}\mathrm{e}$$

The Vanadium detectors are characterized by their simplicity, ruggedness and reliability. They have a small size (a few millimeters in diameter) and are able to operate for years in the harsh reactor core environment without appreciable deterioration in performance. They are sensitive mostly to thermal flux because of the energy dependence of their absorption cross section $\sigma_a(E)$ but their response to flux variations is slow and depends on the β decay of $^{52}_{23}$V which has a half-life of 3.76 minutes. Since the current is produced indirectly as a result of neutrons being captured in the Vanadium, the magnitude of the current will be proportional to the neutron flux $\phi(E, r)$ and is given by:

$$I_D = K \int_{V_D} d^3r \int dE \sigma_a(E) \phi(E, r)$$

where K is a proportionally constant and V_D represents the emitter volume.

Since the flux at the detector site is generally related to the averaged neutron flux in the cell $\phi_C(E)$, we can then define the detector self-shielding factor S_D as:

$$S_D = 100 \left(\frac{I_C - I_D}{I_C} \right)$$

where I_C represents the signal that would be received from the detector in the presence of the flux $\phi_C(E)$:

$$I_C = K V_D \int dE \sigma_a(E) \phi_C(E)$$

In general the factor S_D is included explicitly in the detector signal processing algorithm via the calibration procedure. Our goal here is to evaluate this self-shielding effect and to analyze its dependence on the local core conditions. This self-shielding factor S_D takes into account the fact that the flux will be depressed in the emitter due to the presence of the collector and emitter in the core and will therefore be negative.

III. DRAGON MODELS

The 2-D and 3-D assemblies that are actually available in DRAGON include only cylindric and rectangular regions which means that the fuel cell cluster has to be homogenized. Accordingly, using the standard 37 element CANDU fuel cell, we will generate multigroup homogenized 3 region cross section using a 2-D cluster cell model with lattice square pitch 28.575 cm. The three homogenization regions we will consider are an annular fuel region of outer radius corresponding to the inner radius of the pressure tube, a second annular region which extends to the outer radius of the calandria tube and a square moderator region. The 2-D cluster cell calculations were performed using the WIMS-Winfrith 69-group cross section library, and the final three region macroscopic cross section generated using the same 69-group energy structure.

III.1 3-D supercell model

Here we use a two bundle model like the one represented in Figure 2. The Vanadium detector are normally located midway between the two fuel bundles and occupies one lattice pitch. The fuel elements are represented by 2 regions z-directed cylinders. Similarly, the detector is represented by a y-directed cylinder.

The outside diameter of the detector is 0.3 cm while the central region which contains the emitter has a diameter of approximately 0.17 cm. Because the relative volume of the detector to that of the supercell volume is very small, selecting 3-D tracking parameters for this geometry such that the various regions inside the detector can be crossed by at least a few integration lines can be very difficult. Since the 3-D model will mainly be used to assess the validity of various 2-D model we will further simplify the detector geometry by assuming that it consists of a unique homogeneous region of diameter 0.3 cm containing a mixture of the emitter, the collector and the insulator. This 3-D geometry will be treated by the EXCELL module of the lattice code DRAGON which evaluates the contribution of each integration line to the collision probability matrix in succession, therefore avoiding the memory limitations associated with saving explicitly the tracking file.

For our 3-D model, 84 different integration angles are generated using the EQ_{12} equal-weight quadrature set and a 2-D trapezoidal integration is performed in a plane normal to each angle with 20 lines/cm^2. The neutron 3-D trajectories are then calculated and a numerical estimate for the volume of each of these regions is evaluated. For the specific set of quadrature parameters described above, the maximum error on these volumes is 2%.

The results we obtained for the self-shielding factor and reactivity worth associated with the detector using the above 3-D model can be found in Table 1.

Table 1: Result of simulation for homogenized detector

	S_D	ρ (mk)
3-D Model	4.9	-1.18
2-D Model 1	1.4	-5.54
2-D Model 2	4.9	-2.13
2-D Model 3	5.0	-2.24
2-D Model 4	4.9	-1.18
2-D Model 5	4.7	-0.77

III.2 2-D supercell models

Five 2-D models were selected as they appear the most promising. These different models all involve a cylindric homogeneous detector that is located at different position in the cell while different configurations of the fuel bundles have been considered. We will now examine briefly the geometries associated with the different models. We will also discuss their success in replicating the results obtained using the 3-D model.

- Model 1 (see Figure 3)

  A single CANDU fuel cell is considered with the detector located in the same plane as the fuel bundle and positioned at 13.7875 cm from the center of cell. A 2-D cell cluster calculation is used with an annular discretization of the moderator region. The detector to fuel volume in this case is increased by a factor of 3.4 since only one out of 2 fuel cells is considered and the length of the detector is effectively increased. The results presented in Table 1, indicate that the computed reactivity worth for the detector is -5.54 mk. This is to be compared with the results which can be extrapolated, using the relative change in the detector to fuel volume, from the 3-D model (-4.01 mk). However, the use of such a cluster model seems to be inappropriate because the detector self-shielding effect is reduced to 1.4%. Two facts can explain this reduction. First the detector is located closer to the fuel therefore experiencing a different flux energy spectrum. There is also the problem that the flux distribution in the annular moderator region immediately surrounding the detector will be less affected by the presence of the detector in this case than in the 3-D model.

- Model 2 (see Figure 4)

  In this model all the dimension of the 3-D supercell are conserved but the detector is rotated in such a way as to be parallel to the fuel bundle. Here a 2-D cell assembly calculation with spatial discretization similar to that used in the 3-D model is considered. The detector to fuel volume in this case is 1.7 times larger than than that of the 3-D model due to the fact that the detector length is effectively increased. The results presented in Table 1, indicate that the 2-D to 3-D ratio of reactivity worth (1.8) is compatible with this change in detector volume. In addition the detector self-shielding effect computed in this case is identical to that computed using the 3-D model indicating that this model simulates extremely well the flux behavior inside and in the region surrounding the detector.

- Model 3 (see Figure 5)

  This model is similar to model 2 but with the detector displaced with respect to the fuel bundles. The reason for this displacement is that model 2 simulates a detector which is located at the closest distance between the fuel bundle and the detector. In model 3 the distance between the detector site and the fuel bundle is closer to the value actually observed in the reactor. As one can expect the results obtained in this case are very similar to those obtained for model 2. This shows that the actual location of the detector is not very sensitive to the fuel position provided it is located in a moderator region sufficiently far from the fuel.

- Model 4 (see Figure 6)

  Here the fuel bundles and the structural material are represented by infinite 2-D plates. Their dimensions have been selected in such a way as to preserve the 3-D ratio of the fuel to detector volume. We can observe by looking at Table 1 that both the reactivity worth and the self-shielding factor associated with the detector are very close to the 3-D results. Again this is not surprising since the detector mainly sees the neutrons generated in the moderator nearby which for this model have a spectrum which is identical to that observed in the 3-D model.

- Model 5 (see Figure 7)

  In this case a model using 4 fuel bundles annularized around one central detector site is considered. This model is similar to that used at AECL to condense and homogenize the macroscopic cross sections associated with the stainless steel rods reactivity control devices. It is generally selected because one expect that the neutron flux spectrum observed at the center of such a cell will be similar to that observed at the interface of two cells in the reactor. This observation is confirmed by the fact that the self-shielding factor associated with the detector in the case is only 0.2% lower than that obtained using the 3-D model. However, the reactivity worth of the detector is 1.5 times smaller than that computed using the 3-D model while a reduction factor of about 1.2 is expected from the detector to fuel volume ratio.

From the point of view of the self-shielding factor all the 2-D models except model 1 seems to be equivalent. On the other hand, only model 4 seems to be able to generate the reactivity worth of the detector correctly even if the difference between the computed 2-D reactivity in model 2 and 3 and the 3-D results can be explained easily using the detector to fuel volume ratio. For the remaining of the analysis, which is concerned primarily with the self-shielding factor associated with the detector, we decided to use model 2 for our 2-D simulations.

III.3 DETECTOR ANALYSIS

In the previous section where we describe the process of selecting a 2-D equivalent model for the Vanadium detector, we always considered an homogeneous detector. Moreover, the spatial discretization we selected in all our calculations was a very coarse one, namely we assumed that the flux in the moderator region surrounding the detector would not be strongly affected by its presence. The flux variations inside the detector itself were also neglected. Finally all our calculations were performed at nominal core conditions. In this section we will relax successively each of these constraints and examine their effect on the detector self-shielding factor.

III.4 Effect of using a finer moderator discretization

In this case we considered the detector as being made up of three different annular regions. The internal region is identical to the homogeneous detector described above. The two outer additional regions contain moderator and have external radius of 0.3 and 0.45 cm respectively.

The self-shielding factor using the above discretization remain identical to that observed for model 2 in the previous section. This is because the change in the flux distribution inside the detector region resulting from the additional moderator discretization was not significative. In fact the difference between the flux in the two new and the old moderator region was smaller than 1% in each energy groups.

III.5 Effect of using the explicit detector geometry

The detector is a cylinder divided in three zones of different thickness; the central zone contains the vanadium emitter and is 0.17 cm in diameter; the second zone contains the insulator and the third zone contains the Inconel-600 collector. The calculation were performed here using a 2 zone model where the Vanadium is all concentrated in the most central region and the outer region is made up of an homogeneous mixture of the collector and the insulator.

The replacement of the homogeneous detector by the new configuration had for result to decrease the detector self-shielding effect from -4.9% to -6.4%. This illustrates the fact that by homogenizing the Vanadium with the other material in the detector the number of neutrons absorbed in the Vanadium increases. This is because the concentration of the strongly absorbing Vanadium at the center of the detector causes important local flux depression, therefore reducing the detector efficiency.

III.6 Effect of local parameters

The flux distribution in CANDU reactor is affected by burnup and the local parameters such as the boron concentration, the fuel temperature, the coolant and the moderator temperatures and densities. It is therefore important to learn if such changes in the core condition will affect the detector self-shielding factor. For the burnup effect, we compared the self-shielding factor obtained for fresh core conditions with that corresponding to 80 and 650 days at full power corresponding respectively to 2557.7 and 20781.3 MWD/T. No effect on the detector self-shielding factor could be observed.

It is also interesting to note that the detector is generally insensitive to the variation of the local parameters. In fact the most important deviation obtained in our calculation is -0.27 % due a decrease from 345.7 to 315.7 K of the moderator temperature.

IV. CONCLUSION

In this paper we have modeled the Vanadium detector using a 3-D geometry. We have also shown that several 2-D equivalent model could be constructed to evaluate the detector self-shielding factor consistently while it was a little more difficult to select a model which could also simulate its reactivity worth. We also discuss the effect of detector homogenization and moderator discretization in regions close to the detector. As we have shown, the depression in the signal received from the detector in the case of an homogeneous detector can differ by 1.5% for the signal observed when the Vanadium was concentrated at its center. The effect of using a finer moderator discretization was small. Finally, as a general rule burnup and the local parameters appears to have a very small effect on the detector self-shielding factor.

ACKNOWLEDGMENTS

This work was supported in part by a grant from the Natural Science and Engineering Research Council of Canada and by the CANDU Owner's Group.

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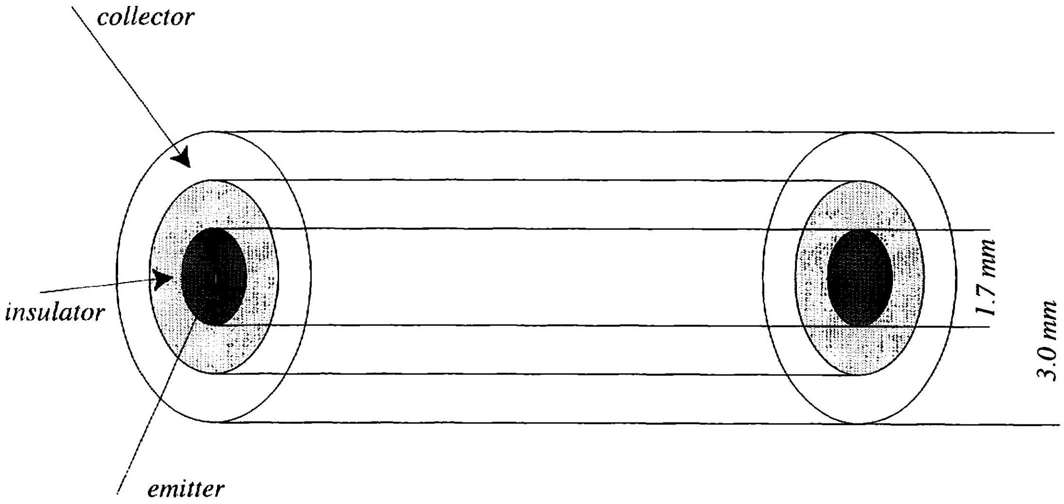

Figure 1: Geometry of a Vanadium detector.

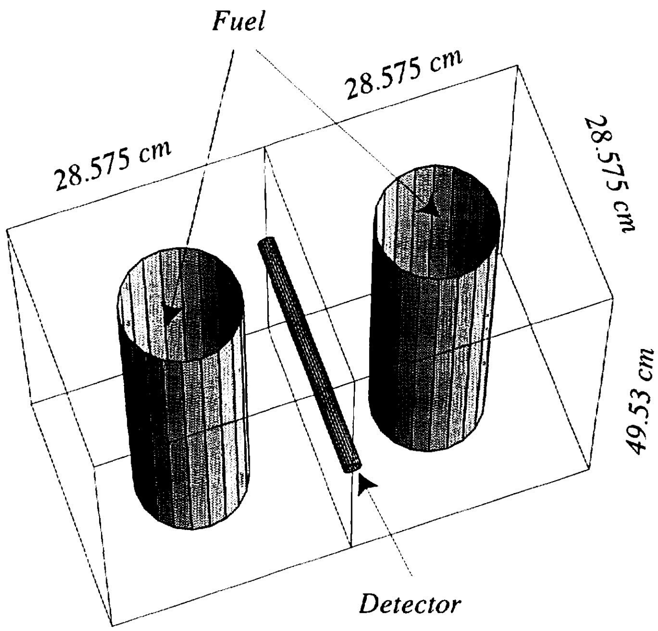

Figure 2: DRAGON 3-D model of the Vanadium detector

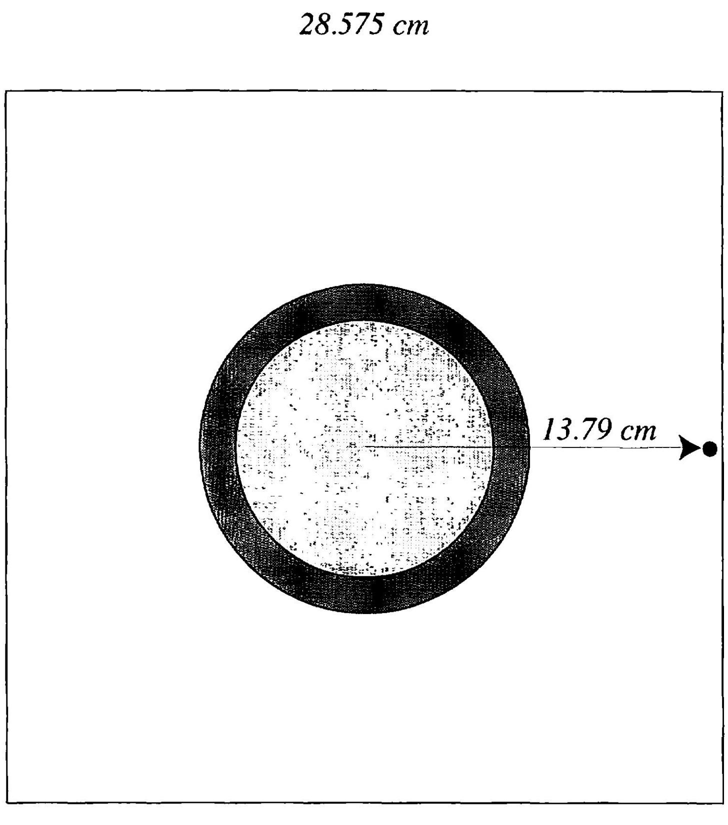

Figure 3: Model 1 for DRAGON 2-D simulation of the Vanadium detector

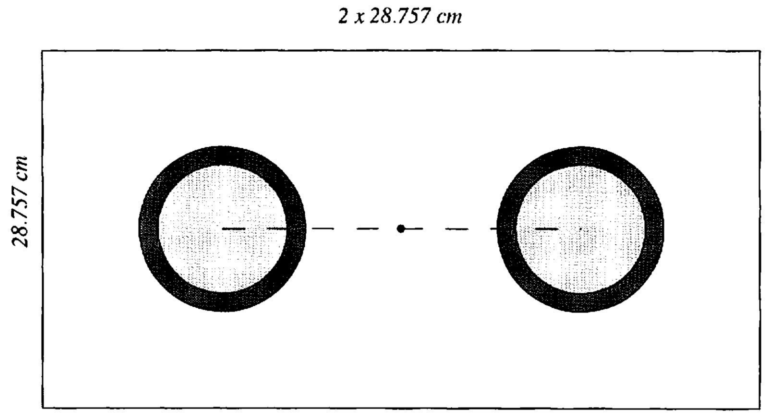

Figure 4: Model 2 for DRAGON 2-D simulation of the Vanadium detector

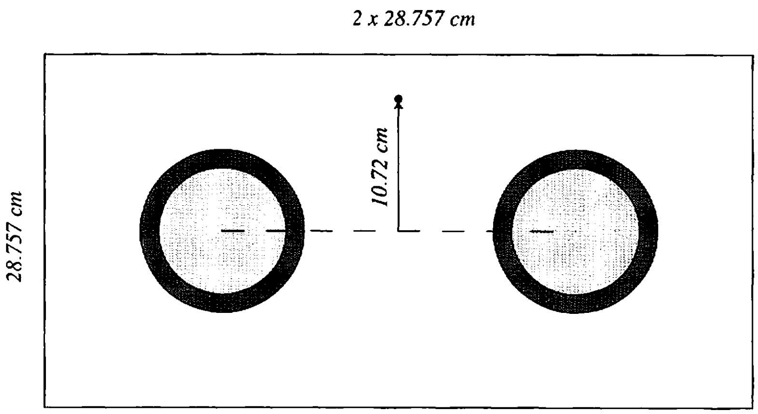

Figure 5: Model 3 for DRAGON 2-D simulation of the Vanadium detector

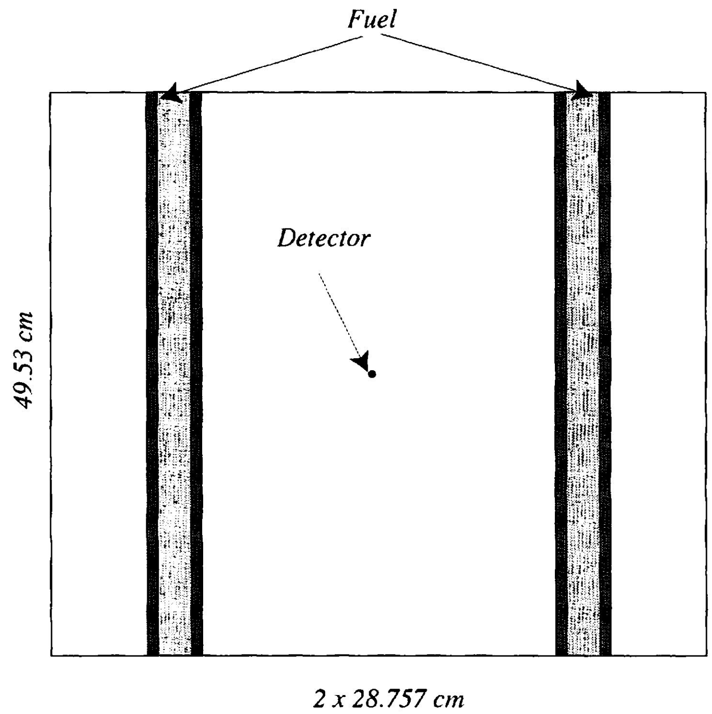

Figure 6: Model 4 for DRAGON 2-D simulation of the Vanadium detector

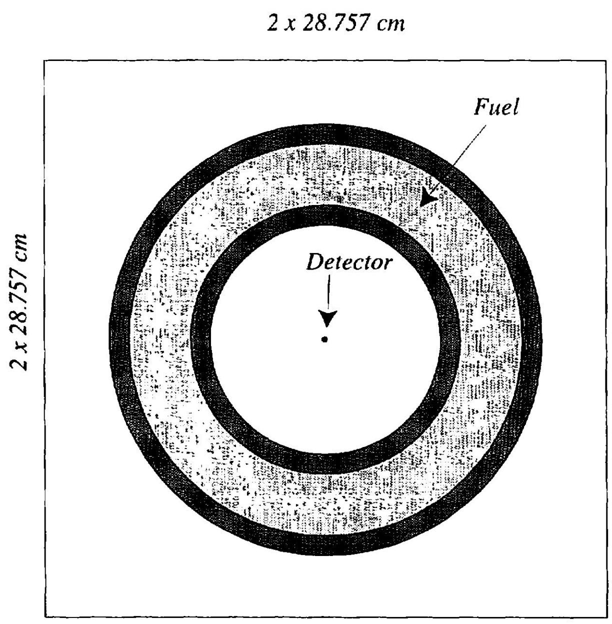

Figure 7: Model 5 for DRAGON 2-D simulation of the Vanadium detector