Proceedings of the Korean Nuclear Society Spring Meeting
Gyeongju, Korea, May 2004

Geometry Determination for New Fixed in-core Detector of Korean Standard Nuclear Power Plant

Kyoon Ho Cha, Yu Sun Choi, Eun Ki Lee, and Moon Ghu Park
Toshio Morita*, Michael D. Heibel*

Korea Electric Power Research Institute
103-16 Munji-dong, Yusung-gu, Taejon, Korea 305-380
* Westinghouse Electric Company, Pittsburgh PA. USA

Abstract

A new long-lived and self-powered fixed in-core detector (FID) was developed for the Korean Standard Nuclear Power Plant (KSNP). To determine the geometry of the detector, a comparative study of the power peaking factor monitoring accuracy for various self-powered fixed in-core detector geometries and a sensitivity calculation related with the diameter of emitter materials were made. According the results the new FID design can be used for both monitoring and protection system of the KSNP plants.

Ⅰ. Introduction

The signal production mechanism in an rhodium (Rh) fixed in-core detector emitter relies primarily on the beta particles resulting from neutron absorptions in either of two Rh isotopes to produce an electric current. The detector signal produced by the detector elements will be a relatively simple function of the local neutron population. As the neutron transmutation process depletes the Rh isotopes, the signal output per unit neutron flux from an Rh detector emitter will decrease. Eventually the Rh detector signal will decrease to a point where the signal to noise ratio becomes too large to support the power distribution measurement uncertainty required for valid power distribution measurements. When this point is reached, the entire detector assembly needs to be replaced. The typical lifetime of an Rh detector assembly is no more than three operating cycles. The cost associated with the periodic replacement of the Rh detector assemblies is the primary driving force for the development of a longer-lived in-core instrumentation (ICI) design.

In order to increase the useable lifetime of an ICI assembly it is necessary either to improve the depletion characteristics of the neutron reaction, or to change the signal production mechanism.

The vanadium detector is typically sensitive to neutron, and has similar reaction time as that of a Rh detector. The benefit of vanadium over rhodium is its low depletion, which is a factor of 20 time less than that of rhodium. The platinum detectors are very sensitive to gamma flux, but mildly to neutron flux. Because the depletion rate of platinum is very small, it can be neglected.

Generally, both gamma and neutron signals are proportional to the assembly power. The gamma response is combined with the neutron response to provide the full detector response to the signal.

From the evaluation of the platinum detector demonstration program of YGN 4 cycle 5[1], it was concluded that i) Generally, non-depletable detectors and detectors of prompt response produce relatively small electric current. Quite often, these are the same order of magnitude as the background wire current, ii) The currents of the background wires show a large variation among the detectors in a reactor, and iii) Therefore, the compensated currents are subject to a large uncertainty. From these conclusions, it was decided to use a detector design without any lead wires within the reactor fuel region.

The functional requirements of a new FID are as follows; i) Detector depletion should be so small that the detectors need no replacement due to the depletion of the emitter material throughout the plant lifetime, ii) The new detector should have a comparable power distribution measurement accuracy with the current rhodium detector system used in the KSNP, and iii) The new detector should also provide the prompt response such that the detectors can be used for the power distribution monitoring as well as the reactor protection.

Recently, KEPRI and WH have developed a new long-lived and self-powered fixed in-core detector, MAPSSEL (Monitoring and Protection Signal Separation, Extended Life), for the Korean Standard Nuclear Power Plant (KSNP), which satisfies above all functional requirements.

II. Determination of the Number of Emitter Strings

The purpose of this section is to make a comparative study of the power peaking factor monitoring accuracy for various self-powered fixed in-core detector geometries and to provide the basis of detector geometry. The axial power shape reconstruction accuracy of the vanadium detector element configuration used in the MAPSSEL design was compared to the axial power shape reconstruction accuracy associated with the five rhodium detector configuration currently used at the YGN units.

The power distribution measurement of the conventional Westinghouse reactors is performed by the movable fission chamber, which provides essentially continuous axial reaction rate distribution measurements for the instrumented assemblies. The measured power distribution can be obtained by using predicted power distribution, and the measured and predicted reaction rate as follows;

$$P_m(x,y,z) = P_p(x,y,z) \times \left[\frac{RR_m(I,J,z)}{RR_p(I,J,z)} \right] \qquad (1)$$

where, P is power, RR is reaction rate, m is measured, p is predicted, x,y,z are coordinates of nodes, I,J are instrumented assemblies, and [ ] is spline fitting.

For the purpose of a comparative study for various FID geometries, the reaction rate distributions will be used in place of the power distributions. The relative FID detector responses can be obtained by integrating the reaction rate distribution between the top and bottom of a FID geometries under study.

$$I_x(I,J,K) = \int_{Zb}^{Zt} RR_x(I,J,z)dz \quad (2)$$

where, I is current, x is m (measured) or p (predicted), I,J,K are FID location, and zb, zt are bottom and top elevation of FID at K-plane.

The simulation of the power distribution monitoring by the reaction rate can be given by

$$RR_m(I,J,z) = RR_p(I,J,z) \times \left[\frac{I_m(I,J,K)}{I_p(I,J,K)} \right] \quad (3)$$

The spline fitting used in the equation provides the node-wise correction factor by interpolating the inputs at the detector elevations. The accuracy of the measurement process can be evaluated by comparing RRm of Eq. (3) with the reaction rate distributions measured by the movable in-core detectors. The later is defined as 'true' reaction rate, RRt(I,J,z). The accuracy, % deviation between RRt and RRm at the flux trace points, △(I,J,z), can be defined by

$$\Delta(I,J,z) = \left(\frac{RR_m(I,J,z)}{RR_t(I,J,z)} - 1.0 \right) * 100.0 \quad (4)$$

Two other features are included in the simulation. The first one is a detector deletion. By user's input, a certain fraction of FIDs can be deleted. The deleted FIDs are determined by a random number process. The second one is a detector noise. All measured FID currents can be perturbed by certain percentages. The magnitude of the perturbations of all FID has a normal distribution, the standard deviation of which is defined by a user's input. Due to the use of a random number in individual detector deletion and the FID noise simulation, calculations need to be repeated for the stabilized or converged answer. Between 10 and 20 iterations are sufficient. The other important feature of the power distribution monitoring method is to use the tolerance factor. The purpose of the tolerance factor is to reduce a weight of individual data points and to take more global trend. This feature is very important for noisy detector signals. Generally, the FID noise is distributed over the reactor. However, the MAPSSEL FID noise tends to increase as the elevation for the bottom loading design. To offset this, an additional elevation dependent tolerance factor is introduced. The calculational procedure described above is automated in a FORTRAN program.

Six types of the FID design were analyzed for their power distribution monitoring accuracy. Table 1 shows a list of the selected SPD geometries. The first group consists of the conventional Rh detector designs currently used in the Combustion Engineering's nuclear reactors such as KSNP plants. The KSNP detector is the reference, which is used as a target for the performance of the MAPSSEL detector design. The second group includes three candidates of the MAPSSEL design, i.e., number of the emitter strings are 4, 5 and 6 respectively. The last group is the MAPSSEL three string design representing the platinum emitter for the CPC (Core Protection Calculator) applications.

A pair of true reaction rate distribution was taken from Westinghouse 3 loop PWR plant. The statistics of % deviations between the measured and true reaction rare distributions for all detector designs of Table 1 were evaluated. The analysis was performed using 75% of detector functioning for assumed detector measurement variability. For the conventional Rh detectors, the past analysis shows the variability of 1.0, 2.0 and 3.0 % cover sufficiently for operating detectors. For MAPSSEL evaluations, the range of the variability is assumed to be one half of the Rh detectors, because of their long emitters and no lead wire design. The tolerance factors are parametrically changed searching the optimum one.

The results are summarized in Table 2. The expected general trend of increasing accuracy with increasing number of detectors per string and decreasing the detector variability is confirmed. Zero tolerance factor, where all detector measurement data are used as they are in the fitting process, makes large deviations in the measured and true reaction rates. This trend is more dominant in the MAPSSEL design than the conventional short length detector design. This is because the upper portion of the detector responses is obtained by differences between long detectors. The % error of the difference of two long detector responses is clearly amplified as the % variation of the long detectors. However, this situation can be corrected successfully by using a proper use of tolerance factors as shown in Table 2. 6 string MAPSSEL detector shows a similar performance of the 5 section YGN4 detector. Thus, MAPSSEL vanadium design using six detector elements is selected for the final design for the Korean Standard Nuclear Power Plant application. The platinum detectors will be used in the CPC for the core protection. The detectors are continuously calibrated to the power distribution measured by the vanadium detectors. The calibration process is performed on an minute basis. Therefore, the power distributions of truth and prediction usually very close each other.

The power distribution measurement in CPC by the platinum detector will be every second interval. Short calculation time is very essential. With this criteria, the 3 string MAPSSEL detector performance is quite acceptable.

Additional analysis for selected three detector designs, 5 section conventional, 6 strings MAPSSEL and 3 strings MAPSSEL, was made for wider range of the measurement variabilities and detector availability of 100% and 50%. The results are summarized in Table 3. This supports the conclusions mentioned above.

The configuration of the optimal detector design was established and verified. The optimal design consists of six overlapping length vanadium detector elements, and three overlapping length platinum elements. The detector assembly also contains a thermocouple.

III. Determination of the Detector Diameter

The mechanical configuration of the MAPSSEL detector assembly was developed and verified. At first to achieve the required signal-to-noise ratio, an evaluation for the minimum necessary signal levels of each platinum and vanadium detector elements was performed. The minimum signal level information was used to establish the minimum detector emitter diameters needed for the platinum and vanadium detector elements. Because the resolution of the in-core detector signal processing devices in KSNP is about 1nA, the minimum signal should be greater than 200nA to achieve 0.5% measurement accuracy. And the detector diameters are also determined based on that fact. The in-core detector elements must be sized to achieve at least 200nanoampere in order to use the existing signal processing electronics and maintain 0.5% measurement accuracy throughout the necessary range of operation.

The sensitivity of vanadium and platinum detectors can be written as follows.[2] The sensitivity of vanadium is

$$S_v = 2.05 \times 10^{-22} D^{1.23} A / nv / cm \quad (5)$$

And the sensitivity of platinum can be calculated using the following equations.

$$S_T = 3.73 \times 10^{-23} D^{1.31} A / nv / cm \quad (6)$$

where, D is the diameter of emitter and the gamma ray sensitivity is defined here in terms of the neutron flux. Also, the current of detector is,

$$I = S \cdot \Phi_{th} \cdot L \quad (7)$$

where, L is the length of detector.

Using the above equations and average neutron flux of YGN4, a minimum platinum detector diameter of 1.1mm is needed to achieve a 200nanoampere signal in the smallest platinum detector element. And a minimum diameter of 1.0mm is necessary to achieve the requisite signals for the smallest vanadium element. In order to keep all the elements the same size to simplify the mechanical design, the MAPSSEL design will use the same diameter for both the platinum and vanadium detector elements. Both the platinum and vanadium detector elements will have diameters of 1.2mm (0.047inch).

The detector elements contained in a detector assembly were configured to maintain the outer diameter (OD) of the thimble used to contain the rhodium detector and thermocouple elements in the ICI assemblies currently at use in the YGN detectors.

The configuration of the electrical connectors used in the MAPSSEL detector design includes separate connectors for the platinum and vanadium signals. The vanadium detector and thermocouple signals are output through a connector identical to the connector currently used on the rhodium detector assemblies installed at the YGN units. The platinum detector signals are output through a separate three pin connector. This configuration allows the MAPSSEL design to be implemented in operating plants to replace the rhodium detectors currently in use, without immediately adding hardware and CPC software changes to utilize the platinum signals in the CPC.

IV. Configuration of MAPSSEL in-core Detector

The axial and radial configuration of the MAPSSEL detector assembly design is shown on Figure 1. The final axial configuration contains six partially overlapping vanadium detector elements and three partially overlapping platinum detector elements. The vanadium detector elements are each an integral multiple of one-sixth of the height of the active core. The bottom of each vanadium detector element starts at the bottom of the active fuel. Each platinum detector element also begins at the bottom of the active fuel and is an integral multiple of one-third of the active core height in length. Each platinum detector element has a corresponding length vanadium detector element. The correspondence between three of the vanadium detectors and the platinum detector elements allows the platinum element signals to be continuously calibrated against the corresponding length vanadium detector elements.

The final radial configuration maintains the OD of the outer thimble sheath of the detector assembly at the 0.45inch diameter of the rhodium detector assembly currently in use at the KSNP plants. There are nine detector elements and one thermocouple sub-assemblies contained within. Each of the detector and thermocouple sub-assemblies has an OD of 0.092inch. The detector emitter diameter of each detector type is 1.2mm. This is larger than the 1.1mm necessary for the platinum detectors to meet the minimum signal level requirements described in section III. The sheath and insulator thickness of the detector element outer sheaths are identical to the rhodium element design currently used at the KSNP units.

V. Implementation Options

The MAPSSEL ICI assembly design contains six vanadium detector elements and three platinum detector elements. The assembly also contains a thermocouple. The vanadium detector elements are used for routine detailed core power distribution monitoring, and to calibrate the response of the platinum elements to the local neutron distribution. The signals from the platinum elements are used to replace the functionality of the signals currently provided by the ex-core detectors in the CPC. In order to use the platinum in-core detector signals in the CPC, the signals from the platinum detector elements must be processed in accordance with all the regulations applicable to Protection System equipment.

The platinum detector signals must be segregated into different protection channels and routed out of the containment. There must be containment penetrations containing sufficient feed-through for the detector signals. The detector signals must be terminated in cabinets that are qualified to process protection system signals. A signal processing card that performs the platinum detector signal conditioning needed to create the calibrated platinum signal inputs to the CPC must be developed or adapted from an existing signal processing device. Ideally, the signal conditioning performed by the platinum detector signal processing electronics would provide an output identical to the characteristics of the signals currently generated by the ex-core detectors.

There are two options associated with the method of implementation that have a direct bearing on the design of the signal processing system associated with the MAPSSEL detector design. The first option is to use the MAPSSEL design variant that can be installed initially to provide only signals from the vanadium detector elements. The vanadium element signals, and the thermocouple signal, can be measured and output from containment using the existing signal processing hardware. The platinum detector signals are output through a separate electrical connector from the detector assembly. The cables, containment penetrations, and signal processing electronics needed to support the use of the platinum detector signals in the CPC can be added when time and funding permit.

The second implementation option is to implement the CPC changes needed to support the MAPSSEL detectors simultaneously with the installation of the MAPSSEL detector assemblies and to utilize two electrical connectors. The primary connector is identical to the connector used on the rhodium detector assemblies currently used at KSNP. The signals from the six vanadium detector elements and the thermocouple are output through the primary connector. This configuration allows the MAPSSEL detector's power distribution monitoring capabilities to be back fit into operating plant without requiring changes to the signal processing cables or electronics. There will be changes to CECOR/COLSS needed to support the use of the vanadium detector element configuration for power distribution measurement purposes. The secondary connector of this variant is used to output only the signals from the platinum detectors. The signals from this connector only need to be used when the CPC methodology and associated systems are updated to use the input from the platinum elements to replace the inputs provided by the ex-core detectors.

The use of the MAPSSEL vanadium detector hardware to replace the signals currently provided by the rhodium, background detector, and thermocouple in the standard rhodium detector assembly design allows the present detector cables and signal processing electronics to remain unchanged. The algorithms used in CECOR and COLSS would need to be modified to use six detector measurements instead of the five used in the rhodium detector design. The basic signal processing hardware list for the MAPSSEL detector assembly design, as a replacement to the current functionality of the rhodium detector assembly design, is no different than for the existing hardware.

VI. Conclusion

A preliminary comparative evaluation of various types of the FID detector geometry has been performed to determine the optimal geometry of MAPSSEL detector. The reaction rate distribution measured by the movable in-core detectors is used for the 'true' power distribution. This enables making a wide variety of geometry evaluation easily without losing the accuracy. It was concluded that the MAPSSEL detector design with six strings of vanadium for the power distribution monitoring and three strings of platinum for the core protection is the optimum design.

The configuration of the MAPSSEL vanadium detectors was found to provide axial power shape accuracy not more than the power shape reconstruction accuracy provided by the five-element rhodium detector configuration currently used at the KSNP plants. In the near future, more comprehensive evaluation for the MAPSSEL detectors will be performed with a real reactor simulation model.

And the implementation options of MAPSSEL FID for the KSNP are suggested. It can be used the monitoring system only with some algorithm changes of CECOR/COLSS, and also can be used both monitoring and protection system with more changes of CPC devices.

References

[1] Yu Sun Choi and Kyoon Ho Cha, "Evaluation of the Platinum Detector Signals for YGN4 Cycle 5," KNS Spring Meeting, May 2003.

[2] C.J. Allen, "Response Characteristics of Self-Powered Flux Detectors in CANDU Reactors," AECL, May 1978

Table 1. FID Geometries for Performance Evaluation

Types of FID Geometry		Geometry
Conventional Rhodium FID Design	S-1	4 Strings
Conventional Rhodium FID Design	S-2	5 Strings
MAPSSEL Vanadium FID Design Candidates	M-1	4 Strings
MAPSSEL Vanadium FID Design Candidates	M-2	5 Strings
MAPSSEL Vanadium FID Design Candidates	M-3	6 Strings
MAPSSEL Platinum FID Design Candidates	P-1	3 Strings

Table 2. Comparison of Power Distribution Measurement Capability by Detector Design

(1) Standard Rhodium FID Design

Measurement Variability	K	Tolerance Factor*	STD**	
			S-1	S-2
1.0%	0.000	0.000	1.659	1.561
	1.000	1.000	1.587	1.612
	5.000	5.000	1.645	1.507
	10.000	10.000	1.637	1.567
	15.000	15.000	1.764	1.660
	20.000	20.000	1.785	1.684
2.0 %	0.000	0.000	2.230	2.066
	1.000	4.000	1.868	1.952
	5.000	20.000	1.981	1.878
	10.000	40.000	1.974	1.841
	15.000	60.000	2.040	1.913
	20.000	80.000	2.103	1.948

(2) MAPSSEL Type Detector Design

Measurement Variability	K	Tolerance Factor	STD*			
			M-1	M-2	M-3	P-1
0.5%	0.000	0.000	8.370	4.154	3.122	17.775
	1.000	0.250	2.370	1.997	1.785	7.816
	5.000	1.250	1.954	1.689	1.608	3.095
	10.000	2.500	1.824	1.694	1.703	3.689
	15.000	3.750	1.870	1.801	1.750	2.886
	20.000	5.000	1.900	1.794	1.796	2.935
1.0 %	0.000	0.000	8.158	6.416	5.158	32.637
	1.000	1.000	2.464	2.342	2.049	3.765
	5.000	5.000	2.131	1.901	1.833	2.774
	10.000	10.000	2.146	2.046	2.122	2.725
	15.000	15.000	2.350	2.144	2.146	2.868
	20.000	20.000	2.309	2.221	2.289	2.752

* Tolerance Factor = K × (Measurement Variability)^2

** Standard Deviation of % Deviation between Measurement and Truth for Node Power > 1.2

Table 3. Evaluation of Power Distribution Measurement Capability

(1) Standard Rhodium FID Design (S-2)

Detector Noise	K	Tolerance Factor*	STD	
			Functioning Detector 100%	Functioning Detector 50%
1.0%	0.000	0.000	1.141	1.911
	0.500	0.500	1.125	1.839
	1.000	1.000	1.165	1.865
	2.000	2.000	1.202	1.875
	5.000	5.000	1.299	1.857
	10.000	10.000	1.409	1.794
	15.000	15.000	1.471	1.852
	20.000	20.000	1.515	1.924
2.0%	0.000	0.000	1.886	2.476
	0.500	2.000	1.656	2.175
	1.000	4.000	1.612	2.159
	2.000	8.000	1.634	2.105
	5.000	20.000	1.651	2.073
	10.000	40.000	1.758	2.082
	15.000	60.000	1.799	2.109
	20.000	80.000	1.869	2.174
3.0%	0.000	0.000	2.589	3.185
	0.500	4.500	2.051	2.531
	1.000	9.000	1.913	2.364
	2.000	18.000	1.926	2.309
	5.000	45.000	1.982	2.293
	10.000	90.000	1.983	2.273
	15.000	135.000	2.024	2.378
	20.000	180.000	2.123	2.532

(2) MAPSSEL 6-String Detector Design (M-3)

Detector Noise	K	Tolerance Factor	STD	
			Functioning Detector 100%	Functioning Detector 50%
0.5%	0.000	0.000	2.584	6.809
	0.500	0.125	1.643	2.603
	1.000	0.250	1.523	2.122
	2.000	0.500	1.491	1.902
	5.000	1.250	1.537	1.837
	10.000	2.500	1.611	1.939
	15.000	3.750	1.662	1.973
	20.000	5.000	1.719	2.028
1.0%	0.000	0.000	4.604	14.562
	0.500	0.500	2.198	2.725
	1.000	1.000	1.991	2.258
	2.000	2.000	1.875	2.166
	5.000	5.000	1.858	2.101
	10.000	10.000	1.952	2.364
	15.000	15.000	2.085	2.379
	20.000	20.000	2.131	2.522
1.5%	0.000	0.000	7.158	8.308
	0.500	1.125	2.435	2.807
	1.000	2.250	2.145	2.519
	2.000	4.500	2.070	2.322
	5.000	11.250	2.053	2.550
	10.000	22.500	2.233	2.764
	15.000	33.750	2.338	2.814
	20.000	45.000	2.411	2.985

(3) MAPSSEL 3-String Detector Design (P-1)

Detector Noise	K	Tolerance Factor	STD	
			Functioning Detector 100%	Functioning Detector 50%
0.5%	0.000	0.000	2.424	14.247
	0.500	0.125	2.264	11.563
	1.000	0.250	2.255	7.286
	2.000	0.500	2.208	5.935
	5.000	1.250	2.312	4.061
	10.000	2.500	2.402	3.191
	15.000	3.750	2.469	3.065
	20.000	5.000	2.449	2.896
1.0%	0.000	0.000	3.301	19.212
	0.500	0.500	2.565	5.698
	1.000	1.000	2.506	5.111
	2.000	2.000	2.594	3.906
	5.000	5.000	2.614	3.318
	10.000	10.000	2.644	2.788
	15.000	15.000	2.619	3.019
	20.000	20.000	2.742	2.991
1.5%	0.000	0.000	4.309	17.981
	0.500	1.125	2.827	4.966
	1.000	2.250	2.717	3.675
	2.000	4.500	2.851	3.399
	5.000	11.250	2.775	2.909
	10.000	22.500	2.885	3.109
	15.000	33.750	2.907	3.117
	20.000	45.000	2.852	3.177

* Tolerance Factor = K × (Detector Noise)^2

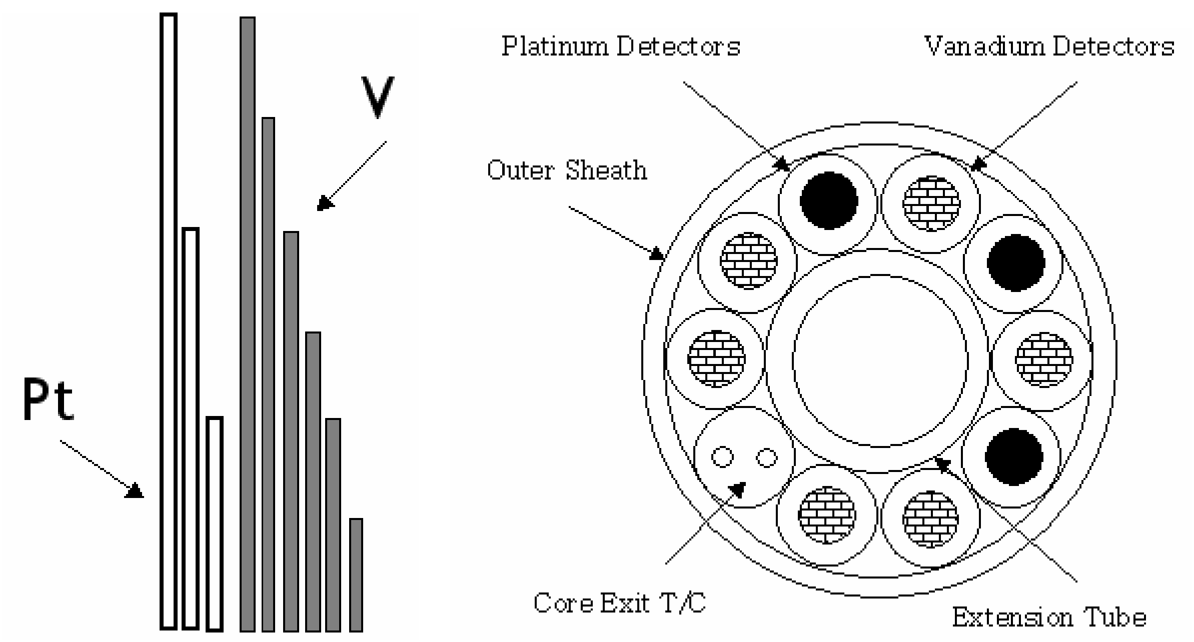

Figure 1. Axial and Radial Configuration of MAPSSEL Detector