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《Original》

A New Technique for Burst Cartridge Detection*

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Abstract

A design of new burst cartridge detection system for gas-cooled power reactor using a spherical sampling chamber with negative electrode is presented. The results of theoretical calculation indicate that the designed system is feasible for a practical application and sensitive enough to detect a 1 cm^2 hole in the fuel cladding.

요 약

음전극을 가진 구형 가스 채집 전리함을 사용한 가스냉각 발전로 핵연료 피복 파열에 관한 검출기술의 새로운 설계에 대한 연구이다. 설계를 위한 이론적인 계산결과에 의하면 이 설계된 씨스템은 실지응용이 가능하고 1cm^2 크기의 핵연료 피복파열을 쉽게 검출할 수 있다는 것이 입증되었다.

1. Introduction

The use of precipitator unit is a well established technique of the burst cartridge detection. [1] [2] In spite of its satisfactory performance, the precipitator system is comparatively expensive to build, and complicates the control unit due to 'phase difference' between input and output of the system when the unit is used for a single channel monitoring.

An attempt was made to find a simple technique using direct monitoring of fission products activities for B.C.D. in a gas-cooled reactor. It was decided to detect gammas from fission products instead of monitoring beta/gamma combination as in a precipitator unit, since all beta particles are stopped by the wall if a simple pressure vessel sampling chamber is used. Among the various fission products, the most reliable isotopes for detection are Krypton and Xenon. Due to their inertness, these gaseous isotopes are neither absorbed by the walls of gas circuit nor stopped by the filter. By using gamma signals from Kr and Xe,

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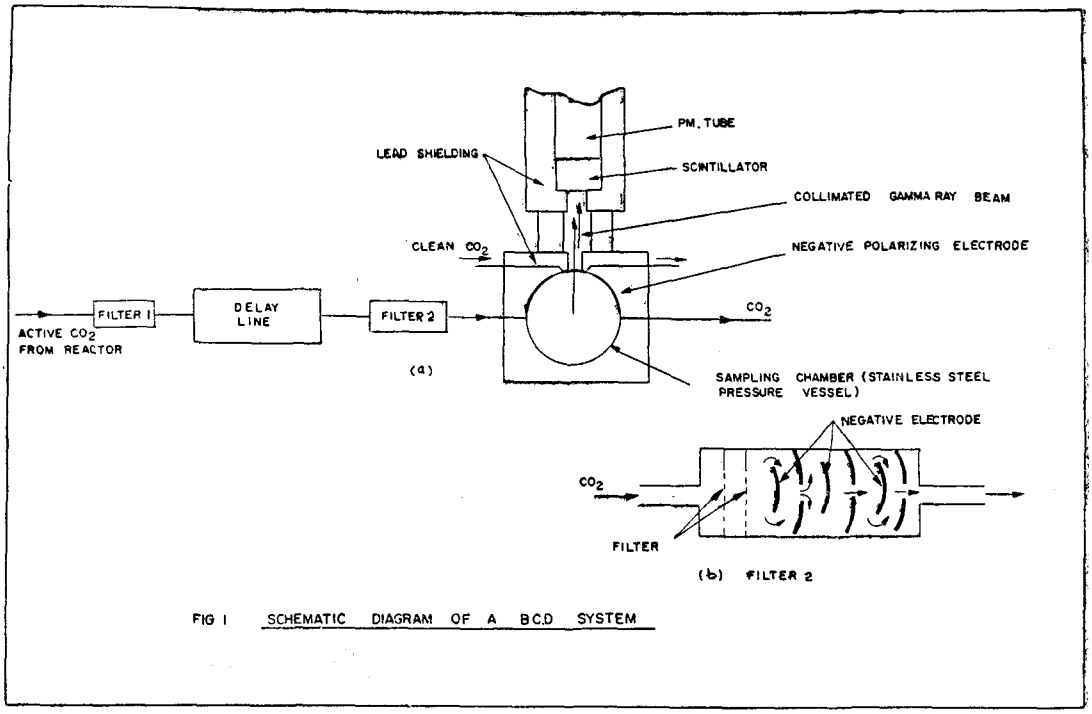

FIG 1 SCHEMATIC DIAGRAM OF A B.C.D SYSTEM

further advantage is obtained from the background discrimination viewpoint, since the gamma energies released by these isotopes are higher (greater than 2.5 Mev) than the known predominant background gamma energy of Argon (1.3 Mev). It is, therefore, readily possible to discriminate the background by setting the threshold bias at 2 Mev.

A spherical sampling chamber is designed with a new concept by introducing a negative polarising electrode in the chamber. A known difficulty in design for a sampling chamber which is used for measurement of the direct fission product activities is a gradual build-up of background due to contamination of the chamber wall by daughter products from gaseous isotope decay in the chamber. Since all daughter-products are produced from precursor by emitting betas, the daughters are positively charged. By an applied electro-static field in the chamber it is possible to collect a major portion of daughter-products(positive ions) to the negative electrode which is shielded from the detecting window by a heavy lead castle. Some details of the system and sampling chamber design are described in the following section. Design calculation for German KKN Reactor B.C.D. System as an example is presented.

2. B.C.D. System and Sampling Chamber

Schematic diagram of the proposed B.C.D. system is shown in Fig. 1 (a). The system consists of two filters, delay line, sampling chamber, collimator and scintillation detector. The known important gas-activities in a CO_2-cooled reactor gas circuit are N^{16}, A^{41} and O^{19}. Since both half-lives of N^{16} and O^{19} are very short (7.36 sec and 29.4 sec., respectively), by delaying the gas flow for 2 or 3 minutes, it is possible to reduce the activities of these isotopes to a negligible level before admitting the gas sample to the chamber. The first filter is inserted to stop any particles which are larger than a half-micron (conventional filters are available in the ranges of 1.2-0.2 micron). The most of spalled oxides, such as Fe, Mn, Co, etc., from the reactor

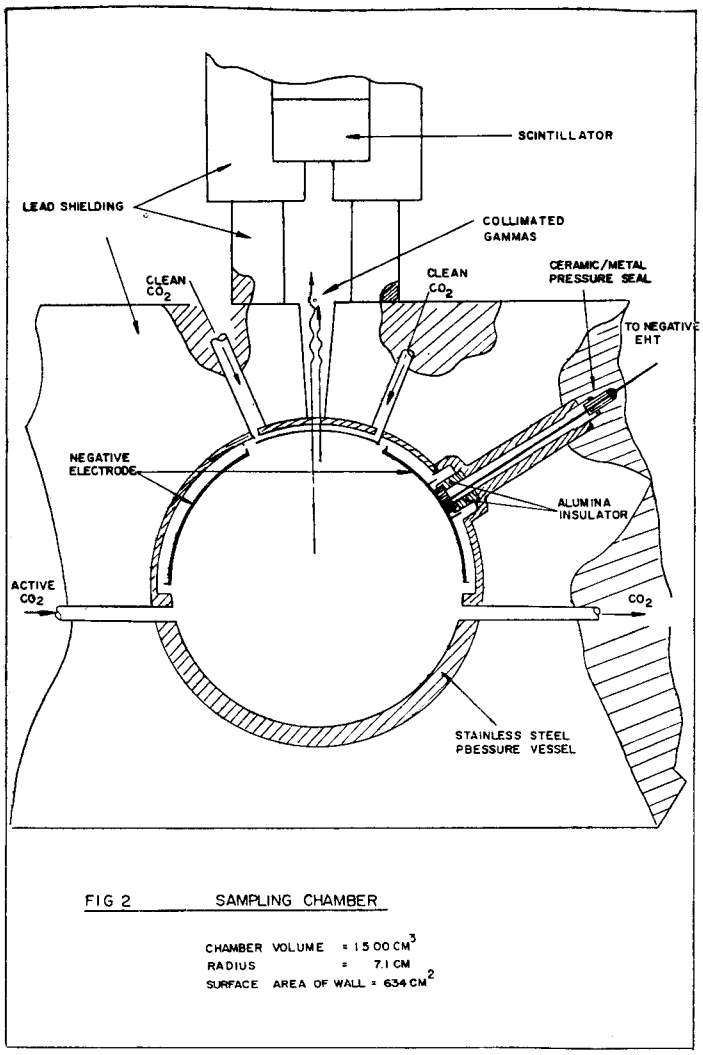

FIG 2 SAMPLING CHAMBER

CHAMBER VOLUME = 1500 CM^3
RADIUS = 7.1 CM
SURFACE AREA OF WALL = 634 CM^2

core are stopped by this filter. It is intended to stop by the second filter (Fig.1(b)) all particles other than gaseous isotopes and the particles filtered by the first one. The second filter consists of two filter plates and a series of alternately placed negative electrodes and baffles. By this arrangement, all positive ions except gaseous ions are collected by the electrodes and a large portion of neutral radio-isotope particles are stopped by the baffles.

To obtain the minimum surface area for a fixed volume, a sphere is chosen for the sampling chamber volume. Sampling chamber is shown with scintillation detector and collimator in Fig. 2. Northern (or southern) hemisphere is negatively polarised by a high voltage (say 2-10 kv) power supply. An area substantially greater than collimator window in the north (or south) pole is kept to earthy potential (positive) and a continuous flow of clean CO_2 on the surface is provided to prevent a possible contamination of the area by the daughter-product isotopes. Daughter-products formed by disintegration of Kr and Xe isotopes are swept away immediately (transit time of less than approx. 1 second) to the electrode by the high electrical field. A suitable scintillation detector is selected to give the optimum sensitivity and resolution of the counting system.

3. Behaviour of Radioisotopes in a Reactor

3.1 Activation of Gas-coolant Impurities in the Core.

General expression[3] can be derived for the specific activity of a coolant circulating through a neutron flux. These equations can be simplified under equilibrium conditions, i.e., when the rate at which atoms are being activated is equal to the rate of decaying atoms.

The definitions of the terms used in these expressions are as follows:

A Specific activity (dis. /sec-cm^3 of coolant)

A(t) Value of A as a function of time outside the neutron flux.

A(t') Value of A at the outlet from the neutron flux.

F Neutron flux density (n-cm^{-2}- sec^{-1})

k Number of circulation cycles undergone by the cubic centimetre of coolant under consideration.

N Total number of nuclei under study per cubic centimetre of coolant.

T Period of complete circulation cycle, i.e., time between two successive entrances of a particular nucleus into the neutron flux, assuming that all the nuclei circulate at the same rate (sec).

t Time measured from the instant the cubic centimetre of gas under consideration enters the neutron flux; t starts at zero again whenever the cubic centimetre of coolant reenters the flux (sec).

t′ Time of exposure of each nucleus in neutron flux (sec).

λ Disintegration constant of activated nuclei (sec^{-1}).

σ Capture cross section of nuclei under consideration (cm^2).

In all cases:

$$A(t)=A(t')\exp[-\lambda(t-t')] \quad (1)$$

For cyclic irradiation the general expressions, after k cycles are

$$A_k(t')=\frac{\lambda NF\sigma\{1-\exp[-(F\sigma+\lambda)t']\}}{(F\sigma+\lambda)} \times\frac{\{1-\exp[-(k+1)(F\sigma t'+\lambda T)]\}}{\{1-\exp[-(F\sigma t'+\lambda T)]\}} \quad (2)$$

and at equilibrium are:

$$A_\infty(t')=\frac{(\lambda NF\sigma)}{(F\sigma+\lambda)}\left\{\frac{1-\exp[-(F\sigma+\lambda)t']}{1-\exp[-(F\sigma t'+\lambda T)]}\right\} \quad (3)$$

For $F\sigma \ll \lambda$ after k cycles.

$$A_k(t')=NF\sigma\frac{(1-e^{-\lambda t'})\ [1-e^{-(k+1)\lambda T}]}{1-e^{-\lambda T}} \quad (4)$$

and at equilibrium,

$$A_\infty(t')=NF\sigma\frac{1-e^{-\lambda t'}}{1-e^{-\lambda T}} \quad (5)$$

For $F\sigma \ll \lambda$ and $\lambda T \ll 1$, after k cycles.

$$A_k(t')=NF\sigma\frac{t'}{T}[1-e^{-(k+1)\lambda T}] \quad (6)$$

and at equilibrium

$$A_\infty(t')=NF\sigma\frac{t'}{T} \quad (7)$$

3.2 Activities of Fission Products.

The fission products may, for calculational purposes, be divided into two groups: (1) those isotopes which are formed directly in fission (denoted by the subscript x) and (2) those isotopes which result from the decay of parent isotopes (denoted by the subscript y). The behaviour of these isotopes in the reactor may be described by the following two differential equations:

$$\frac{dn_x}{dt}=Y_xK-\lambda_x n_x \quad \text{(atoms/sec)} \quad (8)$$

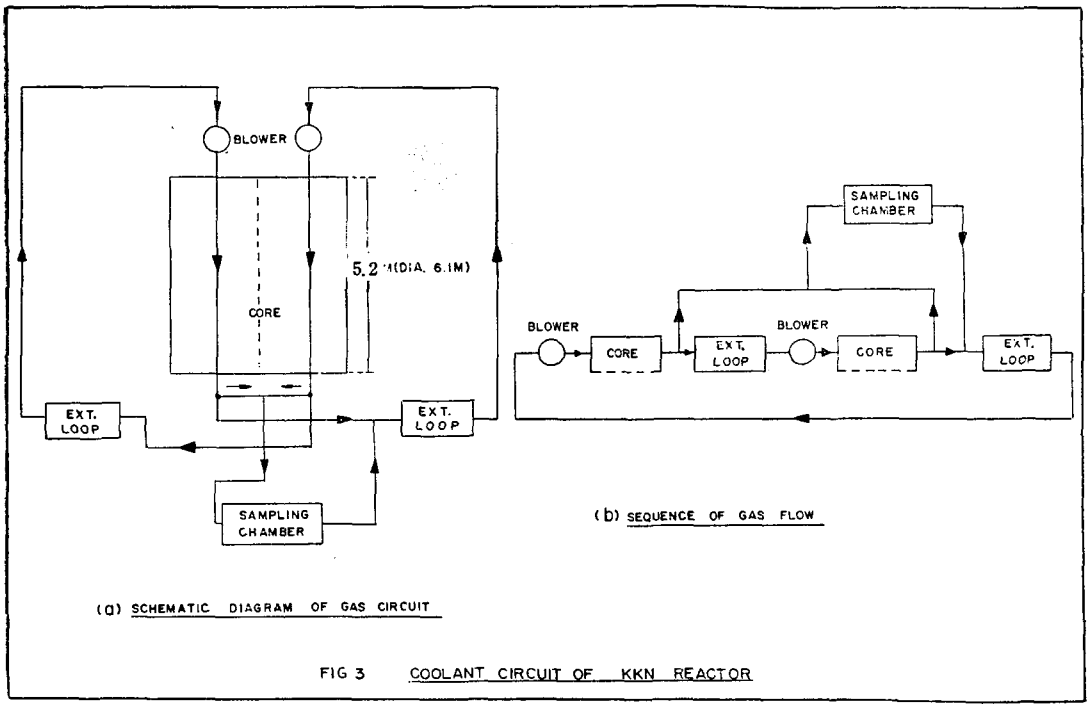

FIG 3 COOLANT CIRCUIT OF KKN REACTOR

$$\frac{dn_y}{dt} = Y_y K + \lambda_x n_x - \lambda_y n_y \quad \text{(atoms/sec)} \quad (9)$$

where n_x=the number of active atoms of isotope x in the core (atoms)

n_y=the number of active atoms of isotope y in the core (atoms)

Y_x=fission yield of isotope x (fraction of number)

Y_y=fission yield of isotope y (fraction of number)

K =fission rate (fission/sec)

λ_x =the decay constant of isotope x (sec^{-1})

λ_y =the decay constant of isotope y (sec^{-1})

The solution of Equ. (8) is given by:

$$\lambda_x n_x = Y_x K(1-e^{-\lambda_x t}) \quad \text{(dis/sec)} \quad (10)$$

where t is the reactor operation time in seconds.

The solution of Equ. (9) is given by

$$\lambda_y n_y = (Y_y + Y_x) K(1-e^{-\lambda_y t}) + \frac{Y_x K \lambda_y}{\lambda_x - \lambda_y} \times (e^{-\lambda_x t} - e^{-\lambda_y t}) \quad \text{(dis/sec)} \quad (11)$$

4. Calculation for Design

Design calculation is carried out for German KKN-Reactor B.C.D. System as an example. Schematic diagram of coolant circuit of the reactor is shown in Fig. 3, and the basic data for calculation is listed in Table 1. The following three schemes are considered.

Scheme 1, The system having Filter 2 and no negative polarising electrode in the sampling chamber.

Scheme 2, The system having both Filter 2 and polarising electrode.

Scheme 3, The system having both Filter 2 and polarising electrode in the chamber, but a series of negative electrodes in Filter 2 are omitted and replaced by baffles.

The up-to-date (1962) list of various fission products was reported by Albrecht[4]. The list, which the present study is based on, is reproduced in Table 2 and 3. For the fission product activity calculation, it is assumed that there are no cartridge bursts, hence the only activities of fission products come from the contaminated uranium (6.26×10^{-2} grams), on the fuel surface.

Activity from the fission product isotope passing up the channel for the first time A_i and recirculated activity R_i are given as follows:

$$A_i = Y_i \lambda_i \gamma_y \left[\frac{1}{M}\right] \quad (\gamma g^{-1}\ sec^{-1})$$

$$R_i = Y_i \gamma_y \left[\frac{1}{m}\right] \quad (\gamma g^{-1}\ sec^{-1})$$

$$r_i = \lambda_i N_i = Y_i K(1-e^{-\lambda_i t}) \quad (\text{atoms } sec^{-1})$$

where r_i =Rate of production of active atoms(sec^{-1})

λ_i =Decay constant of ith atom (sec^{-1})

γ_y =Gamma yield (fraction of number)

M =Mass flow rate (g sec^{-1})

m =Total mass of coolant (g)

Y_i =Fission (thermal) yield (fraction of number)

K =Fission rate (fission sec^{-1})

Fission rate for 6.26 $x10^{-2}$ gram of natural uranium is given by:

$$\text{Fission rate} = \frac{(6.025\times 10^{23})\times 6.26\times 10^{-2}\times 0.0072}{238} \times 590\times 10^{-24}\times (5\times 10^{13}) = 3.38\times 10^{10}$$

(fission sec^{-1})

For equilibrium condition, activities due to fission products and gas impurities in the sampling chamber for various schemes are calculated using the equations (10), (11) and (5). The results are presented in the following tables. The following assumptions are made:

Sampling chamber volume	1500cm^3
Effective sensitive volume	500 cm^3
Overall detection efficiency	5%
Delay time	2 min.

4.1 Activities from Fission Products.

	$A_i(\gamma g^{-1}\ sec^{-1})$		$R_i(\gamma g^{-1}\ sec^{-1})$	
	>2Mev	<2Mev	>2Mev	<2Mev
Scheme 1	6.1	23	270	1.03×10^3
Scheme 2	6.1	23	121	1.03×10^3
Scheme 3	402	206	500	8.95×10^4

	Counting Rate (γsec^{-1})		Background* (γsec^{-1})	
	>2Mev	<2Mev	>2Mev	<2Mev
Scheme 1	18.1	68.5	1.69×10^3	5.96×10^3
Scheme 2	18.1	68.5	360	1.54×10^3
Scheme 3	1.2×10^3	613	1.52×10^3	2.66×10^3

*Activities due to recirculation and chamber wall contamination.

4.2 Activities of Coolant Gas.

(1) A^{41}(γ:1.3 Mev)

Argon activity is calculated using the equation (5).

$N=(6.025\times10^{23})(1.977\times10^{-3})60(0.5\times10^{-6})$
$0.996/40=8.93\times10^{14}$ (cm^{-3})

$F=5\times10^{13}$ ($n\ cm^{-2}\ sec^{-1}$)

$\lambda=1.05\times10^{-4}$ (sec^{-1})

$\sigma=0.53\times10^{-24}$ (cm^2)

$T=13$ (sec)

$t'=0.2$ (sec)

$A_k(t')=3.645\times10^2[1-\exp(-1.365(k+1)\times10^{-3})]$ (dis $cm^{-3}\ sec^{-1}$)

$A(t')=3.645\times10^2$ (dis $cm^{-3}\ sec^{-1}$)

After 2 min. delay,

$3.645\times10^2\times\exp(-1.05\times10^{-4}\times120)$
$=3.6\times10^2$(dis $cm^{-3}\ sec^{-1}$)

Counting rate due to Argon activity in the chamber

$3.6\times10^2\times500\times0.05=9\times10^3$ ($\gamma\ sec^{-1}$)

(2) N^{16} (γ : 7.1 Mev)

Due to lack of information on fast neutron flux, it was decided to calculate Nitrogen activity in the chamber using the given data (Table 1).

0.17 (curie m^{-3})$=0.17\times(3.7\times10^{10})\times10^{-6}$
$=6.29\times10^3$ (dis $cm^{-3}\ sec^{-1}$)

After 2 min. delay,

$6.29\times10^3\times\exp(-9.4\times10^{-2}\times120)=7.8\times10^{-2}$
(dis $cm^{-3}\ sec^{-1}$)

Counting rate due to N^{16} in the chamber

7.8×10^{-2}(dis $cm^{-3}\ sec^{-1}$)$\times500$ (cm^3)$\times0.05$
$=1.95$ ($\gamma\ sec^{-1}$)

Activities of gas impurities other than A^{41} and N^{16} are found to be negligible.

4.3 Total Counting Rates

	Signal* ($\gamma\ sec^{-1}$)		Background ($\gamma\ sec^{-1}$)	
	>2Mev	<2Mev	>2Mev	<2Mev
Scheme 1	18	69	1.69×10^2	1.496×10^4
Scheme 2	18	69	362	1.05×10^4
Scheme 3	1.2×10^3	613	1.52×10^3	1.166×10^4

*Number of gammas due to fission product isotope passing up the channel for the first time.

4.4 Sensitivities of Various Schemes.

During irradiation, fission gas escapes from the fuel structure by a recoil process, since, when fission occurs within about 10μ[5] of the surface of uranium, it is possible for a fission fragment to recoil free of the fuel. It is, therefore, approximately correct to say that a hole of 1 cm^2 in the cladding is equivalent of 18.6 mg of exposed uranium in the core. Since the equivalent mass for 1 cm^2 of exposed fuel calculated above only applies for gaseous fragment, it is necessary to use fission fragment mean range of 12.6mg/cm^2[6] for calculation when all fission fragments are considered. From the above data, the mass of fuel pin contamination (6.26×10^{-2}g) is equivalent of 3.37cm^2 of exposed uranium for scheme 1 and 2 and 5cm^2 for scheme 3.

Sensitivities of various schemes were calculated and are presented below:

COUNTING RATE* (cps) (>2Mev gamma)

	Scheme 1		*Scheme* 2		*Scheme* 3		
Measuring Time (sec)	10	60	10	60	1	10	60
Exposed Fuel Area (cm^2)							
1	5±18.5	5±7.55	5±8.75	5±3.57	240±75.3	240±23.8	240±9.42
2	11±18.5	11±7.56	11±8.76	11±3.58	480±77	480±24.35	480±9.92
3	16±18.55	16±7.57	16±8.8	16±3.6	720±78.5	720±24.8	720±10.2
5	26±18.56	27±7.59	27±8.85	27±3.62	1.2×10^3±81.5	1.2×10^3±25.6	1.2×10^3±10.5
10	54±18.65	54±7.6	54±9.02	54±3.68	2.4×10^3±88.5	2.4×10^3±28	2.4×10^3±11.4
20	107±18.8	107±9.3	107±9.3	107±3.8	4.8×10^3±101	4.8×10^3±32	4.8×10^3±13.1

*Only the signal counting rates with relative deviation are given. Backgrounds are 1.71×10^3, 380, and 2.72×10^3 cps for Scheme 1, 2 and 3, respectively. Mehtod of calculation is given below for Scheme 3 and 5 cm^2 of exposed uranium when the measuring time is 10 seconds.

$$\text{Background}=(2.72\times10^3\times10\pm\sqrt{2.72\times10^4})/10=2.72\times10^3\pm16.5 \quad \text{(cps)}$$

$$\text{Measured Counting Rate}=[(2.72\times10^3+1.2\times10^3)\times10\pm\sqrt{3.92\times10^4}]/10$$
$$=3.92\times10^3\pm19.8 \quad \text{(cps)}$$

$$\text{Signal Counting Rate}=(3.92\times10^3-2.72\times10^3)\pm\sqrt{16.5^2+19.8^2}=1.2\times10^3\pm25.6 \quad \text{(cps)}$$

5. Discussion and Conclusion

The results of calculation on detection sensitivity shown in the previous section indicate that the designed system is feasible and it is essential to have a polarising electrode in the sampling chamber to avoid contamination of the chamber wall by active-isotopes and to be sensitive enough for a small hole detection.

Since instantaneous activity from daughter product in the chamber during a transit time of ions is simply $(1-e^{-\lambda T})$ (where λ=decay constant of daughter-product, T transit time of ion) times of the parent isotope activity, a few seconds of ion transit time can be tolerated unless the half-life of daughter-product is very short. Assuming the mobility of 10^{-2} (cm^2/volt sec) for one of the heavy ion (Xe) at 60 atmospheric pressure, it is possible to obtain the ion drift velocity of 3.5 cm/sec with the electric field of 350 volts/cm. Since the chamber diameter is 14cm, this gives the transit time of 4 seconds. With 5 KV E.H.T. supply, it is possible to obtain a field of approximately 350 volts/cm at the weakest field point in the chamber.

The collection efficiency of ions is not a simple function of electric field due to recombination of ions and an irregular distribution of space charge. A further careful study is necessary to ensure that an applied voltage is high enough to obtain a high collection efficiency of ions.

The results of sensitivity calculation for Scheme 3 is slightly optimistic, since some of active-isotopes are absorbed or stopped before reaching the sampling chamber. Due to lack of knowledge on a mechanism of deposition on the wall of piping, a loss of active isotope during transit is not considered.

It is concluded that the Schemes 2 and 3 investigated in this study are feasible designs. The following further investigations are suggested:

(1) A study of deposition rate of active isotope during transit.
(2) A study of electron-ion and ion-ion recombination in the sampling chamber for a given electrical field.
(3) Some detail design of collimator to obtain the maximum overall efficiency.

TABLE 1. Data for KKN Reactor

1. Neutron Flux Density (Thermal)	5×10^{13} n cm^{-2} sec^{-1}
2. Coolant: Carbon dioxide	
(1) Coolant pressure	60 atm. (882 psia)
(2) Massflow rate in core	1500 ton/hr (4.233×10^5 g/sec)
(3) CO_2 desnity	1.977 g/litre at N.P.T.
(4) Total mass of coolant	10.8 ton (1.079×10^7 grams)
(5) Impurities in coolant	
Argon	0.5 ppm
Oxygen	2.0 ppm
Nitrogen	10–15 ppm
Boron	0.01 ppm
Hydrogen	1.0 ppm
Water	5–15 ppm
CO	3 g/kg
CH_4	10^3 g ppm
(6) Activity due to N^{16}	0.17 curie /m^3
3. Time for one complete circulation	13 seconds
4. Time in the core	0.2 second
5. Amount of fuel surface contamination	6.26×10^{-2} gram of natural uranium.

TABLE 2. Gamma Emitter with Energy of Greater Than 2 Mev.

Note: In column I (Nuclide), m signifies metastable state.

Nuclide	Thermal-Fission Yield (Y) (fraction of number)	Gamma Yield (γ_y) (fraction of number)	Decay Constant (λ) (sec^{-1})
Ga-72	1.6×10^{-7}	0.62	1.35×10^{-5}
Ga-74	3.5×10^{-6}	2×10^{-2}	1.44×10^{-3}
Ge-77	3.1×10^{-5}	1.4×10^{-2}	1.7×10^{-5}
As-78	2×10^{-4}	3.6×10^{-2}	1.27×10^{-4}
Se-83m	2.9×10^{-3}	3.5×10^{-2}	9.9×10^{-3}
Se-83	2.2×10^{-3}	3.5×10^{-2}	4.62×10^{-4}
Br-84	9.2×10^{-3}	0.252	3.63×10^{-4}
Br-87	2×10^{-2}	0.14	1.24×10^{-2}
Kr-87	2.49×10^{-2}	0.28	1.48×10^{-4}
Kr-88	3.57×10^{-2}	0.35	6.95×10^{-5}
Kr-89	4.59×10^{-2}	0.67	3.61×10^{-3}
Rb-88	3.57×10^{-2}	4.92×10^{-2}	6.48×10^{-4}
Rb-89	4.59×10^{-2}	0.566	7.75×10^{-4}
Rb-90	2.285×10^{-2}	1.155	4.23×10^{-3}
Rb-91	7.41×10^{-2}	1.0	9.63×10^{-3}
Sr-93	4.8×10^{-3}	1.5×10^{-2}	1.53×10^{-3}
Y-92	5.3×10^{-2}	1.0×10^{-3}	5.5×10^{-5}
Y-93	6.1×10^{-2}	3×10^{-3}	1.9×10^{-5}
	5.62×10^{-2}	3×10^{-3}	1.9×10^{-5}
Y-94	5.4×10^{-2}	7.5×10^{-2}	5.68×10^{-4}
	5.3×10^{-2}	7.5×10^{-2}	5.68×10^{-4}
Mo-101	5.6×10^{-2}	0.16	7.9×10^{-4}
Rh-106	3.8×10^{-3}	7.4×10^{-4}	2.31×10^{-2}
Ag-112	1.0×10^{-4}	0.169	6.03×10^{-5}
Sn-127	1.3×10^{-4}	1.0	9.39×10^{-5}
Sb-132	4.7×10^{-2}	2×10^{-2}	5.5×10^{-3}
Te-131m	4.4×10^{-3}	2.1×10^{-2}	6.66×10^{-6}
I-132	4.7×10^{-2}	2.05×10^{-2}	8.52×10^{-5}
I-136	3.1×10^{-2}	0.418	7.88×10^{-3}
Xe-138	5.49×10^{-2}	1×10^{-3}	6.79×10^{-4}
Cs-138	5.49×10^{-2}	0.275	3.55×10^{-4}
La-140	6.35×10^{-2}	6.2×10^{-2}	4.78×10^{-6}
	4.5×10^{-2}	6.21×10^{-2}	4.78×10^{-6}
La-142	4.9×10^{-2}	0.337	1.36×10^{-4}
Pr-144	6×10^{-2}	6.5×10^{-3}	6.6×10^{-4}
Eu-156	1.4×10^{-4}	0.13	5.33×10^{-7}
	1.0×10^{-5}	0.13	5.33×10^{-7}

TABLE 3. Gamma Emitter with Energy of Less Than 2Mev.

Note: In column I (Nuclide), m signifies metastable state.

Nuclide	Thermal-Fission Yield (Y) (fraction of number)	Gamma Yield (γ_y) (fraction of number)	Decay Constant (λ) (sec^{-1})
Ge–77	3.1×10^{-5}	0.99	1.7×10^{-5}
As–77	8.3×10^{-5}	7.42×10^{-2}	4.99×10^{-6}
As–78	2.0×10^{-4}	0.964	1.27×10^{-4}
As–79	5.6×10^{-4}	7.5×10^{-2}	1.28×10^{-3}
Se–79m	5.6×10^{-4}	1.0	2.95×10^{-3}
Se–81m	8.4×10^{-5}	1.0	1.88×10^{-4}
Se–81	1.4×10^{-4}	0.11	6.36×10^{-4}
	1.32×10^{-3}	0.11	6.36×10^{-4}
Se–83m	2.9×10^{-3}	0.117	9.9×10^{-3}
Se–83	2.2×10^{-3}	9.968	4.62×10^{-4}
Se–84	9.2×10^{-3}	1.0	3.5×10^{-3}
Br–83	5.1×10^{-3}	0.2	8.02×10^{-5}
Br–84	9.2×10^{-3}	0.876	3.63×10^{-4}
	1.9×10^{-4}	2.34	1.9×10^{-3}
Kr–83m	5.1×10^{-3}	2.0	1.03×10^{-4}
Kr–85m	1.1×10^{-2}	1.0	4.39×10^{-5}
Kr–85	2.93×10^{-3}	4×10^{-3}	4.39×10^{-5}
Kr–87	2.49×10^{-2}	0.81	1.48×10^{-4}
Kr–88	3.57×10^{-2}	0.839	6.95×10^{-5}
Kr–89	4.59×10^{-2}	2.3	3.6×10^{-3}
Rb–88	3.57×10^{-2}	0.381	6.48×10^{-4}
Rb–89	4.59×10^{-2}	1.175	7.75×10^{-4}
Sr–89	4.79×10^{-2}	9.5×10^{-6}	1.59×10^{-7}
	2.0×10^{-3}	9.5×10^{-6}	1.59×10^{-7}
Sr–91	5.81×10^{-2}	0.859	1.99×10^{-5}
	3.8×10^{-3}	0.859	1.99×10^{-5}
Sr–92	5.3×10^{-2}	0.99	7.4×10^{-5}
	3.4×10^{-2}	0.99	7.4×10^{-5}
Sr–93	4.8×10^{-3}	0.334	1.53×10^{-3}
Sr–94	1.0×10^{-2}	1.3	8.45×10^{-3}
Y–90	5.7×10^{-2}	2.0×10^{-4}	3.0×10^{-6}
Y–91m	3.49×10^{-2}	1.0	2.29×10^{-4}
	4.0×10^{-6}	1.0	2.29×10^{-4}
Y–91	5.81×10^{-2}	3×10^{-3}	1.37×10^{-7}
Y–92	5.3×10^{-2}	0.739	5.5×10^{-5}
Y–93	0.117	9.99×10^{-2}	1.9×10^{-5}
Y–94	0.107	0.614	5.68×10^{-4}
Y–95	6.2×10^{-2}	1.0	1.1×10^{-3}
Zr–95	6.2×10^{-2}	1.0	1.23×10^{-7}
Zr–97	5.9×10^{-2}	6×10^{-2}	1.13×10^{-5}
Nb–95m	3.1×10^{-4}	1.0	2.14×10^{-7}

TABLE 3 *(continued)*

Note: In column I (Nuclide), m signifies metastable state.

Nuclide	Thermal-Fission Yiled (Y) (fraction of number)	Gamma Yield (γ_y) (fraction of number)	Decay Constant (λ) (sec^{-1})
Nb-95	6.2×10^{-2}	1.0	2.29×10^{-7}
Nb-97m	5.66×10^{-2}	1.0	1.16×10^{-2}
Nb-97	5.9×10^{-2}	1.0	1.6×10^{-2}
Nb-98	6.4×10^{-4}	0.888	2.26×10^{-4}
Nb-100	6.3×10^{-3}	1.0	1.05×10^{-3}
Mo-99	6.06×10^{-2}	1.06	2.88×10^{-6}
Mo-101	5.6×10^{-2}	1.7	7.9×10^{-4}
Tc-99m	5.27×10^{-2}	1.98	3.19×10^{-5}
Tc-101	5.6×10^{-2}	1.32	8.25×10^{-4}
Tc-105	9.0×10^{-3}	1.0	1.16×10^{-3}
Ru-103	3.0×10^{-2}	0.975	2.01×10^{-7}
Ru-105	9.0×10^{-3}	1.06	4.39×10^{-5}
Ru-107	1.9×10^{-3}	1.0	2.41×10^{-3}
Rh-103m	3.0×10^{-2}	1.0	2.03×10^{-4}
Rh-105m	9×10^{-2}	1.0	1.54×10^{-2}
Rh-105	9×10^{-3}	0.25	5.29×10^{-6}
Rh-106	3.8×10^{-3}	0.331	2.31×10^{-2}
Rh-107	1.9×10^{-3}	1.01	6.02×10^{-4}
Pd-109	3.0×10^{-4}	0.1	1.41×10^{-5}
Pd-111m	1.9×10^{-3}	0.68	3.5×10^{-5}
Pd-111	1.9×10^{-4}	0.317	5.25×10^{-4}
Pd-112	1×10^{-4}	1.0	9.17×10^{-6}
Ag-109m	3×10^{-4}	8.4×10^{-2}	1.73×10^{-2}
Ag-111m	9×10^{-3}	1.0	9.36×10^{-3}
Ag-111	1.9×10^{-2}	8×10^{-2}	1.06×10^{-6}
Ag-112	1×10^{-4}	1.788	6.03×10^{-5}
Ag-113m	1×10^{-4}	1.0	9.63×10^{-3}
Ag-113	1×10^{-4}	0.992	3.63×10^{-5}
Ag-115	7.7×10^{-5}	1.0	5.5×10^{-4}
Ag-116	1×10^{-4}	1.0	4.62×10^{-2}
Cd-115	9.7×10^{-5}	0.405	3.67×10^{-6}
Cd-117	6×10^{-5}	1.0	2.31×10^{-4}
In-115m	9.7×10^{-5}	0.95	4.28×10^{-5}
In-117m	1×10^{-4}	0.45	1.01×10^{-4}
In-117	2×10^{-5}	2.0	2.69×10^{-4}
In-119	1×10^{-4}	1.0	5.5×10^{-3}
Sn-123m	1.3×10^{-5}	2×10^{-2}	6.42×10^{-8}
Sn-123	1×10^{-4}	1.0	2.89×10^{-4}
Sn-125m	7.0×10^{-5}	1.02	1.18×10^{-3}
Sn-125	1.3×10^{-4}	0.124	8.53×10^{-7}
Sn-128	3.7×10^{-3}	1.0	2.03×10^{-4}
Sn-130	2×10^{-2}	1.0	4.44×10^{-3}

TABLE 3 *(continued)*

Note: In column I (Nuclide), m signifies metastable state.

Nuclide	Thermal-Fission Yield (Y) (fraction of number)	Gamma Yield (γ_y) (fraction of number)	Decay Constant (λ) (sec^{-1})
Sb-125	2.1×10^{-4}	1.09	8.45×10^{-9}
Sb-127	1.3×10^{-3}	1.0	2.17×10^{-6}
Sb-128	8.9×10^{-4}	1.0	2.0×10^{-5}
Sb-129	8×10^{-3}	2.0	4.17×10^{-5}
Sb-130	2×10^{-2}	2.0	1.65×10^{-3}
Sb-131	2.6×10^{-2}	1.0	4.99×10^{-4}
Sb-132	4.7×10^{-2}	1.0	5.5×10^{-3}
Sb-133	4×10^{-2}	9×10^{-2}	2.75×10^{-3}
Te-125m	7×10^{-5}	7.03×10^{-2}	1.38×10^{-7}
Te-127m	4.1×10^{-4}	1.02	7.64×10^{-8}
Te-127	1×10^{-3}	9.86×10^{-2}	2.06×10^{-5}
Te-129m	4.1×10^{-3}	1.0	2.4×10^{-7}
Te-129	5.1×10^{-3}	9.7×10^{-2}	1.75×10^{-4}
Te-131m	4.9×10^{-3}	1.19	6.66×10^{-6}
Te-131	2.21×10^{-2}	0.98	4.65×10^{-4}
Te-132	4.7×10^{-2}	1.19	2.48×10^{-6}
Te-133m	6.92×10^{-2}	2.59	1.93×10^{-4}
Te-133	1.12×10^{-2}	0.1	5.78×10^{-3}
I-131	2.21×10^{-2}	0.995	9.85×10^{-7}
I-132	4.7×10^{-2}	2.94	8.52×10^{-5}
I-133	2×10^{-2}	1.11	9.25×10^{-6}
I-134	8.7×10^{-2}	1.43	2.18×10^{-4}
I-135	6.1×10^{-2}	1.4	2.9×10^{-5}
I-139	3.1×10^{-2}	1.673	7.88×10^{-3}
Xe-131m	3.1×10^{-2}	4.8×10^{-2}	6.66×10^{-7}
Xe-133m	1.66×10^{-3}	0.19	3.48×10^{-6}
Xe-133	6.7×10^{-2}	0.41	1.52×10^{-5}
Xe-135m	1.83×10^{-2}	0.84	7.4×10^{-4}
Xe-135	6.5×10^{-2}	1.01	2.11×10^{-5}
Xe-137	6×10^{-2}	1.0	2.96×10^{-3}
Cs-139	7.54×10^{-2}	1.0	1.22×10^{-3}
Ba-137m	5.66×10^{-2}	0.91	4.44×10^{-3}
Ba-142	4.9×10^{-2}	0.992	1.05×10^{-3}
La-142	4.9×10^{-2}	0.85	1.36×10^{-4}
Ce-141	6×10^{-2}	0.7	2.47×10^{-7}
Ce-143	6×10^{-2}	0.706	5.82×10^{-6}
Ce-144	6×10^{-2}	0.117	2.9×10^{-8}
Ce-145	3.98×10^{-2}	1.0	3.85×10^{-3}
Ce-146	3.07×10^{-2}	1.0	8.31×10^{-4}
Pr-144	6×10^{-2}	1.52×10^{-2}	6.6×10^{-4}
Pr-146	3.07×10^{-2}	1.55	4.75×10^{-4}
Nd-147	2.7×10^{-2}	0.518	7.2×10^{-4}

TABLE 3 *(continued)*

Note: In column I (Nuclide), m signifies metastable state.

Nuclide	Thermal-Fission Yield (Y) (fraction of number)	Gamma Yield (γ_y) (fraction of number)	Decay Constant (λ) (sec^{-1})
Nd-149	1.13×10^{-2}	1.2	9.63×10^{-5}
Nd-151	4.4×10^{-3}	2.05	7.7×10^{-4}
Pm-147	2.7×10^{-2}	1×10^{-4}	8.32×10^{-9}
Pm-149	1.13×10^{-2}	3.27×10^{-2}	3.63×10^{-6}
Pm-151	4.4×10^{-3}	1.0	6.79×10^{-6}
Sm-151	4.4×10^{-3}	1.0	2.44×10^{-10}
Sm-153	1.5×10^{-3}	0.922	4.17×10^{-6}
Sm-155	3.3×10^{-4}	0.62	5.29×10^{-4}
Eu-155	3.3×10^{-4}	1.03	1.29×10^{-8}
Eu-156	1.41×10^{-4}	0.901	5.33×10^{-7}
Eu-157	7.8×10^{-5}	1.0	1.25×10^{-5}
Gd-159	1×10^{-5}	0.244	1.07×10^{-5}
Ga-72	1.6×10^{-7}	1.735	1.35×10^{-5}
Ga-73	1.1×10^{-6}	1.21	4.01×10^{-5}
Ga-74	3.5×10^{-6}	0.68	1.44×10^{-5}
Cd-115m	7×10^{-6}	3.3×10^{-2}	1.81×10^{-7}
Sn-117m	1×10^{-7}	2.0	5.37×10^{-7}
Gd-161	7.6×10^{-7}	1.01	3.09×10^{-3}
Tb-161	7.6×10^{-7}	1.0	1.13×10^{-6}
Ge-77m	1.06×10^{-4}	0.22	1.28×10^{-2}
Rb-90	2.285×10^{-2}	0.955	4.23×10^{-3}
Rb-91	2.24×10^{-2}	1.0	9.63×10^{-3}
Cs-138	5.49×10^{-2}	1.4	3.55×10^{-4}
Ba-139	5.4×10^{-2}	0.2659	1.36×10^{-4}
Cs-140	3.8×10^{-2}	2.0	1.05×10^{-2}
Ba-140	3.8×10^{-2}	0.61	6.24×10^{-7}
La-140	3.8×10^{-2}	2.56	4.78×10^{-6}
Ba-141	3.27×10^{-2}	1.08	6.42×10^{-4}
La-141	3.27×10^{-2}	2×10^{-2}	4.99×10^{-5}
La-143	6×10^{-2}	5×10^{-2}	8.25×10^{-4}

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