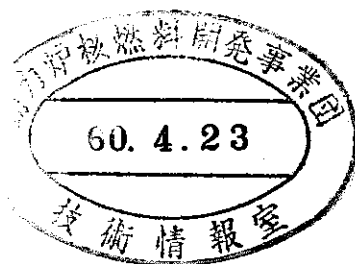


# GAMMA DOSE RATES IN THE PRESSURE TUBES OF FUGEN NUCLEAR POWER STATION

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Station

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Abstracts

Evaluation of gamma dose rates in the pressure tube and the streaming through the lower radiation shield of pressure-tube-type heavy water reactor, Fugen, is necessary for design and maintenance of this type of reactor. Calculations of these values using computer programs were made and compared with the experimental results; dose rates in a pressure tube surrounded with fuels and without fuels in adjacent tubes were calculated and the results were in good agreement with the experimental ones.

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1. Introduction

The Fugen is a 165 MWe prototype of a heavy-water moderated, boiling light-water cooled, pressure tube type reactor (ATR) developed in Japan. It has been in commercial operation since March 20, 1979.

The reactor comprises 224 vertical zirconium-2.5% niobium alloy pressure tubes of 117.8 mm inside diameter and 4.3 mm wall thickness, each of which is surrounded by a zircaloy-2 calandria tube and contains a fuel assembly. The lattice pitch is 240 mm. The principal plant parameters are given in Table 1.

This paper describes the evaluation of gamma dose rates in the pressure tubes and the streaming through the pressure tube penetrating the lower radiation shield using the computer programs ORIGEN and the discrete ordinates transport code, DOT 3.5, compared with their measurements.<sup>1,2</sup>

## 2. Calculations of Gamma Dose Rates

For the in-service inspection of pressure tubes, it is important to evaluate the gamma dose rates in the pressure tube and the streaming before its inspection to know the radiation field strength and to eliminate the risk of radiation exposure to personnel.

### 2.1 Geometric Modeling

The schematic view of the reactor is illustrated in Figure 1. Pressure tubes and the surrounding calandria tubes were treated as the radiation sources in this study. And if there are fuels in adjacent pressure tubes, the irradiated fuel elements are added as the radiation sources. Geometry of the reactor core used for the calculations are shown in Figure 2.

Fuels, pressure tubes surrounded with calandria tubes and heavy water were treated in cylindrical geometry, homogenized in each region. (Fig.2(b))

Table 1. Fugen Parameters

Thermal output	MWt	557
Electrical output	MWe	165
Core diameter	mm	4,053
Core height	mm	3,700
Calandria tank diameter	mm	7,950
Lattice pitch	mm	240
Number of fuel channels		224
Pressure tube (Zr-2.5%Nb) ID	mm	117.8
Pressure tube wall thickness	mm	4.3
Calandria tube (Zircaloy-2) ID	mm	156.4
Calandria tube wall thickness	mm	1.9
Steam drum pressure (gauge)	kg/cm <sup>2</sup>	68
Burnup (average)	MWd/t	17,000

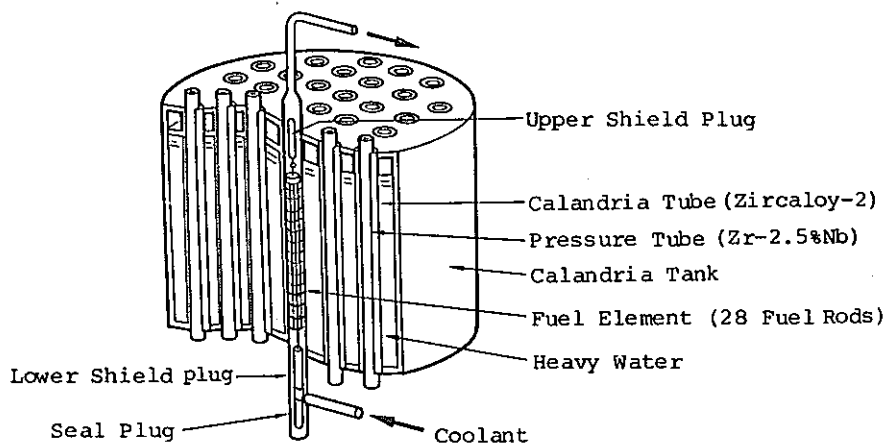


Fig. 1 Schematic View of the Reactor Core of Fugen

Table 2. Neutron energy-group structure

Neutron Group	Energy Range	Neutron Flux (n/cm <sup>2</sup> /sec)
1	10 MeV ~ 0.821 MeV	$1.7 \times 10^{13}$
2	0.821 MeV ~ 5.5 KeV	$3.7 \times 10^{13}$
3	5.5 KeV ~ 0.625 KeV	$4.4 \times 10^{13}$
4	< 0.625 KeV	$7.4 \times 10^{13}$

## 2.2 Calculations

The induced radioactivities of fuels, pressure tubes, and calandria tubes were calculated using ORIGEN code (12 energy groups, for actinide 18 energy groups). The resultant shut-down dose rate below the radiation shield due to both neutron activation and the decay of fission products within the core was calculated.

As the results, main energy ranges were 0.63 MeV and 1.10 MeV. We used seven energy groups for gamma rays in the DOT calculations (0.30, 0.63, 1.10, 1.55, and 1.99 MeV, and added 0.075 and 0.15 MeV). The calculations were performed with the DOT 3.5 code using a 33 x 85 (r, z)

The actual geometry of the pressure tube and calandria tube surrounded with another eight pressure tubes and calandria tubes, shown in Figure 2(a), is used in the modeling of the core structure. (Figure 2(b))

The CO<sub>2</sub> annulus outside the pressure tube was also included in the model. (Figure 2(a))

Vertical cut of Fugen geometry used in the discrete ordinates transport code, DOT 3.5, is shown in Figure 3.

The neutron energy structures adopted for ORIGEN is described in Table 2.

mesh structure.

The reaction cross-sections ( $P_3$ ) for material compositions were obtained using MUG code.<sup>3</sup> Calculations were made for the streaming through a pressure tube with the 96 symmetric quadrature sets (S12), 100 angle biased and 166 angle biased quadrature sets. A biased quadrature data sets are available to use when the gamma flow is highly anisotropic in some preferred direction such as an evaluation of gamma ray streaming from the pressure tube penetrating the lower radiation shield. Typical results of gamma dose rates using various quadrature sets are given in Figure 4.

Gamma dose rates in the pressure tube are similar in each case, but the streaming through the pressure tube penetrating the lower radiation shield is severely underestimated in the case that symmetric quadrature sets are used. Figure 4 shows that the 96-direction S12 is totally inadequate. And it was evaluated to be reasonable to use 100 angle biased quadrature data sets, from the viewpoint of calculation accuracy, as well as computer running time.

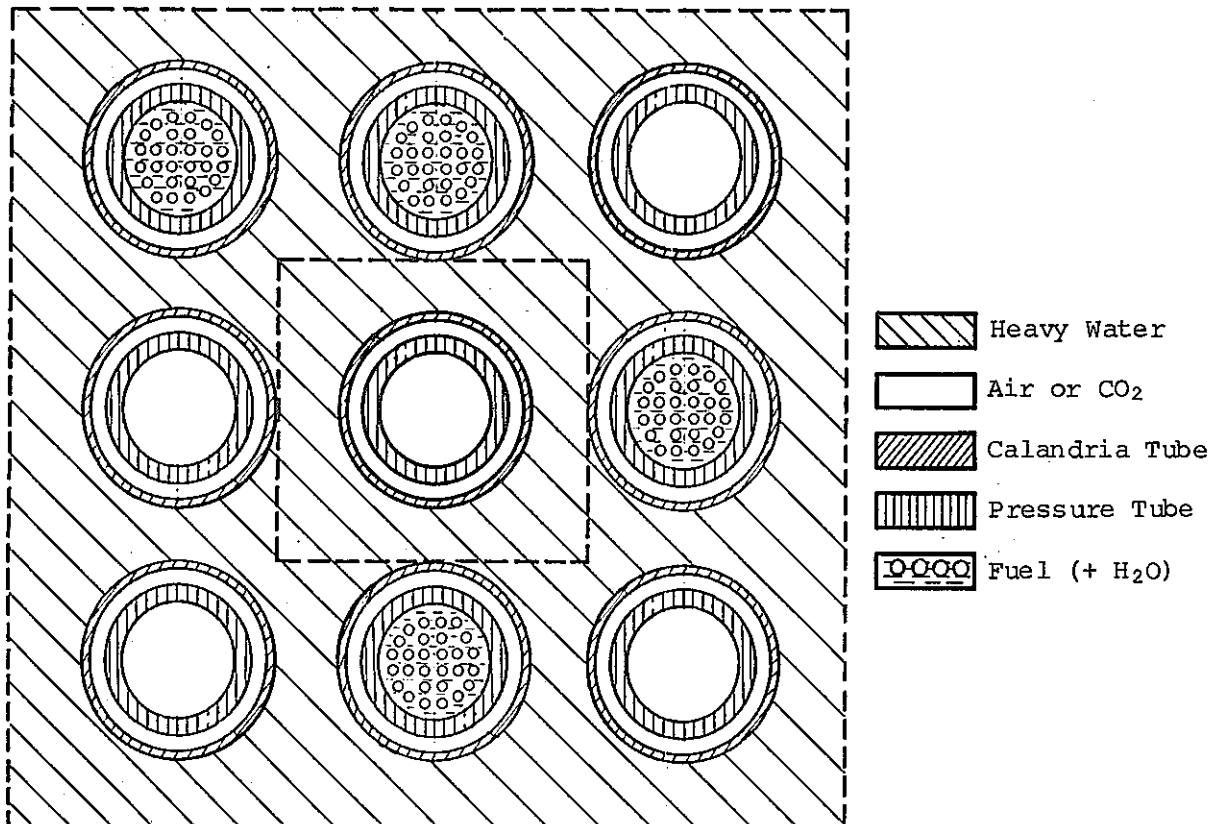


Fig. 2(a) Top View of Geometry for Pressure Tubes and Calandria Tubes Used in DOT Calculations

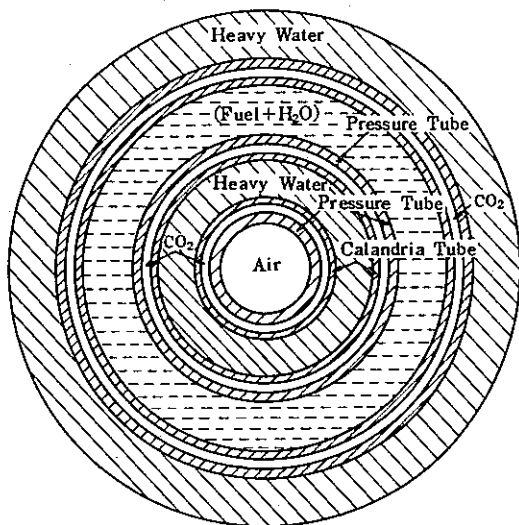


Fig. 2(b) Modeling of core structure (Test 1)

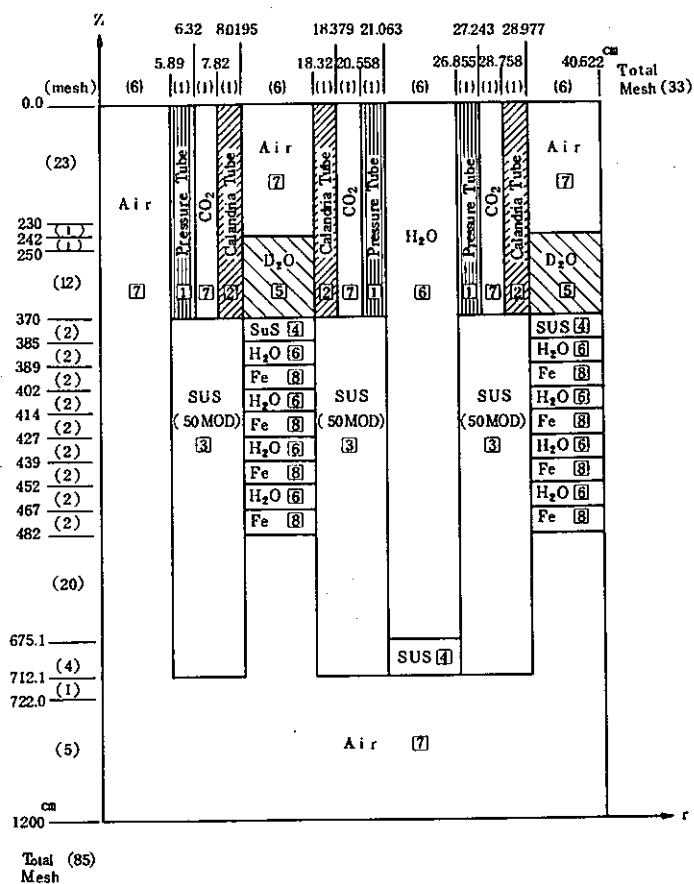


Fig. 3 Vertical cross-section of the core geometrical model for DOT3.5 calculation (Test 1)

#### - Test 1 -

Gamma dose rates in a pressure tube surrounded without fuels in adjacent tubes were calculated. The geometry of the Test 1 is shown in Figure 4. This case is that a whole fuel of 224 channels was removed from the core because a slight leakage was found in a routine inspection in the residual heat removal pipings and the moderator was dumped. The pressure tube of interest has been emptied of fuel and drained of primary coolant water.

In this case, the pressure tubes and calandria tubes as the radiation sources were assumed to distribute uniformly. Energy group between 0.30 and 1.99 MeV corresponds to the group between 8th and 12th of the ORIGEN code (eighteen groups). The two energy groups lower than 0.30 MeV were added for the DOT 3.5 calculations (Table 3). Analytical conditions are listed in Table 4.

Table 3. Energy Groups for DOT 3.5 Calculations (Test 1)

Group No.	Mean Energy (MeV)	Energy Region (MeV)	Radiation Source ( $\gamma/s/cm^3$ )*		Conversion Factors <sup>4)</sup> (mrem/hr per flux)
			Pressure Tube	Calandria Tube	
1	1.99	2.2 ~ 1.8	7.54+3	2.23+4	3.20-3**
2	1.55	1.8 ~ 1.35	8.66+3	3.02+5	2.70-3
3	1.10	1.35 ~ 0.9	6.43+9	1.06+9	2.12-3
4	0.63	0.9 ~ 0.4	1.05+10	1.06+10	1.41-3
5	0.30	0.4 ~ 0.2	3.29+8	2.93+6	7.59-4
6	0.15	0.2 ~ 0.1	0.0	0.0	3.79-4
7	0.075	0.1 ~ 0.05	0.0	0.0	2.58-4

\* 247 days cooling.

\*\*  $3.20 - 3 = 3.20 \times 10^{-3}$ 

Table 4. Analytical Conditions for DOT 3.5

Calculation System	Two-dimensional cylinder
Calculation Code	DOT 3.5
Calculation Area	axial: upper of the core ~ 5 m lower of the core radial: Center of the pressure tube of interest ~ 2nd layer of heavy water
Spatial Mesh	axial: 85 (82) radial: 33 (24)
$P_1$	$P_3$
$S_n$	100 biased quadrature set
Energy Group	Gamma-ray (7 ~ 10 groups)
Boundary Conditions	left : reflected boundary right: reflected boundary lower: vacuum boundary upper: vacuum boundary
Convergence Limit	0.01
Radiation Source	Annual Cylinder
Finite Difference	Weighted difference

- Test 2 -

The DOT 3.5 calculation for the gamma dose rates in a pressure tube with fuels in adjacent tubes is based on the geometric model shown in Figure 6. This case is that the chemical dosimeters were mounted to the pipe (13.8 mm outer diameter) at each 10 cm intervals, which pipe was loaded into a vessel of 60.5 mm outer diameter and 6,980 mm long. And the vessel was inserted in the pressure tubes.

The spatial mesh consists of 24 for radial and 82 for axial direction.

The radiation sources in the pressure tube ( $0 \leq z \leq 370$  cm) is divided into 32 equally spaced bands. Heavy water regions and fuel regions were divided into 3 mesh along the r-axis, respectively.

The fuels were added as the radiation sources in this case, then the energy groups were also increased as shown in Table 5.

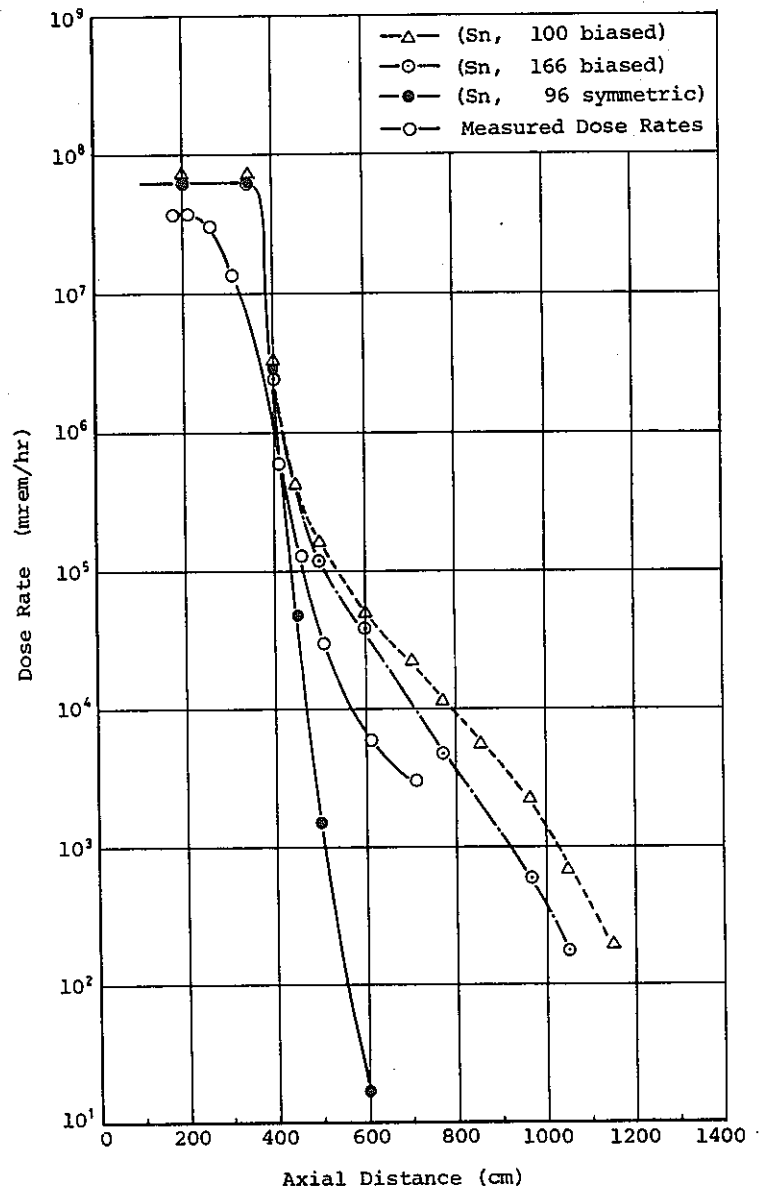


Fig. 4 Comparison of calculated values with the quadrature sets and measured gamma dose rates.

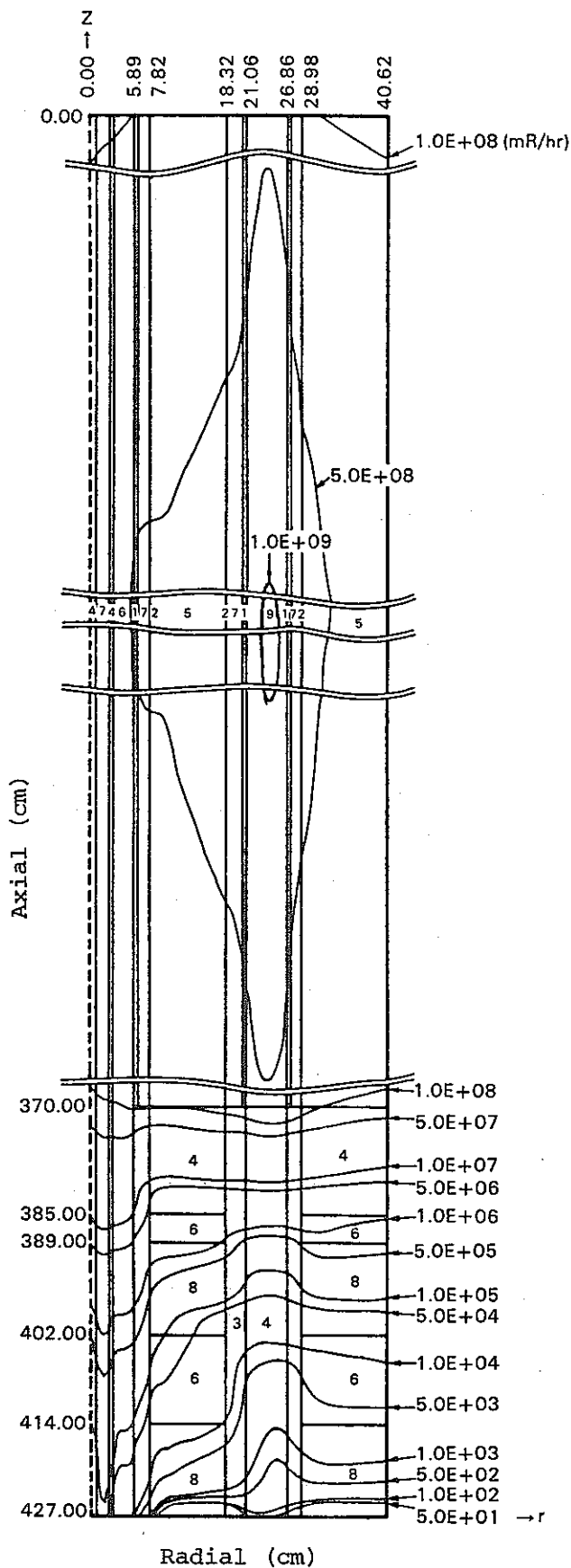


Fig. 5 Isoplots of Calculated Gamma Distributions. (after 247 days cooling)

One of the results of the DOT calculations for the lower radiation shield region is shown in Figure 5, where the radiation distribution around the reactor vessel, in the lower radiation shield (iron and water), and the streaming through the vacant pressure tube became apparent.

Subsequent calculations confirmed that the streaming through the pressure tube was a dominant effect.

Table 5. Energy Groups and Gamma Source Strength for DOT Calculation (Test 2)

Energy Group	Upper Energy (MeV)	Mean Energy (MeV)	Radiation Source ( $\gamma/s/cm^3$ ) *			Conversion Factors (mrem/hr per flux)
			Fuel	Pressure Tube	Calandria Tube	
1	3.5	2.85	7.38E+8**	0.0	7.59E+3	4.054-3
2	2.2	1.99	3.66E+8	3.07E+2	2.77E+6	3.197-3
3	1.8	1.55	2.24E+10	6.32E+4	2.40E+7	2.696-3
4	1.35	1.10	3.89E+9	4.59E+9	2.44E+9	2.119-3
5	0.9	0.63	1.81E+11	1.10E+11	9.05E+10	1.409-3
6	0.4	0.30	2.69E+10	1.69E+8	2.70E+8	8.197-4
7	0.25	0.1875	2.75E+8	0.0	0.0	2.670-4
8	0.125	0.0875	2.63E+8	0.0	0.0	2.670-4
9	0.05	0.0375	2.09E+8	0.0	0.0	3.940-4
10	0.025	0.0175	0.0	0.0	0.0	1.491-4
	0.010					

\* 23 days cooling.

\*\* Read 7.38E+8 =  $7.38 \times 10^8$

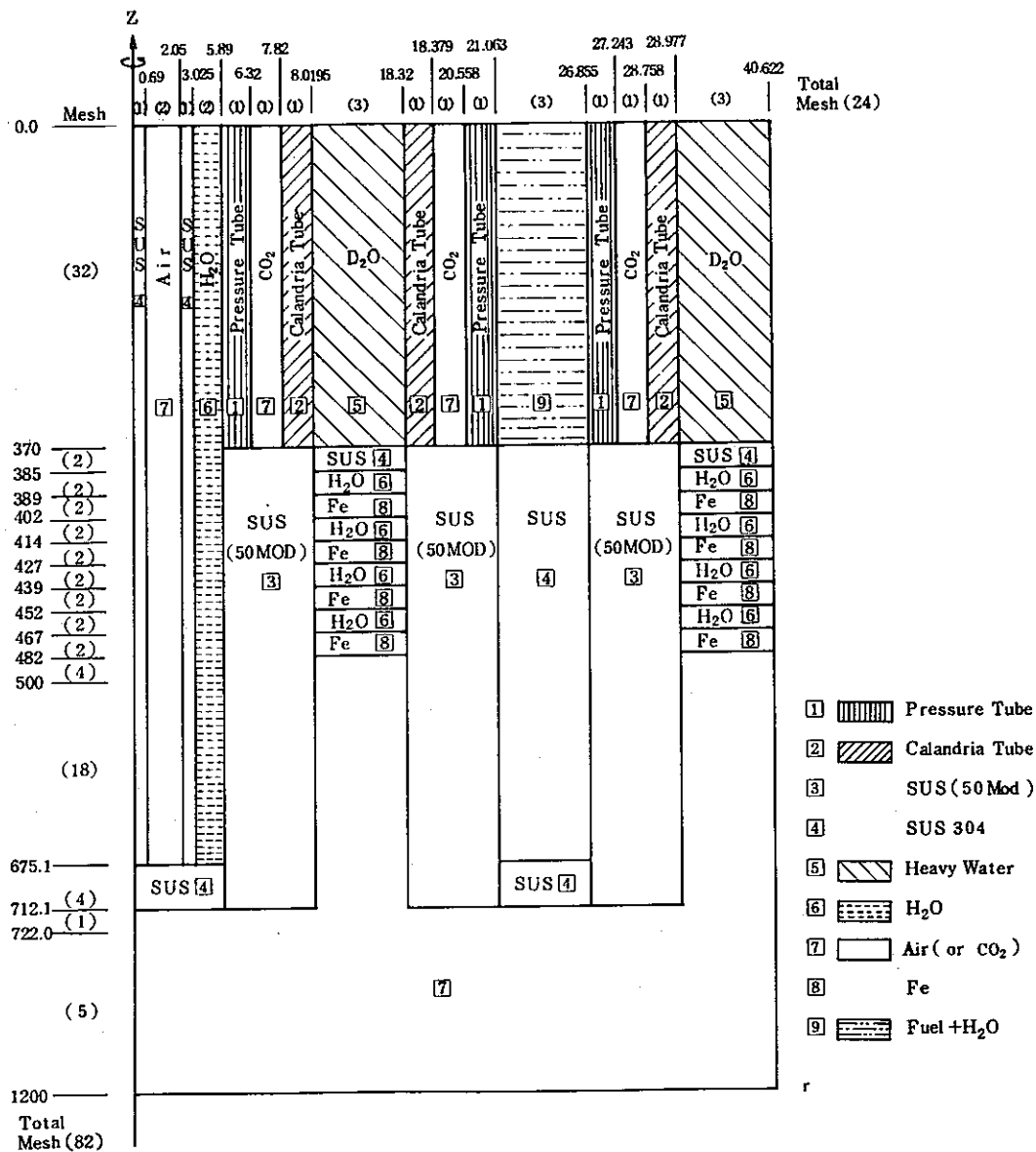


Fig. 6 Geometrical Model for DOT Calculation (Test 2)

### 3. Comparisons between Calculations and Experiments

#### - Plant Measurement 1 -

Measurements were made using an ion chamber detector (6.4 mm diameter and 31 mm long) mounted on the top of the borescope lifter. The whole fuel element was removed from the core, the pressure tube has been emptied of fuel and drained of primary coolant water.

Gamma dose rates of the pressure tube obtained was shown in Figure 7 and compared with calculated values. (Table 6) The dose rates measurement was restricted within the total length of bore scope lifter, about 5 meters from the lower end of pressure tube. The measured values were in good agreement with the calculated ones by a factor of 2 in the pressure tube. In the middle point of the pressure tube, the dose rate was slightly low because the aluminium baffle plate was located in the middle of the core. The values of dose rate below the lower radiation shield were slightly overestimated, compared with the calculated ones, and the lower radiation shield reduces the streaming by a factor of 50. Evaluated ones was about 85.

#### - Plant Measurement 2 -

Measurements were made on the gamma dose rates of pressure tube with chemical dosimeters and thermoluminescent dosimeters (TLDs) rods of BeO mounted on the pipe (SUS 304, 5,885 mm long and 13.8 mm outer diameter) at each 10 cm intervals. Chemical dosimeters (plastic dosimeters: 1.5 mm in thickness x 10 mm x 40 mm) were used in the area of pressure tube where the evaluated gamma dose rates were about  $4 \times 10^8$  mR/h. Three chemical dosimeters were used at each measurement point. They were wrapped in aluminium foil to keep them clean during handling. The absorptivity of chemical dosimeters was determined on a Hitachi Model 228 Spectrophotometer. The TLDs were also used in the area where the evaluated gamma dose values were about  $10^3 \sim 10^5$  mR/h. These dosimeters were irradiated for about 15 hours after 23 days reactor cooling at the 4th shutdown in 1984.

The irradiation time of chemical dosimeters was evaluated using the calculated gamma dose rates in a pressure tube, the correction factor (ratio of measured and calculated dose rate of Test 1), and the effective range of chemical dosimeter from 0.5 Mrad and 6 Mrad. The results are shown in Figure 7, compared with the evaluated values together

with those of Test 1. The power distribution along the axial direction was also included in the calculations.

Calculated results agreed within a factor of two with the experimental results in the pressure tube.

The direct results of DOT calculation are shown in Table 7 and Figure 7. If we use the correction factor ( $C/E=2.13$ ) obtained in the plant measurement 1 to the evaluation of gamma

dose rates of Test 2, the calculated values are in good agreement with the experimental results within a factor of  $0.89 \sim 1.07$ .

Table 6. Comparison of Measured and Calculated Gamma Dose Rates in the Pressure Tube (Test 1).

Distance* (cm)	Mesh Member	Gamma Dose Rate (R/h)		Ratio (Cals./Expt.)
		Calculation**	Experiment <sup>1)</sup>	
180	19	$7.72 \times 10^4$	$3.69 \times 10^4$	2.09
210	22	$7.35 \times 10^4$	$3.74 \times 10^4$	1.96
260	27	$5.01 \times 10^4$	$3.04 \times 10^4$	1.65
310	32	$4.48 \times 10^4$	$1.35 \times 10^4$	3.32
410	45	$1.29 \times 10^3$	$6.00 \times 10^2$	2.15
460	53	$2.41 \times 10^2$	$1.32 \times 10^2$	1.83
510	59	$9.45 \times 10^1$	$3.12 \times 10^1$	3.03
610	69	$3.23 \times 10^1$	6.0	5.38
710	80	$1.31 \times 10^1$	3	4.36

\* Distance from the top of the pressure tube

\*\* 247 days cooling time

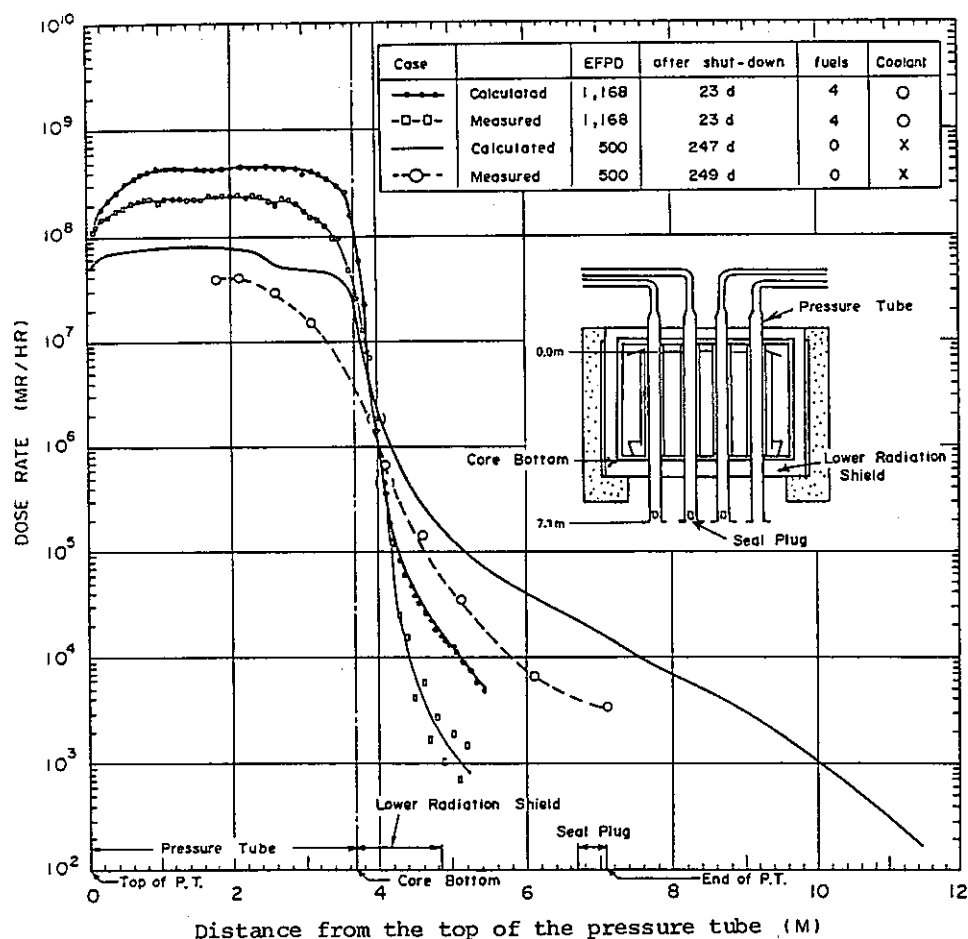


Fig.7. Comparison of calculated results and experimental gamma dose rates along the pressure tube axis<sup>2)</sup>

Table 7. Comparison of Experimental and Calculated Gamma Dose Rates (Test 2)

Distance (cm)	Mesh* Number	Gamma Dose Rate (R/h)		Ratio (Cal./Exp.)	Ratio ** (Cal./C/E x Exp.)
		Calculation	Experiment		
179	16	$4.21 \times 10^5$	$2.37 \times 10^5$	1.77	0.928
214	19	$4.29 \times 10^5$	$2.46 \times 10^5$	1.74	0.892
260	23	$4.21 \times 10^5$	$2.06 \times 10^5$	2.04	1.07
318	28	$3.57 \times 10^5$	$1.66 \times 10^5$	2.15	1.01
463	48	$2.55 \times 10^1$	$1.50 \times 10^1$	1.70	0.799
515	56	8.53	0.689	12.4	5.81

\* mesh number in the Test 2.

\*\* C/E from the Test 1 was used.

Total radiation exposure to the pressure tube inspection (10 pressure tubes) on the 4th shutdown in 1984 was about 5.3 man-rem.

#### 4. Conclusions

1. With the use of simple model of homogenized structure of reactor core, we could obtained the gamma dose rates in the pressure tubes of Fugen Heavy Water Reactor.
2. Calculated gamma dose rates in the pressure tubes surrounded with fuels and without fuels in adjacent tubes were compared with observed values, and agreed within a factor of two.
3. Experimental results and evaluation of gamma dose rates are used for designing pressure tube monitoring apparatus and pressure tube replacing machine, and will provide improved information for pressure tube maintenance or replacement.

#### 5. References

- (1) Y.ANDOH, K.TANIMOTO, K.IMAIZUMI, S.TSUURA, and M.IKEDA, (In Japanese), "Analysis of Gamma Ray in the Pressure Tube and Streaming through the Core of Fugen Heavy Water Reactor", PNC ZN341 82-09 (1982).
- (2) Y.ANDOH, T.NAKAMURA, S.SHIBUYA, "Gamma Dose Rates in the Pressure Tubes of Fugen Nuclear Power Station," *Trans. Am. Nucl. Soc.*, **47**, 381 (1984).
- (3) J.R.KNIGHT and F.R.MYNATT, CTC-1, "MUG A Program for Generating Multi-group Photon Cross Sections" (1970).
- (4) ANSI/ANS-6.1.1-1977, "Neutron and Gamma-ray Flux-to-Dose-Rate Factors".

## Appendix A

For the evaluation of axial gamma dose rates in the pressure tube to be inspected, the effect of the pressure tubes, calandria tubes, and fuels surrounding the pressure tube was analyzed separately using QAD code.

The fraction of gamma dose rates from the outside regions is shown in Table A-1 and Table A-2. The regions to be considered are shown in Figure A-1. From the tables, it is clear that the gamma source strength of the first layer of pressure tubes and of calandria tubes is dominant. And the gamma source strength from the 2nd and 3rd layer may be neglected compared with the total gamma strength.

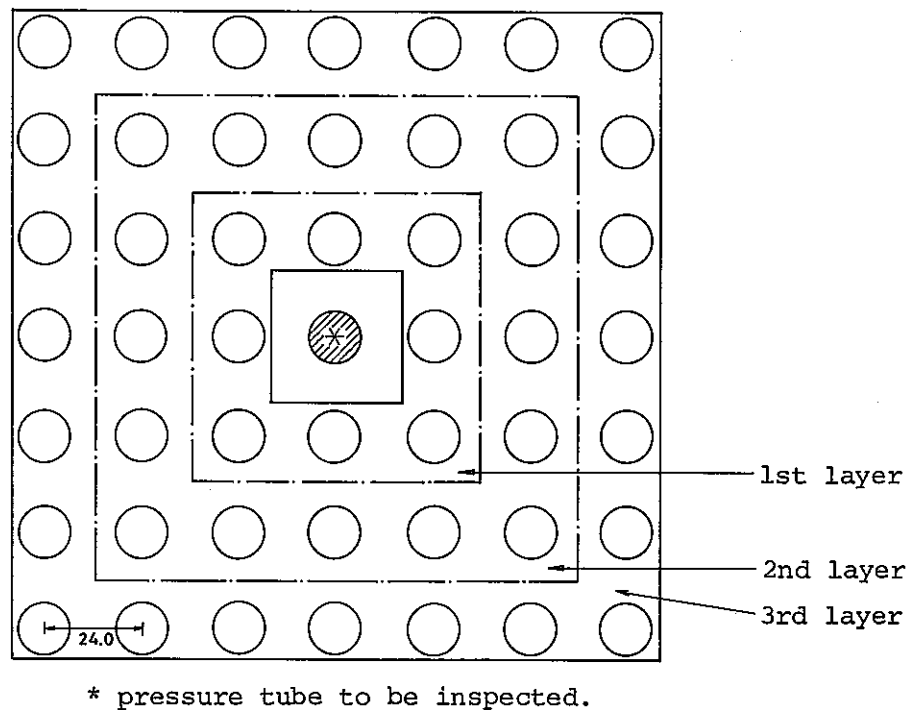


Figure A-1. The arrangement of pressure tubes and calandria tubes

Table A-1 Fraction of gamma dose rate from the  
outside regions (with fuels)

layer	Fuel	Pressure Tube	Calandria Tube	Total
0	-----	15.13	5.55	20.68 %
1st	62.64	6.03	3.68	72.35 %
2nd	5.26	0.45	0.28	5.99 %
3rd	0.94	0.04	0.01	0.99 %

Table A-2 Fraction of gamma dose rate from the  
outside regions (without fuels)

layer	Fuel	Pressure Tube	Calandria Tube	Total
0	-----	42.98	15.77	58.75 %
1st	-----	23.19	12.38	35.57 %
2nd	-----	3.39	1.71	5.10 %
3rd	-----	0.40	0.19	0.59 %

## Appendix B

The fraction of gamma dose rates from the outside regions using discrete ordinate transport code, DOT 3.5, is shown in Table B-1. The gamma source strength from the 2nd and 3rd layer may be negligibly small compared with the total gamma strength.

The Case 3 indicates the results that the whole region of outside 1st layer is homogenized.

Table B-1 Fraction of gamma dose rate from outside regions (with fuels)

layer	Case 1	Case 2	Case 3
0	97.26 %		
1st	97.34 %	97.17 %	98.47 %
2nd	2.66 % 2.74 %	2.74 %	
3rd	-----	0.09 %	
			1.53 %
outside region	-----	-----	

\* confer the definition of Appendix A.