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DEVELOPMENT OF RADIATION DOSE CALCULATION CODE FOR NUCLEAR POWER PLANT
- QAD-FUGEN -

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ABSTRACT

A radiation dose calculation code, QAD-FUGEN, has been developed for a prototype heavy water reactor FUGEN. The code is designed to calculate the radiation dose from many radiation sources at a time. It is a gamma ray shielding calculation code which utilizes the point-kernel method as its analytical procedure, and is developed by modifying the QAD code substantially.

Main characteristics of the QAD-FUGEN code are as follows:
(1) The cylindrical sources can be set at any position and direction in space. The mutual shielding of source regions can be treated in the code. (2) The geometry of shielding structure should be composed of pipes, tanks and rectangular parallelepipeds, and they can be also set at any position and direction. There is no limit in number of sources and shieldings. (3) The geometry of radiation sources and shieldings, obtained with a digitizer which is used to measure the distances on the drawings can be fed to QAD-FUGEN. (4) The check routines are prepared to draw the geometries on two dimensional plane or in three dimensional bird's-eye view. (5) The code has a radioactive nuclide library to calculate the source gamma ray spectra. (6) As the input data on radiation sources can be divided into many sections, the local distribution of source strength along pipes or in vessels can be dealt with.

These modifications made the gamma ray dose rate calculation easy, even in the complicated geometries. With the use of this code, dose rates in the power plant FUGEN can be calculated. The calculated dose rates at the typical points agreed reasonably well with the observed values.

INTRODUCTION

Before the commissioning and stationary operation of a power reactor, it is necessary to estimate the radiation dose at the interested points for inspection and maintenance work during both operation and outage period. There was the same requirements at the period of commissioning of the FUGEN in 1978 which is a 165 MWe heavy water moderated, light water cooled reactor using plutonium mixed oxide fuel, constructed under the national program in Japan.

In gamma ray shielding calculation, there are two principal types of codes, that is, the transport and point-kernel codes. In practical point of view, the latter is superior to the former in the point of easy modeling and the lesser machine time. However, even in this case, it is not practical to use conventional codes as they are, due to the reasons as follows:

(1) There are many radiation sources in a power plant as shown in Fig. 1. Conventional code can deal with only one radiation source and repeated calculations are necessary to obtain the radiation dose rate from multiple sources. And the mutual shielding among pipes, tanks and shielding walls must be considered in the calculation. Due to these requirements, the calculation needs the tedious, time-consuming work which necessitates the modeling work by experienced shielding design engineers. In addition, when the locations of receiver points are changed, most of the geometrical models have to be reconsidered.

(2) Besides the bulk shielding calculation of the reactor core which is out of scope in this code, main radiation comes from the reactor coolant and its steam. It decays with the elapsed time from the outlet of the reactor core as shown in Fig. 2.

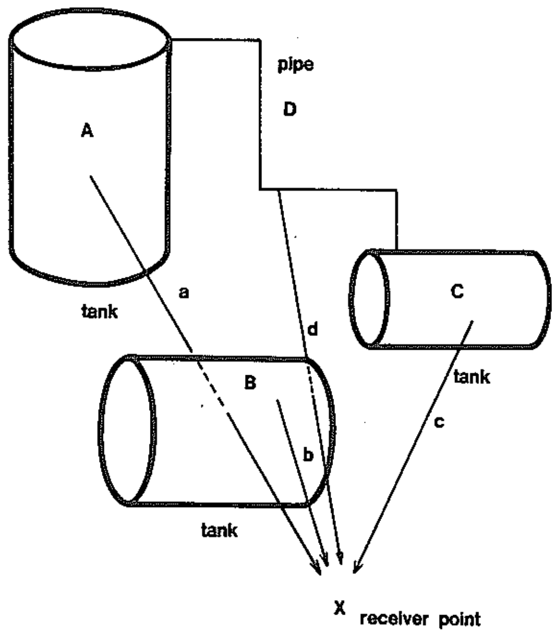

Fig. 1 Schematic diagram of calculation

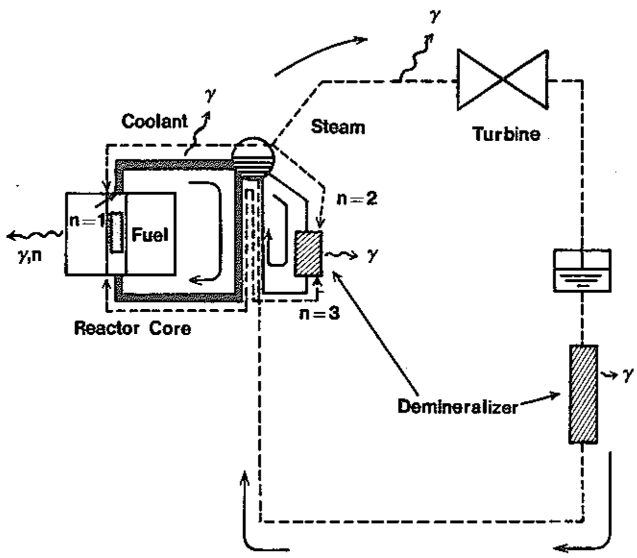

Fig. 2 Schematic diagram of radiation sources

To cope with these difficulties, the QAD[1] code that allows to deal with rather complicated shape of sources and shields which are surrounded with the surfaces defined by second order equations, is combined with three dimensional input of the locations of receiver points, and of the shapes and locations of the radiation sources and shielding walls.

The graphical input and output routine has greatly reduced input manual works and errors by easy recognition of the calculated results. The digitizer is used to read the values of location of the interested point in rectangular coordinates, simply by putting the cursor of a pointer at an interested point on both plane and sectional drawings.

CALCULATIONAL PROCEDURE

Basic Equations

For gamma ray dose calculation, the QAD-FUGEN code utilizes the point-kernel ray-tracing technique. In this method, the point-kernel representing the transfer of energy by the uncollided flux along a line-of-sight path is integrated over the source regions with an appropriate buildup factor to account for the contribution from the scattered photons. The dose rate $D(\vec{r})$ of gamma ray at any point from an isotropic source emitting S photons of energy E per second per unit volume is,

$$D(\vec{r})=K\int_V S(\vec{r})B(\mu|\vec{r}-\vec{r}'|,E)\exp(-\mu|\vec{r}-\vec{r}'|)/(4\pi|\vec{r}-\vec{r}'|^2)\,dV \qquad (1)$$

where,

- $\vec{r}$: location of point at which gamma ray dose rate is to be calculated (receiver point),
- $\vec{r}'$: location of source in source volume V,
- V : volume of source regions,
- μ : total attenuation coefficient at energy E,
- B : dose buildup factor,
- K : flux-to-dose conversion factor.

The buildup factors and total attenuation factors are same as that of the library of the QAD-P5A[1] code. That is, the Capo's fit to the Goldstein-Wilkins data with bivaliant polynomial expression[1] is used to calculate the appropriate buildup factors as a function of the gamma ray energy and the number of mean free paths from the source to the receiver point. The total attenuation coefficient at the specified energy is obtained by the linear interpolation.

The numerical integration of Eq.(1) is performed by dividing the source volume into small segments. Only a cylinder is allowed as the source regions in the QAD-FUGEN code. A cylinder is classified into two types: "pipe" and "tank". If the source cylinder is assigned as "pipe", segmentation for this source is 1 mesh for the radial direction, 2 meshes for the angle around the pipe axis and 1 mesh for 10cm along the pipe axis direction. If the source cylinder is assigned as "tank", segmentation for this geometry is 10 meshes for radial direction, 10 meshes for the angle around the tank axis, and 20 meshes along the tank axis. The automated segmentation can be changed by the input instruction. Any number of the source cylinders such as pipes or tanks can be placed at any position.

Shielding materials in the QAD-FUGEN code are limited to water, steel and concrete. Again, any number of blocks at any position can be set to simulate the actual shielding geometry. The library of the QAD-FUGEN code contains the buildup factors, total attenuation coefficients and dose rate conversion factors. In addition, it has the library for the nuclides that emit gamma rays and simplifies the works to input the activities.

Radiation Source

In coolant, there are two kinds of radioactive substances: one is fission products, the other is activation products. The former originates from the defective fuel rod, if present, and the latter originates from the dissolved substances in coolant and the coolant itself. These activities are transported by coolant as shown in Fig. 2.

The activities in coolant, steam and resin are expressed quantitatively by the following equations:

1. In reactor core

$$C_{1,i} = R_i(1-\exp(-\lambda_i.t_0))/(1-\exp(-\lambda_i.t_1))/(d.Q_1) \quad (2)$$

$$C'_{1,i} = \Sigma_i.f(1-\exp(-\lambda_i.t_0))/(1-\exp(-\lambda_i.t_1)) \quad (2)'$$

2. From outlet of reactor core to inlet of demineralizers

$$C_{2,i} = C_{1,i}.\exp(-\lambda_i.t) \quad (3)$$

3. After passage through demineralizers

$$C_{3,i} = C_{1,i}.\exp(-\lambda_i.t).(1-\eta_i) \quad (4)$$

4. Accumulation in demineralizers

(1) Parent nuclides

$$A_i = C_{1,i}(\exp(-\lambda_i.t).Q_2.\eta_i(1-\exp(-\lambda_i.T)))/(V.\lambda_i) \quad (5)$$

$$A'_i = C'_{1,i}(\exp(-\lambda_i.t).Q_2.\eta_i(1-\exp(-\lambda_i.T)))/(V.\lambda_i) \quad (5)'$$

(2) Daughters formed between outlet of core and that of demineralizers.

(3) Daughters formed by decay of nuclides adsorbed by demineralizers

These activities are calculated by Bateman's equation up to the third daughters.

5. Turbine system

$$CT_i = K.k_i.C_{1,i}/v \quad (6)$$

$$CT'_i = K \cdot k_i \cdot C'_{1,i}/v \qquad (6)'$$

where,

A_i, A'_i: accumulated activity of nuclide i in demineralizers(μCi/cm^3),

$C_{n,i}$: concentration of nuclide i produced by fission reaction in fuel rod at n (n refers to the location given in Fig. 2)(μCi/gr),

$C'_{n,i}$: concentration of nuclide i produced by activation reaction in coolant at n (n refers to the location given in Fig. 2)(μCi/gr),

CT_i, CT'_i : concentration of nuclide i in steam (μCi/cm^3),

d : density of coolant(gr/cm^3),

f : neutron flux(n/cm^2/sec),

K : conversion factor,

k_i : partition coefficient between steam and water of nuclide i(-),

Q_1 : flow rate of recirculation system(cm^3/sec),

Q_2 : flow rate of clean-up system(cm^3/sec),

R_i : fission products release rate of nuclide i(μCi/sec),

t : elapsed time after the outlet of reactor core(sec),

t_0 : in core residence time(sec),

t_1 : cycle time in recirculation system(sec),

T : time of reactor operation(sec),

V : volume of resin(cm^3),

v : specific volume of steam(cm^3/gr),

η_i : removal efficiency of nuclide i(-),

λ_i : decay constant of nuclide i(sec^{-1}),

Σ_i : macroscopic activation cross section of nuclide i(cm^{-1}),

The equations mentioned above describe the radioactivity in both the reactor coolant clean-up system and the turbine system. In another systems such as the heavy water system, the radioactive waste processing system, the basic concept is almost the same. And only minor modifications are necessary.

The constants used in above equations are mostly installed in the QAD-FUGEN code. And the fission products release rate from the fuel rod is assumed to be zero in this paper, because of no defect in the fuel rods, and the design value of the elapsed time is applied to activation products.

Input and Output of Geometry

The data of shielding and source geometries for QAD-FUGEN are read with a digitizer which measures the distances on the drawings. In addition, the diameter and thickness of pipes are assigned indirectly with the nominal size using the schedule number defined by Japanese Industrial Standards. This greatly reduced the input work. The input geometry can be checked with the routines which draw the pictures on two dimensional plane, and if necessary, in three dimensional bird's-eye view.

RESULT

The radiation dose rate was measured by a health physics monitor (ionization chamber). And the activity of the coolant was determined by a Ge(Li) spectrometer after sampling. Typical examples of calculation with observed value are given below. The calculated result is mainly affected by the basic (geometrical) calculation and the source estimation. The first example is a measure of the former, and the remainders are the measure of total accuracy including source estimation.

Example 1. Dose rate calculation in heat exchanger room of iron-water shield cooling system.

This system is designed to remove the heat of iron-water shield by a heat exchanger. Coolant is fed to the iron-water shield around the reactor core, and is returned to the core by the circulation pump. The coolant contains considerable amount of potassium chromate (several hundreds ppm) to prevent the corrosion of the inner surface of the component of the system. The main contribution on the radiation dose rate at the heat exchanger is due to K-42 and Cr-51.

Table 1 Dose rate in the heat exchanger room of iron-water shield cooling system. (at full power)

Receiver point	Dose rate (mR/hr)		
	Calc.*	Obs.**	Calc./Obs.
R1	3.3	1.5	2.2
R2	1.8	1.3	1.4
R3	4.3	3.2	1.3

* : Concentration of radioactive substances is observed value at April 11, 1979.
** : Observed at April 19, 1979.

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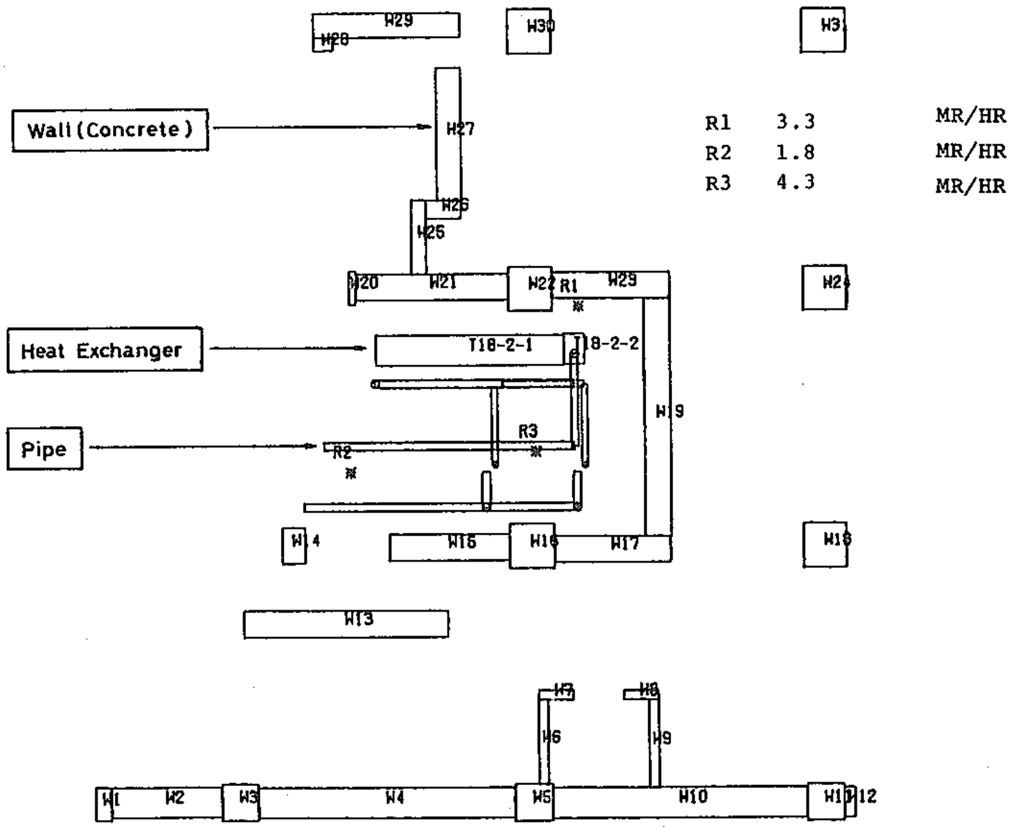

Fig. 3 Configuration of heat exchanger room of iron-water shield cooling system

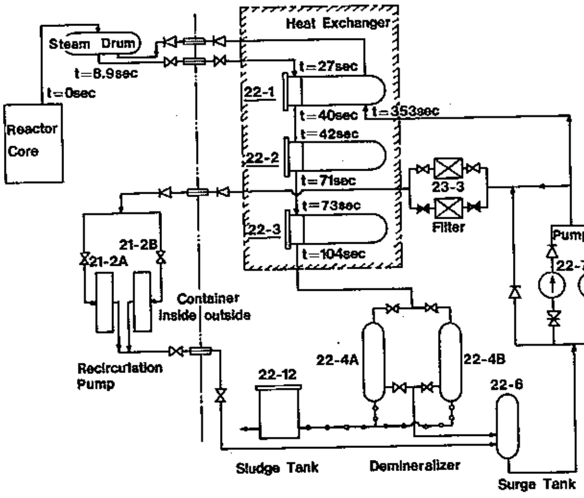

Fig. 4 Flow sheet of reactor coolant clean-up system

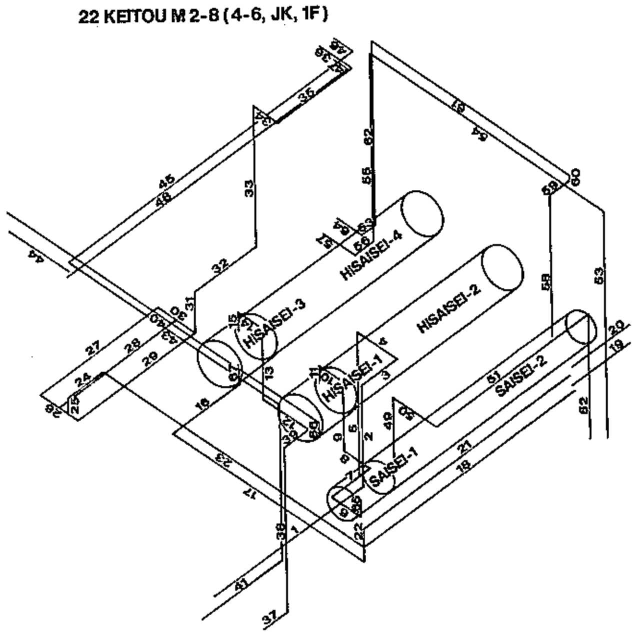

Fig. 6 Bird's-eye view of heat exchangers of reactor clean-up system

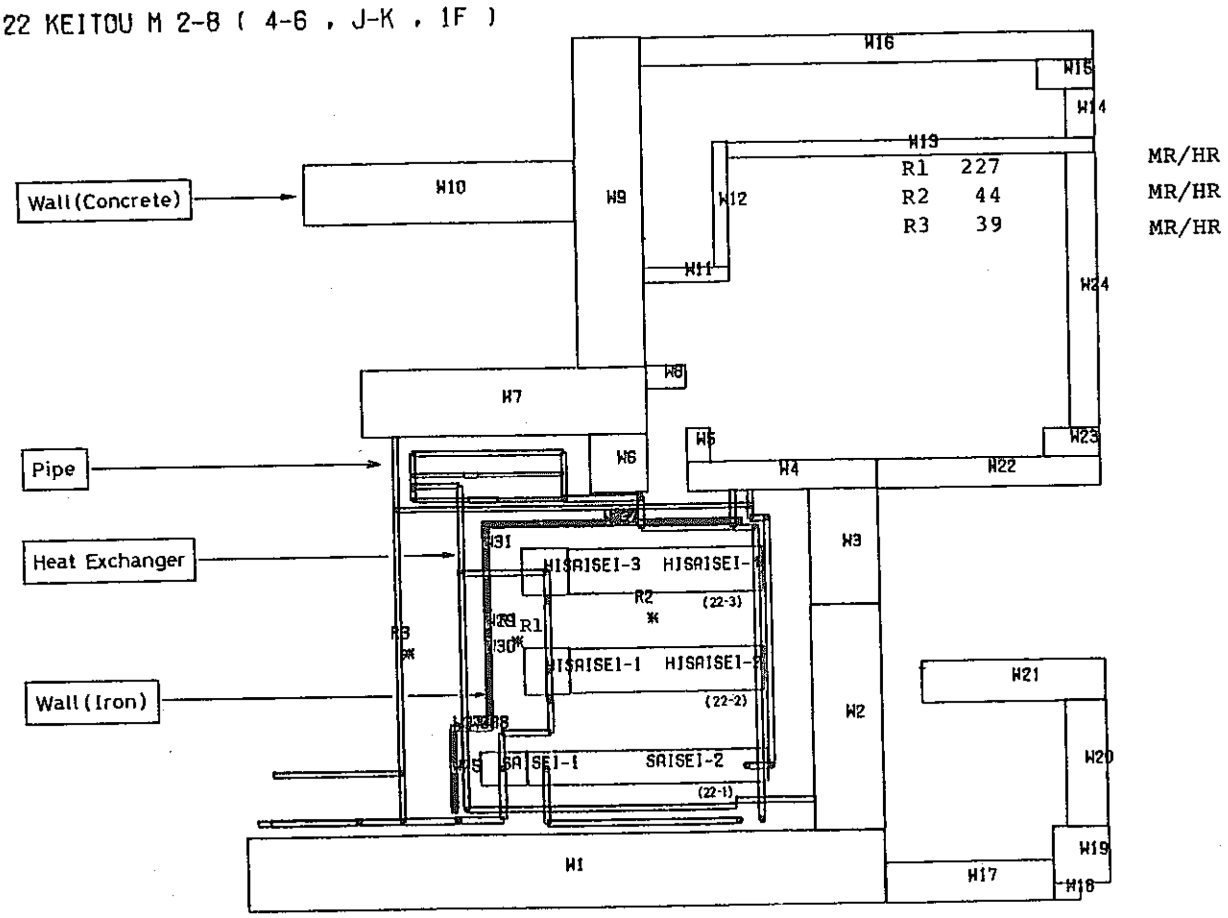

Fig. 5 Configuration of heat exchanger room of reactor coolant clean-up system

In dose rate calculations, the observed activity of the coolant is used. The configuration of the heat exchanger room is shown in Fig. 3. Symbol W wuth numericals shows blocks or walls (concrete or iron). Symbol T followed by numericals is a tank (or cylindrical equipment, e.g. heat exchanger) and the symbols, R1, R2 and R3 represent receiver points, respectively. Narrow parallel lines near heat exchanger are pipings. In detailed check routine, pipes, tanks(or cylindrical equipments) and walls are printed out as diagrams with their allocated systematic number by which all the informations on their input data can be read on the digital printout. And the observed values agreed with the calculated values at factors between 1.3 and 2.2 as shown in Table 1.

Example 2. Dose rate in heat exchanger room of reactor coolant system

Figure 4 gives the flow sheet of the reactor coolant clean-up system which is designed to remove the chemical and the radioactive substances in the coolant by passing through the demineralizers. As shown in Fig. 2, the by-passed coolant is returned to the steam drum. Each elapsed time of coolant in the system is shown in Fig. 4. The main contribution of the activities is due to short-lived activation product N-16 produced by the reaction, $^{16}O(n,p)^{16}N$ in coolant. Calculated activity of N-16 is based on the design value of elapsed time (which is the average value of time at the inlet and outlet of the interested pipes or tanks), the neutron flux and the cross sections. As it was difficult to predict the activities of corrosion products by calculation, the observed value were used and the

Table 2 Dose rate in the heat exchanger room of reactor cooling system. (at full power)

Receiver point	Dose rate (mR/hr)		
	Calc.*	Obs.**	Calc./Obs.
R1	227	130	1.8
R2	44	40	1.1
R3	39	28	1.4

* : Concentration of radioactive substances is calculated value at April 11, 1979.
** : Observed at January 22, 1979.

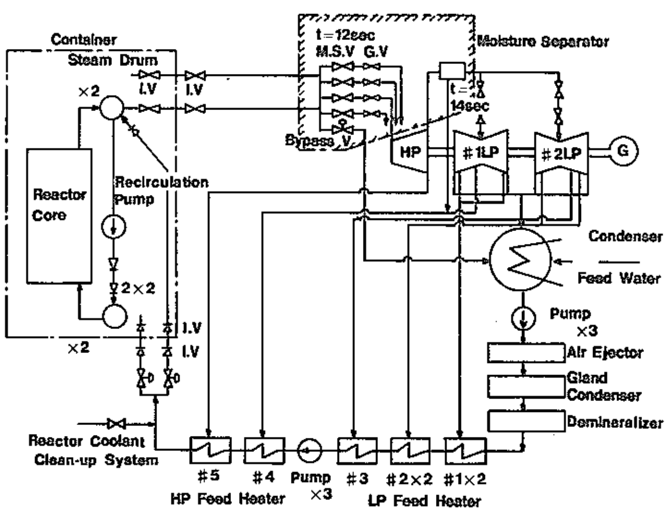

Fig. 7 Flow sheet of turbine system

contribution to the dose rate of this system was negligible. The hatched part in Fig. 4 shows the equipments considered in this calculation. The configuration of the heat exchanger room is given in Fig. 5. The symbols used are almost the same as those in Fig. 3. The bird's-eye view is also shown in Fig. 6. The ratios of the calculated to observed values were between 1.4 and 1.8 as shown in Table 2.

Example 3. Dose rate in turbine room

There are many complicated pipings around the turbine. Figure 7 gives the flow sheet of turbine system. The calculation of the dose rate in this area provides the most typical application of QAD-FUGEN. The hatched part in Fig. 7 shows the equipments considered in this calculation. And in general, an oblique pipe such as A in Fig. 8 is substituted by the equivalent pipes to simplify the input. The activity is calculated by the design value (pressure,temperature and elapsed time). And the dominant nuclide was N-16. Figure 8 gives the configuration of the related radiation sources. The calculated value at R1 is 243mR/h and about five times of the observed value (50mR/hr at full power).

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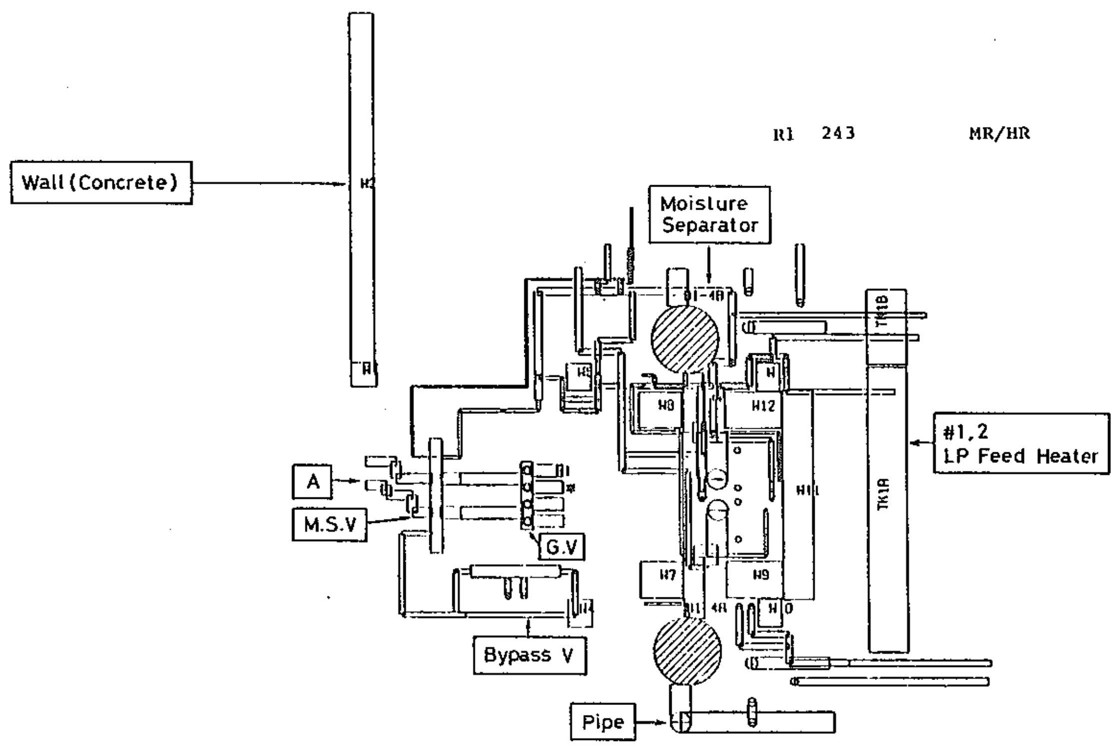

Fig 8 Configuration of turbine room

DISCUSSION

In order to simplify the input of data and save machine time, the axes of pipings and tanks are treated as parallel or perpendicular to each other. And vessels containing the complicated internal components such as heat exchangers are treated as homogeneous substances. Typical machine time to calculate dose rate with QAD-FUGEN is several minutes with the CDC-6600 computer for a receiver point. Of course, there are some exceptional cases such as the oblique pipings in the reactor container, hemi-cylinder in the turbine hall and rectangular sump. Special options are also prepared for them.

The calculated results of example 1, 2 and 3 give the accuracy of a factor of 1.3-2.2, 1.4-1.8 and about 5, respectively. Concerning example 2 and 3, the partition coefficient of nitrogen between steam and water (k_i in Eq.(6)')) is assumed to be unity. According to Avery et al.[2], it is measured to be 0.69±20% at the Steam Generating Heavy Water Reactor(SGHWR) similar type of a reactor to the FUGEN. When this partition coeffiecient is used in the calculation, the dose rate in the vicinity of turbine system is to decrease and that of reactor clean-up system is to increase. Thus, the ratios of calculated to observed value approach to three. As the workers entering the restricted area can read their actual dose rates, these over-estimated dose rates by calculation seem to be enough to plan their work and shielding. The detailed output of the dose rate for each radiation source and for each energy group obtained with QAD-FUGEN seems to be useful for them.

SUMMARY

It is the main characteristics of the QAD-FUGEN code to be able to deal with many radiation sources and shields, and the mutual shieldings at a time. The geometry of radiation sources and shields can be read with a digitizer, and the check routines are prepared to draw the geometries on two dimensional plane or in three dimensional bird's-eye view. The code was used on the period of commissioning of the FUGEN, and the overall ratio of the calculated and observed values considered to be about three.

ACKNOWLEDGEMENT

We would like to appreciate the great efforts of our collegues who worked in the programming and measurements of the dose rate in the plant.

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