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Uncertainty Analysis of Multiple Canister Repository Model by Large-Scale Calculation

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ABSTRACT

A prototype uncertainty analysis has been made by using the multiple-canister radionuclide transport code, VR, for performance assessment for the high-level radioactive waste repository. Fractures in the host rock determine main conduit of groundwater, and thus significantly affect the magnitude of radionuclide release rates from the repository. In this study, the probability distribution function (PDF) for the number of connected canisters in the same fracture cluster that bears water flow has been determined in a Monte-Carlo fashion by running the FFDF code with assumed PDFs for fracture geometry. The uncertainty for the release rate of ^{237}*Np from a hypothetical repository containing 100 canisters has been quantitatively evaluated by using the VR code with PDFs for the number of connected canisters and the near field rock porosity. The calculation results show that the mass transport is greatly affected by (1) the magnitude of the radionuclide source determined by the number of connected canisters by the fracture cluster, and (2) the canister concentration effect in the same fracture network. The results also show the two conflicting tendencies that the more fractures in the repository model space, the greater average value but the smaller uncertainty of the peak fractional release rate is. To perform a vast amount of calculation, we have utilized the Earth Simulator and SR8000. The multi-level hybrid programming method is applied in the optimization to exploit high performance of the Earth Simulator. The Latin Hypercube Sampling has been utilized to reduce the number of samplings in Monte-Carlo calculation.*

Key Words: High-level radioactive waste repository, Performance assessment, Fracture, Uncertainty Analysis, Earth Simulator

1. INTRODUCTION

A prototype uncertainty analysis has been made by using the multiple-canister radionuclide transport code, the VR[TM*] code [1][2], for performance assessment for High-Level Radioactive

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[*] VR[TM] code is the property of the University of California

Waste (HLW) repository. In the previous performance assessments [3], radionuclide release from a repository was modeled based on a single-canister configuration, where radionuclide release from each canister is not influenced by adjacent canisters. Recently, the radionuclide transport code, the VR code, was developed, which incorporates interference effects of multiple canisters. In reality, groundwater mainly flows through fracture clusters in the host rock heterogeneously. Only waste canisters in the repository hydrologically connected with the groundwater flow in the far field by fracture clusters will become sources of contamination in the environment. Therefore the number of connected canisters by fracture clusters is crucial information in the safety performance analysis for the repository, because it principally determines the magnitude of the contamination source in the repository.

Because of heterogeneity of fractures, the number of connected canisters by fracture cluster should be determined statistically by taking into account statistics of fracture-geometry parameters. The FFDF™** code [4], a Monte Carlo code for fracture network generation and mass transport in fracture networks from a single canister, has been modified to handle multiple canisters, and then transplanted to the Earth Simulator [5][6] and SR8000 [7], Japanese supercomputers, to handle a vast amount calculations. The probability density function (PDF) for the number of canisters connected by a fracture cluster in the two-dimensional repository model has been obtained by this FFDF code modified by authors [8]. In this study, the uncertainty associated with the fractional release rate of ^{237}Np from a hypothetical repository containing 100 canisters has been evaluated by using the VR code with the obtained PDF for the number of connected canisters by fracture cluster.

To handle a vast amount of calculation to obtain statistical convergence in Monte-Carlo calculation in the uncertainty analysis, we have tried two things. One is utilization of the Earth Simulator and SR8000, symmetric multiprocessor (SMP) cluster machines. Necessary modification and optimization for the VR code have been made. The multi-level hybrid programming method [9] [10], which is a common programming method for SMP cluster machines, is applied in the optimization. The other is application of the Latin Hypercube Sampling (LHS) to reduce the number of samplings for uncertainty calculations. The computer code for LHS [11] has been coupled with the VR code.

With these models and computational tools, we have performed a prototype uncertainty analysis for the hypothetical 100-canister repository, considering the fracture heterogeneity of host rock and canister-multiplicity effects, which has never done before due to heavy calculation load. The present prototype study is useful to identify hurdles in computational techniques and conceptual models to expand the present approach to full-scale repository performance assessment.

2. CALCULATION MODEL

2.1. VR Model

In the VR model, the repository consists of multiple compartments, each containing a waste

** FFDF™ code is the property of the University of California canister, the buffer backfilling the space between the waste canister and the disposal tunnel surface, and the near field rock. The compartments are positioned in the direction of groundwater flow. Radionuclides are first assumed to be released from the waste canister after failure, to diffuse through the buffer, and then to be released to the near field rock. From the upstream compartment, radionuclides are carried in to the near field rock of the compartment of interest, and then carried out to the downstream compartment by advection. (Fig. 1)

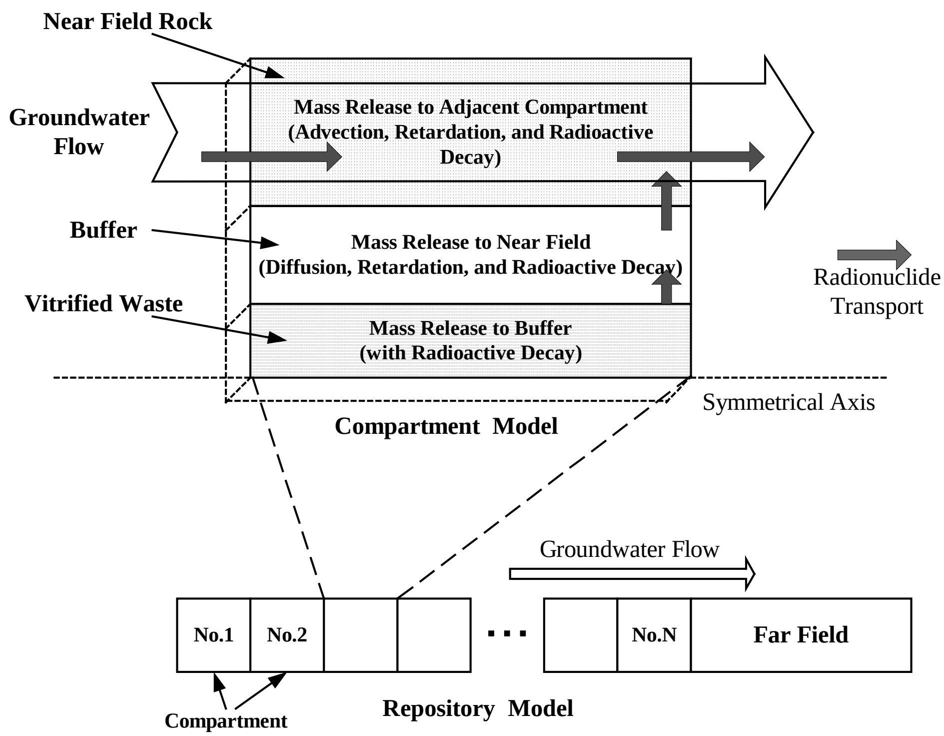

Figure 1. Compartment Model for the Repository assumed in the VR model.

2.2. FFDF Model

In the FFDF code, a two-dimensional circular model space in which a waste canister of interest is located at the center of the model space is considered. The central waste canister is surrounded by the buffer and the host rock. In the host rock, fractures are generated based on PDFs for the orientation angle, length and aperture of fracture segments. After generation of individual fracture segments, inter-connection among the generated fractures is checked, and Flow-Bearing fracture Cluster (FBC) is determined. FBC is a cluster that connects the outer boundary of the circular model space and the outer boundary of the buffer in the central waste canister.

Fracture networks generated in the model space with the total numbers of fractures of 15000 are shown in Fig. 2. Once the FBSs are identified, the canisters included in FBC can be determined.

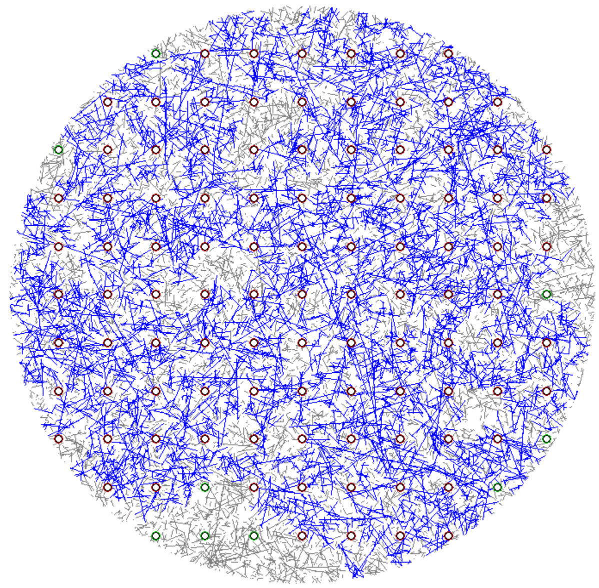

Figure 2. Flow Bearing Clusters of fractures for 15000 fractures. The blue lines indicate the FBCs, and gray lines indicate the fractures not included in the FBC. The red and the green circles indicate the canisters included and not included in the FBCs, respectively.

3. CODE OPTIMIZATION

3.1 The VR code optimization to the Earth Simulator

3.1.1 The architecture of the Earth Simulator

The Earth Simulator utilizes symmetric multiprocessor (SMP) cluster architecture, in which identical processors are connected to a single shared memory in a SMP node. The Earth Simulator is composed of 640 SMP nodes, each of which is composed of 8 vector processors and one shared memory. The peak performance of the PE (processor element) is 8 GFLOPS, so the peak performance of the Earth Simulator is 40 TFLOPS. Each SMP node has 16 GB memory and the total memory of the system is 10GB. (Fig. 3)

To exploit high calculation performance of the Earth Simulator, multi-level hybrid programming method [9] [10], a common programming method for SMP cluster machines, is applied. In this method, both coarse and fine grain parallelization of the program is achieved. The coarse grain parallelization of the program is achieved by performing domain decomposition of the whole calculation, assigning divided calculation to each SMP node, and sending messages between SMP nodes using Message Passing Interface (MPI) [12]. The fine grain parallelization is achieved by loop-level parallelization using microtask like compiler directives. Furthermore, the lowermost level parallelism for each vector processor is added to multi-level hybrid programming method.

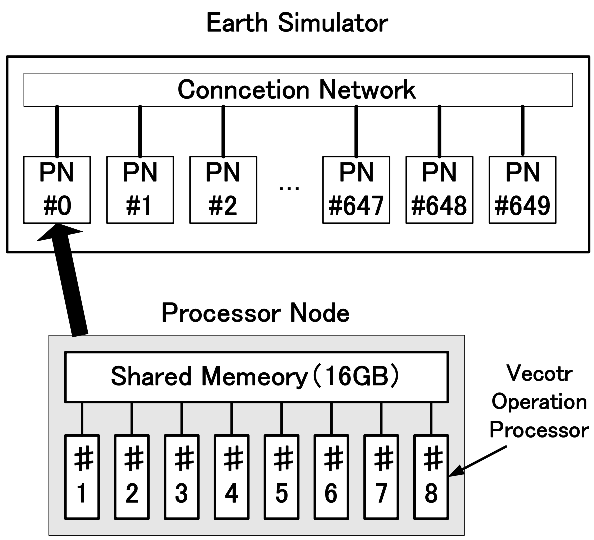

Figure 3. The Architecture of the Earth Simulator.

In this study, the following three-level parallelism is considered:

- Inter-node parallelism achieved by communication by MPI
- Intra-node parallelism achieved by compiler directive
- Processor element parallelism achieved by compiler directive.

3.1.2 The VR Code Abstract

The mass transport calculation solvers of the VR code are summarized in Table I. The code is written by C++ and fortran90 languages. The solvers are written by fortran90, and the rest of the code is written by C++.

Table I. Solvers of the VR Code.

Model	Model description	Numerical scheme
Vitrified waste	Time dependent radionuclide release model from the vitrified waste with radioactive decay (Solubility limit and congruent model)	Finite difference method Explicit method
Buffer	Time dependent one-dimension diffusion model with radioactive decay and retardation	Finite difference method Implicit method
Near field	Time dependent mixed tank model with radioactive decay and retardation	Finite difference method Explicit method
Far field	Time dependent point model with radioactive decay and retardation	Finite difference method Explicit method

3.1.3 The VR Code Optimization

The VR code has been modified to be parallelized and vetorized by three-level hybrid programming method.

(a) Parallelization of inter node calculation
The whole calculation is decomposed by assigning the same numbers of canister-wise calculations to each SMP node of the Earth Simulator. The nuclide release data between SMP nodes are communicated by using MPI.

(b) Parallelization and vectorization of intra node calculation
The mass transport calculation is composed of glass, buffer, and near field calculations. The buffer model consumes the largest computational cost in the three models. Tri-diagonal matrix inversion scheme in the buffer calculation is one of the program parts consuming large computation time. The tri-diagonal matrix inversion calculation part in the original code is executed in fourfold loop structure, which is composed of nuclide chain, nuclide member, compartment, and mesh loops. The loop structure of the part is converted to the triple loop structure in this study. (Fig. 4) The nuclide chain, nuclide member, and compartment loops are converted to two loops, corresponding with the outermost and innermost loops. The outermost loop is used by parallelization in intra SMP node, so the loop length (total numbers of iteration) is set to be 8. The innermost loop is used by vectorization of each processor. The middle loop corresponds with mesh loop, which cannot be parallelized nor vectorized due to recursive character. The loop structure of the program is converted to achieve continuous memory access and long innermost loop length.

```
do i = 1,8                  ← intra node parallelizaion loop
   do j = 1,N               ← mesh loop
       do k = 1,max(i)    ← vectorization loop
           l  = initial_no(i) + k;
           u [l][j] = r[l][j] - s[l][j] * u[l][j-1] / y[l][j-1];
        end do
    end do
end do

     N: Total numbers of meshes
```

Figure 4. Conceptual Source Program.

3.1.4 The measured performance of the code

The VR code has been optimized to the Earth Simulator, so the vectorization ratio of 96.54%, and the parallelization ratio of 99.99% with using 512 SMP nodes, the available limit of node numbers for a user, has been achieved. The measured calculation performance is about 354GFLOPS, which corresponds with about 1.1% of the peak performance of 512 SMP nodes.

3.2 The VR code optimization to SR8000

As SR8000 is a SMP cluster machine composed of 128 SMP nodes, the multi-level hybrid programming method is applied to the optimization of the VR code to SR8000. The measured calculation performance of the VR code is about 535MFLOPS for one SMP node utilization in SR8000, which is about 3.7% of the peak performance of one SMP node.

4. COMPUTATIONAL PERFORMANCE OF THE CODES

We have measured the computational performance of the FFDF code with the repository model with a radius of 20m containing 10 waste canisters. The CPU time consumption for fracture calculation part of the code is measured by varying parameters of the numbers of fractures. The measured computational performance is as follows. The total numbers of fractures in the repository dominates the CPU time for fracture calculation. The CPU time is approximately proportional to the total numbers of fractures raised to the second power. From this result, because a full-scale HLW repository would contain more than 100 million fractures, the viewpoint of the numbers of fractures, the FFDF code with the present calculation schemes and the optimization condition cannot be used for calculating the fracture interconnection judgment for the full-scale HLW repository model even with the Earth Simulator with full SMP nodes.

5. UNCERTAINTY ANALYSIS

5.1 Input parameters

Among many parameters used in the VR model, we consider uncertainty associated with two parameters only: (1) the porosity of the near field rock and (2) the number of connected canisters by FBC. We consider that among the canisters in the repository model only *n* canisters are included in FBC. The probability for the event that a row of compartments composed of *n* canisters occurs is assumed to be given by the PDF for the total number of connected canisters by fracture cluster obtained by the Monte-Carlo calculations by the FFDF code. The cumulative probability distribution function (CDF) generated from the PDF are shown in Fig.5.

In the VR code analysis, a different value for the porosity of the near field rock has been assigned for each compartment. The CDF generated from PDF for the porosity of the near field rock are shown in Fig.5.

The PDF for the peak value of the ^{237}Np fractional-release rate to the far field has been obtained as the primary output of this analysis. The fractional release rate is obtained by dividing the release rate by the total mass of the radionuclide initially included in the 100 canisters in the model space. The peak value of the ^{237}Np release rate distribution in each trial calculation is recorded and the PDF for the peak value of the ^{237}Np fractional release rate is obtained. The input parameters are summarized in Table II.

5.2 Numerical Results

5.2.1 Model 1: Single Canister Model

Uncertainty analysis has been performed for the case with a single compartment. The variation of near field rock porosity is only considered in the uncertainty analysis. The resultant CDF for the peak value of the ^{237}Np fractional release rate is shown in Fig. 6.

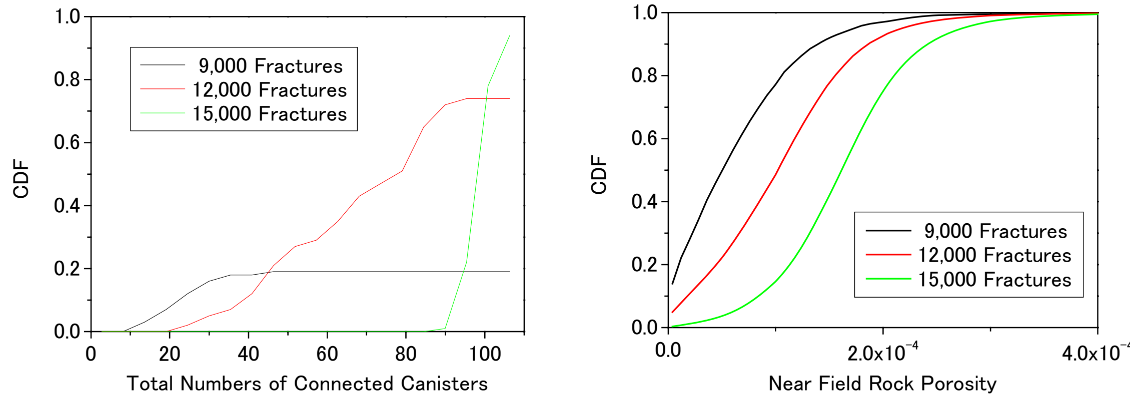

Figure 5. The CDF (left) for the number of connected canisters by FBC, and the CDF (right) for the near field rock porosity, obtained based on fracture volumes generated by FFDF with parameters shown in Table II.

TABLE II. Calculation Parameters.

Values of Fixed Parameters for the VR code

Group	Parameters	Input data	Unit
Geometry	Surface area of the waste matrix.	1.81	m^2
	Distance between waste canisters.	10	m
	Thickness of the buffer region.	0.98	m
	Volume of the buffer region in a compartment.	1.77	m^3
	Volume of the NF rock region in a compartment.	9.05	m^3
Fracture	^{237}Np decay constant.	3.23×10^{-7}	y^{-1}
	Initial mass of ^{237}Np in a single waste matrix.	4.31	mol
	The duration for the waste matrix dissolution.	10,000	y
	Diffusion coefficient in the buffer.	0.03	m^2/y
	Volumetric flow rate of groundwater through the interface between two adjacent compartments in a row.	0.905	m^3/y
	Porosity in the buffer region.	0.30	-
	Darcy velocity of groundwater.	1.0	m/y

Parameters for the FFDF code

Group	Parameters	Input data	Unit
Geometry	Radius of the near field outer boundary	60	m
	Radius of the surface of the buffer of the central waste	1	m
	Radius of the surface of the canister of the central waste	0.35	m
Fracture	Scale parameter* (β_L) of aperture	7.068E-5	m
	Shape parameter* (α_L) of aperture	0.83255	-
	Scale parameter* (β_L) of length of the primary fractures	1.0	m
	Shape parameter* (α_L) of length of the primary fractures	1.0	-

*: The shape and scale parameters are defined in the normalized lognormal function as follows, with χ as a variable:

$$f(\chi) = \frac{1}{\chi \alpha_L \sqrt{2\pi}} \exp\left[-\frac{1}{2} \left(\frac{\ln[\chi / \beta_L]}{\alpha_L} \right)^2 \right], \alpha_L > 0, \beta_L > 0, \chi > 0$$

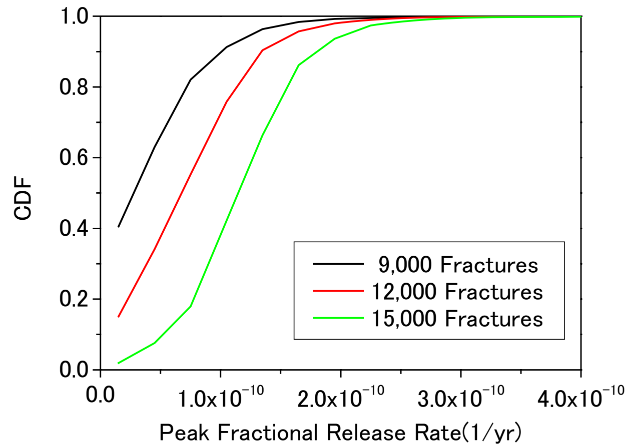

Figure 6. The CDF for peak release rate for single canister model.

5.2.2 Model 2: Scaled Single Canister Model

The result of the single compartment calculation is scaled by the PDF of total number of connected canisters by fracture cluster. The release rate to the far field has been calculated by

$$F(t) = \sum_j jP_j R_1(t) \tag{1}$$

where $F(t)$ is the release rate from the repository to the far field at time of t, P_j the probability for the number of connected canisters by a fracture cluster to be j, $R_j(t)$ the release rate from a row of j compartments at time of t obtained by the VR model. The resultant CDF for ^{237}Np peak fractional release rate is shown in Fig. 7.

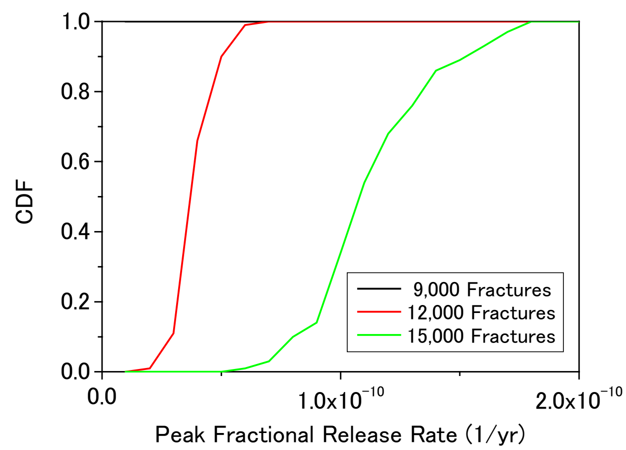

Figure 7. The CDF for peak release rate for scaled single canister model.

The physical meaning of the scaled single canister model can be explained as follows. In the model, whose total number is decided by PDF of total numbers of connected canisters by fracture cluster, there exists no interference effect between canisters. Hence the sum of mass of radionuclide release from canisters is equivalent to that from the whole repository model.

5.3. VR model

In the VR model, the repository is modeled as a one-dimensional row of multiple compartments connected linearly, whereas in the FFDF code, the repository is modeled as two-dimensional array of canisters. To utilize the PDF obtained by the FFDF analysis, we consider two extreme cases: the case with sparse fracture network and dense fracture network.

5.3.1 Model 3: VR Model with Sparse Fracture Network

In this case, we assume that there exists a sparse fracture cluster connecting the central waste and the one part of the repository boundary. (See Fig.8) The canisters are connected in a linear manner, similar to the configuration assumed in the VR model. Therefore, it is assumed that the PDF of the number of connected canisters obtained by Monte-Carlo calculations by the FFDF code can be utilized directly. The release rate to the far field has been calculated by

$$F(t) = \sum_j P_j R_j(t), \tag{2}$$

where $F(t)$ is the release rate to the far field at time of t, P_j the probability for the number of connected canisters by a fracture cluster to be j, $R_j(t)$ the release rate from a row of j compartments at time of t obtained by the VR code. The release rate is calculated by 100 realizations, and each realization is composed of 20 realizations of VR calculations. The resultant CDF for the peak value of the ^{237}Np fractional release rate is shown in Fig..9.

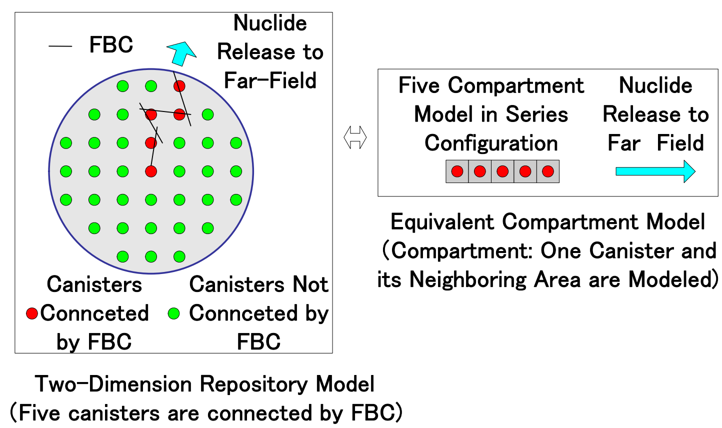

Figure 8. VR model application for sparse fracture network.

5.3.2 Model 4: VR Model with Dense Fracture Network

In this case, we assume that one large FBC covers nearly the entire model space, connecting the central waste with most of the canisters in the model space and the repository boundary. We also assume that there exist N sub-clusters within the FBC. Each sub-cluster connects the central canister and the outer boundary of the model space. (See Fig.10) If M_j canisters are included in sub-cluster j, then the release rate to the far field for this realization has been calculated by

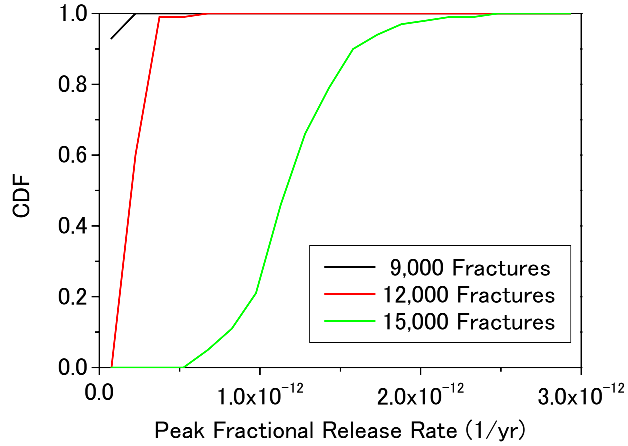

Figure 9. The CDF for peak release rate for the VR model with sparse fracture network.

$$F(t) = \sum_{j=1}^{N} R_{M_j}(t) \quad (3)$$

where $R_{Mj}(t)$ is the release rate to the far field from the j-th sub-cluster at time of t. For a certain total number, m_1, of fractures generated in the model space, we have obtained N and Mj by the following procedure:

- The total number of connected canisters by a FBC, M_s, is sampled from the PDF of total numbers of connected canisters for m_1 fractures in the model space.
- The total number M_j of connected canisters by sub-cluster j is sampled from the PDF of total number of connected canisters for m_1 fractures. Sampling for M_j is made for N times so that the summation of M_j is not less than M_s.

The resultant CDF for the peak value of the ^{237}Np fractional release rate is shown in Fig..11.

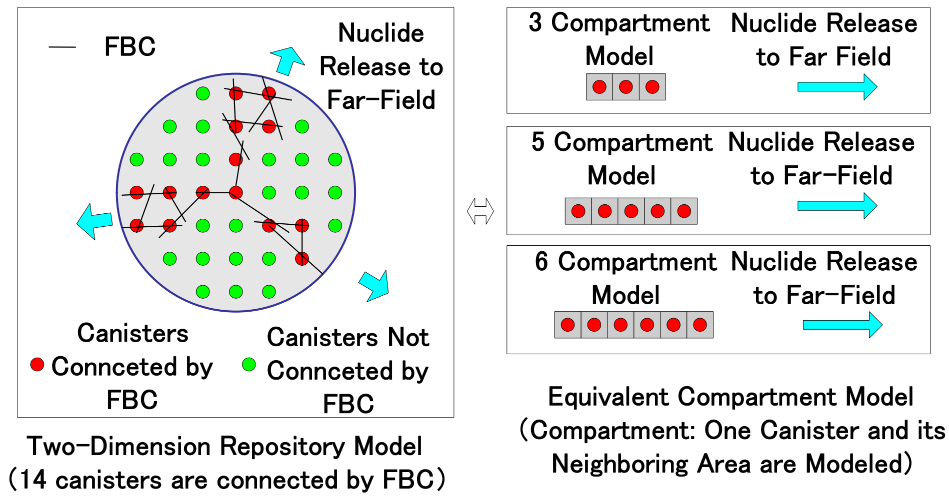

Figure 10. VR model application for dense fracture network.

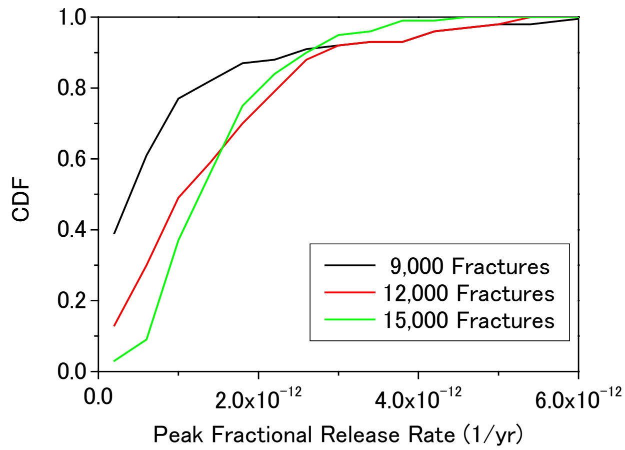

Figure 11. The CDF for release rate for the VR Model with dense fracture network.

6. DISCUSSIONS

6.1 Results of the Uncertainty Analysis

The statistical data of the present uncertainty analysis is summarized in Table III, from which we observe the followings: The model 2 (scaled single canister model) overestimates the peak release rate approximately by a factor of 10 or more. The model 1(single canister model) more overestimates the peak release rate than the model 2.

TABLE III. The statistical data of peak ^{237}Np fractional release rate

No	Model	Data*	Total numbers of fractures in the model space		
			9000	12000	15000
1	Single Canister Model	A	5.3E-11	8.6E-11	1.3E-10
		S/A	0.88	0.62	0.40
2	Scaled Single Canister Model	A	2.3E-12	3.8E-11	1.1E-10
		S/A	0.37	0.20	0.23
3	VR model for sparse fracture network	A	1.0E-13	6.3E-12	1.3E-12
		S/A	0.38	0.17	0.25
4	VR model for dense fracture network	A	1.0E-12	1.6E-12	1.6E-12
		S/A	1.27	0.78	0.51

(*A: average, S: standard deviation)

The major difference in the physical assumptions among models 1,and 2 is that the model 1 does not incorporate the PDF for connected canisters by FBC, while the model 2 do. Thus the release rate to the far field of the model 2 is about 10 times smaller than that of the model 1 for 9000 fractures due to that for 9000 fractures case, about 20 percents of the total canisters in the model space are connected by fractures. Therefore the connectivity of waste canisters by fracture cluster considering fracture heterogeneity is crucial in the safety performance of the repository. For example, because of heterogeneity resulting from fracture clusters, some canisters would be included in flow-bearing fracture clusters, while others are isolated from groundwater flow.

The major difference in the physical assumptions among models 2, 3, and 4 is that the model 2 does not incorporate the canister interference effect (concentration interference effect), while models 3 and 4 do. Due to the concentration interference effect, the release rate from the buffer to the near field rock becomes saturated in the downstream compartments. Hence the release rate of the model 2 is larger than those of the models 3 and 4. Therefore the concentration interference effect among waste canisters is important in the safety performance of the repository.

If we compare the fracture number variation on the average of peak release rate, we observe that the more fractures in the model space, the greater average value of the peak ^{237}Np fractional release rate is. This tendency is observed for all the models. This is because more fractures in the model space, more canisters are involved in the FBCs.

In Table III, the S/A values are also shown. We observe that the more fractures in the model space, the smaller S/A value for the peak release rate is. This is because with more fractures included in the model space, the near field rock approaches a homogeneous porous medium, so that the heterogeneity of the near field rock decreases.

Thus the results of the uncertainty analysis show two conflicting tendencies: the more fractures in the model space, the greater average value but the smaller S/V value of the peak ^{237}Np fractional release rate is. These conflicting tendencies are important in the safety performance assessment of HLW repository, because the increase of the number of fractures in the repository model space causes both the increase of average and the decrease of uncertainty of the Np release rate to the far field.

If we compare the S/A values of the peak release rate among models, model 4 gives the highest S/A value and model 2 gives the smallest one. This is because in model 2, only one canister exists in a repository model and the PDF for the number of connected canisters is used to multiply the release rate obtained from the one canister model. The large S/A values of the model 1 are diminished by the considering the PDF, because only a limited number of canisters are connected for low fracture numbers. In model 3, the number of connected canisters is determined directly by the PDF. In model 4, multiple rows are assumed to exist in the repository model, for each of which the number of canisters is determined by the PDF. Because we assumed that the S/A values for more realistic repository model exist between the extreme results of the model 3 and 4, more realistic uncertainty analysis with VR model is needed.

While we have considered two extreme cases of the repository model for uncertainty analysis: the repository model with (1) sparse fracture network and (2) dense fracture network, the PDF for the number of connected canisters by fracture cluster should be applied for more realistic compartment models, in which two-dimensional connection among canisters are incorporated. Thus we need to develop a two-dimension VR code, in which canisters are positioned in two-dimension array. Furthermore it is necessary to apply the groundwater velocity distribution calculated by the FFDF code considering the fracture heterogeneity to the two-dimension VR code, because the groundwater has strong effects on the Np release rate to the far field. These are future tasks.

It is necessary to compare the magnitude of uncertainty of fracture network with uncertainties resulting from other parameters such as the radionuclide solubility, and buffer retardation to apply the uncertainty calculation to the safety performance assessment of the HLW repository.

6.2 Computational performance of the FFDF code

From the estimation of the computational performance of the FFDF code, it is shown that the present FFDF code is not able to calculate the fracture calculation for the full-scale HLW repository model with more than 1.0E+6 fractures by using the Earth Simulator with full SMP nodes, while the geological survey data shows that the full-scale HLW repository contains about 1.0E+7 - 1.0E+8 fractures.

To overcome this difficulty, the more efficient optimization of the FFDF code, the development of a more efficient fracture calculation algorithm, and the improvement of the calculation model of HLW repository are needed. For example, the development of the more efficient fracture interconnection judgment algorithm and the development of the homogenization model of the canister and its surrounding materials is the promising method to improve the HLW repository calculation model to reduce the CPU time. These are future tasks.

7. CONCLUSIONS

We have successfully ported and optimized the VR code to the Earth Simulator by applying multi-level hybrid programming method, and combined with the Latin Hyper Cube sampling code for the uncertainty analysis. The multi-level hybrid programming method is composed of (1) Inter SMP node parallelization by MPI, (2) Intra SMP node parallelization by compiler directive, (3) Processor vectorization by compiler directive. To obtain the probability distribution function for the number of connected canisters, we have modified the FFDF code, where fracture network is generated statistically and connection of canisters by fracture clusters is quantitatively analyzed.

With the code, we have made statistical simulation to obtain uncertainty associated with the peak fractional release rate of ^{237}Np from the hypothetical repository consisting of 100 canisters resulting from the uncertainties associated with the number of connected canisters by fracture cluster and the porosity of the near field rock. We have reached the following observations.

1. From the estimation of the computational performance of the FFDF code, it is shown that the present FFDF code is not able to calculate the radionuclide transport calculation for the full-scale HLW repository model with detailed fracture heterogeneity taken into account even by using the Earth Simulator with full SMP nodes. To overcome this difficulty, the development of a more efficient fracture calculation algorithm, or a homogenization model of the canister and its surrounding materials for the HLW repository calculation model is needed, but this is the future task.

2. We need to develop a two-dimensional VR code, in which canisters are positioned in two-

dimensional array, to perform uncertainty analysis in more realistic repository model. Application of appropriate compartmentalization could also be a measure to overcome the difficulty in the above. Furthermore the groundwater velocity distribution calculated by the FFDF code considering the fracture heterogeneity should be applied in the two-dimension VR code. These are the future tasks.

3. We observed the two opposite tendencies from the present uncertainty analysis. The more fractures in the model space are included, the greater average value but the smaller uncertainty of the peak ^{237}Np fractional release rate is. For safety performance assessment of HLW repository, the increase of the average value of the peak release rate indicates an adverse effect for highly fractured host rock, while the decrease of the uncertainty is favorable.

4. From the uncertainty analysis, we observed that the mass transport in facture network medium is greatly affected by (1) the magnitude of the radionuclide source in the repository determined by the number of connected canisters by the fracture cluster considering fracture heterogeneity, and (2) the canister concentration effect in the same fracture cluster. These phenomena should be incorporated in the safety performance assessment of HLW repository.

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