THREE DIMENSIONAL KINETICS CODE RANCER AND ANALYSIS OF NEACRP ROD EJECTION BENCHMARKS.

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ABSTRACT

A three-dimensional (3D) nodal kinetics code RANCER* has been developed. This code is an extension of the steady state three-dimensional diffusion code ANC (1). RANCER code adopted the theta-weighted for time integration method which treats the kinetics equation exactly. In order to verify the adequacy of this code, we have performed several benchmark problems, including the TWIGLE(2), the LMW(3) and the SPERT-III(4). In this paper, we calculated the rod ejection benchmark problem of NEACRP. This benchmark has been widely used as the standard benchmark for PWR transient code. However, Reactivity Initiated Accident (RIA) benchmark problems at hot zero power (HZP) have high sensitivity of the inserted reactivity. In order to reduce uncertainty and compare with other kinetics codes, we calculated the sensitivity in each benchmarks. And we also confirm the adequacy of the code in this paper.

* RANCER: **R**evised **ANC** for **E**valuations of t**R**ansients

1. INTRODUCTION

For the analysis of Reactivity Initiated Accident (RIA), 3D calculations play very important role to achieve higher accuracy. However, 3D analysis needs exorbitant calculational time. Therefore, the 3D nodal kinetics code RANCER based on the nodal expansion method (NEM) has been developed to reduce the calculational time while maintaining the calculational accuracy. This nodal kinetics code employs the same neutronic methodology as the 3D nodal diffusion code ANC. RANCER and ANC use the same calculational databank and RANCER starts transient calculation from ANC static calculation. RANCER adopts the theta-weighted method, which has been adopted in the currently licensed code TWINKLE (5), for time integration and this method can treat the kinetics equations exactly. RANCER can calculate the enthalpy of each fuel rod with the pin power reconstruction method under transient conditions. RANCER treats two neutron energy groups and six delayed precursor families.

MIDAC (6) is the 3D drift flux thermal hydraulic code. MIDAC code calculates distribution of moderator density and fuel temperature by solving 3D mass, energy and momentum equations and thermal conduction model of fuel rods. RANCER can be coupled to MIDAC. RANCER-MIDAC accurately calculates transient problems under voided conditions. In this paper, we calculate NEACRP benchmark problems by RANCER because RANCER and RANCER-MIDAC give almost the same results under such fast transient as RIA where no void is generated.

This paper describes the RANCER code and calculational results of NEACRP rod ejection benchmarks (7) (8).

2. Outline of RANCER

2.1 KINETIC MODEL OF RANCER

It is important to determine the time integration method for developing a kinetic engine. The theta-weighted method, which has been adopted in the currently licensed code TWINKLE, has been adopted as the first approach.

The time dependent diffusion equations are:

$$\frac{1}{v_1}\frac{d\Phi_1}{dt}+\left(-D_1\nabla^2+\Sigma_{a1}+\Sigma_r\right)\Phi_1=(1-\beta)\left(\nu\Sigma_{f1}\Phi_1+\nu\Sigma_{f2}\Phi_2\right)+\sum_{i=1}^{6}\lambda_i C_i \qquad (1)$$

$$\frac{1}{v_2}\frac{d\Phi_2}{dt}+\left(-D_2\nabla^2+\Sigma_{a2}\right)\Phi_2=\Sigma_r\Phi_1 \qquad (2)$$

for precursors:

$$\frac{dC_i}{dt}=\beta_i\left(\nu\Sigma_{f1}\Phi_1+\nu\Sigma_{f2}\Phi_2\right)-\lambda_i C_i \qquad (3)$$

where

V_i : Neutron speed in energy group i (i=1,2)

Φ_i : Neutron flux in energy group i (i=1,2)

D_i : Diffusion coefficient in energy group i (i=1,2)

Σ_{ai} : Absorber cross section in energy group i (i=1,2)

Σ_r : Removal cross section in energy group i (i=1,2)

$\nu\Sigma_{fi}$: Production cross section in energy group i (i=1,2)

C_i : Concentration of precursor group i (i=1,6)

β_i, λ_i : Delayed neutron fraction and decay constant of precursor group i (i=1,6)

By defining the two-group fluxes as:

$$\Phi_g(t=t)=(1-\theta)\Phi_g(t=t_0)+\theta\Phi_g(t=t_0+\Delta t) \qquad (g=1,2)\ (4)$$

according to the above equations and treatment of the source term which includes the time dependent term and precursor term, a steady state diffusion equation is obtained as follows.

$$-D_g\nabla^2\Phi_g(u)+\Sigma_{a0_g}\overline{\Phi}_g(u)=Q_g(u)-L_{u_g}(u) \qquad (g=1,2)\ (5)$$

Where $Q_g(u)$: Source term $L_g(u)$: Traverse leakage term u : Direction (x,y,z)

Thus, the flux is calculated with the equation of the Nodal Expansion Method (NEM) in ANC.

The Doppler model, i.e. fuel temperature calculation for neutronic feedback, is important for this kind of transient code. In the developed code, a typical fuel rod is assumed for each node. The fuel rod is divided into multi-radial regions (of equi-volume) and a heat conduction model is used to solve the temperature distribution in a pellet. Teff and Doppler models are shown as follows.

$$T_{eff} = T_{\mathrm{mod}} + W_C \left[W_P \overline{T}_{fuel} + (1 - W_P) T_{fuel}^{surf} - T_{\mathrm{mod}} \right] \quad , \tag{6}$$

where	T_{mod}	Local moderator temperature
	T_{fuel}	Local fuel temperature
	W_C	Doppler weighting factor
	W_P	Pellet weighting factor

$$\Sigma_{a1} = \Sigma_{a1}^{\;ref} + b \left(\sqrt{T_{eff}} - \sqrt{T_{eff}^{\;ref}} \right) \quad , \tag{7}$$

where	b	Fitting parameter.

3. PWR rod ejection benchmark

3.1 OUTLINE OF BENCHMARK AND A CALCULATIONAL MODEL OF RANCER

NEACRP PWR rod ejection problems at HZP and hot full power (HFP) were calculated by RANCER and obtained results were compared with the published reference and the revised reference solution(8)(9). This benchmark core is derived from the actual reactor geometry. The transients are initiated by a rapid ejection of control rod (CR) at HZP or HFP condition. Calculational geometries and conditions of six cases are described as follows:

A1: Octant core geometry and Ejection of the central CR at HZP
A2: Octant core geometry and Ejection of the central CR at HFP
B1: Octant core geometry and Ejection of the peripheral CR at HZP
B2: Octant core geometry and Ejection of the peripheral CR at HFP
C1: Full core geometry and Ejection of one peripheral CR at HZP
C2: Full core geometry and Ejection of one peripheral CR at HFP

The normal power of the reactor is 2775MW. There are 157 fuel assemblies and 64 reflector elements, each of width 21.606cm. The detailed condition of six benchmark problems is described in the NEACRP specification (7). A calculational model of RANCER consists of 36 vertical meshes and each assembly is divided by 2x2 node, a time step is 0.001sec and steam table is the same as the Westinghouse model(10).

3.2 THERMAL HYDRAULICS MODEL IN THIS BENCHMARK

The feedback model of RANCER for transient calculations was modified to meet the specification of benchmarks (7). The benchmark specifications make obligatory assumptions on the thermal hydraulic (T/H) model. These assumptions are that gap conductance is constant, rod expansion and cross flow effects are not considered and power distribution in the fuel rod is flat.

RANCER had to be modified to treat these assumptions with new inputs. The main assumptions of the T/H model are as follows:

I. DOPPLER TEMPERATURE

The Doppler temperature T_D is found from the fuel temperature at the fuel rod center $T_{F,C}$ and on the fuel rod surface $T_{F,S}$ via the relation

$$T_D = (1-\alpha)T_{F,C} + \alpha T_{F,S} \tag{8}$$

where α is set to 0.7.

II. THERMO PHYSICAL PROPERTIES

The NEACRP benchmark imposes the participants to use the following reference relations for the heat conductivity λ (W/m K), specific heat capacity Cp(J/KgK) of fuel and cladding and the conductance of the gap between fuel and cladding (K_{gap})

$$\lambda_{UO2} = 1.05 + 2150/(T - 73.15) \tag{9}$$

$$\lambda_{Zirkaloy-4} = 7.51 + 2.09\times10^{-2}T - 1.45\times10^{-5}T^2 + 7.67\times10^{-9}T^3 \tag{10}$$

$$C_{p,UO2} = 162.3 + 0.3038T - 2.391\times10^{-4}T^2 + 6.404\times10^{-8}T^3 \tag{11}$$

$$C_{p,Zirkaloy-4} = 252.54 + 0.11474T \tag{12}$$

$$K_{gap} = 10^4 \qquad (W/m^2K) \tag{13}$$

Where T is the temperature (K)

Expansion effects of fuel and cladding are not considered in this benchmark.

3.3 STEADY-STATE RESULTS

Table.1 shows steady-state results of case A1, B1 and C1 defined at HZP and case A2, B2 and C2 defined at HFP. References are the published reference at 1991 and the revised reference at 1997 which are calculated using in PANTHER. Results of critical boron concentration and control rod worth (CR-worth) using in RANCER on each benchmark case are in good agreement with the reference solution. Therefore, feedback models and control rod models for the NEACRP benchmark are correctly treated in RANCER.

3.4 TRANSIENT RESULTS

The summary of transient results and a comparison with the PANTHER reference solution is given in Table.2. Results of peak time and peak power in respective cases are in good agreement with the reference. In HZP and HFP benchmarks, RANCER accurately predicts the maximum fuel temperature, the Doppler fuel temperature and the coolant outlet temperature. On the other hand, the peak time and the peak power have sensitivity on the inserted reactivity.

The benchmark problem of case C1, where a peripheral control rod is ejected at HZP, is a very severe calculation,. Comparison between RANCER and PANTHER (9) for case C1 is shown in Fig.1. The error of peak power is 2.5% and the difference of peak time is 0.009sec. If the CR-worth of RANCER is changed from 951.8pcm to 949.1pcm, the peak power is changed from 4.30 to 4.22 and the peak time is changed from 0.262sec to 0.264sec. The sensitivity of reactivity in this benchmark is very large as pointed out by Chao and Sung (10). We also confirmed this tendency by using RANCER. Case A1 and Case B1 also have the same tendency.

Figure.2 shows the power distribution of RANCER at time 0sec and the error distribution between RANCER and PANTHER. Figure.3 shows the power distribution of RANCER at the peak time and the error distribution between RANCER and PANTHER. Both power distributions are normalized so that the peak value at axial layer number 13 is equal to 1. Power distributions of RANCER are in good agreement with the reference.

Figure.4 shows the maximum fuel centerline temperature versus time of HZP cases. Figure.5 shows the Doppler fuel temperature versus time of HZP cases. The maximum fuel centerline temperature and the Doppler fuel temperature at 5 sec are less sensitive than the behavior of peak power. The behavior of these fuel temperatures obtained with RANCER is almost the same as those with other codes.

3.5 THE SENSITIVITY STUDIES OF BENCHMARKS.

In these benchmarks, cross sections and a feedback model of CR are described. But the reactivity worth of an ejected rod has uncertainty due to each calculational code. On the other hand, the inserted reactivity has a large sensitivity under RIA condition. This reactivity also depends on the vertical mesh size. In order to reduce uncertainty and compare with other kinetics codes, sensitivity of the CR worth and the vertical mesh effect should be considered in each HZP benchmark.

3.5.1 THE SENSITIVITY OF THE VERTICAL MESH EFFECT

The fuel region of the reactor is divided by 10 layers and the vertical mesh size is 30cm/mesh. In 1997, M.P.Knight re-calculated reference the solution and recommended that the vertical mesh size of the fuel region was 15cm/mesh. However, this mesh size was decided by the static survey calculation of CR worth and boron concentration. Therefore, sensitivity of vertical mesh is surveyed with RANCER. In this survey, the inserted reactivity is constant and the mesh widths are changed as follows:

30cm/mesh, 25cm/meah, 20cm/mesh, 15cm/mesh, 12cm/mesh, 10cm/meah

Figure.6 shows the results of the survey calculations. In Figure.4, x-axis is the axial mesh size and y-axis is the ratio of maximum peak power in each survey calculation. A vertical mesh size less than 15cm/mesh has low impact of mesh size effect and low sensitivity.

In the transient calculation, vertical mesh size is proposed to be less than 15cm/mesh.

3.5.2 THE SENSITIVITY OF THE INSERTED REACTIVITY

We performed the survey calculation of the inserted reactivity. The perturbation of the inserted reactivity is set at +/–10pcm and +/-5pcm. Figure.7 shows the ratio of the inserted reactivity versus the ratio of the maximum peak power. The inserted reactivity of CASE A1 and CASE B1 are almost the same and CASE A1 and B1 have the same tendency in sensitivity. When the inserted reactivity is increased by 10 pcm, the 20% error in the maximum peak power appears. In CASE C1, the inserted reactivity is about 950pcm. When the inserted reactivity is increased by 10 pcm, the 10% error in the maximum peak power appears. In each case, we confirm that the sensitivity of reactivity is large.

3.6 RESULTS OF RE-CALCULATION

We re-calculated the benchmark problem with the reference reactivity. Table.3 shows the results of re-calculations. The Doppler temperature, the maximum fuel temperature and the outlet coolant temperature at 5sec have little sensitivity in this benchmark. In HFP benchmark problems, it is obvious that each benchmark has less sensitivity of CR-worth because the inserted reactivity is about 90pcm (0.12$) and each HFP benchmark is not RIA condition

The calculational results of RANCER are in good agreement in each calculation.

CONCLUSIONS

1. We developed a 3D kinetics code RANCER for use in the calculation of RIA analysis. It has been confirmed that RANCER can reproduce almost the same results as the reference solution.

2. We confirmed that the sensitivity of reactivity on the NEACRP benchmark is very large. In HZP benchmarks, we propose the calculational conditions as follows:

    I. The vertical mesh size in the fuel region is less than 15cm/mesh.
    II. The inserted reactivity is set at the new reference reactivity calculated with PANTHER. The recommended reactivity of each case are written as follows:

CASE A1	824.2pcm
CASE B1	826.1pcm
CASE C1	949.1pcm

The developed code RANCER can be useful for other PWR transients and this code will be applied to core design and safety analysis of cores with high burnup fuel in the future.

REFERENCES

1. Y. S. Liu, et. al., ”ANC – A Westinghouse Advanced Nodal Computer Code”, WCAP-10966-P-A (Nonproprietary), (December 1985)
2. L.A. Hageman and J.B. Yasinsky, ”Comparison of alternating direction time differencing method and other implicit method for the solution of the neutron group diffusion equations”, Nucl. Sci. Eng. 38,8, (1969),
3. S. Langenbuch, et.al., , ”Coarse mesh flux expansion method for the analysis of space time effects in large light water reactor cores”, Nucl.Sci.Eng.63, (1977)
4. R.K. McCardell et al.,, ”Reactivity accident test results and analysis for the SPERT-III E-Core a small oxide fueled pressurized water reactor,” IDO-17281, (1969).
5. .F.Barry, ”TWINKLE A multi dimensional neutron kinetics computer code description and user’s manual”,WCAP-12761-P
6. Yoshiei Akiyama et al., ”Void fraction measurement of PWR fuel assembly and improvement of PWR core analysis method”, the 3rd international seminar on subchannel analysis, Stockholm,(1995)
7. H.Finnemann, A.Galati,”NEACRP 3-D LWR core transient benchmark. Final specifications”, NEACRP-L-335(Revision1),(January 1992)
8. H.Finnemann, H.Bauer, A.Galati and R.Martinelli, ”Results of LWR core transient benchmarks”, NEA/NSC/DOC(93)25,(Octorber 1993.)
9. M.P. Knight and P. Bryce, “ Derivation of a refined PANTHER solution to the NEACRP PWR rod-ejection transients”, Proc. Of the joint Int. Conf. On Mathematical Methods and Supercomputing for Nuclear Applications, Saratoga Springs, N.Y., American Nuclear Society, **vol.1** pg302-313. (October, 5-9,1997)
10. Y. A. Chao,Y.X Sung, ”The Coupled ANC-K/VIPER three-dimensional kinetic PWR core analysis system”,Proc. Of the Int. Conf. On the physics of Nuclear Science and Technology, October 5-8,1998,Long Island, New York, American Nuclear Society, **vol.1**pg365-371, (1998)

Table.1 NEACRP PWR rod ejection benchmark of statics condition
comparison between reference values and calculational results of RANCER

Case	A1	A2	B1	B2	C1	C2
Core condition	HZP	HFP	HZP	HFP	HZP	HFP
Boron (ppm)						
Published reference	567.7	1160.6	1254.6	1189.4	1135.3	1160.6
Reviced reference	561.2	1156.6	1248.0	1183.8	1128.3	1156.6
RANCER	567.9	1161.3	1253.4	1188.7	1132.8	1161.4
CR-WORTH (pcm)						
Published reference	821.8	89.5	831.0	99.1	958.0	78.1
Reviced reference	824.3	91.6	826.2	99.5	949.1	79.2
RANCER	827.1	92.8	827.2	99.1	951.8	81.3

Table.2 NEACRP PWR rod ejection benchmark of transient condition
comparison between reference values and calculational results of RANCER

Case	A1	A2	B1	B2	C1	C2
Core condition	HZP	HFP	HZP	HFP	HZP	HFP
Time to the power preak (sec)						
Published reference	0.560	0.100	0.517	0.120	0.268	0.100
Reviced reference	0.538	0.095	0.523	0.100	0.271	0.095
RANCER	0.510	0.095	0.496	0.095	0.262	0.095
Power at preak						
Published reference	1.18	1.080	2.44	1.063	4.77	1.071
Reviced reference	1.27	1.083	2.32	1.064	4.41	1.073
RANCER	1.33	1.083	2.36	1.065	4.30	1.076
Power at 5sec						
Published reference	0.196	1.035	0.320	1.038	0.146	1.030
Reviced reference	0.197	1.036	0.320	1.039	0.146	1.031
RANCER	0.194	1.035	0.324	1.039	0.144	1.033
Average Doppler temperature at 5sec (degree)						
Published reference	324.3	554.6	349.9	552.0	315.9	553.5
Reviced reference	324.9	555.2	350.0	552.4	315.9	553.9
RANCER	325.8	562.3	352.5	559.7	316.4	561.3
Max fuel temperature at 5sec (degree)						
Published reference	673.3	1691.8	559.8	1588.1	676.1	1733.5
Reviced reference	679.3	1679.6	559.7	1576.1	674.2	1723.8
RANCER	676.6	1691.9	565.0	1568.1	687.0	1729.1
Coolant outletl temperature at 5sec (degree)						
Published reference	293.1	324.6	297.6	324.7	291.5	324.5
Reviced reference	293.2	324.9	297.7	325.0	291.5	324.8
RANCER	292.8	324.5	296.8	324.5	291.3	324.4

Table.3 NEACRP PWR rod ejection benchmark of transient condition
comparison between reference values and re-calculational results of RANCER

Case Core condition	A1 HZP	A2 HFP	B1 HZP	B2 HFP	C1 HZP	C2 HFP
Time to the power preak (sec)						
Reviced reference	0.538	0.095	0.523	0.100	0.271	0.095
RANCER(adjusted CR worth)	0.515	0.095	0.499	0.095	0.264	0.095
Power at preak						
Reviced reference	1.27	1.083	2.32	1.064	4.41	1.073
RANCER(adjusted CR worth)	1.26	1.083	2.32	1.065	4.22	1.076

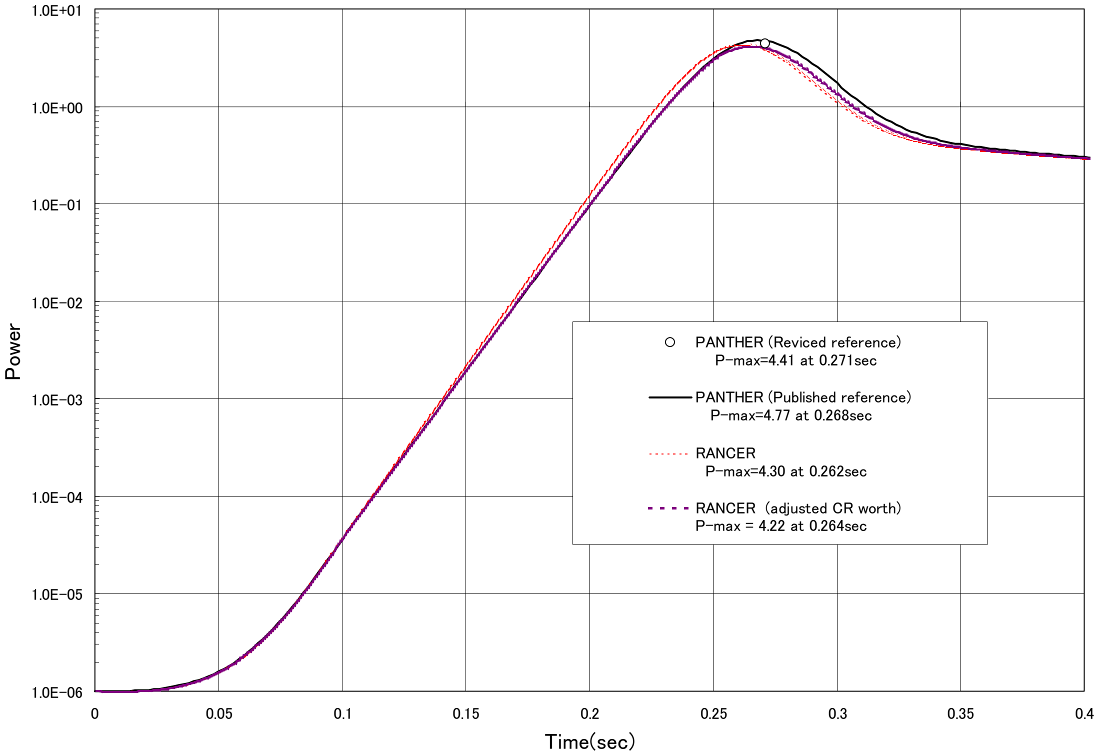

Fig.1 Comparison between reference and calculational results of RANCER
(CASE C1)

						0.46	0.52	0.46						
				0.60	0.89	0.80	0.44	0.80	0.89	0.60				
			0.45	0.82	0.94	1.00	0.96	1.00	0.94	0.82	0.45			
		0.45	0.34	0.74	0.95	0.98	1.00	0.98	0.95	0.74	0.34	0.45		
	0.60	0.82	0.74	0.79	0.74	0.76	0.68	0.76	0.74	0.79	0.74	0.82	0.60	
	0.89	0.94	0.95	0.74	0.34	0.45	0.27	0.45	0.34	0.74	0.95	0.94	0.89	
0.46	0.80	1.00	0.98	0.76	0.45	0.37	0.29	0.37	0.45	0.76	0.98	1.00	0.80	0.46
0.52	0.44	0.96	1.00	0.68	0.27	0.29	0.17	0.29	0.27	0.68	1.00	0.96	0.44	0.52
0.46	0.80	1.00	0.98	0.76	0.45	0.37	0.29	0.37	0.45	0.76	0.98	1.00	0.80	0.46
	0.89	0.94	0.95	0.74	0.34	0.45	0.27	0.45	0.34	0.74	0.95	0.94	0.89	
	0.60	0.82	0.74	0.79	0.74	0.76	0.68	0.76	0.74	0.79	0.74	0.82	0.60	
		0.45	0.34	0.74	0.95	0.98	1.00	0.98	0.95	0.74	0.34	0.45		
			0.45	0.82	0.94	1.00	0.96	1.00	0.94	0.82	0.45			
				0.60	0.89	0.80	0.44	0.80	0.89	0.60				
						0.46	0.52	0.46						

Power distribution of RANCER

						-0.2	-0.2	-0.2						
				-0.3	-0.2	-0.1	-0.1	-0.1	-0.2	-0.3				
			-0.2	-0.1	0.0	0.0	0.1	0.0	0.0	-0.1	-0.2			
		-0.2	-0.2	0.0	0.1	0.2	0.2	0.2	0.1	0.0	-0.2	-0.2		
	-0.3	-0.1	0.0	0.2	0.1	0.3	0.2	0.3	0.1	0.2	0.0	-0.1	-0.3	
	-0.2	0.0	0.1	0.1	0.5	0.3	0.7	0.3	0.5	0.1	0.1	0.0	-0.2	
-0.2	-0.1	0.0	0.2	0.3	0.3	0.5	0.5	0.5	0.3	0.3	0.2	0.0	-0.1	-0.2
-0.2	-0.1	0.1	0.2	0.2	0.7	0.5	0.7	0.5	0.7	0.2	0.2	0.1	-0.1	-0.2
-0.2	-0.1	0.0	0.2	0.3	0.3	0.5	0.5	0.5	0.3	0.3	0.2	0.0	-0.1	-0.2
	-0.2	0.0	0.1	0.1	0.5	0.3	0.7	0.3	0.5	0.1	0.1	0.0	-0.2	
	-0.3	-0.1	0.0	0.2	0.1	0.3	0.2	0.3	0.1	0.2	0.0	-0.1	-0.3	
		-0.2	-0.2	0.0	0.1	0.2	0.2	0.2	0.1	0.0	-0.2	-0.2		
			-0.2	-0.1	0.0	0.0	0.1	0.0	0.0	-0.1	-0.2			
				-0.3	-0.2	-0.1	-0.1	-0.1	-0.2	-0.3				
						-0.2	-0.2	-0.2						

ERROR(%)
(RANCER-PANTHER)/PANTHERx100

Fig.2 Power distribution of RANCER at 0sec and
error distribution between RANCER and PANTHER (CASE C1)

						0.06	0.07	0.07						
				0.06	0.10	0.10	0.06	0.14	0.17	0.13				
			0.04	0.08	0.10	0.12	0.14	0.18	0.20	0.20	0.13			
		0.03	0.03	0.07	0.10	0.12	0.16	0.19	0.23	0.23	0.14	0.25		
	0.03	0.05	0.05	0.06	0.08	0.10	0.11	0.17	0.22	0.32	0.39	0.53	0.43	
	0.05	0.05	0.06	0.05	0.03	0.06	0.05	0.12	0.13	0.38	0.60	0.70	0.76	
0.02	0.04	0.05	0.06	0.05	0.04	0.05	0.06	0.12	0.21	0.45	0.70	0.90	0.94	0.62
0.03	0.02	0.05	0.06	0.04	0.02	0.04	0.04	0.10	0.14	0.43	0.76	0.99	1.00	0.84
0.02	0.04	0.05	0.06	0.05	0.04	0.05	0.06	0.12	0.21	0.45	0.70	0.90	0.94	0.62
	0.05	0.05	0.06	0.05	0.03	0.06	0.05	0.12	0.13	0.38	0.60	0.70	0.76	
	0.03	0.05	0.05	0.06	0.08	0.10	0.11	0.17	0.22	0.32	0.39	0.53	0.43	
		0.03	0.03	0.07	0.10	0.12	0.16	0.19	0.23	0.23	0.14	0.25		
			0.04	0.08	0.10	0.12	0.14	0.18	0.20	0.20	0.13			
				0.06	0.10	0.10	0.06	0.14	0.17	0.13				
						0.06	0.07	0.07						

Power distribution of RANCER

						2.2	1.2	0.6						
				4.1	2.6	2.5	2.0	1.4	0.7	0.5				
			2.9	3.3	3.6	3.5	3.2	2.1	1.2	-0.3	-1.6			
		3.6	3.6	4.5	4.7	4.0	3.2	2.5	1.6	0.8	-1.2	-1.0		
	6.1	4.9	5.7	5.3	4.5	4.3	3.4	2.5	1.7	1.1	0.6	-0.8	0.7	
	5.7	6.0	6.2	6.2	5.2	4.3	3.0	1.9	1.2	1.3	0.6	0.0	-0.1	
5.5	6.2	6.7	6.9	6.4	5.6	4.5	2.8	2.9	1.7	1.1	1.0	0.7	-0.8	-0.7
4.9	6.4	7.3	6.8	7.0	5.2	4.0	2.7	2.0	1.3	1.5	0.7	1.1	0.0	-0.7
5.5	6.2	6.7	6.9	6.4	5.6	4.5	2.8	2.9	1.7	1.1	1.0	0.7	-0.8	-0.7
	5.7	6.0	6.2	6.2	5.2	4.3	3.0	1.9	1.2	1.3	0.6	0.0	-0.1	
	6.1	4.9	5.7	5.3	4.5	4.3	3.4	2.5	1.7	1.1	0.6	-0.8	0.7	
		3.6	3.6	4.5	4.7	4.0	3.2	2.5	1.6	0.8	-1.2	-1.0		
			2.9	3.3	3.6	3.5	3.2	2.1	1.2	-0.3	-1.6			
				4.1	2.6	2.5	2.0	1.4	0.7	0.5				
						2.2	1.2	0.6						

ERROR(%)
(RANCER-PANTHER)/PANTHERx100

Fig.3 Power distribution of RANCER at peak time
error distribution between RANCER and PANTHER (CASE C1)

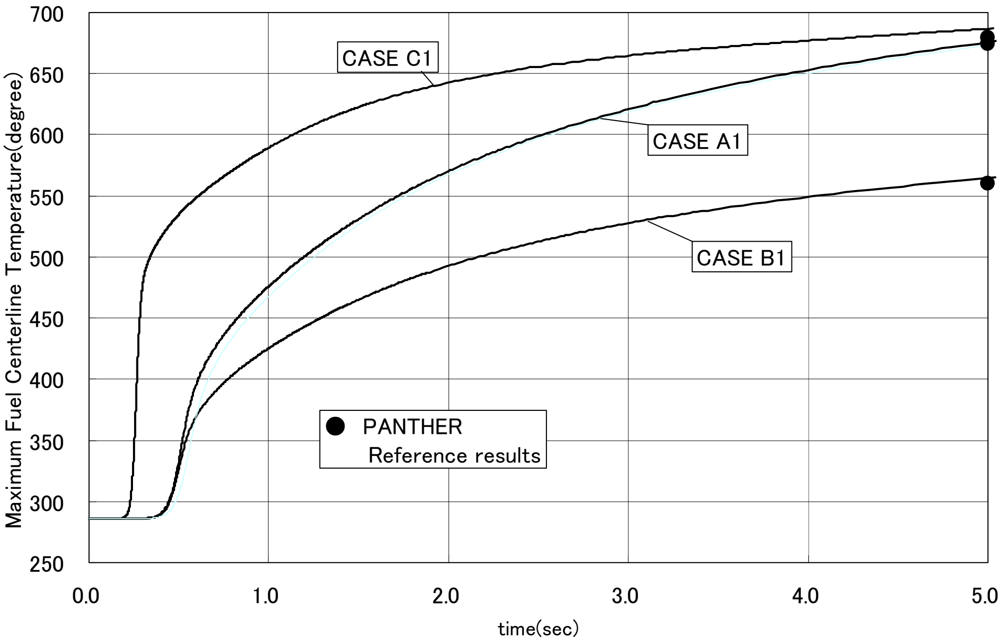

Fig.4 The maximum fuel temperature versus time

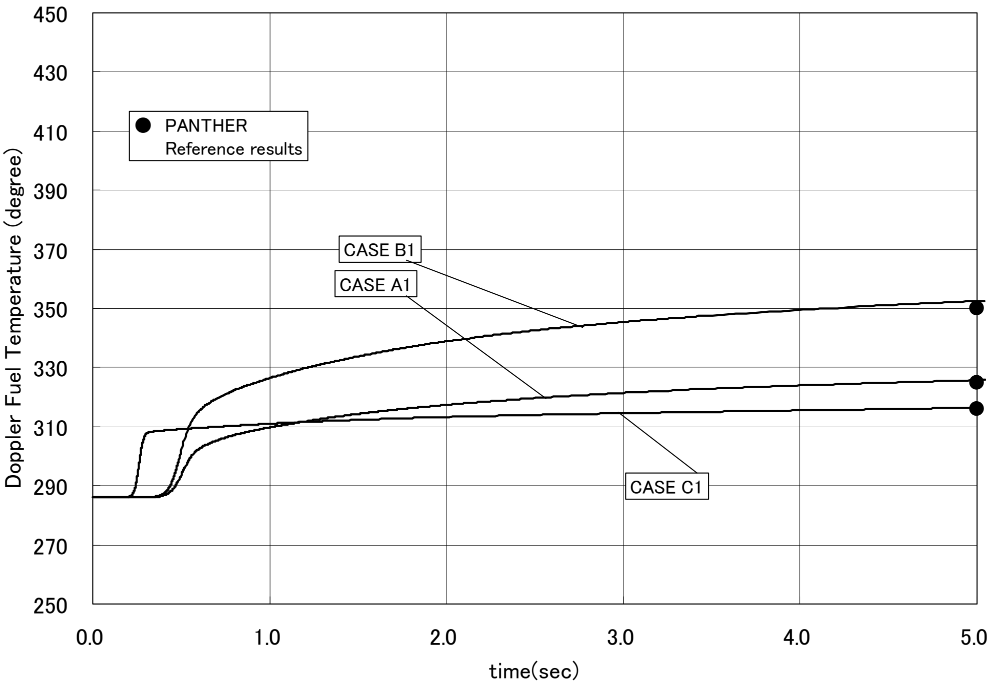

Fig.5 The Doppler fuel temperature versus time

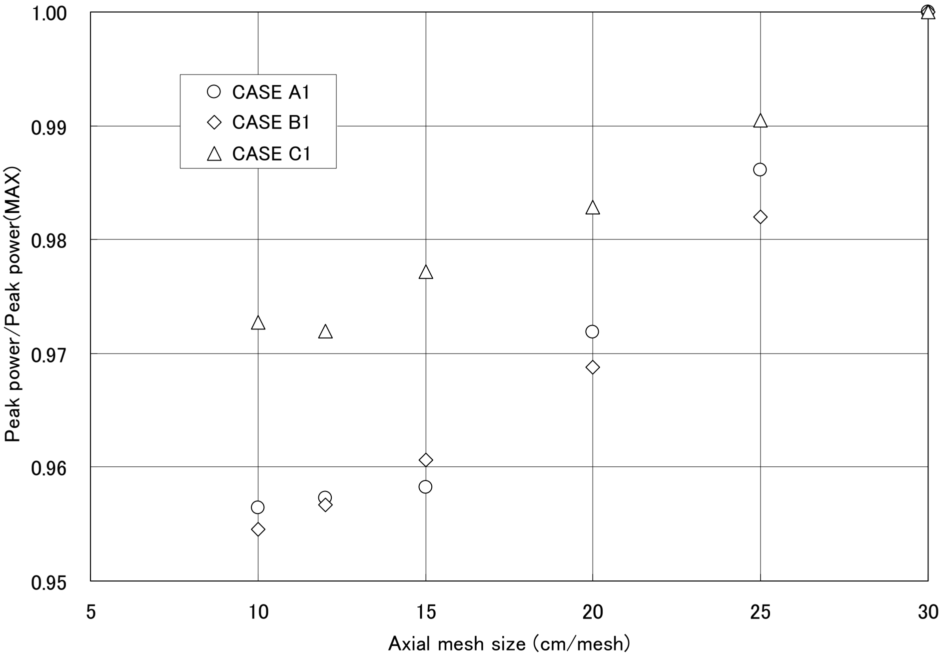

Fig.6 The sensitivity of axial mesh size

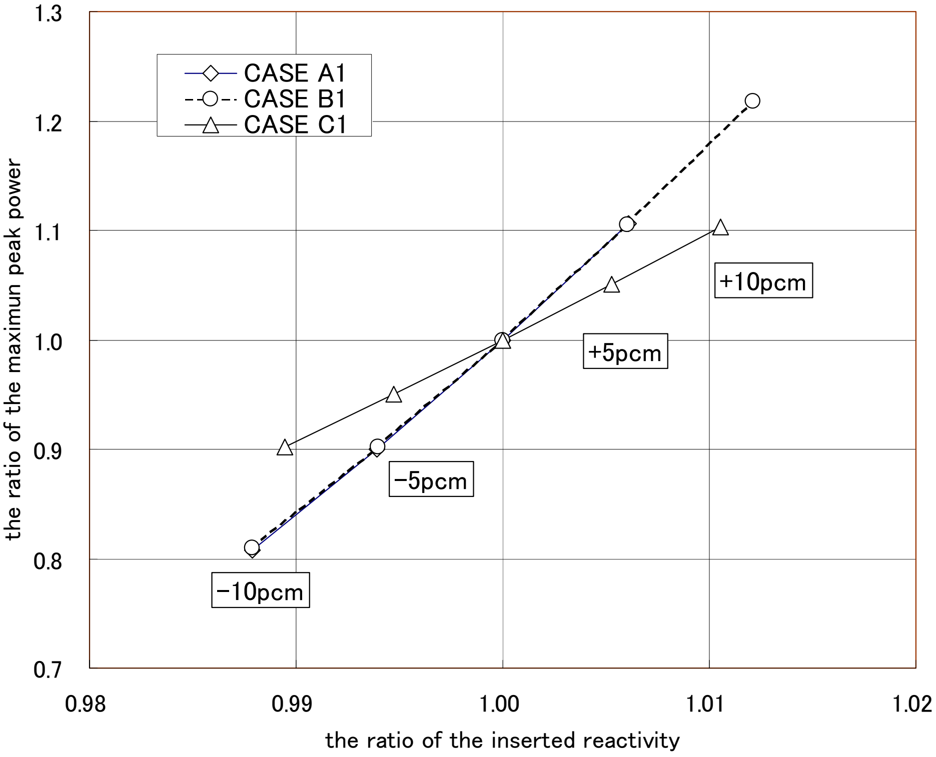

Fig.7 The sensitivity of the inserted reactivity