NUCLEAR CHARACTERISTICS EVALUATION FOR A SUPERCRITICAL EXPERIMENT FACILITY USING LOW-ENRICHED URANIUM SOLUTION FUEL, TRACY

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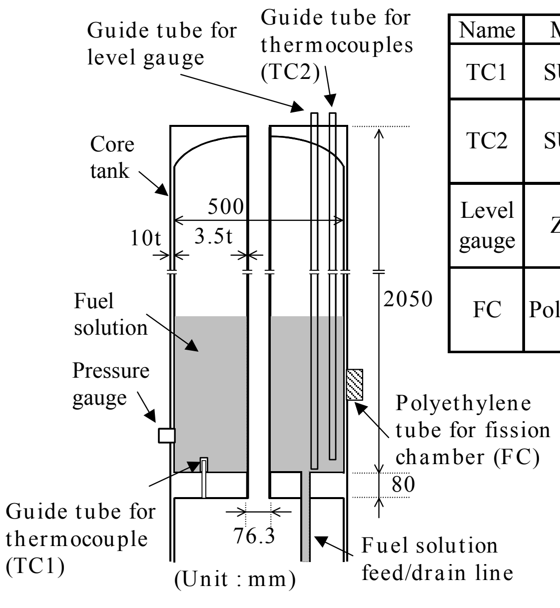
ABSTRACT

The nuclear characteristics of TRACY, such as the criticality, the β_{eff}/Λ ratio, the peak power, the energy of pulse, and the total energy, have been evaluated using the experimental data. TRACY is a supercritical reactor fueled with low-enriched uranyl nitrate aqueous solution to simulate criticality accidents in a fuel processing facility, such as a spent-fuel reprocessing plant.

In this evaluation, the availability of criticality calculation and the models to evaluate the power and energy have been studied.

1. INTRODUCTION

TRACY is a supercritical reactor fueled with about 10wt% enriched uranyl nitrate aqueous solution to simulate criticality accidents in a fuel processing facility, such as a spent-fuel reprocessing plant[1-3]. The core tank of TRACY with peripheral instruments is illustrated in Figure 1. The core tank is a 50 cm diameter cylinder made of stainless steel with a central hole (about 8cm diameter) for positioning a transient rod. The transient rod is made of B_4C, and it is driven either by a pneumatic system or by an electric motor. The excess reactivity up to 3$ is inserted by continuous feed of fuel solution or by withdrawing the transient rod to conduct the supercritical experiments. The integral power in an experiment is limited to 32MJ, which corresponds to 10^{18} fissions. TRACY achieved its first criticality in 1995 and the first supercritical experiment was conducted in 1996. To the present, about 100 times of supercritical experiments have been performed.



Name	Material	Size (mm)
TC1	SUS304L	OD:15, ID:15,
TC2	SUS304L	OD:25.2, ID:19.4, Length:202
Level gauge	Zircaloy	OD:22.94, ID:18.26, Length:204
FC	Polyethylene	OD:47.0, ID:7.0, Length:100

OD: Outer diameter
ID: Inner diameter

Figure 1. TRACY core

In the present study, the nuclear characteristics, such as the criticality, the β_{eff}/Λ ratio, the peak power, and the total energy are evaluated using the TRACY experimental data. Those evaluated characteristics are very useful for the validation of nuclear calculation methods, as well as for the criticality accident study.

2. EVALUATION OF CRITICALITY

In the TRACY experiment, adjusting the solution height generally controls the criticality. Thus, we have obtained the critical heights of solution as the criticality data. The measured critical heights with different uranium concentration are shown in Table I. As seen in the table, the critical height decreases with increasing uranium concentration with a rate of about -0.15 cm/(gU/liter). The measured differential worth of solution height around 50 cm is about 0.35 $/cm, and hence the sensitivity of uranium concentration is evaluated at -0.05 $/(gU/liter). Since the uncertainty in uranium concentration is about 0.1 gU/liter, its effect on the criticality is negligible.

Table I. Criticality data of TRACY

Case name	Run64	Run102	Run134
U concentration (gU/liter)	430.0	395.6	373.7
Acidity (N)	0.76	0.71	0.67
Temperature (°C)	25.6	26.3	26.0
Critical height (cm)	45.31	49.57	53.68

To calculate the effective neutron multiplication factors for these critical cores, we have employed the continuous energy Monte Carlo code MVP[4] with the Japanese Evaluated Nuclear Data Library JENDL-3.2[5]. As shown in Figure 1, various instruments are installed to the core tank of TRACY, which will affect the criticality. We have investigated these reactivity effects by modeling those instruments in the calculation. The following calculation models were used.

- Model 1 (Reference model): No instruments are considered as shown in Figure 2.
- Model 2: Add the guide tube for TC1 to Model1.
- Model 3: Add the feed/drain line filled with fuel solution to Model2.
- Model 4: Add the guide tube for TC2 to Model 3.
- Model 5: Add the guide tube for the level gauge to Model 4.
- Model 6: Add the pressure gauge to Model 5.
- Model 7: Add the polyethylene tube for the fission chamber (not used for Run 64).

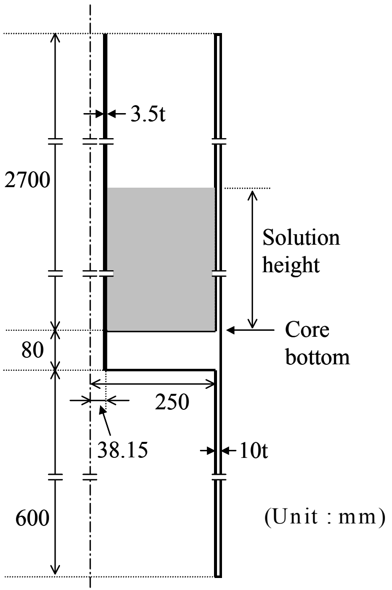


Figure 2. Calculation model No.1

The calculated results are shown in Figure 3. As seen in the figure, the guide tubes for TC2 and the level gauge have largest reactivity effects, about 0.2-0.3%dk in total. These effects are not so large, but they should be considered in the criticality calculation because they give a constant bias to the multiplication factor. The calculations with exact models (Model 6 or 7) still show the overestimation of about 1% for all the cores. It was pointed out that this overestimation was caused by the inaccuracy of ^{235}U and ^{14}N cross sections in the JENDL-3.2[6]. They were replaced to the latest evaluations in the JENDL-

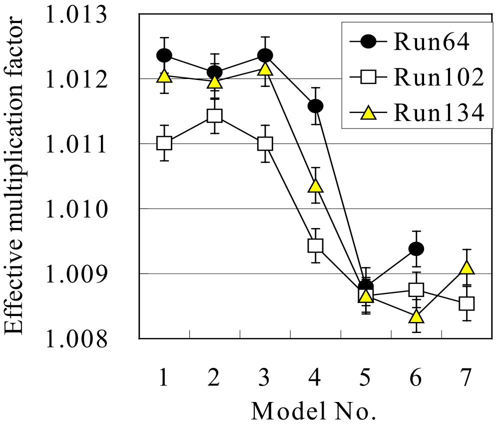


Figure 3. Calculated effective multiplication factors

3.3[7] that have just released; therefore, the calculated results will be improved by using the JENDL-3.3.

3. EVALUATION OF POWER PULSE CHARACTERISTICS FOR SUPER-PROMPT CRITICAL EXPERIMENTS

3.1 SUPER-PROMPT CRITICAL EXPERIMENTS

A series of super-prompt critical experiments with step reactivity insertion have been conducted using TRACY. In these experiments, reactivity from 1.50 to 2.97$ was inserted by withdrawing the transient rod within 0.2 s using the pneumatic system, and the fuel conditions were almost same for all the cases as shown in Table II. The power was measured with a highly enriched ^{235}U fission chamber, located about 2.5 m from the core tank, and covered by a cadmium sheet to detect epi-thermal neutrons, because the time delay effect of detecting thermal neutrons is not negligible in the measurement of fast pulse[8]. The stable inverse period was obtained by differentiate a logarithmic signal of the chamber. The measured power pulse profiles for 1.50$ and 2.97$ of inserted reactivity are shown in Figure 4. The results of experiments are summarized in Table III.

For the evaluation of kinetic characteristics of those experiments, the kinetics parameters, such as the effective delayed neutron fraction, the prompt neutron generation time and the temperature coefficient of reactivity, have been calculated by a two-dimensional transport code TWODANT[9] with 17-group cross sections generated from the JENDL-3.2 library using the SRAC code system[10]. The uranium concentration of 390 gU/liter was used as the representative value in the calculation, and the effective multiplication factor for a critical core is set to about 1.01 by taking account of calculation bias, which is shown in the previous section. The calculated parameters are shown in Table IV.

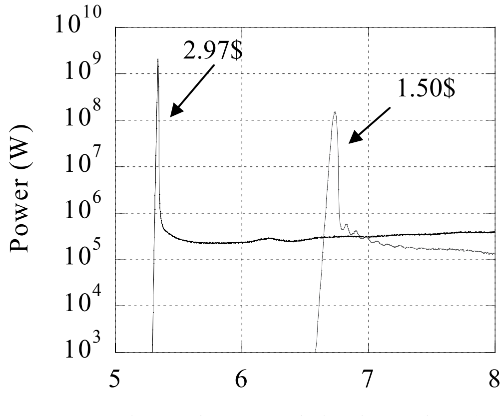


Figure 4. Power pulses for step insertion of reactivity

Table II. Conditions of pulse experiments

Inserted Reactivity ($)	Critical solution height (cm)	Initial Solution height (cm)	Uranium concentration (gU/liter)	Free nitric acid molarity (N)
1.50	50.28	55.14	391.0	0.56
1.80	51.14	57.41	387.6	0.58
2.00	51.17	58.25	386.8	0.60
2.40	51.43	60.41	385.5	0.58
2.97	50.96	62.38	388.2	0.58

Table III. Results of pulse experiments

Inserted Reactivity ($)	Inverse period (s^{-1})	Peak power density (W/cm^3)	Energy density at peak power (J/cm^3)	Energy density in pulse (J/cm^3)
1.50	86.5	1.43? 0^{3}	31.7	57.7
1.80	137.0	3.38? 0^{3}	47.2	73.9
2.00	169.4	5.07? 0^{3}	54.5	85.2
2.40	234.3	9.36? 0^{3}	65.7	110.5
2.97	333.5	1.74? 0^{4}	86.1	151.3

Table IV. Calculated kinetics parameters

Uranium concentration (gU/liter)	Free nitric acid molarity (N)	Critical solution height (cm)	Effective multiplication factor	Effective delayed neutron fraction βeff (-)	Prompt neutron generation time Λ (s)	β/Λ ratio (s^{-1})	Temperature coefficient of reactivity α_T □$/□ Ž
390.0	0.58	50.88	1.0111	0.007505	4.552? 0^{-5}	164.9	-0.04843

3.2 EVALUATION MODEL

To evaluate of the power pulse characteristics, we have used the Nordheim-Fuchs model[11]. This model is derived from the one-point reactor kinetics equations with the following assumptions.

1) Reactivity greater than 1$ is inserted instantly (step reactivity insertion),
2) Excursion is terminated by the feedback reactivity of temperature only, and
3) Delayed neutron effect is neglected.

The stable inverse period ω, the peak power density N_p, the energy densities at the peak power E_p and at the end of pulse E_b are express by the following equations in this model.

$$\rho_\$ = \left(\frac{\beta_{eff}}{\Lambda}\right)^{-1} \omega + 1 \tag{1}$$

$$N_p = \frac{C_P d}{2|\alpha_T| W}\left(\frac{\beta_{eff}}{\Lambda}\right)^{-1} \omega^2 \tag{2}$$

$$E_p = \frac{C_P d}{|\alpha_T| W}\left(\frac{\beta_{eff}}{\Lambda}\right)^{-1} \omega \tag{3}$$

$$E_b = \frac{2C_P d}{|\alpha_T| W}\left(\frac{\beta_{eff}}{\Lambda}\right)^{-1} \omega \tag{4}$$

where $\rho_\$$ is the inserted reactivity in dollar, α_T is the temperature coefficient of reactivity, C_P and d are the specific heat and density of fuel solution, respectively, and W is a weight to compensate the space effect of temperature distribution, which is not considered in the one-point reactor model. The supplemental calculation shows that the value of about 1.5 is appropriate for the W when the temperature distribution is proportional to the initial power distribution.

3.3 β_{eff}/Λ RATIO

The ratio of the effective delayed neutron fraction to the prompt neutron generation time (β_{eff}/Λ) has been evaluated using the super-prompt critical experiment data.

The relation between the stable inverse period and the inserted reactivity is plotted in Figure 5. The broken line in the figure is determined by fitting Eq.(1) to the experimental data. Then, the β_{eff}/Λ ratio is obtained as $(5.91\times10^{-3})^{-1} = 169\ \mathrm{s}^{-1}$. On the other hand, the calculated ratio is 164.9 s^{-1}, and hence the calculation to experiment ratio (C/E) is 0.95. The evaluated β_{eff}/Λ ratio is sensitive to the accuracy of the inserted reactivity and the stable inverse period, and we have estimated these values have a few percent of uncertainty. Then, the 5% difference of the ratios between calculation and experiment is considered to be within the experimental error.

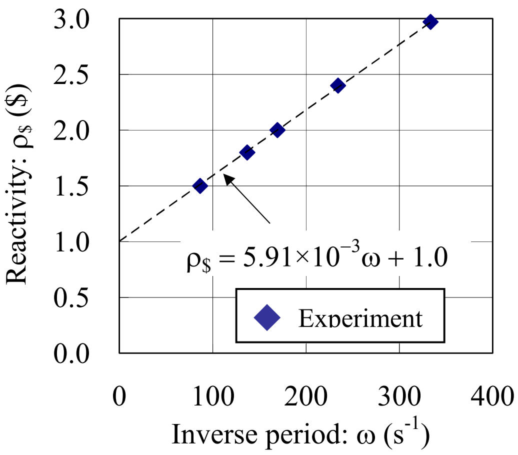


Figure 5. Inserted reactivity as a function of stable inverse period

3.4 PEAK POWER

The peak power density as a function of the stable inverse period is plotted in Figure 6. The lines in the figure show the calculated peak power density using Eq.(2) with *W* of 1.0 and 1.5. As seen in the figure, Eq.(2) with *W* = 1.5 reproduces the experiments well, although it slightly underestimates for the case of the largest inverse period. Thus, it is concluded that the assumptions in the Nordheim-Fuchs model are valid, and the temperature distribution at the peak power is proportional to the initial power distribution. Consequently, we can estimate the peak power density for the super-prompt critical experiments using the Nordheim-Fuchs model.

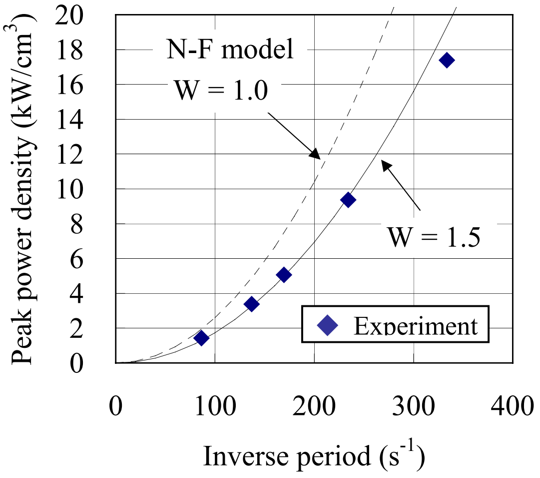


Figure 6. Peak power density as a function of stable inverse period

3.5 ENERGY OF PULSE

Figures 7 and 8 show the energy densities at the peak power and at the end of pulse, respectively, in comparisons with the Nordheim-Fuchs model. At the peak power, the model (Eq.(3)) with *W* = 1.5 agrees with the experiments for smaller inverse period, but it overestimates for the cases of larger inverse period as shown in Figure 7. At the end of the peak, the model (Eq.(4)) with *W* = 1.5 overestimates for almost all cases. The reason of the overestimation is the reactivity feedback effect caused by the radiolytic gas void produced in the fuel solution becomes significant especially near and after the peak power. Since the gas void has a large reactivity effect, the measured energy density becomes smaller than the estimation. This also causes the overestimation of peak power density for the largest inverse period. Since the energy of pulse is very sensitive to the change of power near the peak, the small decrease of peak power results in the large decrease of energy. Then, it is hard to estimate the energy densities using the Nordheim-Fuchs model, unlike the peak power density.

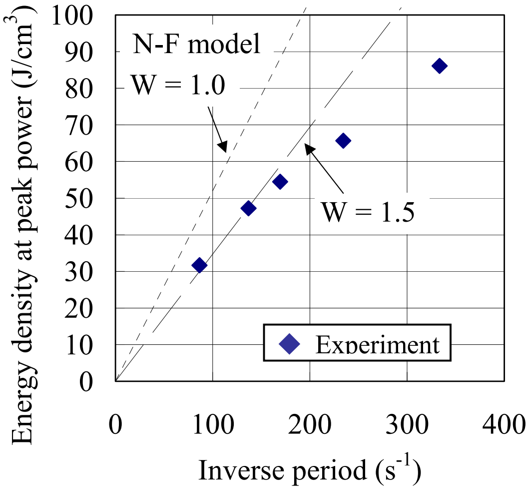


Figure 7. Energy density at peak power as a function of stable inverse period

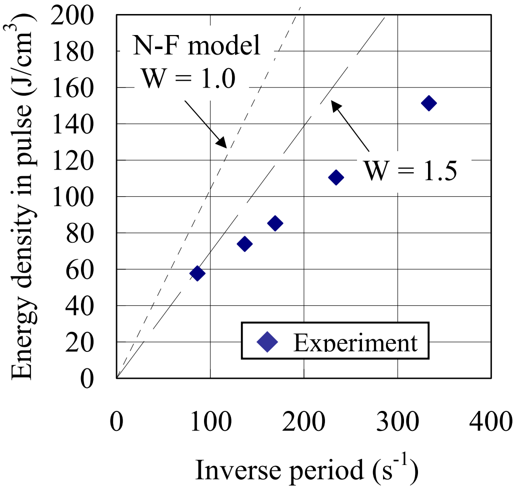


Figure 8. Energy density in pulse as a function of stable inverse period

4. EVALUATION OF TOTAL ENERGY

4.1 EVALUATION MODEL

To evaluate the total energy released in a supercritical experiment, we have assumed that the nuclear excursion was terminated when the inserted reactivity was fully compensated by the temperature feedback reactivity. Under the adiabatic condition (i.e. heat removal is negligible), the following equation is obtained.

$$\rho_{\$} = \left|\alpha_T\right| T_E = \left|\alpha_T\right| \frac{E_E}{C_P d} \tag{5}$$

where T_E is the temperature when the excursion terminated, and E_E is the corresponding energy density, that is, the total energy density. We call this model as “reactivity balance model[12].”

4.2 EXPERIMENTAL DATA AND TOTAL ENERGY EVALUATION

In general, supercritical experiments using TRACY are terminated in a couple of minutes, and the power is still in a significant level at the end of experiments. Since the energy at the end of those experiments is not saturated yet, those are not appropriate for the total energy evaluation. Then we have selected six long-sustained supercritical experiments. These experiments were performed to observe the cooling effect on the power behavior, and they lasted for about 5 hours. As the experimental data of total energy, we use the energy of these experiments at the time of about 10 min

Table V. Conditions and results of long-sustained supercritical experiments

Reactivity insertion method	Inserted Reactivity ($)	Critical solution height (cm)	Initial Solution height (cm)	Uranium concentration (gU/liter)	Free nitric acid molarity (N)	Total energy density (J/cm3)
Solution feed	0.51	52.42	54.12	379.5	0.60	57.7
	0.83	52.29	55.11	380.4	0.61	85.1
	1.25	52.10	56.47	379.8	0.61	128.3
	1.52	51.69	57.00	382.3	0.62	155.5
Rod withdrawal	0.52	51.11	52.74	388.4	0.60	60.1
	1.50	51.26	56.37	384.9	0.61	154.5

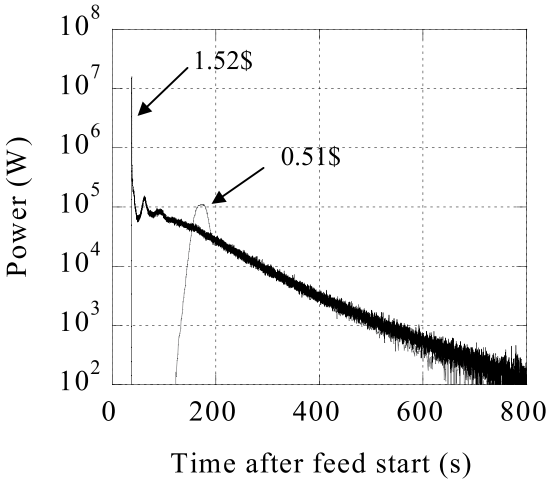


Figure 9. Power profiles for long-sustained excursions

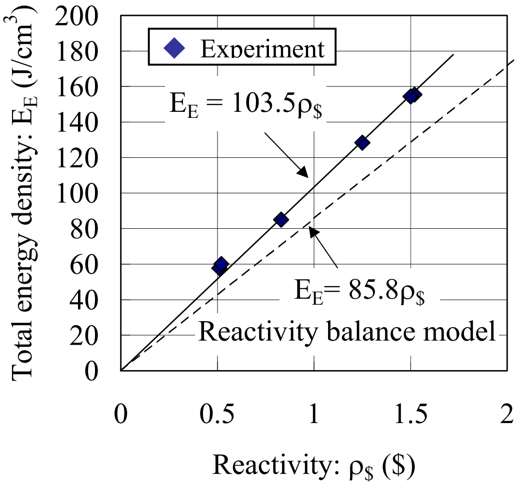


Figure 10. Total energy density as a function of inserted reactivity

where the power decreases to very low level but the cooling effect is not significant. Figure 9 shows examples of the measured power profiles. The experimental data are shown in Table V.
The total energy density as a function of the inserted reactivity is plotted in Figure 10. As seen in the figure, the total energy density is proportional to the inserted reactivity. The solid line in the figure shows the result of linear fitting to the experiments, meanwhile the broken line is drawn using Eq.(5). The evaluated total energy using Eq.(5) are about 20% smaller than the experiments. This difference is caused by the heat removal, especially to the core tank.

CONCLUSIONS

The nuclear characteristics of TRACY, such as the criticality, the β_{eff}/Λ ratio, the peak power, the energy of pulse, and the total energy, have been evaluated using the experimental data, and the availability of the criticality calculation and the models to evaluate the power and energy were studied. The following findings were obtained.

- The criticality evaluation shows that the instruments installed to the core tank have the reactivity effect of about 0.3%dk, and the calculation using exact model still overestimates the effective multiplication factor about 1%.
- The β_{eff}/Λ ratio evaluated using Eq.(1) is 5% larger than the calculation. This would be mainly caused by the uncertainty of experimental data.
- The Nordheim-Fuchs model is applicable to estimate the peak power density for the super-prompt critical experiments. But it overestimates the energy densities at the peak power and at the end of pulse.
- The total energy density is proportional to the inserted reactivity as expected by the reactivity balance model, but the model underestimates the experiments about 20%. This difference is caused by the effect of heat removal, which is not considered in the model.

ACKNOWLEDGEMENT

The author would like to thank K. Futakami of Chiyoda Maintenance Co. for his help in handling the TRACY data.

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