A PRELIMINARY SIMULATION OF TRADE DYNAMICS

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Abstract

The TIESTE-MINOSSE code, developed at the ENEA to preliminarily investigate core dynamics relevant to metal cooled fast reactor and ADS, has been implemented to analyse transients in the RC1 1 MW swimming pool TRIGA reactor existing at the Casaccia Centre. In the first part of the work, the TIESTE-MINOSSE improvement and validation on TRIGA dynamics is described. In particular, reactivity insertion measurements made during the first tests of the RC1 TRIGA are analysed and the resulting fuel feedback features are compared with statically measured temperature and power coefficients, obtained by measuring both the fuel temperature and the reactivity of a calibrated control rod at different power levels. The comparison shows a significant agreement between the mentioned analysis of TRIGA dynamics and the more recent power coefficient static measurements. In the second part of the work, some transients in sub-critical core configurations relevant to TRADE are preliminary analysed.

I. Introduction

The interest in TRIGA transients comes from the TRIGA Accelerator-driven Experiment (TRADE) proposal that aims to realise the first example of ADS component coupling "at real size" on the TRIGA reactor at the ENEA Casaccia Centre (European Technical Working Group on ADS, 2001; Working Group on TRADE, 2002). The TIESTE-MINOSSE code is a simple tool developed at the ENEA by coupling a core channel time dependent thermal-hydraulics code with a neutron point-kinetics code to preliminarily investigate the core dynamics of liquid metal cooled ADS (Bianchini *et al.*, 1999; Bosio *et al.*, 1999; d'Angelo *et al.*, 1999).

In order to be applied to the TRIGA thermal-hydraulics, the fuel clad to water convective heat transfer in free-convection regime and the achievable nucleate boiling phenomenon at the same fuel clad-water interface have been implemented in TIESTE thermal-hydraulics. The improved TIESTE code has been validated by using the fuel temperature measurements at different power levels in the RC1 1 MW swimming pool TRIGA reactor. The TIESTE-MINOSSE dynamics has been validated by analysing the power transient measurements performed in the frame of the RC1-TRIGA nuclear test campaign (Di Palo, 1968). Thanks to a co-operation with the Politecnico di Torino University, the same TIESTE core-channel module is being coupled with the more complex spatial kinetics codes allowing reference calculations (Bianchini *et al.*, 2000).

The work is presented in the three sections following this introduction. In section II, the TIESTE improvement and validation are briefly presented. In order to be applied to the RC1-TRIGA, a water coolant option in free-convection regime has been implemented in the TIESTE module and validated on available fuel temperature measurements. Assuming the RC1-TRIGA operation conditions up to 1 MW, due to the limited level of the heat flux through the fuel pin surface, only two heat exchange mechanisms have to be considered: convective heat transfer and nucleate boiling for the water coolant in free-convection regime

Section III describes the TIESTE-MINOSSE optimisation and validation on RC1 TRIGA dynamic tests. Results show that the power trends calculated by the TIESTE-MINOSSE code are generally close to the experimental ones.

Section IV contains a preliminary analysis of some transients in sub-critical core configurations relevant to TRADE experiment. In particular, a simple parametric study of the thermal feedback impact on TRADE dynamics has been carried out in function of the core power and sub-criticality level.

II. Tieste module improvement and validation

At each axial mesh point of the (single-pin) fuel-channel, the TIESTE module solves the (one-dimensional-R) Fourier equation for the temperature distribution inside the fuel and the clad, assuming as "right" boundary condition the coolant temperature at the external coolant ring, previously calculated by solving the energy balance in a one-dimensional Z coolant channel (or assumed as a guess value in the first time step). "Left" boundary condition is reflective; at present axial conduction is neglected.

II.1 Convective heat transfer in free-convection regime

The clad to water convective heat transfer in free-convection regime has been classically considered to be proportional to the difference of temperature between the external clad surface ($T_{ExtClad}$) and the coolant mass temperature($T_{coolant}$):

$$\left|q/A\right|_{Convection} = C\frac{k}{D}\left(N_{Ra}\right)^{a}\left(T_{ExtClad} - T_{Coolant}\right) \qquad (1)$$

Where:

q/A is the heat flux through the clad external surface;

k is the water conductivity;

D is the characteristic length for the flow; the hydraulic-diameter of the average coolant-channel is assumed to be 2.1 cm;

N_{Ra} is the dimensionless Rayleigh number;

C and *a* are two dimensionless constants; it is assumed *a*=0.25 and *C*=0.52 (Murray, 1954).

If the temperature of the clad external surface would exceed the water boiling temperature, the nucleate boiling phenomenon is also considered in the following way.

II.2 Nucleate boiling in free-convection regime

In the case of the nucleate boiling mechanism of heat exchange, many correlations force the equation to be linear:

$$\left|q/A\right|_{NuclBoil} = h_{NuclBoil}\left(T_{ExtClad} - T_{Sat}\right) \qquad (2)$$

but it is well known that the $h_{NuclBoil}$ coefficient is clearly dependent on the *q/A* heat flux through the clad external surface.

In the present case, T_{Sat} is the water boiling temperature at the atmospheric pressure.

The $|q/A|_{NuclBoil}$ heat flux inducing the nucleate boiling phenomenon has been assumed to be the part of the heat flux through the clad external surface that exceeds the $|q/A|_{Convection}$ allowing the clad external surface to reach the water boiling temperature.

As recommended by Collier and Thome (1994), the following Cooper’s correlation is used to obtain the water $h_{NuclBoil}$ as a function of the heat flux:

$$h_{NuclBoil} = \delta\left(\left|q/A\right|_{NuclBoil}\right)^{0.67} \qquad (3)$$

Where the $\boldsymbol{\delta}$ factor is defined in (Collier and Thome, 1994) as a function of the coolant molecular weight, reduced pressure conditions and surface roughness (1.0μm is recommended as default value). Cooper also recommended multiplying h by a factor 1.7 for boiling on horizontal cylinders (Collier and Thome, 1994). This recommendation has been retained also the case considered here of vertical RC1 fuel rods.

In the TIESTE module, eq.3 is used to obtain the $h_{NuclBoil}$ coefficient to be used in the eq.2 by the following simple procedure:

1. in the initial condition of the steady-state, the total heat flux through the clad, to be used to determine $|q/A|_{NuclBoil}$ in eq.3, is the fuel linear-power in the considered axial point divided by the clad external circumference.
2. during a transient, the total heat flux through the clad is approximated to be equal to the total heat flux relevant to the previous time step.

II. 3 Validation

The mentioned comparison between RC1-TRIGA experimental fuel temperature and TIESTE results is reported here below in Tables 1 and 2. Table 1 shows the temperature results obtained during a recent power coefficient measurement campaign, in which the position of the "Shim 2" calibrated rod (Festinesi, 2001) and the induced power level variations are monitored. An analogous comparison is reported in Table 2 for temperature measurements performed in the former "nuclear tests" RC1-TRIGA configuration (only 74 fuel elements) at the beginning of each of the 10 cents reactivity insertion measurements that will be analysed in section III (Di Palo, 1968).

Table 1. **TIESTE validation on recent RC1-TRIGA fuel temperature results**

Power (KW)	**Fuel pin temperatures** (K)				
	Experiment	**TIESTE calculated values and discrepancies** (%)			
	T3	T3 Position inside the Fuel Rod	(E-C)/C	Average value inside the Fuel Rod	$(E-C_{Aver})/C_{Aver}$
100	336	348	-3.4	346	-2.9
200	369	383	-3.7	378	-2.4
300	399	409	-2.4	404	-1.2
400	409	422	-3.1	420	-2.6
500	427	434	-1.6	432	-1.2
600	437	446	-2.0	444	-1.6
700	454	458	-0.9	455	-0.2
800	462	469	-1.5	466	-0.9
900	476	480	-0.8	477	-0.2
1 000	487	491	-0.8	488	-0.2

Tables 1 and 2 generally show a good agreement between experimental results and TIESTE temperature calculations. The best agreement is for temperatures relevant to reactor powers higher than 300 kW, where the nucleate boiling mechanism clearly prevails in the clad to coolant heat exchange. For lower reactor power levels, where only the convection mechanism is involved (because the external clad temperature is lower than the water boiling temperature), TIESTE results looks to be worse. At the present time, no theory to explain of this different TIESTE's capability to reproduce experimental results is available. In the next future, a further verification of the calculation hypotheses, and in particular of the eq. (1) correlation will be worthwhile

Table 2. **TIESTE validation on the former "nuclear tests" RC1-TRIGA configuration**

Power (KW)	**Fuel pin temperatures** (K)				
	Experiment	**TIESTE calculated values and discrepancies** (%)			
	T1	T1 Position inside the Fuel Rod	(E-C)/C	Average value inside the Fuel Rod	$(E-C_{Aver})/C_{Aver}$
100	331	368	-10.1	362	-8.6
215	387	413	-6.3	407	-4.9
300	421	429	-1.9	425	-0.9
400	436	447	-2.5	443	-1.6
500	468	465	0.6	459	2.0
600	480	482	-0.4	476	0.8
700	495	499	-0.8	492	0.6
800	506	516	-1.9	508	-0.4
900	526	532	-1.1	524	0.4
1 000	545	549	-0.7	539	1.1

III. Tieste-Minosse validation

The dynamics measurements relevant to the power transients induced by reactivity insertion, that were performed among the RC1-TRIGA nuclear tests (Di Palo, 1968), are analysed by using the TIESTE-MINOSSE code. The fuel temperature feedback coefficient used in the calculations is approximated as a constant during each of the considered power transients, and the value corresponding to the best agreement with the experimental trend is obtained tentatively. Figure 1 shows an example of this comparison between calculated power trends and experimental ones (red line). The blue line of Figure 2 represents synthetically the results of this experimental analysis for the fuel temperature coefficient function. It can be seen that the present work results significantly agrees with the results obtained statically on the present RC1-TRIGA configuration (green and black lines) by measuring the position of a calibrated control rod corresponding to different asymptotic power levels and the fuel temperature (Festinesi, 2001). The same figure shows also an agreement with the of the other available sources of information on the RC1-TRIGA power coefficient.

Moreover, the tentative fit of both the statically measured coefficients and the reactivity insertion transient information (grey line in Figure 2) is assumed as default temperature coefficient function for the dynamic calculations. Using this fuel temperature dependent coefficient, it is verified that TIESTE-MINOSSE is also able to reproduce experimental results concerning very large power transients: as, for instance, the asymptotic power transient from 1 MW to 30 kW due to an insertion of the "Shim 2" control rod corresponding to about -2.7 USD (Festinesi, 2001).

Figure 1. **Transients induced by 10 cents reactivity insertion during the RC1-TRIGA nuclear tests**

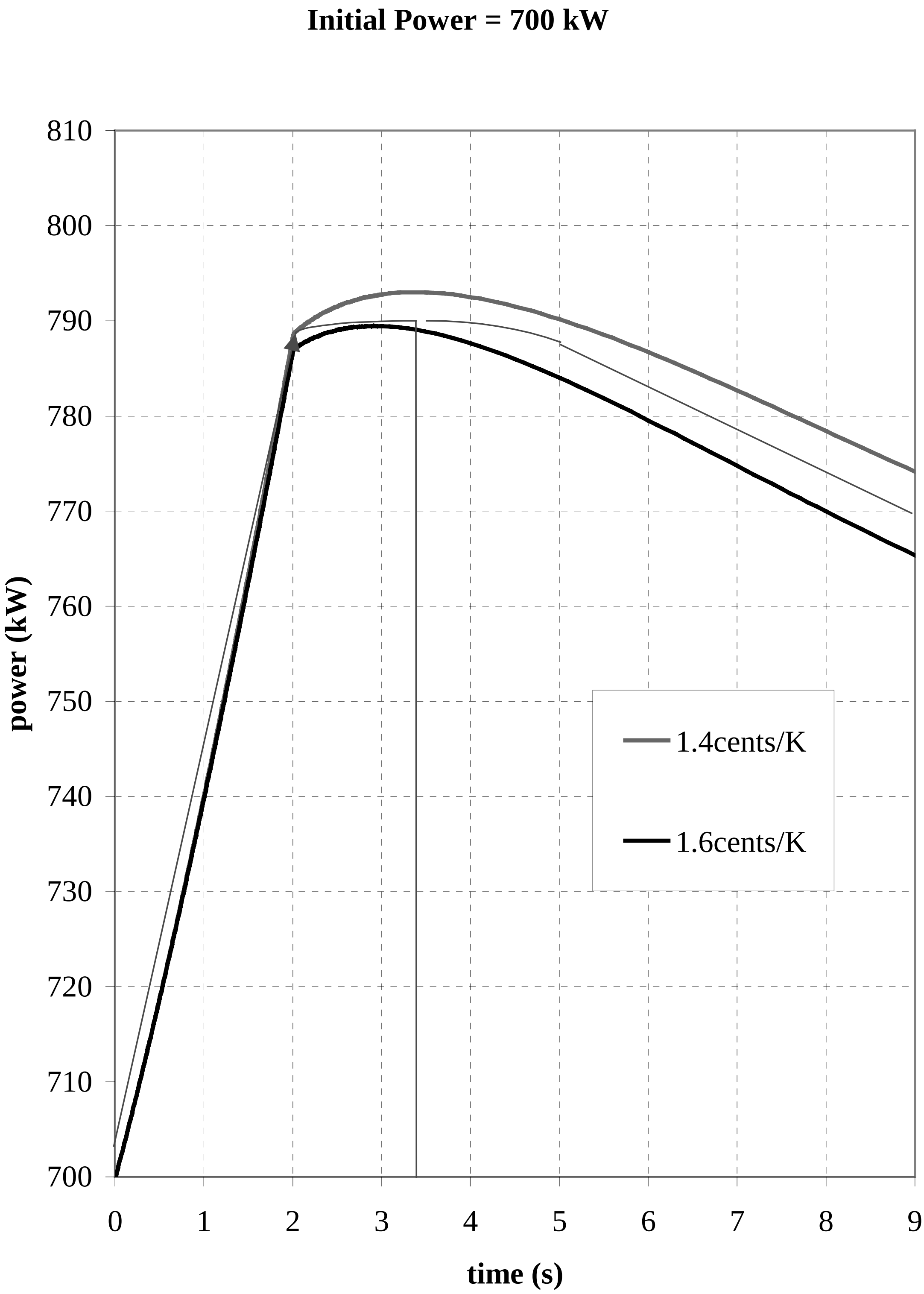
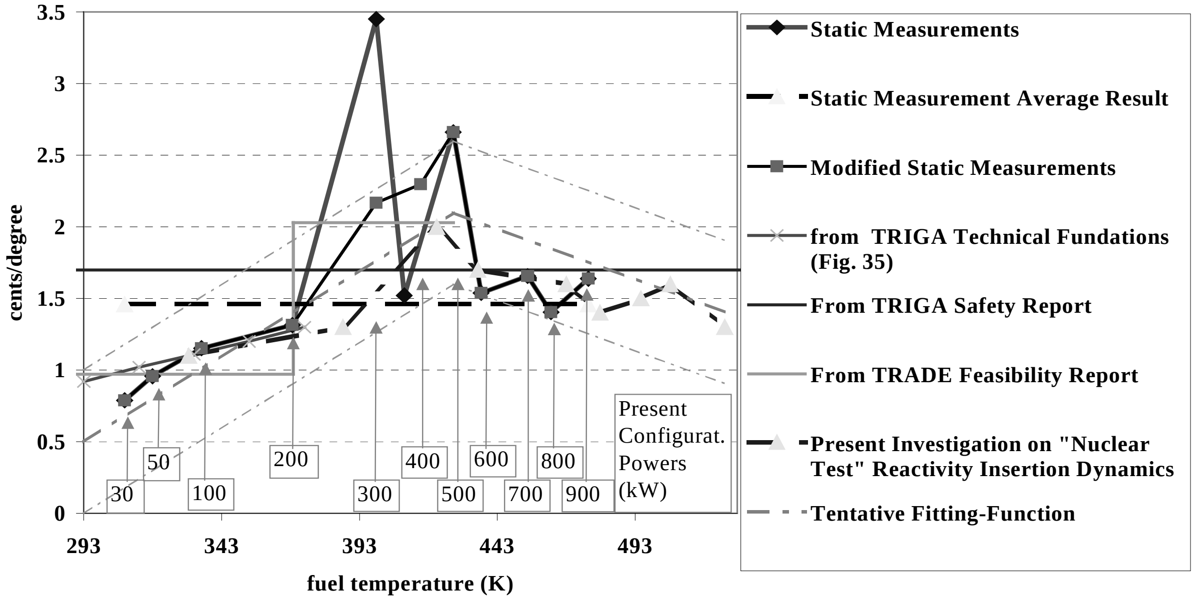


Figure 2. **The RC1-TRIGA fuel temperature coefficient**



IV. Preliminary simulation of trade dynamics

The validated TIESTE-MINOSSE tool allows to preliminary investigate transients in sub-critical core configurations relevant to the TRADE experiment. In this aim, “classic” reactivity insertion transients are simulated assuming three different sub-criticality levels (-3.81 USD, -1.74 USD and -0.72 USD) and two different power levels (80 and 200 kW) at the transient beginning. Finally, to evaluate the impact of the fuel temperature feedback on the results, all the transient calculations are repeated either by taking into account (TIESTE-MINOSSE calculation) or by neglecting (MINOSSE pure point-kinetic calculation) the fuel temperature feedback effects. Figures 3 through 8 show the results of this simple parametric study to preliminarily investigate the thermal feedback impact on TRADE dynamics. In particular, they show the power transients induced by two different reactivity linear ramps: 10 cents and 50 cents in 2 s. The comparison of different thermal feedback impacts on power transients of fig.s from 3 to 8 allows to evaluate to what extent feedback effects on the experimental power transients will decrease by decreasing:

- the multiplying system effective multiplication factor, K_{eff};
- the multiplying system power level.

Therefore, TRADE experiments made in experimental configurations closer to the criticality conditions will be more representative of the ADS dynamics relevant to higher power density systems.

It can be also worthwhile to underline that the reactivity insertion rate of about 5 cents/s (leading to the 10 cents in 2 s) considered in the present investigation corresponds to the fastest reactivity insertion allowed in the Casaccia RC1 TRIGA reactor at the present time. This limitation comes from the control system specifications, including the current ban to move more than one control road at the same time. In order to perform experiments significantly sensitive to fuel feedback, i.e. useful to validate codes for ADS dynamics, results in Figures 3 through 8 suggest the opportunity to increase the reactivity insertion rate currently allowed in RC1-TRIGA.

Figure 3-5. **Transients induced by reactivity insertions from 80 kW in TRADE configurations having different sub-criticality levels**

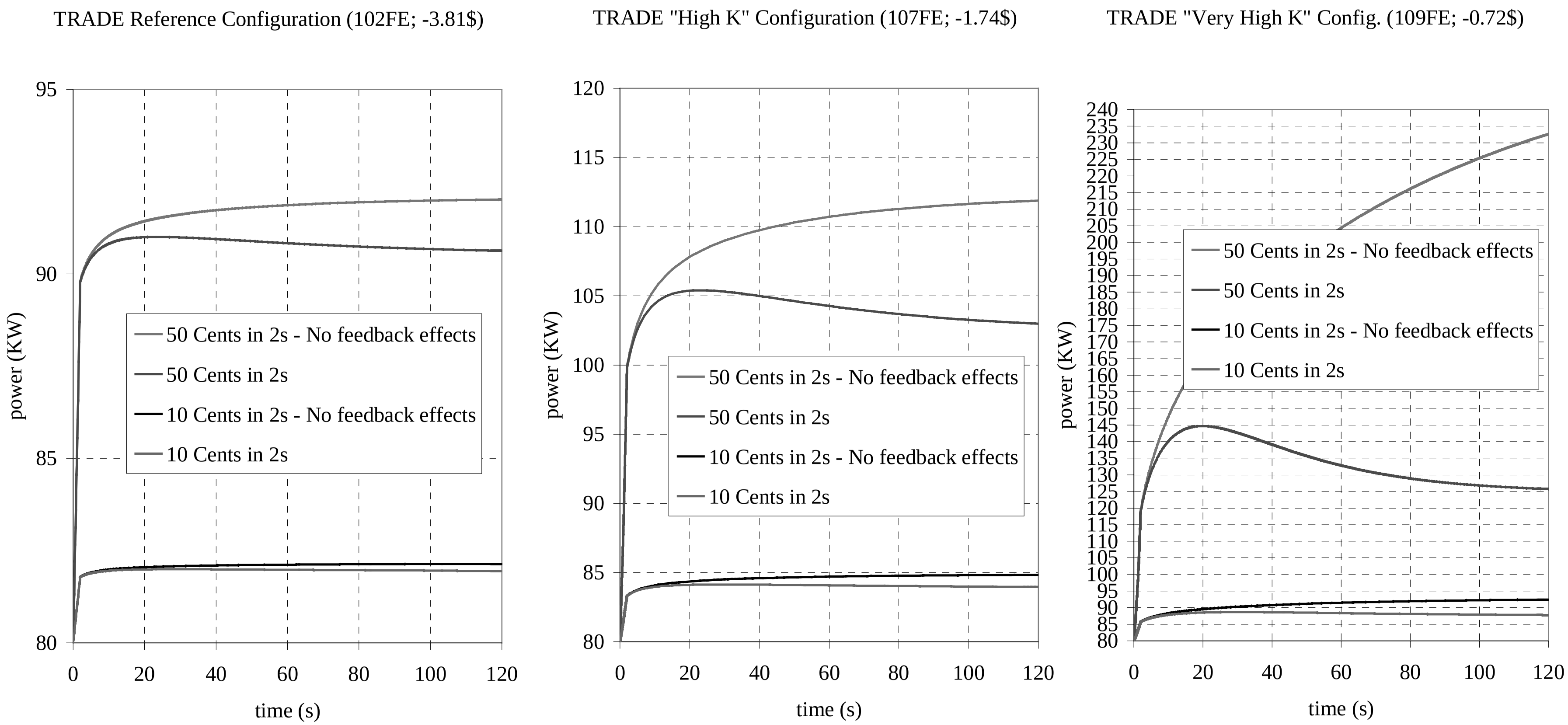


Figure 6-7. **Transients induced by reactivity insertions from 200 kW in TRADE configurations having different sub-criticality levels**

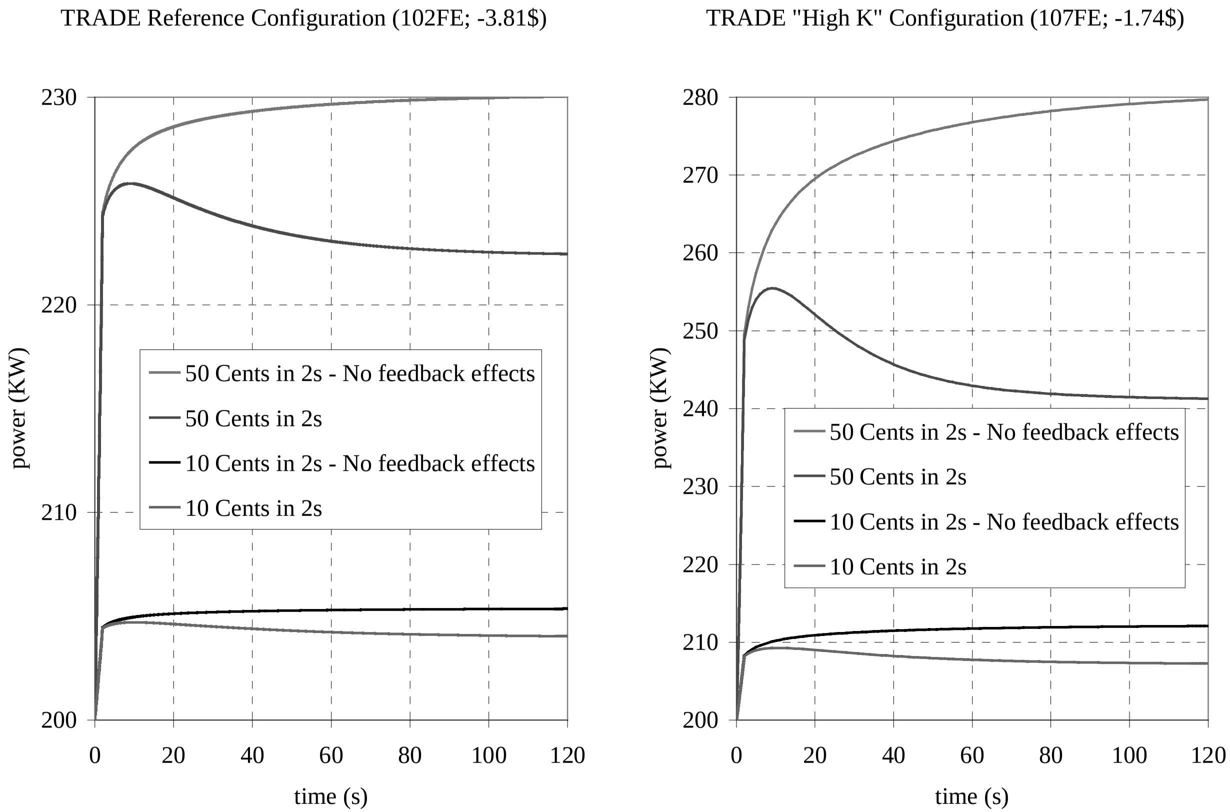
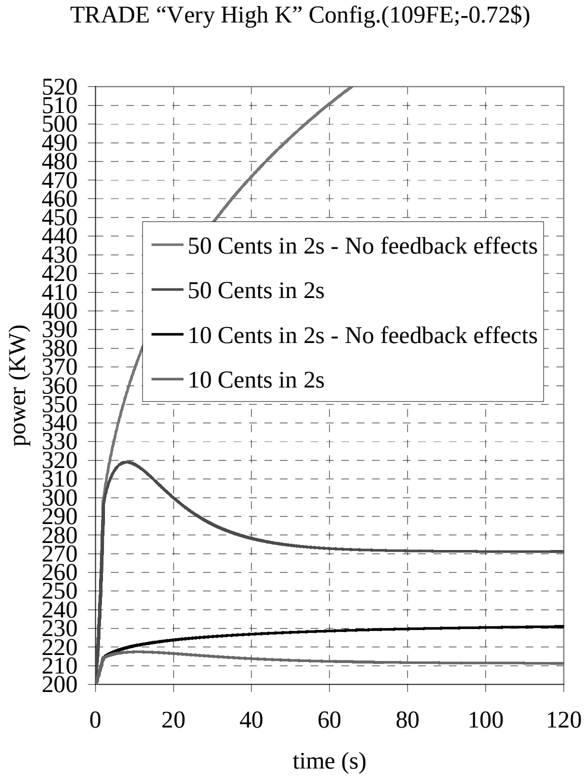


Figure 8. **Transients induced by reactivity insertions from 200 kW in TRADE configurations having different sub-criticality levels**



V. Conclusions

The first part of the present work, devoted to the TIESTE-MINOSSE validation on the power transients relevant to critical RC1-TRIGA configurations, shows that:

1. as indicated by General Atomic (1958), the main part of the RC1-TRIGA feedback effect depends on the fuel temperature only;
2. there is a good agreement between statically measured fuel temperature coefficients and the coefficients that allow to simulate RC1-TRIGA dynamics;
3. the TIESTE-MINOSSE code is able to simulate also large fuel temperature variations corresponding to very large power transients (from few kW to 1 MW).

The second part of the present work, devoted to the TRADE experiment dynamics, shows in what extent feedback effects decrease by decreasing:

1. the sub-critical configuration effective multiplication factor;
2. the sub-critical configuration power level.

TRADE experiments made in experimental configurations close to the criticality conditions will be more representative of the ADS dynamics relevant to higher power density systems. Moreover, if TRADE experiments have to include those transients that are significantly sensitive to fuel feedback effects, the present work investigation suggests the opportunity to increase the value of the maximum reactivity insertion rate allowed in the Casaccia RC1 TRIGA.

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