Electron versus proton accelerator driven sub-critical system performance using TRIGA reactors at power.

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Abstract

This paper provides a comparison of the performance of an electron accelerator-driven experiment, under discussion within the Reactor Accelerator Coupling Experiments (RACE) Project, being conducted within the U.S. Department of Energy's Advanced Fuel Cycle Initiative (AFCI), and of the proton-driven experiment TRADE (TRiga Accelerator Driven Experiment) originally planned at ENEA-Casaccia in Italy. Both experiments foresee the coupling to sub-critical TRIGA core configurations, and are aimed to investigate the relevant kinetic and dynamic accelerator-driven systems (ADS) core behavior characteristics in the presence of thermal reactivity feedback effects. TRADE was based on the coupling of an upgraded proton cyclotron, producing neutrons via spallation reactions on a tantalum (Ta) target, with the core driven at a maximum power around 200 kW. RACE is based on the coupling of an Electron Linac accelerator, producing neutrons via photoneutron reactions on a tungsten-copper (W-Cu) or uranium (U) target, with the core driven at a maximum power around 50 kW.

The paper is focused on analysis of expected dynamic power response of the RACE core following reactivity and/or source transients. TRADE and RACE target-core power coupling coefficients are compared and discussed.

KEYWORDS: RACE, TRADE, ADS

1. Introduction

The Reactor-Accelerator Coupling Experiments (RACE) Project [1] is being conducted within the U.S. Department of Energy's Advanced Fuel Cycle Initiative (AFCI) with the participation of several European organizations in the frame of the EURATOM 6th Framework Program, Integrated Project EUROTRANS (EUROpean TRANSmutation). In the RACE project a series of ADSS (Accelerator-Driven Subcritical Systems) experiments are investigated, which should be performed both at low core power and high core power. These ADSS experiments have been performed both in a compact, transportable subcritical assembly at low power at the Idaho State University's Idaho Accelerator Center (ISU-IAC) in 2005-2006, and in TRIGA reactors at the University of Texas at Austin. Higher power

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experiments could be conducted at UT-Austin or at the Texas A&M University possibly starting in 2007. In these experiments, source neutrons are generated by using electron accelerators to induce bremsstrahlung photon-neutron reactions in W-Cu or U target targets. The achievable neutron source strength depends on the maximum power achievable in the target during the planned experiments at high power, which will span a range from about 10^{12} to $6 \cdot 10^{13}$ n/s.

TRADE [2] was based on the coupling of an upgraded proton cyclotron, producing neutrons via spallation reactions on a Ta target, with the ENEA Rc-1 Casaccia TRIGA core in a subcritical configuration ($k_{eff} \sim 0.97$) driven at a maximum power around 200 kW by a neutron source strength of $\sim 4 \cdot 10^{14}$ n/s.

The purpose of this paper is the discussion of the energetic gain expected in the RACE core and the analysis of the expected thermal reactivity feedback effects following reactivity transients. It is assumed that the thermal power dissipated by W-Cu or uranium RACE target during the high power phase will be ~ 25 kW, which corresponds, on the basis of preliminary MCNPX calculations on a depleted uranium multi-disk target undergoing a 1.0 mA - 25 MeV electron beam, to a source strength of $\sim 6 \cdot 10^{13}$ n/s.

Different MCNPX [3-4] and TRIPOLI4 [5] calculations have been performed to analyze the coupling between a TRIGA subcritical core and a photoneutron source. The calculations were performed to have a first assessment of the RACE target-core power coupling coefficients (energetic gain) with respect to those obtained for the TRADE core configurations. For comparison with TRADE some calculations have been performed assuming an electron beam impinging on a W-Cu target surrounded by the subcritical ENEA Rc-1 Casaccia TRIGA core. These cases will be indicated in the following as TRADE-e (TRADE-electrons).

2. Background

The relationship linking up the core power to the neutron external source may be written as (<> denotes integration over the phase space):

$$P = \left[-\frac{E_f}{<\nu>} \right] \cdot \frac{<S>}{\rho_s} \qquad (1)$$

where P= core power (W); E_f= energy from fission (J/fis); $<\nu>$= neutrons average number emitted per fission in the subcritical core (n/fis); $<S>$= external neutron source (n/s); ρ_s= *source* reactivity defined by $<S>/<\nu\Sigma_f\varphi>$. The neutron source term may be expressed as:

$$<S> = \left[\gamma_t (1+\varepsilon_c)\right] \cdot i_{e/s} \qquad (2)$$

where γ_t= target neutron yield (electron energy dependent) (n/e); $\varepsilon_c = \gamma_c/\gamma_t$= core contribution to neutron production by photo-nuclear reactions, with γ_c core neutron yield (n/e); $i_{e/s}$ = electron current (e/s). Taking into account Eq. (2), Eq. (1) may be written in terms of the source importance $\varphi^* = \rho_{eff}/\rho_S$ as:

$$P = \left[-\frac{E_f}{<\nu>} \right] \cdot \left[\gamma_t (1+\varepsilon_c)\right] \cdot \varphi^* \cdot \frac{i_{e/s}}{\rho_{eff}} \qquad (3)$$

In particular, the energetic gain G, defined as the ratio between the core power and the beam power, is given by:

$$G = \left[-\frac{E_f}{<\nu>} \right] \cdot \left\{ \left[\gamma_t (1+\varepsilon_c) \right] \cdot \varphi^* \right\} \cdot \frac{1}{E_e} \cdot \frac{1}{\rho_{eff}} \equiv \left[-\frac{E_f}{<\nu>} \right] \cdot g \cdot \frac{1}{E_e} \cdot \frac{1}{\rho_{eff}} \qquad (4)$$

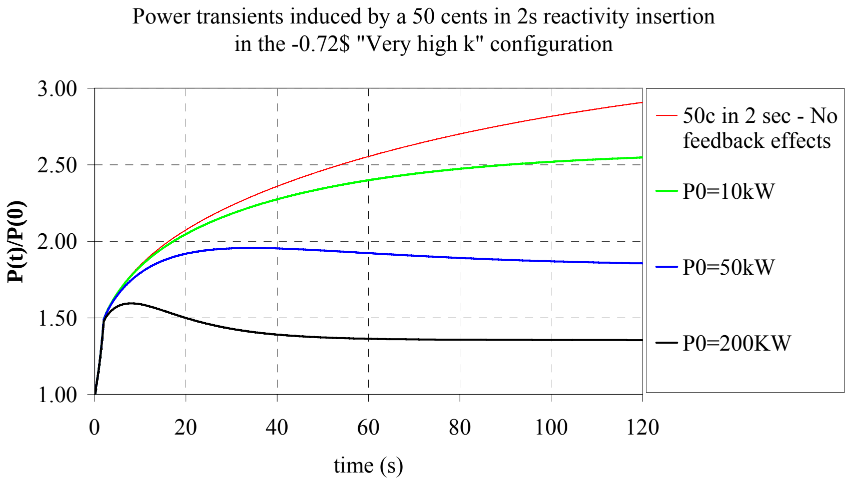
It may be worthwhile to mention that from Eq. (4), when knowing G and ρ_{eff}, we can obtain the coupling term (indicated as g).

3. Preliminary analysis of the influence of thermal reactivity feedback in RACE

The dynamic (transient) behavior, that is specific and particular to subcritical ADS systems, is to be verified experimentally at different subcriticality levels.

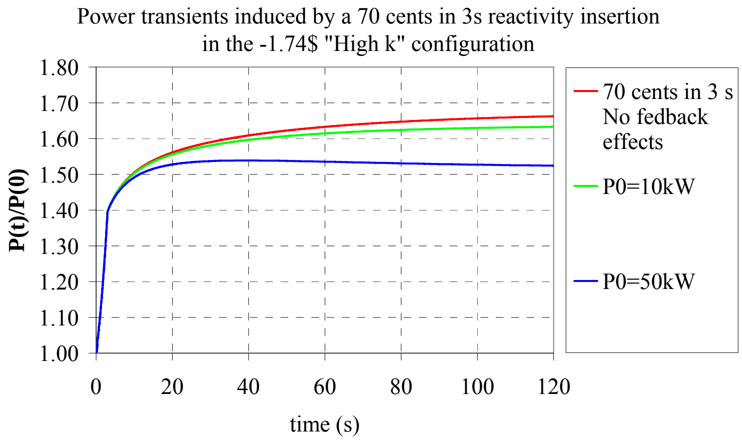
The impact of thermal reactivity feedback effects on the dynamics of subcritical configurations of a TRIGA reactor at different power levels has been estimated carrying out some time dependent simulations by using the TIESTE-MINOSSE [6] fast running transient computer code. The feedback coefficients of the RACE TRIGA reactor have been approximated to be the same as the Rc-1 TRIGA reactor of the Casaccia ENEA Centre, on which the TRADE experiments were planned on. In this approximation, the comparison between an electron accelerator driven sub-critical system (RACE) and a proton driven one (200 kW TRADE experiment) results only from the (different) experimental power levels. Fig. 1 shows the transient power response induced by a reactivity insertion ramp of 50 cents in 2 seconds in an experimental configuration quite close to criticality, the so-called "Very high k" configuration (–72 cents sub-critical) in TRADE [2] at 3 different power levels (10kW, 50kW, 200kW). In order to facilitate the comparison of the transient shapes at different power levels, all data are normalized to the initial power level. The red line, which indicates the transient power response obtained by assuming no thermal reactivity feedback effects (kinetic response at zero power) , can be useful to evaluate the magnitude of feedback effects by comparing the dynamic response at different power levels with this point kinetics transient from zero power, assuming the level of sub-criticality is known a priori.

Figure 1: Predicted dynamic power responses at different power levels to a reactivity insertion (TRIGA –TRADE configuration: –72 cents subcritical, driven by a constant neutron source).



In a more subcritical TRIGA configuration, the influence of the thermal reactivity feedback on the transient behavior (induced by the same reactivity insertions) is predicted by the simulation tools to be clearly reduced. In order to investigate this effect, the level of sub-criticality in the TRIGA configuration was assumed to be reduced to –1.74 $ instead of the -72 cents previously considered. Fig. 2 shows that, even when increasing the total reactivity inserted into the system from +50 to +70 cents, both the increase in relative power and the impact of the feedback on the power transient response are predicted by the computer models to look significantly subdued. These simple considerations lead to the conclusion that transients at lower levels of subcriticality have to be experimentally investigated at a quite higher power levels.

Figure 2: Predicted dynamic power responses at different power levels to a reactivity insertion (TRIGA –TRADE configuration: –1.74 $ subcritical, driven by a constant neutron source).



4. Source-core coupling in TRADE-e configurations

4.1. MCNPX calculations

Two core configurations, representative of the SC0 (-500 pcm) and SC2 (-3000 PCM) TRADE configurations [2], have been coupled with the three type of targets described in the following. The simulations were performed taking into account the electrons, photons and neutrons transport using the MCNPX code.

Three target types have been considered. An alloy of W-Cu (75% wt and 25% wt respectively, bulk density 14.7 g/cm^3) was employed as material of two geometrical shapes: raw cylindrical (h=8.89 cm, r=3.49 cm) and conical (aperture angle 16.5 degree, h=34.8 cm, r_{max}=1.5 cm, radial thickness 0.19 cm), as shown in Fig. 3 [7]. A third target type is represented by a set of coaxial disks of depleted Uranium with aluminium cladding and water coolant, as shown in Fig. 4 [8].

Figure 3: TRADE-like conical shaped target. (dimensions in mm).

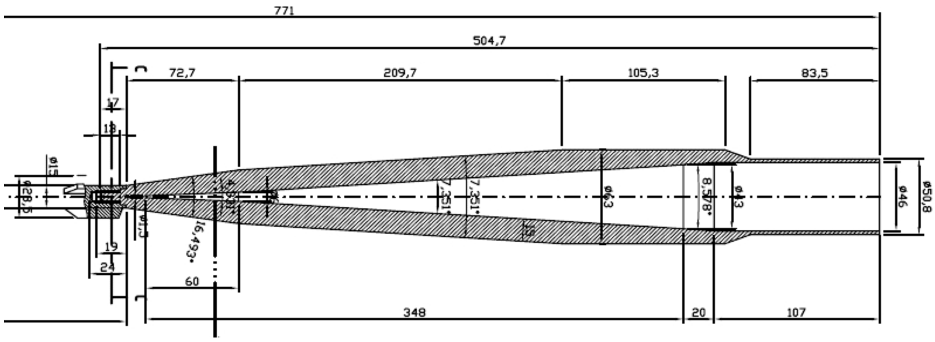
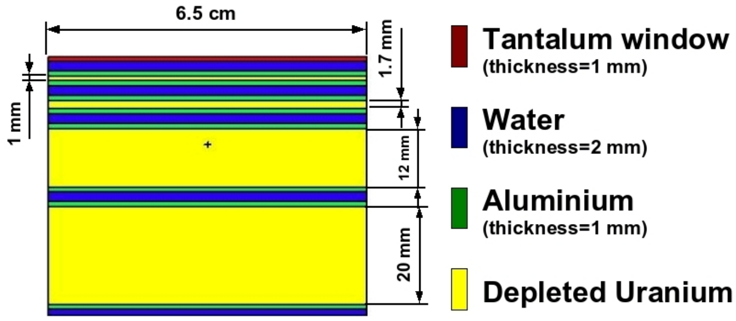


Figure 4: Multi-plate Target



Tab. 1 reports the main results concerning the energetic gain for each configuration.

Table 1: Results for SC2 and SC3 TRADE-e configurations
(25 kW beam energy, 25 MeV electron energy).

	W-Cu Cylinder		W-Cu Conical		U Multi-plate	
Configuration	SC0	SC2	SC0	SC2	SC0	SC2
Target neutron yield γ_t (n/e)	4.12E-03	4.12E-03	3.86E-03	3.86E-03	7.99E-03	7.99E-03
Core (γ,n) contribution ε_c	0.11	0.11	0.16	0.16	0.09	0.07
Total neutron yield (n/e)[(a)]	4.57E-03	4.57E-03	4.48E-03	4.46E-03	8.74E-03	8.55E-03
k_{eff}	0.99323	0.97748	0.99041	0.97157	0.99450	0.97875
ρ_{eff} (pcm)	-682	-2304	-968	-2926	-553	-2171
φ*	1.17[(b)]	1.03[(b)]	0.97[(b)]	0.91[(b)]	0.97[(b)]	1.12[(b)]
ρ_s (pcm)	-583	-2246	-997	-3225	-569	-1943
<S> (n/s)	2.86E+13	2.86E+13	2.80E+13	2.79E+13	5.46E+13	5.34E+13
$g=\gamma_t\cdot(1+\varepsilon_c)\cdot\varphi^*$	5.35E-03	4.69E-03	4.35E-03	4.05E-03	8.48E-03	9.55E-03
P reactor power (kW)	62.70	16.25	35.92	11.05	122.59	35.14
G	2.51	0.65	1.44	0.44	4.90	1.41

(a) γt·(1+εc).
(b) The φ* variation with the subcritical level can be due only to large statistical errors (especially near criticality) in its evaluation.

4.2. MCNPX "reconstructed" calculations

The main requirement for the target is the production of a neutron source for the core as high as possible. Even if the neutron source depends, given a fixed electron beam, mainly on the target material, also the detailed feasible target configuration has to be considered. Uranium is the material providing the highest photoneutron production [9]. Some target concepts have been analyzed in [8]: the coolability of the system, the choice of the materials, the thermo-mechanical behaviour, the safety issues have been faced and discussed. Calculations by MCNPX have been performed, with the main purpose of estimating the different neutron sources (besides the power deposition distribution).

The first target configuration taken into account here is a bare uranium cylinder with r=3.25 cm and h=8 cm. This is not a feasible target solution since, for example, it does not allow a proper cooling, but it is useful for the estimation of the maximum achievable neutron yield (some geometrical constraints have to be taken into account since the target is to be placed in the central channel of the core).

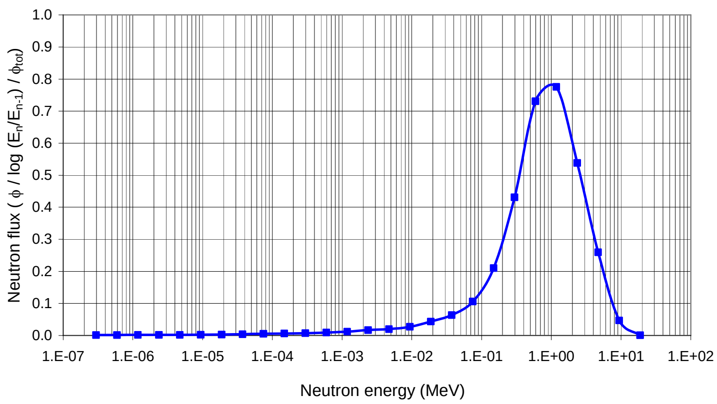
The second and the third target configurations are based on the conical geometry shown in Fig. 3. The materials considered are depleted uranium and tantalum. Tantalum was the choice

for the TRADE target, whose feasibility was already analyzed in [7]. The last configuration concerns a hollow uranium cylinder irradiated by the electron beam in its inner surface, where the power deposition is spread in order to allow the cooling.
The photonuclear reaction data used for the MCNPX simulations are the LA150u and the BOFOD libraries, both collected and reported in the IAEA photonuclear data library [10].

The neutron yields for the target configuration described above and calculated by MCNPX are reported in Tab. 2. The result for the uranium cylinder is compatible with that deduced from [9] ($1.03\cdot10^{-2}$ n/e), where total neutron yields for infinitely thick targets of different materials and at different electron energies are reported (the accuracy is quoted to be 20%). From Tab. 2 it can be deduced that these target configurations provide a neutron source close to the highest possible value (for a 25 MeV electron beam), while the tantalum solution provides a reduction of more than a factor of 2.

The spectrum of the neutron source, as escaping from the target (isolated from the core) is shown in Fig. 5. The peak of the curve is close to 1 MeV.

Figure 5: Spectrum of the neutron source.



Considering the SC2 configuration in the last column of Tab. 1, the transposition reported in Tab. 2 can be obtained.

Table 2: Parameters of the sub-critical systems.
(25 kW beam energy, 25 MeV electron energy)

Target type	Tantalum Conical	Uranium cylinder	Uranium Conical	Uranium Hollow Cylinder
Target neutron yield γ_t (n/e)	4.69E-03	1.09E-02	1.10E-02	1.09E-02
Core (γ,n) contribution ε_c	0.16[(a)]	0.07[(a)]	0.07[(a)]	0.07[(a)]
Total neutron yield $\gamma_t\cdot(1+\varepsilon_c)$ (n/e)	5.44E-03	1.16E-02	1.17E-02	1.17E-02
k_{eff}	0.97875	0.97875	0.97875	0.97875
ρ_{eff} (pcm)	-2171	-2171	-2171	-2171
Φ*	0.94	1.05	1.05	1.05
ρ_s (pcm)	-2310	-2068	-2068	-2068
<S> (n/s)	3.40E+13	7.26E+13	7.34E+13	7.29E+13
$g=\gamma_t\cdot(1+\varepsilon_c)\cdot\varphi^*$	5.11E-03	1.22E-02	1.23E-02	1.23E-02
P reactor power (kW)	18.81	44.91	45.39	45.09
G	0.75	1.80	1.82	1.80

[(a)] Values from Tab. 1.

5. Source-core coupling in UT-NETL and TAMU TRIGA configurations

5.1. MCNPX calculations for UT-NETL

Some analyses were performed for the 1-MW TRIGA reactor at the Nuclear Engineering Teaching Laboratory (NETL) at the University of Texas (UT). The UT-NETL core was explicitly modeled using MCNP-5 in a coupled electron/photon/neutron problem. Photonuclear data were taken from T-16 at LANL and the electron source was a 25 MeV beam with a 1-cm diameter beam spot. It was assumed a 25 kW beam power. Simulations were used to predict heat generation rates in fuel, neutron and γ-ray fluxes in detectors, and dose rates to personnel. A cylindrical uranium target was assumed in the central position (Fig. 6). Some results are summarized in Tab. 3.

Figure 6: UT-NETL core with central cylindrical uranium target.

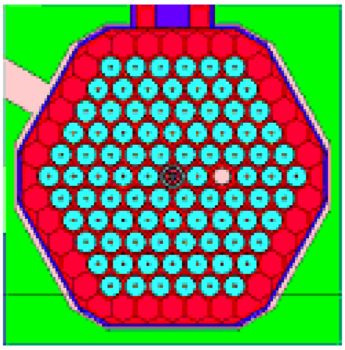


Table 3: Results for UT-NETL core.
(25 kW beam energy, 25 MeV electron energy)

k_{eff}	0.99200	0.97700	0.95300
ρ_{eff} (pcm)	-806	-2354	-4932
$g=\gamma_f\cdot(1+\varepsilon_c)\cdot\varphi^*$	4.34E-03 [(a)]	6.66E-03 [(a)]	9.01E-03 [(a)]
P reactor power (kW)	43.00	22.60	14.60
G	1.72	0.90	0.58

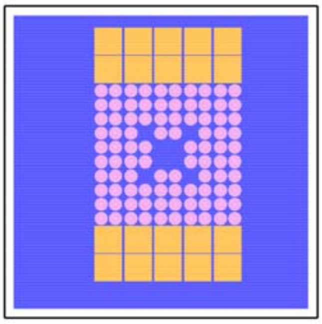
[(a)] Obtained by Eq. (4).

5.2. TRIPOLI calculations for TAMU configurations

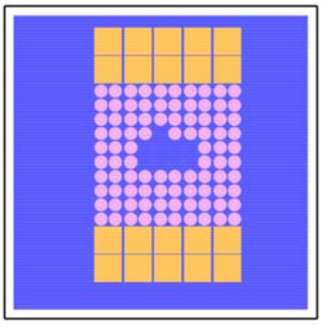
For the calculations performed by TRIPOLI4 Monte Carlo code [5], the geometry was a simplified "clean" TAMU (Texas A&M University) TRIGA core (Fig. 7) having the same fuel composition as for TRADE [2]. Cross sections were obtained from JEF2.2 nuclear data library [11-12], except lead and zirconium hydride which are not available. These data were obtained from ENDF/B-VI release 4.

Two core configurations, representative of SC2 (-3000 pcm) and SC3 (-5000 pcm) TRADE configurations [2], have been considered, with the external source located in central core position (Fig. 7).

Figure 7: Geometrical models.



$SC2 - k_{eff} = 0.96816$



$SC3 - k_{eff} = 0.95037$

The external neutron source was assumed to have a spectrum like photo neutrons obtained by a 20 MeV electron LINAC .electron's interaction with a Pb target. Tab. 4 show the obtained results , normalized to a source intensity $1 \cdot 10^{14}$ n/s.

Table 4: Core power and source importance for SC2 and SC3 configurations in TAMU TRIGA cores.

	SC2	SC3
Pfiss U5 (MeV/s)	3.04E+17	1.76E+17
Pcapture U5 (MeV/s)	1.90E+15	1.09E+15
Pfiss U8 (MeV/s)	9.37E+14	5.53E+14
Pcapture U8 (MeV/s)	9.11E+14	5.30E+14
total (watt)	4.93E+04	2.85E+04
Keff	0.96816	0.95037
M (amplification)	38.81988	22.31249
Ks = M / (1+M)	0.97489	0.95710
$\varphi^* = \rho_{eff} / \rho_s$	1.28	1.17

By assuming an Uranium Multiplate target working a 25 kW power, irradiated by a 25 MeV electrons beam (even if the spectrum used in the original data is relative to 20 MeV electrons), the following results can be reconstructed.

Table 5: Reconstructed results for SC2 and SC3 configurations in TAMU TRIGA cores. (25 kW beam energy, 25 MeV electron energy)

	SC2	SC3
Target neutron yield γ_t (n/e)	7.99E-03[(a)]	7.99E-03[(a)]
Core (γ,n) contribution ε_c	0.07[(a)]	0.07[(a)]
Total neutron yield $\gamma_t \cdot (1+\varepsilon_c)$ (n/e)	8.55E-03	8.55E-03
k_{eff}	0.96816	0.95037
ρ_{eff} (pcm)	-3289	-5222
φ^*	1.28	1.17
ρ_s (pcm)	-2590	-4486
<S> (n/s)	5.34E+13	5.34E+13
$g = \gamma_t \cdot (1+\varepsilon_c) \cdot \varphi^*$	1.09E-02	9.95E-03
P reactor power (kW)	26.36	15.22
G	1.05	0.61

[(a)] Values from Tab. 1.

6. Discussion

Figs. 8 and 9 show the core power vs. the subcritical level for the different targets taken into account. The results are normalized at 25 kW beam power. Some (somehow arbitrary) assumptions for the source importance φ* have been made when plotting the results.

Figure 8: Core power vs. subcritical level for no fissile targets

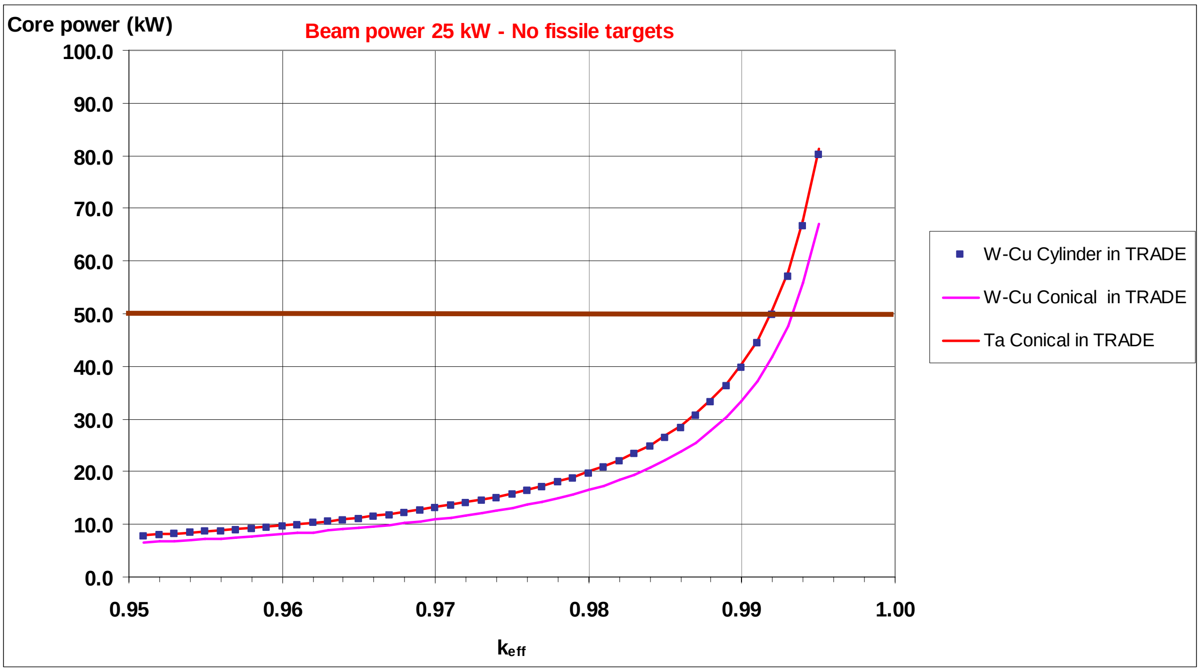
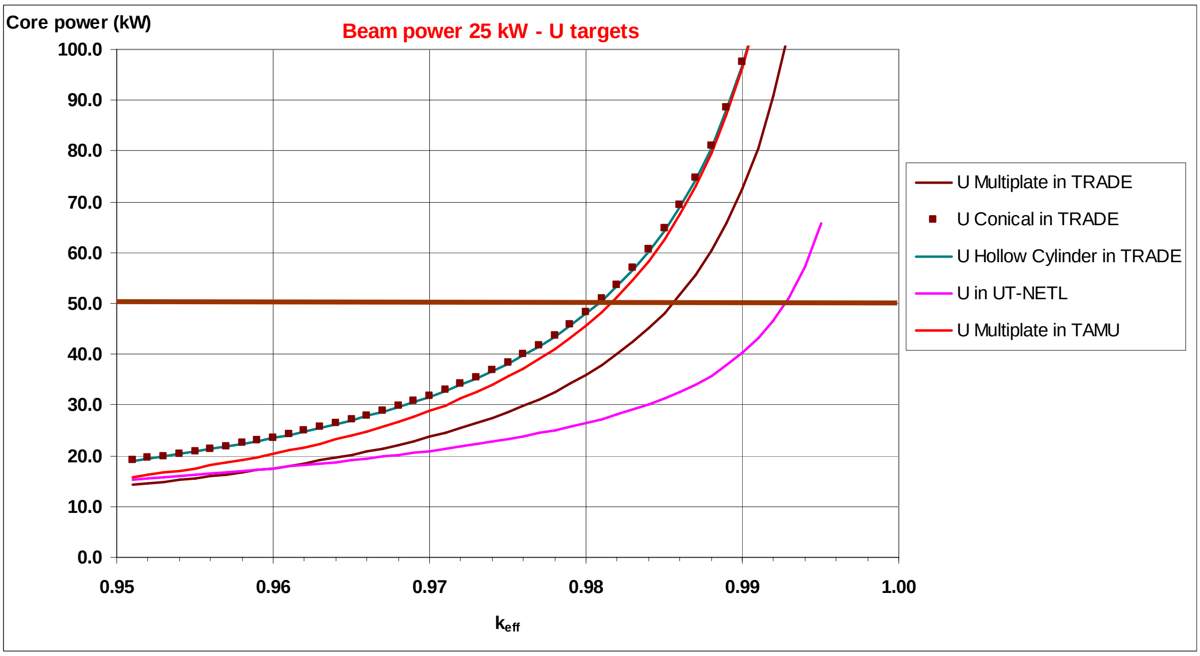


Figure 9: Core power vs. subcritical level for uranium targets



The analysis shows the requirements for an electron-driven coupling experiment in order to provide significant validation elements on the dynamic behavior of ADS, both in terms of target performance and of beam power characteristics.

The results show that it is necessary to have a U target in the central position of the TRIGA reactor to obtain a core power larger then 50kW for k_{eff}>0.98. Such a minimum power is required to appreciate feedback effects in the system responses in presence of source/reactivity transients, as indicated by a preliminary analysis of the influence of thermal reactivity feedback in RACE.

Some results for TAMU TRIGA configurations indicate a tighter target/core coupling with respect to the one relative to Casaccia Triga RC-1 (TRADE-e). This can be seen by comparing results in Fig. 9 relative to the same multi-plate target in central position in TAMU TRIGA and TRADE-e. Further investigations are needed.

The final check should be performed, in any case, for the actual core loading which could be envisaged for RACE-HP, when these experiments will be finally agreed.

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