# Possible Experiment for Study of ADS Dynamics

**D. G. Naberejnev[1*], M. Salvatores[2], F. G. Kondev[1], G. Palmiotti[2], G. Imel[2], T. Bauer[2] and F. Harmon[4]**

[1] *Technology Development Division , Argonne National Laboratory, USA*
[2]*Reactor Analysis and Engineering Division , Argonne National Laboratory, USA*
[4]*Idaho Accelerator center, USA*

## Abstract

The dynamics of an ADS must be experimentally explored across its full range of operation. This includes start-up, shutdown, and possible accident scenarios that include power excursions at different levels of subcriticality. With an ADS the transient behavior in "source dominated" deeply subcritical configurations will be very different from "core dominated" behavior in configurations near criticality (as quantified by the core delayed neutron fraction) when the standard feedback effects are dominant.

In this paper we propose coupling the low power, graphite moderated Transient Reactor Test Facility (TREAT) at Argonne National Laboratory with a centrally positioned external neutron source to be generated by photonuclear interactions (**TREACS**: **TR**eat **E**xperiments for **A**ccelerator-driven **S**ystems). We intend to address a number of issues related to the feasibility of ADS dynamics experiments in TREACS.

## 1 Introduction

Accelerator-driven systems are being considered as a valuable option to deal with the transmutation of spent nuclear fuel accumulated during the operation of conventional fission reactors over the past 50 years. Potentially serious problems exist in operating a conventional reactor using fuel made from stockpiles of spent nuclear fuel. Specifically, the low fraction of delayed neutrons and the presence of only small amounts of fertile materials in the fuel can lead to major difficulties in terms of control and reactivity coefficients (e.g. low Doppler effect). One possible solution is to consider a subcritical Accelerator Driven System (ADS) system, in which an external neutron source is used to maintain the proper level of system power.[1]

The dynamics of an ADS must be explored across its full range of operation. This includes start-up, shutdown, and possible accident scenarios that include power excursions at different levels of subcriticality. With an ADS the transient behavior in "source dominated" deeply subcritical configurations will be very different from "core dominated" behavior in configurations near criticality (as quantified by the core delayed neutron fraction) when the standard feedback effects are dominant.

So far, the dynamics of an ADS has been explored only through calculations. To advance the ADS concept, however, extensive experimental validation is required. Experimental investigations must be performed over a wide range of core powers and subcriticalities. Specifically, there is a strong need to experimentally validate theoretical

[*] Corresponding author: ANL, Bld.208, Argonne, IL 60439, USA, dimitri@anl.gov, tel: +1 630 2527402, fax: +1 630 2525287

models in the cases where (1) core dynamics regulates the system's response to external perturbations, (2) core power levels are high enough for core dynamics feedback to be important, and (3) external source behavior determines the core dynamics behavior.

Most ADS experiments to date have been performed using fast critical facilities, such as the MUSE program at Cadarache[2], and have mainly addressed a number of reactor physics issues related to these systems. In facilities such as MASURCA, physics measurements of parameters such as reaction rate distributions, source importance, and reactivity are made. In the last case in particular, fast critical assemblies can be used to determine and qualify methods of 'on-line' reactivity measurements that potentially can be used in a full-power ADS.

Although these experiments can provide much of the validation of the basic physics needed for ADS qualification, there are nevertheless important elements missing. For example, a zero power assembly cannot investigate the relationship among source importance, current, power and reactivity. For this, some heat rejection capability is needed that is not found in zero power critical facilities. In the same vein, the dynamic behavior of feedback effects induced by power and temperature cannot be studied at zero power.

The simplest approach to address the above two deficiencies in the current programs is to use an existing reactor that has sufficient power capabilities to study feedback effects. Moreover, one can obtain a kind of generic validation if one shows that the methods developed in a critical experiment (e.g., for on-line reactivity monitoring) are applicable to a full-power ADS as well. Specifically, C. Rubbia has recently proposed (within the frame of the European roadmap for developing ADS) coupling an existing TRIGA reactor with a proton accelerator that feeds a spallation target located at the core center.

As an intermediate step towards such a "full scale demonstration experiment", we propose coupling the low-power TREAT reactor at Argonne National Laboratory with a centrally-positioned external neutron source to be generated by photonuclear interactions.

In this paper we address the feasibility and significance of ADS dynamics experiments with the TREAT reactor. Details of the facility and a possible experimental program, including measurement techniques and physical phenomena to be studied are provided.

As specified in the Ref. 3, three levels of validation of an ADS should be considered. First is the validation of the different concepts for components: accelerator, target, and physical characteristics of subcritical cores. Second is the validation of the coupling of these different components. Finally, the third is 'proof of principle' experiments. In these experiments an ADS should be validated as a system in all its modes of operation. The proposed experiment in TREAT is of the type required by the level 2 of validation.

## 2 Characterization of different TREACS components

### 2.1 External neutron source

A neutron source produced by an electron accelerator is an attractive choice for the TREACS experiment due to accelerator availability, cost, and construction considerations. The interaction of electrons with the target nuclei directly releases relatively few neutrons. The most significant neutron contribution comes from interactions of high-energy photons (bremstrahlung) with the target nuclei, mainly through (γ,n) and (γ,2n) processes in the energy range of the so-called ``giant dipole resonance``. In general the neutron yield increases with the atomic number of the target material and the energy of the incident electrons. When a fissionable material, e.g. Th, U or Pu, is used as a primary target, there is an additional increase in the yield due to the emission of prompt fission neutrons. The resultant photoneutron spectrum has two components. The largest one (Maxwellian) is due to the evaporation of neutrons from excited nuclei, and it is nearly isotropic. The second, smaller component comes from direct reactions and the emitted neutrons follow the direction of the incident electrons. The energy composition of the photoneutron spectrum is similar to that expected from a proton spallation target.[4]

We have performed a dedicated analysis to characterize photoneutron production in the target using the MCNPX code (Version 2.2.6)[5]. Specifically, we carried out the assessments of the target's material composition, its geometry and, finally, the choice for the energy of the electron beam. Calculations suggest that a metallic uranium target would have one of the best photoneutron production characteristics. Figure 1 shows the neutron yield as a function of the target thickness (Δt), when 20 MeV electrons collide with a cylindrical U target (5 cm in radius). The calculations indicate that the neutron production rises significantly when the thickness increases within the range of 0 to1 cm. The yield, however, saturates at Δt>2-3 cm with a typical value of 0.00638 n/e- (Δt=3 cm).

We also investigated one of the possible ways to increase neutron production, for example the use of a beryllium shell of various thicknesses (typically 10-20 cm) that surrounds the target.

It was concluded that the effect of Be on neutron production can be significant, if the thickness of the U target is kept below 1 cm. For instance, in this case one might achieve up to 50% increase in yield mainly due to the lower (γ,n) threshold for Be ($B_n$=1.7 MeV). However, the gain from the Be shell becomes negligible when the thickness of the production target exceeds 2 cm, due to the severe attenuation of the bremstrahlung intensity in the U converter.

The dependence of the neutron yield on the electron beam energy is shown in Figure 2. One concludes that the beam energy in the 35-40 MeV range would be optimal in order to achieve necessary neutron production, as well as to compensate for energy losses in the target cooling system window.

Calculations indicate that 40 MeV electrons incident on a 5 cm thick cylindrical U target would produce approximately 0.0244 neutrons per electron. Hence, a yield of ~$5*10^{13}$ n/s can be expected when the average beam intensity approaches 300 µA (12 kW beam power on the target). An accelerator with such characteristics will be assembled at the Idaho Accelerator Center (IAC), which is one of the premier electron beam facilities in the U.S. (http://www.physics.isu.edu/sac). Future experiments, aimed at benchmarking the predicted photoneutron yield, energy and angular distributions, are planned at IAC. These measurements would be especially important for the high-energy ($E_{e-}$>20 MeV) regime, where the photonuclear cross-sections are not very well characterized. In order to address radiation shielding and safety issues, measurements of the bremstrahlung spectra from the designed U target are also envisioned.

We consider two possible designs of the target. One is to use a metallic uranium cylinder. The second design is to use EBR-II reactor pins assembled in a bundle. In both cases a cooling system must be used to remove the heat accumulated from the electron and gamma interaction in the target.

A significant fraction of the incident electron beam's kinetic energy will end up as heat in the target. Thus, the "vehicle" for positioning the target at the center of the TREAT core must (1) ensure its isolation from the TREAT fuel and (2) provide an efficient mechanism for target cooling. Present target vehicle concepts envision a long (~4 m) vertical tube, one end containing the target at the center of the TREAT core and the other end terminating at a heat exchanger above the reactor. A preliminary concept for efficient heat transfer between the target and heat exchanger utilizes a closed boiling water cycle employing evaporation at the target surface, free two-phase convection upward through the tube, and condensation in the heat exchanger.

## 2.2 TREAT reactor description and criticality study of different configurations

### *2.2.1 General core design and composition*

The Transient Reactor Test Facility (TREAT), located at the Argonne National Laboratory-West site in Idaho, has been used for more than 30 years for in-pile transient testing of a wide range of reactor-related fuels, components, and assemblies. The TREAT core, fueled by uranium dispersed within a graphite matrix with a near thermal neutron spectrum, is basically an assembly of solid, vertically-elongated 4" square fuel elements. Removal of some of these elements allows for creation of a large "hole" for experimental access to the core center. Additionally, multiple control rod elements allow for large reactivity swings that may be used for robust transient operation and attainment of criticality under a wide range of core and experimental configurations. TREAT is capable of safely operating in a high-power pulse mode, where transients are limited thermally by near-adiabatic heating of the fuel elements, as well as in a low-power steady-state mode utilizing a limited-capacity forced (or natural-convection) air cooling through small engineered gaps between the fuel elements. Allowable TREAT configurations and operating parameters include: (1) test hole sizes up to 20 cm, (2) reactivity swings up to ~8% from critical, (3) forced air heat rejection for power levels up to ~100 kW, and (4) up to ~2000 MJ energy release in pulse mode.

TREAT's core can accommodate 361 fuel elements in a square, 19 x 19 matrix. The total core size is approximately 193 x 193 cm. The reactor is air cooled by natural convection and forced convection can be imposed at high power levels if necessary.

Standard fuel element consists of three axial zones. The fuel zone of TREAT is ~120 cm high and is filled with a $UO_2$-graphite mixture. The fuel is canned in zirconium and is sandwiched between zirconium spacers at the top and bottom. The upper and lower (both ~60 cm tall) reflectors follow the spacers. The reflectors are CP-2 (Chicago Pile 2) graphite canned in aluminum.

The fuel is a homogeneous mixture of uranium dioxide $UO_2$ and CP-2 graphite with a total reported fabrication density of 1.7248 g/cc. The ratio of carbon to $^{235}U$ atoms is 10000. The $^{235}U$ enrichment is 93.24 wt %. Reported boron and iron impurities in the fuel are 7.6 ppm and 600 ppm correspondingly.

The uncertainty in the boron impurity level in the fuel in TREAT has a significant impact on the results of reactor physics analysis. According to Ref. 2, 1.25 g of core fuel samples were analyzed for boron impurities in the past. The spectrochemical and chemical analyses of the samples showed that the boron content in the fuel ranged from 4 to 13 ppm. The average value given by the authors of Ref. 6 is 7.6 ppm. From our preliminary analysis we concluded that a change in the boron content in fuel by 1 ppm results in nearly a 1% change in $k_{eff}$ of the system. In the absence of detailed information on the boron impurity, we used the value of 7.6 ppm in our work.

The control rod fuel element has the same geometry as the standard fuel element except for a circular hole in the center where a standard TREAT control rod ( ~4.5 cm O.D.) is placed. Axially the control rode consists of 3 different sections. First, the poison section is a carbon steel tube (~150 cm long) filled with boron carbide $B_4C$. Second, the follower section is a Ziorconium tube (~150 cm long) filled with CP-2 graphite. The last steel follower section is a carbon steel tube (~225 cm long) also filled with CP-2 graphite.

Besides the standard fuel elements there exists a number of modified elements. These include graphite dummy elements (filled with CP-2 graphite, no fuel), and slotted fuel elements (with a 24' or 48' opening in the center) that provide the access for the hodoscope to the center of the core. This allows one to have an important flexibility in arranging the core for ADS type experiments to provide the access of the electron beam, cooling of the target, etc.

An axial reflector surrounds the core. The reflector is made of blocks of CP-2 graphite with a total thickness of ~60 cm. It is separated from the core by an air gap of about 5 cm.

Using the information described above we constructed a detailed 3D MCNP model of the TREAT reactor. There exist in the literature descriptions of various critical configurations of the TREAT core. We used two of them to benchmark our calculations.

### *2.2.2 Study on the critical configurations of the TREAT core*

The initial, so-called 'minimal critical core' is shown in Figure 3. The initial critical configuration of the core consisted of 122 standard fuel assemblies, 11 thermocouple assemblies and 8 control rods. The dummy graphite assemblies were used to load the rest of the core. In this case all 8 control rods were pulled out of the core so that the $B_4C$ poison section was above the upper reflector.[7]

The resulting effective multiplication factor of the system computed with MCNP is $k_{eff}=1.00945\pm0.00201$. This result is considered satisfactory since the exact boron content in the fuel is not very well known and its impact is crucial.

The second critical configuration we consider here is related to the M8 CAL series experiments.[8] In these experiments an experimental vehicle was placed in the center of the core. The experimental vehicle has been used in TREAT to hold pins of fuel to be tested. In the M8 CAL configuration the experimental vehicle was empty. Half-width fuel assemblies surrounded this vehicle. The full slotted core for this configuration with the corresponding positions of the control rods in the critical state was modeled with the MCNP code. The geometry is shown in Figure 4. The body of the experimental vehicle contains a small quantity of dysprosium. We do not have MCNP libraries for Dy, so in our calculation Dy was replaced with Gd. The effect of the presence of the dysprosium on keff versus air was estimated at ~1 %. The resulting $k_{eff}$=0.99965 ± 0.00284 reflects a good agreement between calculated and experimentally observed quantities.

In Figure 5 we show the proposed experimental arrangement of the core for TREACS. It was decided to keep the hodoscope in place for use in future experiments. The 5 cm in radius and 5 cm thick $^{238}U$ cylinder target was placed in the central assembly. The resulting $k_{eff}$=1.07904 ± 0.00298 shows that one has sufficient control rod reactivity to operate at the desired (keff = 0.9 to 1) subcriticality levels.

## 3 Coupling of the components. Point kinetics study of different transients in TREACS

In this section we describe a coupling of the accelerator with the TREAT core and the study of different power excursions at different subcriticality levels. A modified version of the TREAT point kinetics program TREKIN, which includes the external neutron source, was used to study subcritical transients, some beginning from deeply subcritical condtions and some from conditions closer to critical.

Operating at high power at a substantial subcriticality level (say –0.1 Δk/k) requires a powerful external neutron source. In other words the initial power $p_0$, the external source capacity q and initial subcriticality level $\rho_i$ are interrelated quantities: $p_0 = -q\Lambda/\rho_i$. Here Λ is the neutron lifetime. This value in TREAT equals $9*10^{-4}$ s.

The TREKIN code contains tabulations of the TREAT temperature reactivity feedback. The major temperature feedback in TREAT is the increase in "average neutron temperature" as the reactor power increases. TREAT fuel is a mixture of graphite and $^{235}U$ in proportion of about one atom of $^{235}U$ for 10000 atoms of C. When the temperature of the fuel rises, this increases the kinetic energy of the atomic thermal vibrations pushing the effective neutron energies towards higher values. Since in the thermal range the fission cross section of $^{235}U$ decreases at higher neutron energies, this produces a negative effect on the TREAT reactivity.

It is worth mentioning what limitation of the power excursion in TREAT one should expect. The important characteristic for the safety of experiments is integrated power. The safety considerations for the reactor impose the peak power limitation of ~ 10000-16000 MW. The integrated power must be limited to the range of 1400 to 2100 MJ. Finally, the introduced reactivity should not exceed 4.5-5.8 % Δk/k. Nevertheless, the only severe limitation on transients in TREAT is the average core temperature. It is set to the maximum of $600^o$ C.

Table 1 illustrates the external neutron source required to sustain different power levels at different subcriticalities of interest to the present investigation. As seen from this table, to operate at substantial power levels requires a high production neutron source. To keep the cost of the accelerator low and the accelerator part of the project compact, the neutron production should not exceed ~5-7E13 n/s. This allows us to work at power levels around ~50 kW depending on the subcriticality level.

Two types of transients are of interest to the TREACS experiments. The first one is related to accelerator power excursions. To compensate for the burnup during fuel cycle (and consequent lowering of $k_{eff}$), the accelerator power should have a reserve that exceeds its initial neutron production by the factor of ~2. The concept of an ADS system might be based on a core without control rods. This is to avoid any possibility of an accident related to the presence of an externally imposed reactivity in the core. Therefore it is important to study the behavior of the core in the case of accelerator power excursions even if the probability of such an accident is extremely small, as seen from the point of view of the accelerator expert. In this note we compare the simulation of the accelerator power change by the factor of 1.8 used in the previous work on accident analysis in an ADS.[1] This number is taken from the reference and changes as a function of the system type and fuel composition. Control rod movement initiates the second type of transient. This issue is still under discussion whether or not ADS power should be maneuvered with control rods. We study this type of transient in this paper bearing in mind that in TREACS the control rod movement can be used to simulate the burnup process. At any rate, independent of the presence of control rods, the situation which was studied corresponds to a generic reactivity insertion in the subcritical core.

In Figure 6 we show the 'source initiated' transients at different TREAT power levels and at different subcriticality levels. These levels cover the range from 'source dominated' regimes (several dollars subcritical, where one dollar corresponds to the fraction of delayed neutrons), to 'core dominated' transients (keff close to 1). The response of the near critical system is dominated by the core feedback. This effect is rapid and very pronounced at high power levels. At lower powers the feedback effect is less pronounced and is delayed in time, since the integrated power is not sufficient for the feedback to be effective. There is no significant difference between power excursions at k=0.95 and k=0.995 at lower power levels (2 kW for instance). To accommodate the possible experiment to the given level of external neutron source, operation at a power level around 50 kW is a good option.

As an example, we considered rod initiated transients with consequent total accelerator shutdown at initial power level of 50 kW (Figure 7). At t=10, 500 pcm of reactivity is inserted with control rods. The qualitative behavior of the system is very similar to the previous case. At t=500 s we simulated the accelerator shutdown after which the power level of the core rapidly decreases.

## 4 Physics measurements

A number of physics measurements are planned for performance in TREACS. The expertise accumulated during MUSE series experiments can provide support for the TREACS project.

Several fundamental measurements will be done. Among these we cite the investigation of the external source importance i.e. the ratio of contribution of source neutrons to fission neutrons.

[1] M. Eriksson and J. E. Cahalan, *Applicability of passive safety to accelerator-driven systems*, ANS meeting, Reno, 2001.

The relation of the accelerator power and core power in the presence of feedback can be investigated. This can be done only in a system with sufficient power levels and substantial feedback.

The TREAT reactor is a thermal system. The presence an external source assures a large number of high-energy neutrons in the vicinity of the target. Thus, threshold fission reactions such as U238 and Np137 can be used to deduce spectral information. This information as a function of distance might be needed to study the behavior of different buffers and assess the eventual material damage rates in the buffer zone of a real size ADS.

It will be necessary to develop or improve existing methods of subcriticality measurements and expand them to the systems at power. Until now these kinds of measurements were only performed at zero power systems (MUSE). An extensive experimental validation of these methods in a subcritical system at power is needed.

## 5 Conclusion

The description of the first validation experiment for ADS using the TREAT reactor is given. Different components of TREACS (**TR**EAT Experiments for **AC**celerator-driven **S**ystems) were described. Possible photonuclear target designs for the experiments are described. Point kinetics studies show that the proposed TREAT reactor coupling experiments are very prototypic of the dynamic behavior of an ADS. The reactivity reserve, movement of control rods, and core arrangement of the TREAT reactor can be easily used to accommodate the needs for this type of experiment.

## Acknowledgment

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| | | Initial reactor power (kW) | | | |
|---|---|---|---|---|---|
| | | 2 | 10 | 50 | 80 |
| $k_{eff}$ | $\rho$ | | | | |
| 0.90 | -1.11E-01 | 7.72E+12 | 3.86E+13 | 1.93E+14 | 3.09E+14 |
| 0.91 | -9.89E-02 | 6.87E+12 | 3.43E+13 | 1.72E+14 | 2.75E+14 |
| 0.92 | -8.70E-02 | 6.04E+12 | 3.02E+13 | 1.51E+14 | 2.42E+14 |
| 0.93 | -7.53E-02 | 5.23E+12 | 2.61E+13 | 1.31E+14 | 2.09E+14 |
| 0.94 | -6.38E-02 | 4.43E+12 | 2.22E+13 | 1.11E+14 | 1.77E+14 |
| 0.95 | -5.26E-02 | 3.65E+12 | 1.83E+13 | 9.14E+13 | 1.46E+14 |
| 0.96 | -4.17E-02 | 2.89E+12 | 1.45E+13 | 7.23E+13 | 1.16E+14 |
| 0.97 | -3.09E-02 | 2.15E+12 | 1.07E+13 | 5.37E+13 | 8.59E+13 |
| 0.98 | -2.04E-02 | 1.42E+12 | 7.09E+12 | 3.54E+13 | 5.67E+13 |
| 0.99 | -1.01E-02 | 7.01E+11 | 3.51E+12 | 1.75E+13 | 2.81E+13 |
| 0.995 | -5.03E-03 | 3.49E+11 | 1.74E+12 | 8.72E+12 | 1.40E+13 |
| 0.9995 | -5.00E-04 | 3.47E+10 | 1.74E+11 | 8.68E+11 | 1.39E+12 |

Table 1. Correspondence between reactor power, subcriticality level and required external neutron source (in neutrons/s)

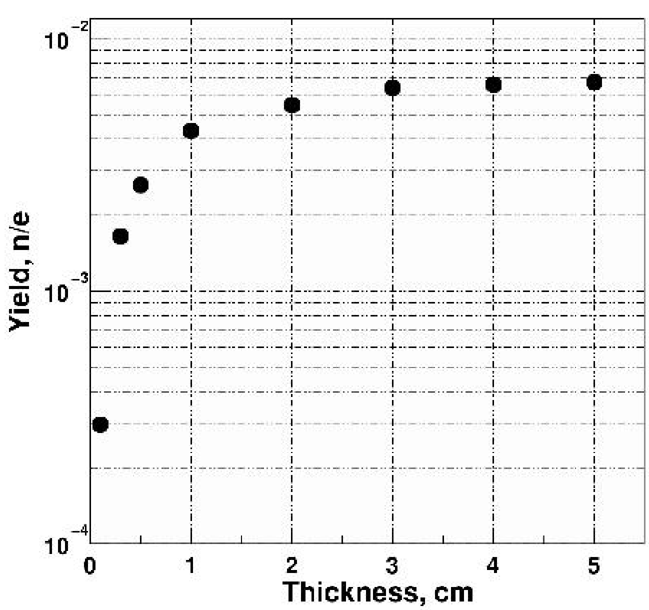


Figure 1. The photoneutron yield produced from a cylindrical U target for 20 MeV electrons incident on target of various thickness

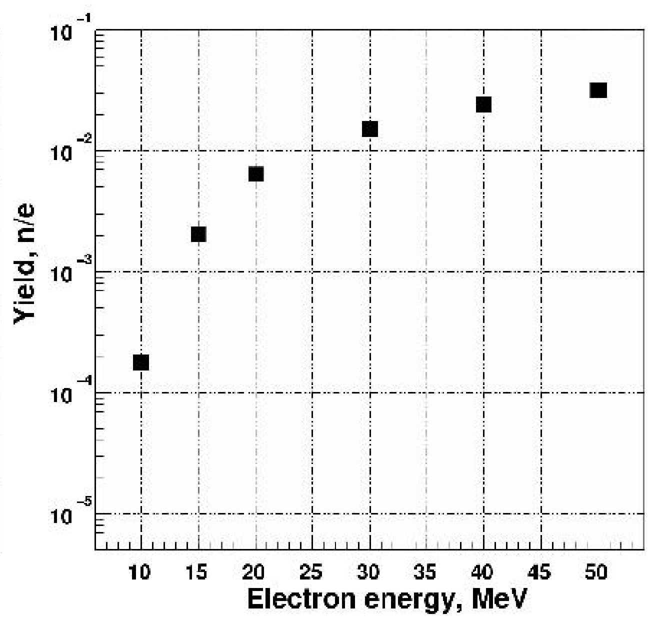


Figure 2 The photoneutron yield produced from a cylindrical as a function of the electron beam energy from a 3 cm thick target.

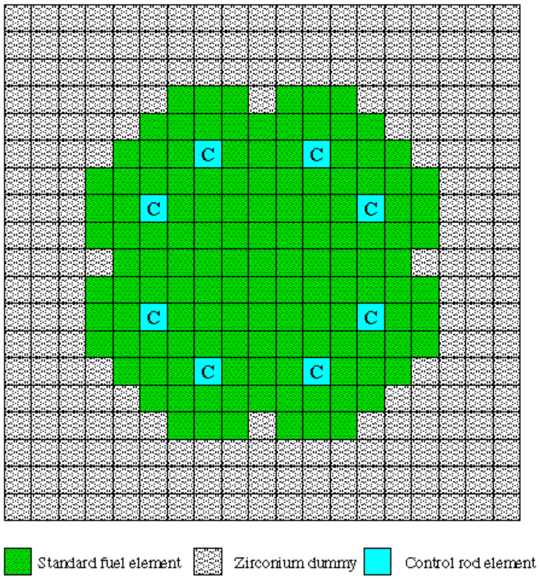


Figure 3. Minimal critical configuration of TREAT

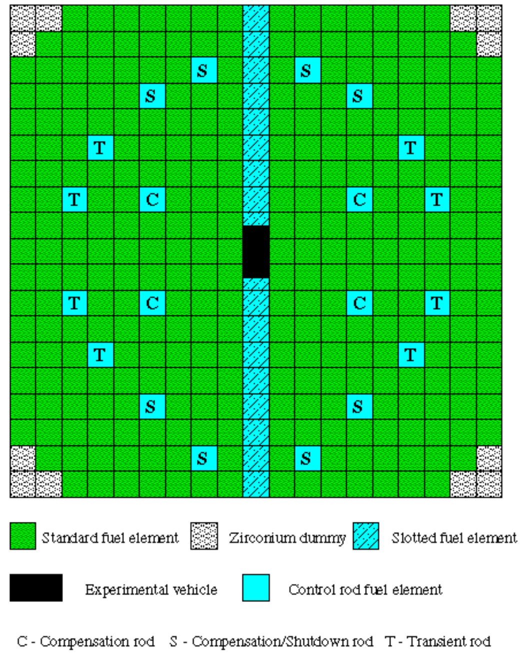


Figure 4 M8CAL critical configuration

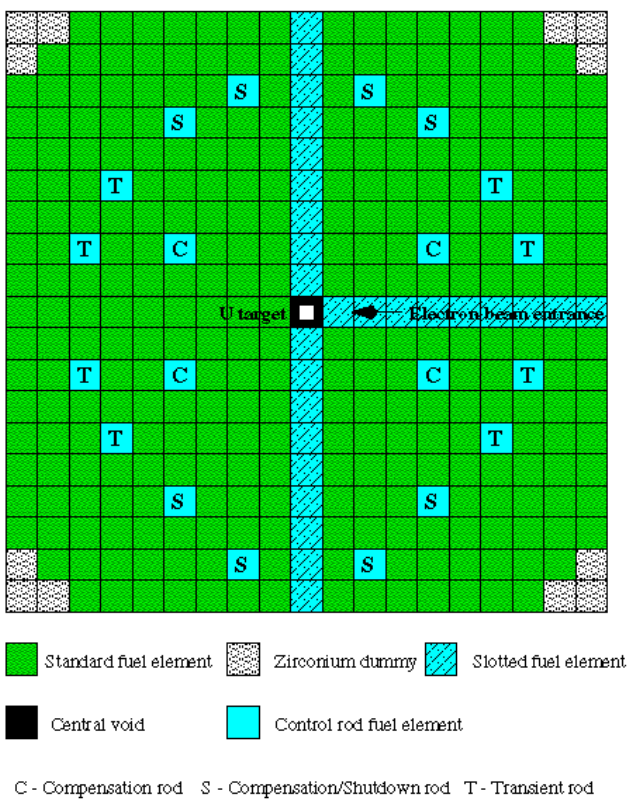


Figure 5. Proposed setup of the TREAT core for TREACS experiments

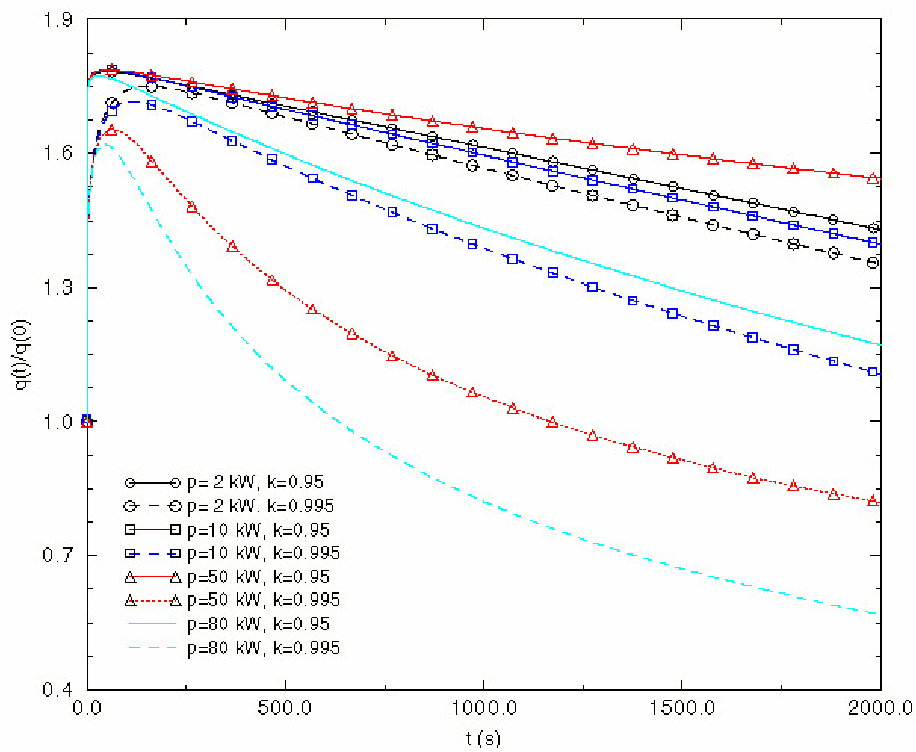


Figure 6. Source initiated power excursions in TREAT. At t=s the accelerator power is increased by the factor 1.8.

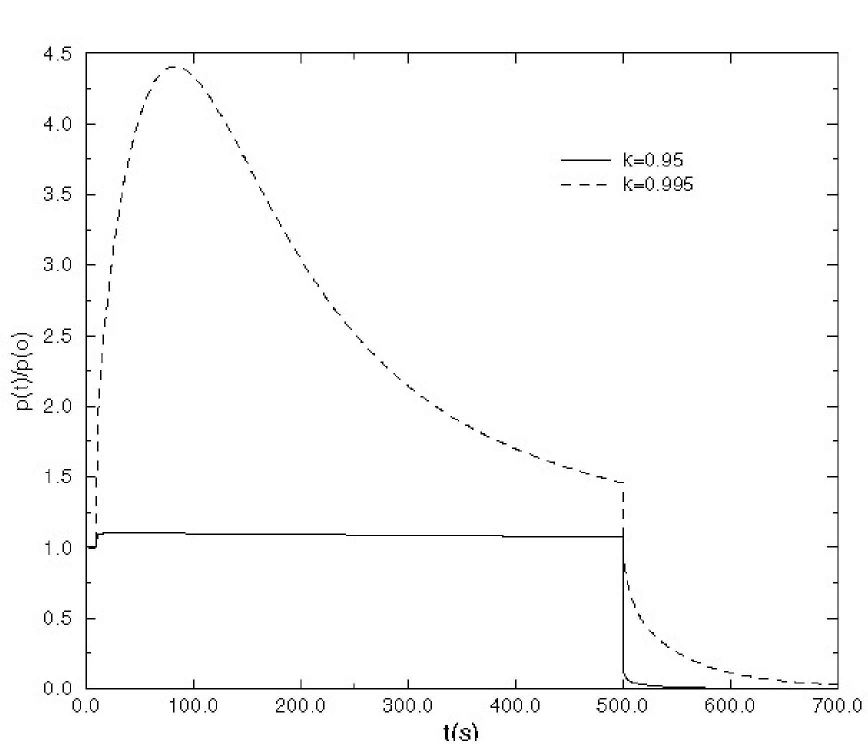


Figure 7. Control rods initiated power excursion in TREAT at 50 kW. Insertion of 500 pcm of reactivity at t=10 s. At t=500 s the accelerator is shut down.

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