Requirements for experimental activities on the coupling of an accelerator, a spallation target and a sub-critical blanket

compiled by

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1. Introduction

Within the original structure of the IP EUROTRANS experimental information on the coupling of an accelerator, a spallation target and a sub-critical blanket was expected from the TRADE-Plus programme to be performed in the TRIGA reactor at Cassacia, Italy. The objectives of this programme were defined as follows[6]:

Realisation and Operation of the experimental facility TRADE to demonstrate the coupling between proton accelerator, spallation target and sub-critical blanket at sizeable power (several 100 kWs) in presence of thermal reactor feedback effects. The expected outcomes of this domain – in terms of proof of stable operability, dynamic behaviour and definition of licensing issues of an ADS - are crucial for and give input to the future i.e. to Domain 1: Design.

The proposed Work Plan of DM2_TRADE-PLUS addressed the following main issues:

- Design, follow-up of construction and commissioning of the specific modifications to the existing TRIGA reactor, including system transient analysis, safety and licensing.
- Target system design, realisation and qualification.
- Design, follow-up of construction and commissioning of the Beam Transport Line and of the Test Station for out-of-pile beam adjustment and final target qualification under irradiation.
- Shielding, dose and radiation damage analysis of the whole system from the accelerator complex to the reactor building.
- Development of instrumentation adapted to sub-critical systems for reactivity monitoring and control and sub-critical power diagnostics.
- Preliminary in-pile experiments for sub-critical core characterisation and instrumentation assessment.
- Commissioning tests of the whole system up to full power.
- Performance and assessment of in-pile sub-critical experiments under steady state and transient operational conditions of an ADS.

Transposition of experimental results and safety and licensing issues of the TRADE facility in support to the design of the ETD as defined in DM1 DESIGN.
At the end of 2004 ENEA decided to withdraw from the TRADE-PLUS project and therefore it became necessary to evaluate possibilities whether there are alternative experimental projects on the way or planned which could provide similar information as the one expected to be provided by the TRADE-PLUS Programme. On the other side this development gave the opportunity to review the requirements for experimental support to improve the knowledge about the impact of the coupling of an accelerator, a target and a sub-critical blanket on operational and safety aspects. Results of this review will be reported hereafter.

As a consequence of the elimination of the TRADE-PLUS domain from the IP EUROTRANS a new domain ECATS was introduced with the following objectives [5]:

DM2 ECATS: With a view to assisting the design of XT-ADS and EFIT, provide validated experimental input from relevant experiments at sufficient power (20-100 kW) on the coupling of an accelerator, a spallation target and a sub-critical blanket. These experiments should provide design input on the dynamics and experimental techniques of such a coupled system with feedback effects, together with shielding, safety and licensing issues. The work programme of this domain and the domain coordinator will be specified after the completion of a feasibility study that will be started at the beginning of the project. (Interim Domain Co-ordinator: FZK, DE).

2. Background information

Results of the PDS-XADS project [7] define the initial status of recommendations of the most probable outcome of design specifications of the XT-ADS and EFIT to be developed in more depth and detail within the Domain Design during the initial phase of the IP EUROTRANS. Respective preliminary recommendations related to design aspects of the two design variants of an ADS system to be considered in the IP EUROTRANS are listed in Table I. From these data it can be seen that the two designs cover a relatively large spectrum of design options which implies that the supportive experimental programme must cover a quite broad spectrum of initial and transient conditions as well.

Conclusions drawn at the end of the MUSE project [8] and first results of experiments performed in the YALINA facility [9] define the currently achieved status of measurement techniques for determination of the reactivity level to be applied in an ADS system. Based on the results of the different measurement performed in the different configurations with various methods during the MUSE FP5 Project, it became clear that no unique measurement technique can be proposed to measure the different kinetic parameters and especially the on-line reactivity monitoring.

As the final goal is to provide an accurate and robust on-line measurement of the reactivity during power operation and during loading operations no single experimental technique can accomplish these tasks. Since only few techniques can act as an on-line indicator for reactivity and these techniques require additional information to extract the reactivity, additional measurement techniques are needed. Therefore only a combination of techniques will be able to solve the task and a step-wise and in-depth approach of reactivity determination will be proposed.

For on-line reactivity monitoring, the current-to-power indicator seems the most appropriate choice since it seems to be a simple and robust indicator with a small relative uncertainty. This reactivity prerequisites the knowledge of a proportionality factor containing the detector

Table I Preliminary design characteristics of the XT-ADS and EFIT designs

	XT-ADS	**EFIT**
Design level	Advanced design	Conceptual design
Coolant	Pb-Bi	Pure Lead (backup: Gas)
Primary System	Integrated	Integrated
Power	50 to 100 MWth	≥ 300 MWth
Core Inlet Temp	300°C (350°C)	400°C
Core Outlet Temp	400°C (430°C)	480°C
Target Unit interface	Windowless	Windowless (backup: window)
Target Unit geometry	Off-center / Centered	Centered
Fuel	MOX (accept for a few MA Fuel Assemblies)	(Pu, Am)O_2 + MgO (or Mo)
Av. Fuel Power density	700 W/cm³	450 to 650 W/cm³
Fuel pin spacer	Grid	Grid
Fuel Assembly type	Wrapper	Wrapper / Wrapperless
Fuel Assembly cross section	Hexagonal	Square (based on BREST and PWR design)
Fuel loading	Top / Bottom TBD	Top
Fuel monitoring	T and FF (per FA)	T and FF (per regions)
External fuel handling	RH oriented	TBD
Primary coolant circulation in normal operation	Forced with mechanical pumps	Forced with mechanical pumps
Primary coolant circulation for DHR	Natural + Pony motor	Natural + Pony motor
Secondary coolant	Low pressure boiling water	Superheated water cycle
Reactor building	Below grade	Below grade (partially)
Seismic design	TBD (site specific)	Antiseismic supports (horizontally)
Structural Material	T91 and A316L	TBD
Accelerator	LINAC (power: 2 ~ 5 MW)	LINAC (power: TBD)
Beam Ingress (1)	Top	Top

(1) Proton beam specifications of the two designs show that the envisaged machines belong to the category of the so called HPPA (High-Power Proton Accelerators) with a proton energy ranging from about 350 MeV for the XT-ADS up to the range of 800 to 1000 MeV for the EFIT design with a maximum beam intensity of up to 20 mA CW on the target in case of the EFIT design. The proton beam structure recommended is a CW-based time structure with additional short and well defined (sharp edge) beam interruptions of about 200 μs with a repetition frequency in the order of 1 Hz. These beam holes, shutting down the neutron

power source from time to time, should enable continuous and accurate on-line measurements and monitoring of the reactor sub-criticality.

efficiency and the source importance. Since both parameters can change during reactor operation and loading, it is important to check this proportionality constant on a regular basis. In between checks, one should then be able to guarantee that the proportionality constant remains constant over the considered period. This can be accomplished by monitoring signals which together determine the source characteristics such as the beam position, proton energy etc. By calculating the reactivity sensitivity coefficients for these source signals, the overall bias due to an unknown variation in the proportionality constant can be limited by bounding the acceptance range of the source signals. In this way, the current-to-power reactivity indicator can serve as a reliable and accurate on-line reactivity monitoring technique.

The verification of the proportionality constant of the current-to-power indicator will have to be accomplished by independent measurement techniques. To limit the perturbation to the power operation of the ADS, benefit would be taken from the unavoidable occurrence of beam trips. At every beam trip the response of the reactor could be recorded. Since the repetition-rate of these beam trips is unpredictable and probably not sufficient to obtain desired statistics on the measured parameters, an imposed repetition of induced beam trips could be foreseen.

The candidate measurement techniques to be used in these experimental conditions are either a Prompt Decay fitting technique or the ADS Prompt Jump technique. The ADS Prompt Jump technique is based on the determination of the removal of the prompt neutron part as in the rod-drop technique. In practice, the levels before and after the beam trip will be measured.. By averaging the level after the beam trip over a certain time period (in the order of some hundreds of microseconds), the uncertainty will be strongly decreased, but a possible small bias may arise due to the decay of the delayed neutron population. Measurements will have to evaluate how the investigated period can be optimized in terms of uncertainty and bias, but also with respect to operational conditions of the ADS. The main advantage of this technique is related to the fact that no fitting, based on an interpretation model, has to be performed.

In the Prompt Decay fitting technique, the investigated period after a beam trip can be much shorter, since only the die-away of the prompt neutron population is recorded. From the measurements in MUSE it was demonstrated that the decay of the prompt neutron population cannot adequately be represented by a mono exponential. Therefore more complex interpretation models are needed among which the kp-method seems to be the most robust and promising one. The kp-method however heavily depends on calculation input which could be considered as a drawback. One still has to be cautious in extrapolating the results obtained in MUSE for the Prompt Decay fitting techniques to a real ADS since the beam structure in both situations is different. For a real ADS the decay after the interruption of a continuous beam will be investigated instead of the response to an impulse as in MUSE. Since the prompt neutron decay in both situations is different, the extrapolation of the results with regard to the applicability has to be confirmed by future experiments.

In order to calibrate the above mentioned techniques, additional independent and robust measurement techniques have to be applied. The standard approach followed in critical reactors by using a rod-drop and in combination with the MSM-technique is not feasible in ADS, since the critical state of the system is not intended to be reached. For the purpose of calibration dedicated experimental conditions can be envisaged, such as zero-power conditions. These calibrations could be incorporated in the loading and start-up procedures of the ADS. In these circumstances, dedicated external sources could be used to drive the system. One possibility could be to use a pulsed neutron source as in MUSE and apply the PNS Area method which has been shown to be a very simple and robust measurement technique. The use of an external isotopic source in a standard source jerk measurement was seen to be less attractive for reasons of radioprotection, practical implementation and measurement accuracy.

3. Needs of experimental support

Seen from IP-Eurotrans DM1 a robust on-line and continuous sub-criticality monitoring based on first principle measurement has to be established. This on-line monitoring technique has to yield valuable information about the rapid relative change of the reactivity. The simplest approach is based on a measurement of the current I and on the power level P (through a fission chamber). Given the fact that the source strength is proportional to the beam current and that the power level is proportional to the fission chamber response one can get access to the reactivity through the following formula:

$$P=q\frac{\langle S\rangle \varphi^*}{-\rho}$$

where P stands for the thermal power, q is the energy released per neutron fission, S is the source, ρ the reactivity (Keff-1/Keff) and φ^* the importance of the source. Any change in the reactivity is accessible through the current I and the power P. The theory associated to that type of measurement is the Multiplied Source (MS) method. This method is a relative measurement and one needs an absolute measurement at first and then from time to time to verify that the other terms remains constant

The absolute value of the reactivity of this on-line indicator has to be provided by an absolute sub-criticality measurement technique which will be checked at different k_{eff} values. Various techniques are available for acquiring absolute reactivity values such as:

the **Prompt Neutron Decay method (PND)** and
the **Source Prompt Jump method (SPJ).**

which can be used in different stages of the start-up procedure and during ADS operation. As mentioned above there are some feedbacks from MUSE experiments which demonstrate that these techniques need to be further validated. In particular, all these techniques rely in fission chambers and these fission chambers should be located within the core. Moreover the space-dependent and source-dependent validity of the sub-criticality monitoring techniques will have to be guaranteed.

Besides the kinetic behaviour, also the dynamic behaviour (including thermal effects) will need to be fully mastered because transient dynamics (safety) of sub-critical systems is significantly different from critical systems. The experimental study of the transient dynamics of sub-critical systems will validate the current theoretical simulation capabilities. The study of transient characteristics implies the study of the combined transient behavior of:

a. source neutrons, and
b. prompt fission neutrons, and
c. delayed fission neutrons, and
d. influence of target design and target/core coupling issues as well as temperature dependent core reactivity feedbacks

Required are experiment series that allows the study of the combined dynamic behavior of the target, the target/core coupling and the core configuration with temperature dependent reactivity feedback effects. Therefore, the modelling tools for assessment of reactivity thermal feedback should be validated at various k_{eff} values.

For this kind of the validation experimental facilities with a meaningful and well qualified temperature dependent reactivity feedback effects are needed. Any well defined temperature dependent reactivity feedback effect is sufficient (does not necessarily have to correspond to a specific temperature reactivity effect associated with an actual transmuter) because in the set of Kinetic Equations, that describe the dynamic behaviour of sub-critical systems, the coupling term, that describes the combined effect of all the different temperature dependent reactivity feedbacks is universal, i.e.; not plant specific. We know that shutdown characteristics of sub-critical systems are significantly different from critical systems, depending on the level of sub-criticality. To reach a high precision for simulation of the transient dynamics at various levels of sub-criticality it becomes necessary to evaluate consequences different initiators for reactivity insertion rates into the reactors. For example large positive reactivity insertions (> 1 $ in reactivity), insertion of negative reactivities into the reactor (how far does the power level drop in comparison to a critical reactor), large source strength increases and decreases, respectively (+/- 30 to 50 %), impact of differences in target/core coupling design solutions, impact of core cooling transients as inlet temperature increases or coolant mass flow decreases and/or increases, respectively.

Start-up and shut-down operational procedures should also be established based on representative, experimental experience. In this framework, means for power control such as control rods and beam current could be evaluated experimentally. The reactivity effect of safety rods in different representative, experimental conditions should be investigated. Shielding, safety and licensing issues of coupling of an accelerator, spallation target and sub-critical core also need to be covered experimentally.

Since the envisaged XT-ADS and EFIT will operate with a CW-based time structure of the proton beam, we will need for at least some part of the experiments an accelerator in CW accelerator regime with sufficiently high intensity allowing good statistic. In order to validate the reactivity monitoring it will be essential that the level of sub-criticality can be changed in a range representative for ADS operation.

In order to check the space-dependent and source-dependent validity of the sub-criticality monitoring techniques a representative geometrical set up of the XT-ADS or EFIT respectively with variable reactivity values will be needed. Such a representative geometrical set-up with sufficient power is also required to analyse some shielding, safety and licensing issues.

4. Conclusions

The validated input data base to be provided for the ADS feasibility study to be performed in the IP EUROTRANS should cover mainly the following aspects:

- Qualification of sub-criticality monitoring,
- Validation of generic dynamic behaviour of an ADS in a wide range of sub-critical levels, sub-criticality safety margins and thermal feedback effects,

- Validation of the core power/beam current relationship,

- Start-up and shut-down procedures, Instrumentation validation and specific dedicated experimentation,

- Interpretation and validation of experimental data, Benchmarking and code validation activities etc

- Qualification of the proton beam reliability and the beam transport line, Pb-Bi or Pb-spallation target design in association with relevant proton beam and the effects of spallation residues including that of polonium,

- Safety and licensing issues of different component parts as well as that of the integrated system as a whole,

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