Advanced Gas-cooled Accelerator-driven Transmutation Experiment – AGATE

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Abstract

The reduction of risks associated with high radioactive waste is a big challenge in the future of nuclear power. There are several concepts and studies to incinerate radioactive wastes, including long-lived minor actinides (MA) and fission products (FP) in accelerator-driven systems (ADS). Several concepts based on different cooling systems are being discussed. Currently, concepts based on liquid metal coolant like lead or lead-bismuth are being preferred. The Institute of Nuclear Fuel Cycle (RWTH-Aachen), the Research Centre Jülich (FZJ), the Frankfurt Institute for Advanced Studies (FIAS) and the SIEMENS company investigate the feasibility of a gas-cooled ADS, which has also been previously considered by French and other European research groups. This study will demonstrate the coupling of a linear accelerator, a neutron spallation target and a subcritical core. Complementary to the design of the basic system, the critical points of the whole system will be addressed, to identify the research and development (R&D) needs, to define the safety and licensing issues and last but not least to assess the cost of the installation. The paper will present the preliminary results of the study.

Introduction

Transmutation is a method to reduce the high-level wastes (HLW), which also contain long-lived minor actinides. Those can be transmuted into short-lived isotopes in a high neutron flux [1]. Apart from fission reactors, the accelerator-driven system (ADS) is predetermined as a high-intensity fast neutron source. The fundamental reaction is the spallation process, which yields 20-30 neutrons per initial proton. This is one order of magnitude more than in a fission reaction. Pulsed spallation sources can also be used for basic research (e.g. SNS, J-PARC, SINQ).

In former European and national projects, different gas-cooled ADS concepts were developed (e.g. XADS, EUROTRANS, GNEP, TEF, HYPER) [2,3], up to preliminary designs of 100 MW_{th} experimental facilities. Within the European Facility for Industrial Transmutation (EFIT), the gas-cooled concept was chosen as back-up solution. However, further research was focused on lead-cooled concepts [4]. It is proposed to complement the ADS development by investigations of gas-cooled ADS reactor with independent cooling circuit for the solid and changeable spallation target, to benefit from synergies with other ADS and gas-cooled fast reactor developments (e.g. MYRRHA, GoFastR, ALLEGRO) [5].

The feasibility study

The motivation of the feasibility study is to investigate the technical properties of a gas-cooled ADS reactor with independent cooling circuit for the solid and changeable spallation target: higher fuel temperature, but linear neutron line density. In this study the goals are to identify by simulations a nuclear fuel, compatible with the specifications of transmutation. The technical properties of the accelerator, the beam window and spallation target are investigated depending on the requirements of the ADS. Furthermore a simplified safety case study and the contribution of the ADS to a HLW disposal concept are part of the feasibility study. The term of study will end in the second quarter of 2011. Final results will be published in the second half of 2011.

Preliminary results

The 6 MW accelerator concept is based on a continuous wave (CW) proton linac, or on a two-step compact cyclotron facility as back-up solution. By factor 2 beam current “swing” in AGATE is required to compensate for changes in reactivity during burn-up of solid fuel [6]. Focused on a 10 mA and 600 MeV proton linac concept, the advantages of the two CEA CW linacs (175 MHz and 350/700 MHz) are combined [7,8]. Above 28 MeV the accelerator will be superconductive. The back-up solution is based on the PSI concept for a two-step cyclotron facility, which will enable up to 10 MW DC beam power for 1 GeV protons [9]. Injection of short 1.2 MeV bunches at 44 MHz into the 120 MeV cyclotron needs special attention. A challenge is the design of the cyclotron magnet with 1.3 T and 4 m extraction radius. CIAE Beijing is presently assembling a compact and innovative four-sector cyclotron magnet for their CYCIAE-100 cyclotron [10], 1.4 T and 2 m extraction radius.

For the neutron production the proton beam will be focused on a spallation target. The penetration length of the 600 MeV proton beam in tungsten is approximately 15 cm, but for an adequate illumination of the nuclear fuel a linear neutron source is essential. Different target designs with independent cooling circuit will be investigated. The first design is a conical target with a length of 120 cm. First simulation results show that a step-shaped spallation target is inapplicable, because the energy deposition is too high for the structural stability of the target material. Therefore simulations with smooth-shaped conical target were done (see Figure 1). The temperature calculations of the flat-shaped conical target cooled by helium shows that the inner temperatures reach over 3 300 K. These temperatures are in the range of the melting point of structural material tungsten. The preliminary result shows that a conical target is not coolable with gas. Further developments will investigate a segmented spallation target, which is coolable and changeable (Figure 2). The principle benefit of a solid target is that the radioactive spallation products are generally confined to the solid target material and are localised in the target proper (baring catastrophic failure) [6].

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Figure 1: Cross-section of the spallation target

The left diagram shows the energy deposition of a 10 mA proton beam in the conical target, the right diagram shows the neutron flux around the conical target

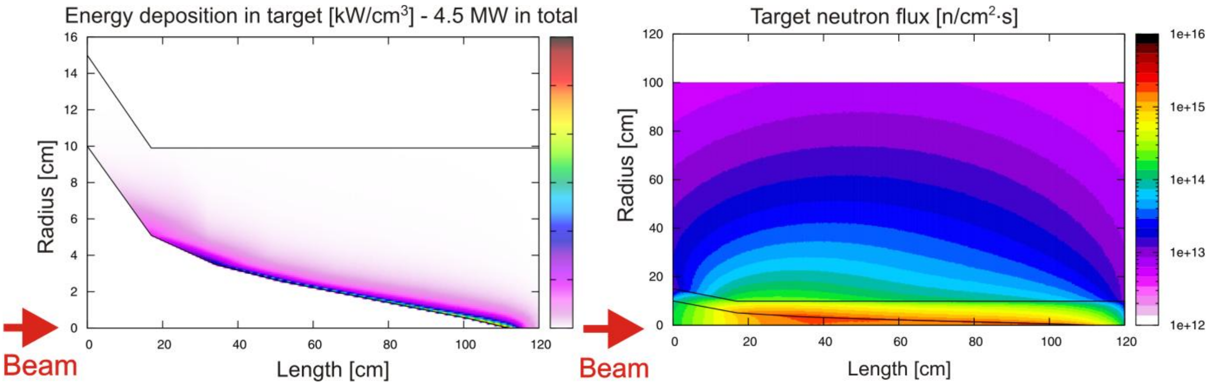
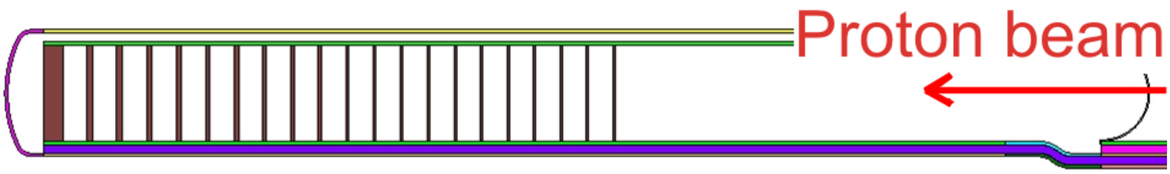


Figure 2: Segmented spallation target, which is coolable and changeable



The nuclear fuel in the start-up phase will be a MOX-fuel with less than 20 wt.% of Pu content. In the past facilities worked on the fabrication of fuel with less than 30 wt.% Pu content (e.g. SNR-300 and Superphénix). A lot of expert knowledge is still available. Innovative ADS and fast spectrum nuclear fuel is in R&D. Up until now the production of this kind of fuel has only been possible in the laboratory. In the EUROTRANS project, part of the 6th EU-FP, a composite fuel (Pu, Am)O_{2-x} – ^{92}Mo (93% enrichment) was chosen for a future European ADS demonstrator. The back-up fuel is a ceramic-metallic composite (Pu, Am)O_{2-x} – MgO (cermet). This fuel will also be investigated in this feasibility study.

The AGATE reactor core consists of 10 920 fuel pins with a length of 150 cm. For a maximum power of 100 MW_{th}, the maximum of the linear pin power is set to < 85 W/cm. In Figure 3 the cross-section of the reactor shows the fuel elements and the cladding of the spallation target. Detailed MCNP and MCNPX studies investigate the neutron flux and power density in the spallation target and reactor core. The neutron flux distribution in the core is also presented in Figure 3. The first calculations were made with MOX fuel and show that more MA will be bred than burnt. The MOX composition is presented in Table 1. A positive transmutation effect should be achieved with optimised fuel composition like the EFIT fuel (Pu-MA without U). The first simulations with EFIT fuel in the AGATE core produced results, which agree with the results of Artioli, *et al.* [11]. AGATE main design parameters are presented in Table 2. Under investigation is pure Am/Cm as fuel for the transmutation phase, proposed for the US SMART ADS design [12,13].

The reactor cooling was analysed considering the neutronic calculations. Different parameter sets were calculated for the coolants CO_2 and He. The parameters for helium are presented in Figure 4. Detailed calculations with the core reference case (p = 6 MPa, w_{in} = 50 m/s) result in an inlet temperature of $T_{He,in}$ = 523 K and an outlet temperature of $T_{He,out}$ = 678 K. The cladding temperature reaches a maximum temperature of $T_{clad,max}$ = 803 K, with a maximum fuel temperature of $T_{fuel,max}$ = 1 084 K. A helium mass flow of 110 kg/s is necessary to cool the reactor core under these conditions. Further considerations will investigate the heat transfer to a secondary circuit to use the reactor heat in a steam turbine.

Figure 3: The left picture shows the cross-section of the reactor, the right picture is a top view of the reactor core which shows the neutron flux distribution

Changeable solid spallation target, 30 cm in diameter, requires seven fuel elements

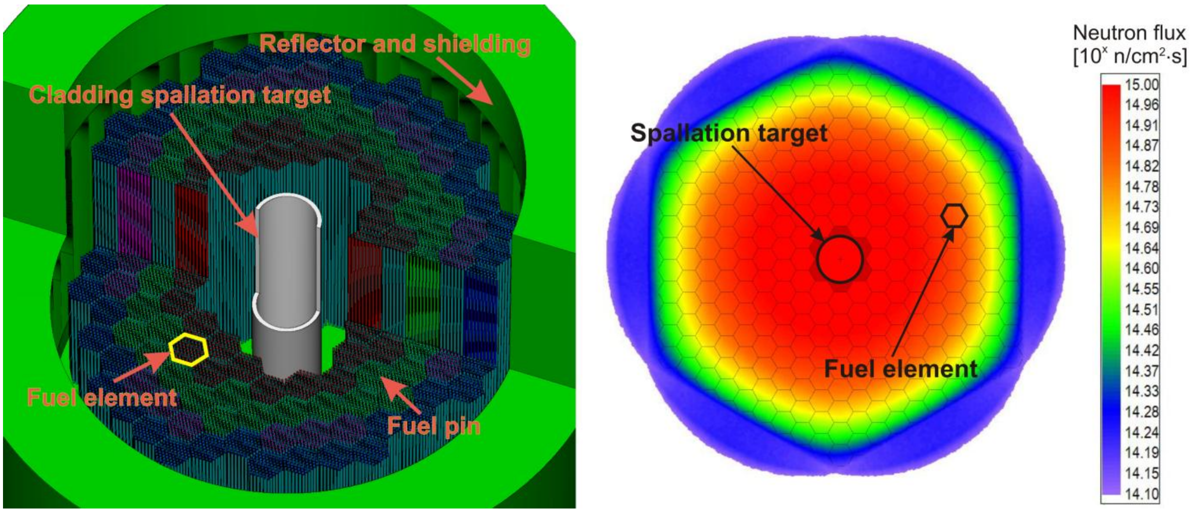


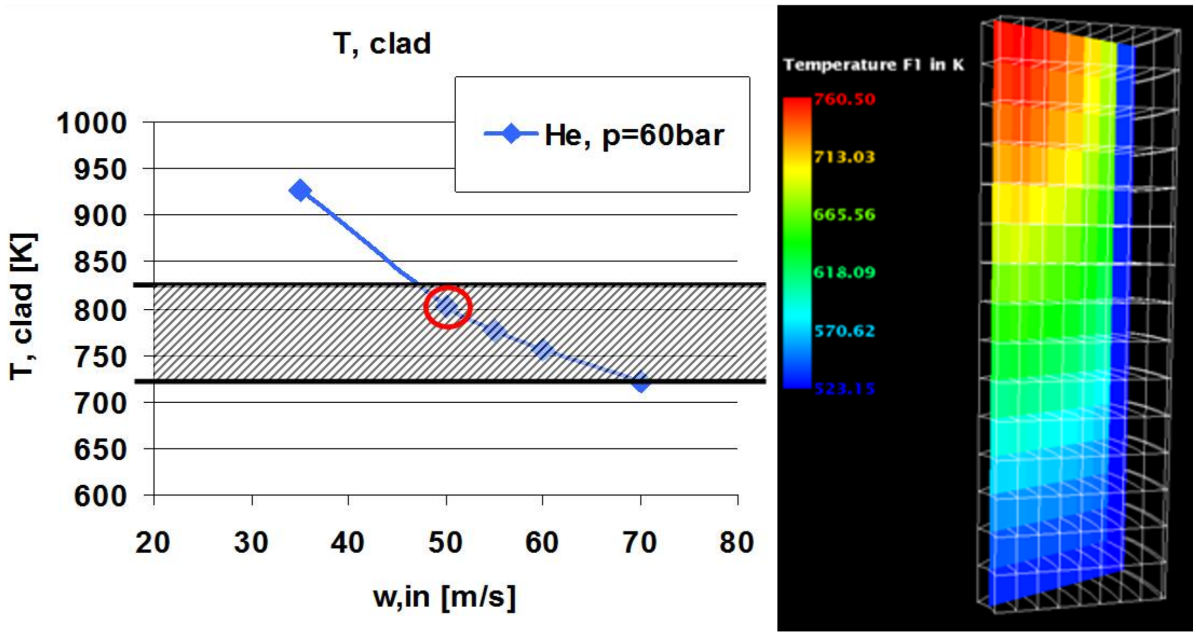
Table 1: MOX fuel with 20 wt.% Pu; U-vector + Pu-vector

Element	^{235}U	^{238}U	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Rel. content [%]	0.71	99.29	2.61	54.00	23.62	13.05	6.72

Table 2: Main design parameter of AGATE

Parameter	Material/ Value
Coolant	He/CO_2
Maximum thermal power	100 MW
Maximum power of the accelerator	6 MW
Energy of the protons	600 MeV
Current maximum	10 mA
Accelerator mode	Continuous wave (CW)
Spallation target form	Conical or segmented plates
Spallation material	Tungsten
Nuclear fuel – start-up phase	MOX, ≤ 20 wt.% Pu
Nuclear fuel – transmutation phase	EFIT or Am/Cm
Multiplication factor – k_{eff}	0.95-0.97
Cladding	HT-9
Gas pressure	6 MPa
Fuel assembly length	1 500 mm

Figure 4: Determination of possible cases for the reactor cooling; the right picture shows the He temperature [K] in 1/8th of the core geometry (thermo-hydraulic analysis)



Conclusions

The preliminary results of the feasibility study show the technical properties of gas-cooled ADS reactor with independent cooling circuit for the solid and changeable spallation target. The 6 MW accelerator design is based on extensively developed concepts of CEA and PSI [7-9]. By factor 2 beam current "swing" in AGATE is required to compensate for changes in reactivity during burn-up of solid fuel. More research effort is needed to develop the spallation target. Linear conical targets are not coolable with gas. Relatively high temperatures expose structural materials to extensive stress. Next, a segmented spallation target based on well-designed tungsten plates will be investigated. Much effort is focused on the neutronic calculation for the AGATE reactor design. For the start-up phase of the ADS a MOX fuel with 20 wt.% of Pu content was considered. Preliminary results show a negative transmutation trend of MA. Instead of MOX fuel an advanced fuel like the EFIT fuel is necessary for an acceptable transmutation rate. Simulations with EFIT fuel in the AGATE core produce results which agree with the results from the EFIT core design [11]. Pure Am/Cm fuel is under investigation as fuel for the transmutation phase comparable to the United States' SMART proposed ADS design [12,13].

The ongoing feasibility study will focus on the simulation of the neutronics and thermo-hydraulics of the spallation target, beam window and reactor core. A simplified safety case study will also be performed, as well as the contribution of the ADS to a HLW disposal concept.

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References

[1] Lensa, W. von, R. Nabbi, M. Rossbach (Eds.), *RED-IMPACT, Synthesis Report*, ISBN 978-389336-538-8 (2008).

[2] ENEA, *A European Roadmap for Developing Accelerator Driven Systems (ADS) for Nuclear Waste Incineration*, ISBN 88-8286-008-6 (2001).

[3] Mikityuk, K., *et al.*, "Comparison of the Transient Behaviour of LBE- and Gas-cooled Experimental Accelerator-driven Systems", *Nuclear Engineering and Design* (2006).

[4] Blomgren, J. (Ed.), *Partitioning and Transmutation Current Developments*, SKB, TR-10-35 (2010).

[5] Giraud, B., *Preliminary Design Study of an Experimental Accelerator Driven System – Overall Description of the Gas-cooled System*, Framatome ANP SAS (2003).

[6] Henderson, S., E. Pitcher, *Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production*, DoE white paper, September (2010).

[7] Mosnier, A., *et al.*, "The Accelerator Prototype of the IFMIF/EVEDA Project", *Proceedings IPAC 10*, Kyoto, Japan (2010).

[8] Biarrote, J-L., A.C. Mueller, "European ADS and Its Challenge to Accelerators", *Beam Dynamics Newsletter*, 49, pp. 39-49, August (2006).

[9] Grillenberger, J., M. Seidel, "Cyclotron Based High Intensity Proton Accelerators", *Beam Dynamics Newsletter*, 49, pp. 61-72, August (2006).

[10] Zhang, Tianjue, *et al.*, "Construction Status of Main Magnet for CYCIAE-100", *IEEE Transaction of Applied Superconductivity*, Vol. 20, No. 3, p. 352, June (2010).

[11] Artioli, C., *et al.*, "Minor Actinide Transmutation in ADS: The EFIT Core Design", *International Conference on the Physics of Reactors "Nuclear Power: A Sustainable Resource"*, Interlaken, Switzerland (2008).

[12] Sheffield, Richard L., Eric J. Pitcher, "Application of Accelerators in Nuclear Waste Management", *Beam Dynamics Newsletter*, 49, p. 1639, August 2006.

[13] Sheffield, Richard L., "Subcritical Minor Actinide Reduction Through Transmutation – SMART", *OECD Workshop Karlsruhe*, Los Alamos Report LA-UR 10-00820, March (2010).