PROPOSED SUB-CRITICALITY LEVEL FOR AN 80 MW_{TH} LEAD-BISMUTH-COOLED ADS

L. Mansani, R. Monti and **P. Neuhold**
Ansaldo Nuclear Division, C.so Perrone, 25, 16161 Genova, Italy, *Mansani@ansaldo.it*

Abstract

The degree of operational sub-criticality of an Accelerator-driven System (ADS) on the one hand directly affects key accelerator system parameters, such as the proton beam current required to sustain the selected rated power level and, on the other, the likelihood of approaching or attaining criticality under abnormal or accident conditions. Then, if in all such conditions the safety goal is pursued to design the sub-critical core so that it stays away from criticality with adequate margin, the required operational sub-criticality level must be determined by a properly balanced approach between excessively demanding accelerator system performances and risk of accidental criticality. The approach must necessarily include evaluation and appropriate combination of the relevant reactivity effects (e.g. from system cool-down, postulated accident scenarios, geometrical variations) and proper consideration of specific design features (such as, for instance, the absence of safety rods, intended as neutron absorbing devices having a role equivalent to the shutdown rods in critical reactors).

The paper presents a possible approach to the determination of the operational sub-criticality level of an 80 MW_{th} Lead-Bismuth-cooled pool type ADS, initially conceived and developed by a team of Italian Organisations led by Ansaldo, with funding from the Ministry of University and Scientific and Technological Research, and currently in the process of being assessed, versus a gas-cooled concept, in the frame of a contract with the Commission of the European Communities.

After a brief description of the Lead-Bismuth-cooled ADS concept relevant features and of the key safety goals in terms of required sub-criticality margin, the evaluated reactivity effects are presented, a method to combine them is discussed and a proposed operational sub-criticality level is derived.

1. Introduction

The transmutation of transuranics (TRUs) and selected long-lived fission products (LLFPs) using an accelerator-driven system (ADS) is a promising solution for reducing the amount of long-lived radionuclides to be disposed. Its usage could be tailored to the different nuclear policies of the European Union members. Its practicability on an industrial scale requires to be demonstrated by an eXperimental ADS (XADS).

Following a preliminary design developed in 1998, which was based on the Energy Amplifier concept proposed by CERN, [1] the Reference Configuration [2] of a Lead-Bismuth Eutectic-cooled Experimental ADS (LBE-XADS) was worked out in the period 1999-2001 by a group of Italian organisations led by Ansaldo, with the aim of assessing the feasibility of a small-sized (80 MW_{th}) ADS. The Italian consortium (Ansaldo, ENEA, INFN, CRS4, CIRTEN, SIET and SRS) design activities were performed under the aegis of MURST (the Italian Ministry of University and of the Scientific-Technological Research); two main tasks were funded, the first addressing the design of the target unit and the sub-critical multiplier and the second the accelerator system.

The activity is now progressing within the 5th Framework Programme of the European Commission, in the context of the research on Fission Reactors Safety, with funding to a project named PDS-XADS (Preliminary Design Studies of an Experimental Accelerator-driven System) with a three-year contract involving the participation of 25 partners (industries, research organisations and Universities). The European Project focuses on the comparative assessment of the above mentioned Pb-Bi-cooled and a gas-cooled ADS concept. It is the first major step of a consistent European effort that, as a key-milestone, will allow to design in detail an XADS for the transmutation technology demonstration. The main objective of this experimental facility will be to demonstrate the technological feasibility of coupling the accelerator with the nuclear reactor. The experimental ADS will be designed to demonstrate first the feasibility and safety of coupling an accelerator with a sub-critical reactor and, later on, the feasibility of transmutation of transuranics (plutonium and minor actinides, according to different countries strategies) and LLFP's transmutation, this being the anticipated mission of the follow-on programme on the eXperimental Accelerator-driven Transmuter (XADT).

In the meantime, in Italy, MURST continues to fund the development of the lead-bismuth technology in the large-scale CIRCE experimental facility. [3]

2. Pb-Bi-cooled XADS key choices and features

A few key choices in the early design phase of the XADS aimed to delimit the number of variables and overcome any potential drawback associated with the adoption of innovative solutions, notably the accelerator-core coupling and the use of the Pb-Bi eutectic. A more general aim was to conceive a reasonably simple XADS, based to the largest extent on proven technology. The basic approach can be summarised as follows:

- small size, though significant and scalable, 80 MWth core;
- target unit and molten LBE target designed to match core size and power;
- low coolant temperature (300÷400°C) for lessening corrosion and thermal loads;
- fuel type based on proven FRs (U, Pu) MOX;

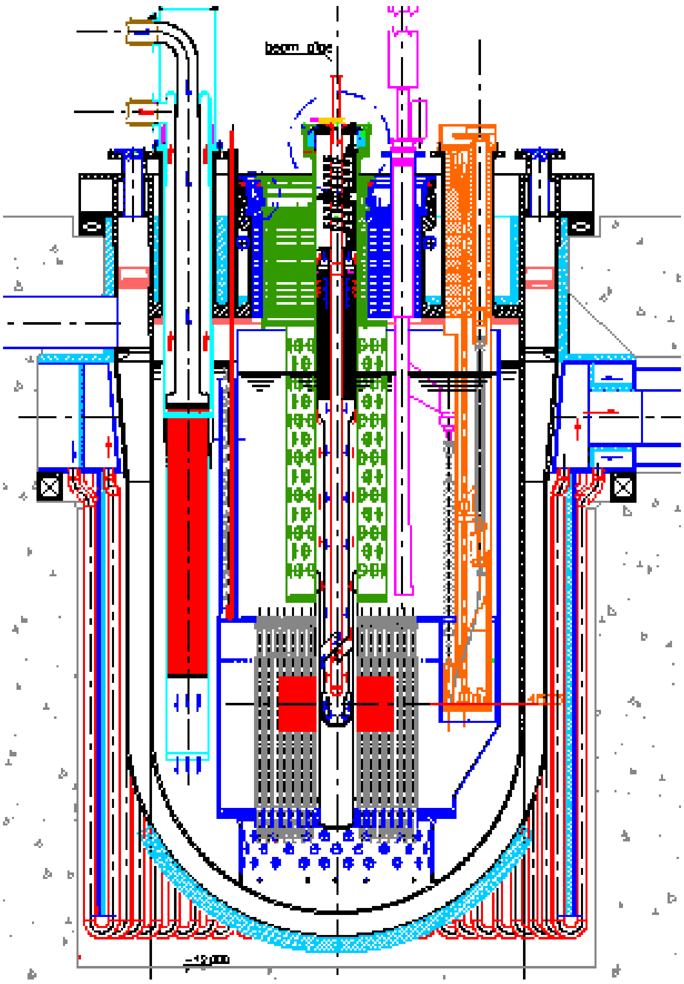
- short in-core residence time of the fuel assemblies to safely assess material behaviour in LBE;
- core keff range chosen to maintain adequately safe sub-criticality margin during Design Basis Conditions (DBC's) and Design Extension Conditions (DEC's);
- enhanced-natural-circulation core cooling in normal operation and passive removal of residual core power;
- proton accelerator design derived from proven technologies however with improved proton beam characteristics.

Relevant features and associated working principles of the XADS are listed as follows:

- Simple Primary System layout. The Reactor assembly (Figure 1) presents a simple flow path of the primary coolant with a Riser and a Downcomer. The heat source (the Core), located below the Riser, and the heat sink (the Intermediate Heat Exchangers) at the top of the Downcomer, allow an efficient natural circulation of the coolant. The additional means provided to enhance the primary coolant flowrate is not a mechanical pump, but relies on the principle of gas lifting: Argon of the cover gas plenum is injected into the bottom of the Risers and generates the gas-coolant mixture that, being lighter than coolant alone in the Downcomer, promotes coolant circulation at a higher flowrate, the level of which can be controlled by the amount of gas injected.
- Consequent to the elimination of the mechanical pump and to the natural-circulation configuration of the primary circuit, there is no high speed of the coolant, not even across the smallest cross-sectional areas of the primary coolant flow path. This technological option helps to reduce the erosion/corrosion of the structural material brought about by flowing Lead-Bismuth Eutectic (LBE), and creates a large gas bubbles to primary coolant interface area for a quick attainment of the equilibrium dissolution of atomic Oxygen into the LBE.
- All primary coolant remains inside the Reactor Vessel, including the coolant that circulates through the LBE purification unit, which is immersed in the Reactor pool.
- Use of LBE as the primary coolant, to exploit its low melting point, and to allow a relatively low operating temperature, in order to eliminate risks of creep damage of the Reactor structures and to reduce their corrosion rate.
- Use of an organic diathermic fluid as the secondary coolant with low vapor pressure and chemically inert against the primary coolant.
- Components and construction materials of proven technology.
- Removable main components (Intermediate Heat Exchangers, Fuel Handling Machines, Target Unit).

The LBE-cooled XADS embodies features that are adapted to its demonstration duties and is flexible enough to cope with requirements that cannot be precisely specified at present, but are predicted to be focused at a later stage. Among these duties there is the capability to accommodate different cores, minor actinides and long-lived fission fragments assemblies at locations where neutrons have the required intensity and the appropriate energy level. This capability is ensured by the long, absorber-free path in the LBE that has been provided in the reactor vessel for the scattering neutrons, which thus offer a continuous, isolethargic energy spectrum on their way to gradual thermalisation. The first core will be fed with U and Pu MOX fuel of the proven SPX1 isotopic composition or slightly more enriched in Pu, in order not to unnecessarily delay the operational availability of the XADS, because the development of new fuel is a long-lasting task. As a second example of flexibility, the primary coolant can be operated at different flowrates and pressure losses, in order to permit cooling of cores with different configurations. The requirement of large operational flexibility can be better achieved if no constraints from electric energy generation are superimposed to the XADS, and hence the reactor power will be dissipated to the external atmosphere.

Figure 1. **LBE-cooled XADS cross-section**



3. Core description

The core layout is shown in Figure 2 and Figure 3. The hexagonal fuel assemblies (Figure 4) are arranged in an annular array of five rounds, the circumscribed and inscribed circles of which have diameters of 183 cm and 58 cm respectively. The outermost round is only partially filled by six peripheral couples that have been added to reach the specified core reactivity and to provide smoothening of the radial power peaking. The total number of fuel assemblies amounts to 120. The active core height is 870 mm with 23.25 % uniform Pu enrichment.

Figure 2. **Core region vertical section**

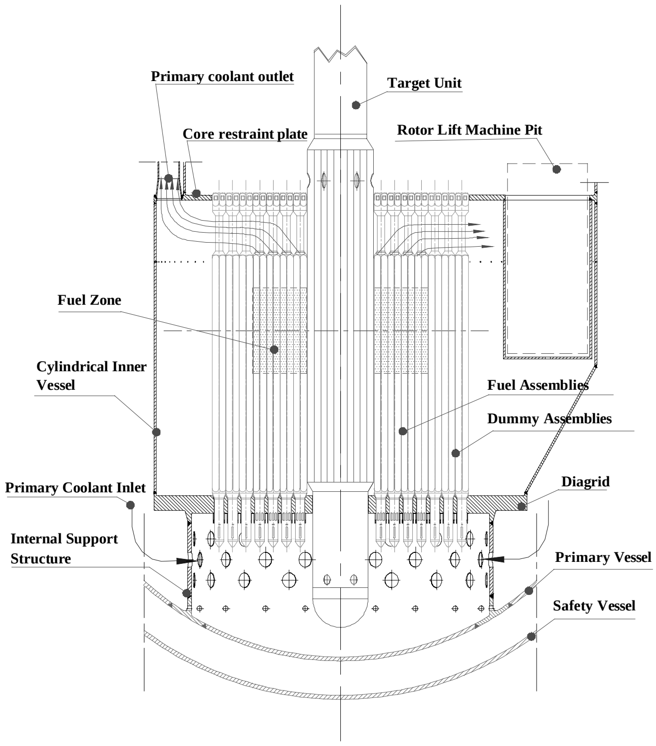
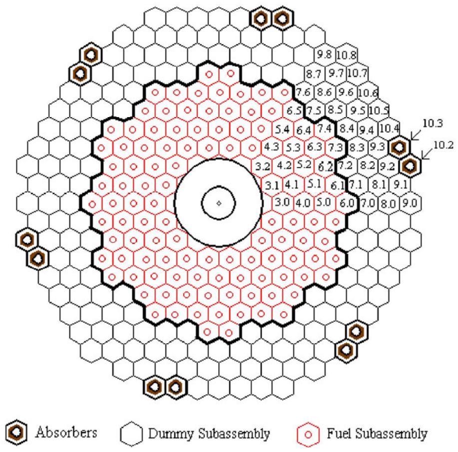
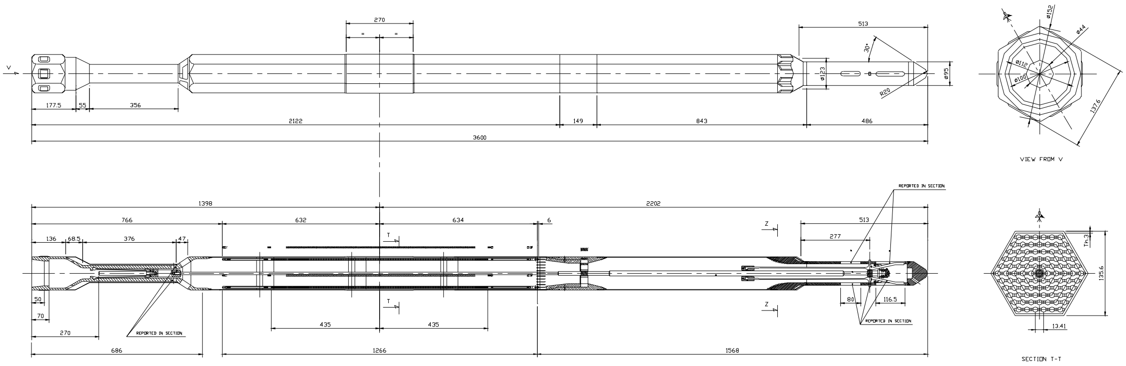


Figure 3. **Core cross-section**



The core is surrounded by a region of three filled-in rows of dummy assemblies, the circumscribed circle of which has 267 cm diameter, plus one partially filled inner round (the complementary assemblies of this round are the peripheral fuel assemblies of the outermost round of the core). The dummies have the same hexagonal cross-section as the fuel, but are empty duct structures.

Figure 4. **The LBE-cooled XADS fuel assembly**



This design choice allows:

- to create a buffer region, which keeps the fixed internal structures away from the high fast neutron flux, in order to protect them from suffering excessive radiation damage;
- to mechanically couple the core, through the assemblies handling heads, with the core radial, outer restraint plate.

The proposed configuration offers:

- a continuous fast-to-thermal neutron flux region, useable to fission minor actinides and transmute selected long-lived fission fragments, particularly where the neutron energy corresponds to the resonance absorption of the waste, thus maximising the incineration yield;
- an adequate mass of LBE surrounding the core, to exploit the reflecting capability of LBE for improving neutron economy and flattening the flux profile;
- the flexibility of initially operating the XADS with a proven core and later on converting it to a core tailored for burning Pu and nuclear waste, after irradiation test results provide sufficient confidence.

The core radial inner restraint is ensured by the Target Unit, the cylindrical shell of which has been designed to fit its inner outline.

There are no shutoff rods nor control assemblies dispersed in the core. There is, however, a set of 12 neutron absorbers, which are kept parked, during operation, at the periphery of the buffer region. At scheduled outages, these absorbers will be moved close to the core by means of the in-vessel handling machine, before extraction of the Target Unit. This allows to compensate for any reactivity insertion brought about by the extraction and to maintain the core at safe shutdown with the sub-criticality required during refuelling. A suitable absorbers management strategy would also allow the possibility to control the excess reactivity at BOL of prospective core designs.

Each fuel assembly contains a 90 pin gridded bundle spaced on a triangular pitch of 13.41 mm partially evolved from the SPX 2nd reload fuel. The fuel cladding is 8.5 mm nominal outer diameter and the material 9Cr-1Mo ferritic-martensitic, high-chromium alloy steel. Starting at the bottom end closure, the first section of 150 mm length forms the fission gas lower storage plenum. Inside the plenum a stainless steel tube supports the fuel stack. The fuel comprises an 870 mm long stack of annular pelleted mixed oxide (UO_2 and PuO_2) fuel at a nominal smear density of 95% theoretical density. On both ends of the fuel stack a 15 mm thick layer of depleted uranium oxide serves as thermal shielding. The top section of cladding, of 162 mm length, forms the upper gas storage plenum. A fuel stack retaining spring is inserted in the plenum to prevent axial movement of the fuel during pre-irradiation handling. The pins are evacuated and filled with helium at nearly the atmospheric pressure. A complete pin has an overall nominal length of 1 272 mm.

The fuel pin bundle is contained within a hexagonal wrapper tube. The top of the wrapper tube is welded to the handling head assembly and the bottom to the spike assembly. The overall length of the fuel assembly is 3 600 mm, and the external across flat size is 134 mm. The pitch between adjacent fuel assemblies is 138 mm. The fuel assembly is anchored to the diagrid by means of a locking device, because of the net upward force acting upon it.

The hexagonal wrapper forms the major part of the fuel assembly envelope. It has a nominal overall length of 2 400 mm, an internal across flats dimension of 130 mm and is made from 9Cr-1Mo with a finished wall thickness of 2 mm minimum.

The pin-to-pin spacing is maintained by three 9Cr-1Mo honeycomb grids axially spaced to give radial support and to prevent vibration induced by coolant flow. The grids are fabricated by spot welding on array of 90 cells. Each grid cell is hexagonal in shape and features three hemispherical dimples, pressed into the cell wall, which radially support the pin with a small diametrical interference. A support grid is provided at the bottom of the pin bundle. The grid is made of lamellar rails, which fit in the corresponding female part of the pins and hold them down.

The lower end of the fuel assembly is terminated by a spike assembly which plugs into the corresponding hole drilled in the forged diagrid plate and machined pintle underneath, a design choice that has replaced the traditional support tube as connection between fuel assembly and coolant supply. The spike cell contains the locking device that is actuated through a rod laid out along the centreline of the fuel assembly. In the hold-down position, three pins, radially spread from the spike, engage with the edge of the pintle and prevent the fuel assembly from lifting. Coolant enters the spike through slots arranged circumferentially at two levels. The slots of the lower level face the cold plenum and allow free entrance to the coolant, whereas the slots at the upper level happen to be located inside the pintle, so that corresponding slots had to be machined in the pintle.

The fuel assembly is terminated at its upper end by a 9Cr-1Mo machined tube of 686 mm overall length with expanded, formed ends. One end is welded to the wrapper and is provided with outlet ports in the transition cone. With this design choice, the coolant flows out radially. The tube is machined inside to house the mechanism that drives the locking pins in the spike. The upper end is machined internally as handling head. Externally the handling head has machined plane spacing pads.

4. Sub-criticality

In a sub-critical system, like an ADS, with an external neutron source and no control/shutdown devices, it is necessary to prevent by design neutron flux divergence both in normal operating conditions and in abnormal and accident conditions, including Design Extension Conditions (DEC). The effective multiplication factor k_{eff}, independent from the external neutron source, is a meaningful measure of the actual safety characteristic of the system, that is $1\text{-}k_{eff}$ is a gauge of the distance from criticality. Hence prevention of reactor power divergence is achieved if the effective multiplication factor is maintained below one.

The degree of sub-criticality directly affects, for a given XADS design, key accelerator system parameters (e.g. the proton beam current) required to sustain the predefined power level. Additional requirements can derive from the selected approach to compensate fissile material burn-up (e.g. increasing the proton beam current vs. keeping it constant and moving neutron absorbing devices).

Small sub-criticality levels imply low proton beam current (and hence "moderate" accelerator system performances) but increased risk of approaching or attaining criticality under abnormal or accident conditions; higher sub-criticality levels imply higher proton beam current (and hence "demanding" accelerator system performances) but reduced risk of approaching criticality. The selected level of sub-criticality must be therefore determined by a properly balanced approach.

From the point of view of safety, it is mandatory that the nuclear design ensures that criticality conditions are not attained, with adequate margin, under any foreseeable occurrence pertaining either to Design Basis Conditions (DBC) or DEC. The above can be achieved, in principle, with or without reliance on neutron absorbers. A margin of 0.016 ΔK is proposed for DBCs (0.016 ΔK is derived assuming ~3$ of margin and ~2$ of allowance for measurements errors). Hence the effective multiplication factor (k_{eff}) shall not exceed the limiting value of 0.984 at any time during DBCs. A reduced sub-criticality margin could be acceptable for DEC scenarios. The sub-criticality margin chosen is also consistent with standard practice for LWRs safe shutdown conditions.

Based on the above, the operational sub-criticality level (i.e. the effective multiplication factor k_{eff} under normal operating conditions, excluding refuelling[1] must be such that in any DBC (i.e. following any postulated transient, incident or accident DBC which causes reactivity insertion) the reactivity level of the core remains below 0.984.

Therefore, the choice of the operational sub-criticality level shall be made based on transient and safety analysis, taking into account the reactivity balance from zero power to full power conditions, as well as the reactivity effects associated to abnormal conditions and accident scenarios such as excessive cool-down, target flooding or core voiding or the geometrical variations associated to seismic events. Moreover it should be kept in mind that:

- the lower the operational sub-criticality level the more unfavourable and more peaked the power shape (measures can be taken to flatten the power shape but they will have to be managed for any change of sub-criticality level);
- in order to operate the reactor core at a given power level, the expected reactivity decrease along the fuel cycle needs to be compensated; if this is done with the help of the accelerator its duty is strong impacted by the choice of the operational sub-criticality level.

The use of control rods (intended in the traditional meaning of automatically driven absorbing devices) or burnable poisons to compensate some of the reactivity effects has a strong impact on the choice of the operational sub-criticality level. Control rods similar to those used in critical reactors should be avoided in the XADS.

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1. During refueling a maximum value of the effective multiplication factor less than 0.95 has been proposed. ANSI Standard N18.2 ("Design Objectives for LWR Spent Fuel Storage Facilities at Nuclear Power Stations") specifies k_{eff} not to exceed 0.95 in spent fuel storage racks and transfer equipment flooded with pure water and not to exceed 0.98 in normally dry new fuel storage racks, assuming optimum moderation. No criterion is given for the refueling operation. However, a 5% margin, which is consistent with spent fuel storage and transfer, is considered adequate for the controlled and continuously monitored operations involved.

Figure 5. **Proposed operational sub-criticality level**

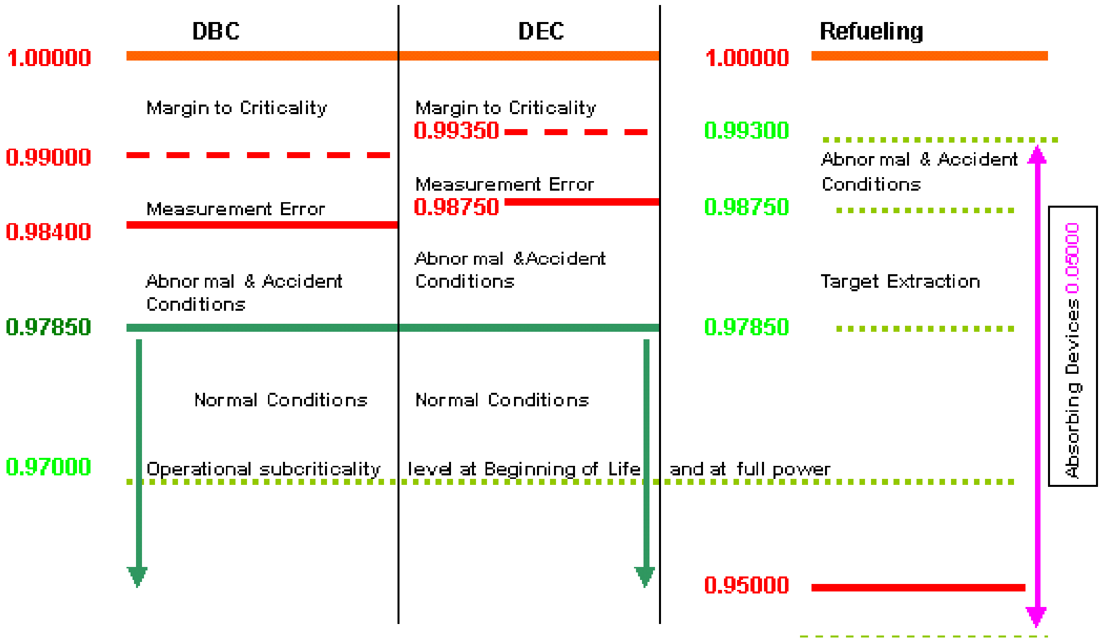

Table 1 summarises the estimated LBE-cooled 80 MW_{th} core power XADS reactivity variations in representative normal conditions as well as DBC's and DEC's. Core cooling from operation at full power down to ambient temperature plus target unit-beam pipe flooding by LBE due to mechanical failure, or core compaction from Design Basis Earthquake loading account for the widest reactivity insertions predictable under DBC for the LBE XADS (approximately 1.4% total, including Doppler, coolant density and thermo-structural effects). The core multiplication factor for normal operation at full power and BOL is thus set at k=0.984-0.014=0.97, that is the sub-criticality margin is -3%, see Figure 5. Accidents like those involving large core compaction may be allocated to DEC scenarios; based on the core and fuel assembly design, the associated reactivity effect may be worth about 0.5÷0.6%, so that it still allows the system to remain sub-critical, though with a reduced safety margin, see Figure 5. A 0.97 core multiplication factor at BOL and rated power is therefore considered sufficiently low to ensure the safe operation of the LBE XADS without need of shutoff rods. During the irradiation cycle, the core reactivity drops at a rate of about 0.004%/day due to fuel depletion. The depletion rate is mainly related to the fuel type (both matrix composition and enrichment) and to the neutron spectrum. It also depends on the general core design and performances, as these relate to the fuel lattice, the fuel management and the power density. Considering also the fuel residence time, the total core cycle reactivity depletion should not exceed 4%, i.e. the operating multiplication factor reduces from 0.97 at BOL to 0.93 at EOL.

Figure 5 also reports the reactivity effects associated to refueling. The required k_{eff} <0.95 during refueling implies the need to use neutron absorbing devices (the ones located far from the core during operation at power, see Figure 3). In fact cooling the system to cold zero power, extracting the target structure and postulating a Design Basis Earquake and additional cooling to ambient temperature would bring k_{eff} around 0.9930 (Figure 5); neutron absorber worth approximately 5 000 pcm would then be required to decrease k_{eff} below 0.95.

Table 1. **Estimated LBE-cooled XADS reactivity effects**

Analysed condition or event	**Condition or event category**	**ΔK_{eff} (Pcm)**	**Notes**
System cool-down • from HFP to HZP • from HFP to CZP • from CZP to 20°C	 normal normal DBC	 740 850 330	Fuel Doppler, coolant temperature and thermostructural effects included in all cases
Target related effects • Target extraction • Target flooding	 normal DBC	 900 190	Required to perform refueling
Core Compaction • Compaction from earthquake • 2 mm FA gap reduction	 DBC DEC	 ~ 200 570	Estimated from SPX data. This has to be considered the maximum possible compaction
Coolant voids • Microbubbles entrainment • Extended Voiding - one FA - one (inner) row of FA - whole core	 normal DBC DEC DEC	 < – 100 no significant 300 -700	For void fractions less than 1% physical consistency of extended voiding to be verified (voiding may be impossible)
Fuel assembly misloading • (121 loaded FA instead of 120)	DBC/DEC	~ 100	
Acronyms: HFP Hot Full Power; HZP Hot Zero Power; CZP Cold Zero Power; DBC Design Basis Condition; DEC Design Extension Condition; FA Fuel Assembly			

5. Summary and conclusions

An approach to the determination of the operational sub-criticality of an 80 MW_{th} Lead-Bismuth-cooled pool type ADS, the design of which does not include shutoff or control devices, is proposed. Under these conditions sub-criticality must be provided by design with adequate margin (possible larger for Design Basis Conditions than for Design Extension Conditions).

Besides defining the margin itself it is mandatory to evaluate and properly combine the relevant reactivity effects associated to normal, abnormal and accident conditions.

Evaluations performed for the MOX fuelled LBE concept allow to propose an operational k_{eff}=0.97 at beginning of life and full power; the corresponding 3% sub-criticality poses reasonable performance requirements on the proton accelerator system and allows to achieve an acceptable fuel burn-up by compensating the fissile inventory depletion with an increasing proton current.

The ADS refuelling can be managed by manually moving neutron absorbers, worth approximately 5 000 pcm, from the far core periphery (where they would be stored during operation at power) to the near core periphery, if it is required to perform refuelling with k_{eff}<0.95.

It is noted that the while proposed operational k_{eff} for the 80 MWth Lead-Bismuth-cooled ADS will have to be confirmed by safety analysis as the detailed design progresses, the described approach can be tailored to a different ADS design.

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