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XT-ADS : Feedback to the designers from research and from safety

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Abstract

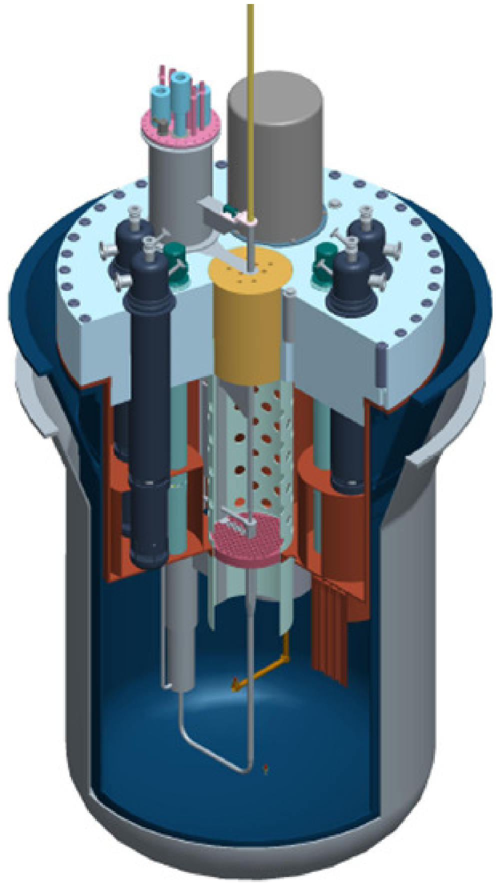
- Within the EUROTRANS project, the design activities have started from the very beginning while R&D activities were running in parallel either within the same project (like the other domains related to fuel – AFTRA - and to materials – DEMETRA) or outside. Once a first version of the design was made available, the safety calculations could start (most of the time at least one year after the start of the design).
- Only at the very end of the project, R&D results and safety calculations become available and there is no room available (be it in time or in manpower) to perform a complete iteration. But at least a list of both the verified assumptions or the required modifications should be drawn before the start of a new project, like the CDT.
- In this paper we present the different assumptions that the engineering teams have taken and the possible consequences for the design, should those assumptions be inaccurate.

XT-ADS, Feedback to the designers from research and from safety

Contents

General Basic assumptions

- The Accelerator Driven System is attractive for Minor Actinides transmutation
- The Accelerator Driven System is not developed as a plant dedicated for electricity production (not the major goal even if it is possible)
- The industrial feasibility presumes:
  - A reliable system (*i.e.,* limitation of spurious shutdown and limitation of the shutdown state duration)
  - A high-performance transmutation capability in economical conditions
- The industrial attractiveness needs acceptance by licensing authorities
- ➔The demonstration of these objectives requires to develop, license and operate a demonstrator



Basic assumptions (1/3)

- **The development of the Accelerator Driven System is based on the following assumptions :**
  - **High core flexibility (MOX/MA fuel composition and core batch loading)**
  - **Increase high power accelerator reliability (spurious shutdown number limited to a few per year) (current experience feed back on accelerator is not yet favourable)**
  - **Robust safety**
  - **Challenging radioprotection issue (in particular due to Polonium, spallation products and location of the target and accelerator inside the reactor)**
  - **Design according standard design rules for nuclear plants (*e.g.,* based on RCC-MR)**
  - **Economical manufacturing and operation**

Basic assumptions 2/3

- **For that, the following options are considered:**
  - **Use of a reliable linear proton beam as neutronic source via the windowless spallation target**
  - **Use of heavy metal liquid technologies offering high thermal inertia before reaching fluid or structure critical temperature (favourable for unprotected transient and natural convection cool-down: lead-bismuth or pure lead)**
  - **Use of proven steel material sufficiently robust with regard to corrosion risk by lead or lead-bismuth**
  - **Monitoring and control of the lead inventory (*e.g.,* control of lead oxidation)**
  - **Design of the reactor structures and sub-structures with significant margins for both normal and accident conditions including uncertainties**
  - **Implementation of redundant, diverse and segregated safeguard systems**

and also…

Basic assumptions 3/3

- Operation in a safe sub-critical level and control of the sub-criticality
- Account for In Service Inspection and Repair capabilities (to consider early in the design process)
- Develop and implement advanced Plant Control and Management System
- Develop and qualify remote handling for fuel and primary components and specifically for the target
- Develop and qualify remote ISIR

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Program organisation to validate the assumptions

Program organisation to validate the assumptions

- The first important step for the demonstration is the construction of an Experimental Transmutation Accelerator Driven System
- XT-ADS (MYRRHA) project is proposed to respond to this need
- In the medium term (2020) the emphasis will be on the construction of MYRRHA/XT-ADS
- In the long term an European Facility for Industrial Transmutation (EFIT) is envisaged as the final step of development prior to full commercialization
  - Development and qualification of innovative fuel (especially Minor Actinide bearing inert fuel) with appropriate cladding and associate reprocessing technique are challenging items
  - Having these innovative fuels is mandatory to prove the technological feasibility of transmutation
- R&D for MYRRHA/XT-ADS as well as the feedback from its plant performance will also serve for the technological development of the LFR Gen IV systems

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Program organisation to validate the assumptions

- Ongoing design activities for MYRRHA/XT-ADS will produce by 2012 the functional and technical definition of all components
- Dedicated R&D on materials and fuel will be conducted in parallel
- In the medium term (2020) the emphasis will be devoted on the construction of MYRRHA/XT-ADS
  - Components fabrication & Installation
  - Civil engineering works
  - Materials and fuel demonstration & qualification Program
- In the long term the coming feedback from MYRRHA/XT-ADS operation will influence the further EFIT design

Program organisation to validate the assumptions

- **Dedicated R&D topics have been identified to support the MYRRHA/XT-ADS design activities**
  - **Completing the design and construction of accelerator test sections to demonstrate the beam operational stability and control reliability**
  - **Completing the support experiments for the spallation target design**
  - **Completing the experiment to validate the on-line sub-critical monitoring techniques**
  - **Continuing to improve and validate the high energy nuclear reaction models**
  - **Experiments in support to develop ultrasound camera for ISI&R**
  - **Proof of principle of the feasibility of liquid metal submerged remote handling**
  - **Development of nuclear instrumentation able to operate in lead-alloy and under high energy irradiation fluxes**

Program organisation to validate the assumptions

- **Material qualification program**
  - **MYRRHA/XT-ADS can extensively use the large available data also produced for the LFR**
  - **Austenitic steels are candidate for components operating at low temperature and low irradiation fluence**
  - **Ferritic-martensitic steels (T91) are candidate for fuel cladding and heat exchangers because of their resistance against swelling under high fast neutron flux and corrosion resistant at high operating temperature**
  - **However to go to higher operating temperature it is necessary to qualify T91 material coated with protective layers such as alluminization**

Program organisation to validate the assumptions

- **Fuel qualification program**
  - **Only well demonstrated and qualified fast reactors fuel is used to respect the construction time for MYRRHA/XT-ADS**
  - **MOX fuel has been chosen for the driving core**
  - **Cladding-fuel compatibility of MOX with T91 has not been demonstrated and qualified, hence in the middle term a demonstration and qualification program for MOX fuel cladded with T91 and possibly coated by aluminium by the GESA technique will be necessary**
  - **In the long term test assemblies with MA fuel will be constructed and loaded in the MYRRHA/XT-ADS**

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Design Needs from DEMETRA

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Material for Heat Transfer

- **Structural Material, in flowing Lead or LBE, shall be protected to avoid excessive corrosion by:**
  - **Controlled Oxygen environment to form a thin, compact and stable surface** layer of oxide
  - **Protective** surface treatment **like alluminization (GESA)**
  - ……
- **Whatever is the surface protection, it could strongly affect the <u>heat transfer</u>**
- **Designer shall know for the protective layer:**
  - **the necessary initial** thickness
  - **the kinetics for oxide layer,** build-up **as function of time and operating conditions**
  - **the** conductivity **of native material &** total conductivity **of combination with protective layer (oxide and/or alluminization)**
  - **the behavior under** neutron irradiation
  - **The ranges** oxygen activity **in the melt**

Design Assumptions

- **For** heat exchangers**:**
  - **Exchanging tube material -** T91
  - **Oxide layer thickness after 20 years of equivalent full power operation (Lead or LBE side) -** 40 µm
  - **Oxide conductivity -** 1.1 W/ m K
  - **Fouling (secondary side) equivalent to an oxide layer of -** 10 µm
- **For** cladding:
  - **Cladding material –** T91
  - **Protective surface treatments –** alluminization

- Ongoing R&D should confirm these assumptions or provide new values

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Impact of the Assumptions on Components Size

- XT-ADS heat exchangers
  - 18% increases in heat transfer surface
  - Strong secondary system operating pressure variation:
    - operation at a power of 70 MW: P=30 bar at BOL and 17 bar at EOL
    - operation at a power of 50 MW: P=40 bar at BOL and 28 bar at EOL
- EFIT Steam Generators
  - 15% increases in heat transfer surface
- ELSY Steam Generators
  - 23% increases in heat transfer surface

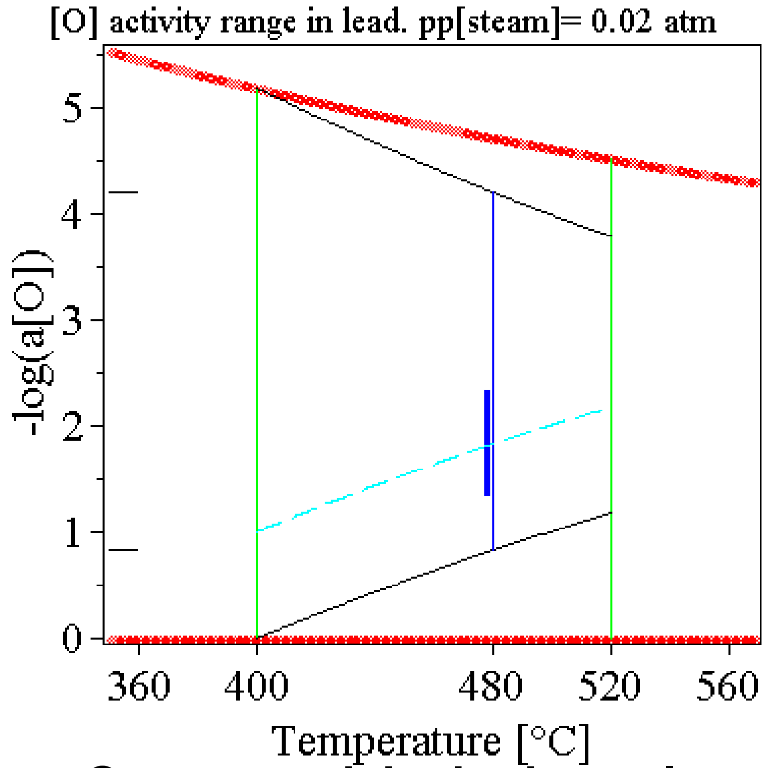
    or

  - 28% increase in heat transfer surface using AISI316 instead off T91

Corrosion Protection of Structural Steel in Lead by controlled Oxygen

Ongoing R&D activities should answer to the questions:

- What is the suitable oxygen activity to have the formation of a stable and compact oxide layer ?
- How many Oxygen Sensors are necessary and which are their more suitable location for the [O] concentration control ?



Oxygen activity in the melt vs T

For EFIT the level of [O] has been assumed at hot nominal condition 1.8

Neutron Irradiation Effects on Structural Material

- **Mechanical properties of structural material in flowing Lead or LBE and with concomitant neutron irradiation could degrade.**
- **Designer shall know the structural material mechanical properties as function of neutron irradiation (dpa), such as:**
  - **Ultimate Tensile Strength**
  - **Yield**
  - **Creep**
  - **Swelling**
  - **Embrittlement**
  - **……**

Design Assumption on dpa Limit

- **Non-replaceable structural components (e.g. Reactor Vessel) – Maximum** 2 dpa **for the whole life**
- **“Frequent” Replaceable structural components (e.g. Fuel Rods) – Maximum** 100 dpa
- **“Infrequent” Replaceable structural components (e.g. XT-ADS Inner Vessel/Reactor Barrel and Diagrid) – Maximum** 5÷7 dpa **for the whole life**

- Ongoing R&D should confirm these assumptions or provide new values

Design Assumption on XT-ADS Operating Temperature

- **Constant LBE core inlet temperature of 300°C for power operation between 50 and 70 MW**
- **LBE core outlet temperature maximum 400°C**
- **Increasing LBE core inlet temperature from ~ 200°C to 300°C from zero power to 50 MW (for start-up/shutdown and DHR operation)**

- Ongoing R&D should confirm these assumptions or provide new values **(ductile to brittle transition temperature issue)**

Further Design needs

- Heat transfer correlations and relation with oxide layer build up
- Fuel assembly pressure drop and its dependence from spacer designs (effect of -> corrosion / erosion / fretting)
- Fuel pin design optimization
  - ✓Fission gas plenum length
  - ✓Fuel pin failure detection and control
- SG design issues
  - ✓Pressure drop and fouling
  - ✓Consequences of SGTR (LBE/water interaction)
- Windowless target and free-surface flow

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MYRRHA/XT-ADS
Safety analysis

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Design ⇔ Safety

PDS-XADS (EC-FP5) — MYRRHA_Draft2

↓ Safety analysis

EUROTRANS (EC-FP6) — XT-ADS

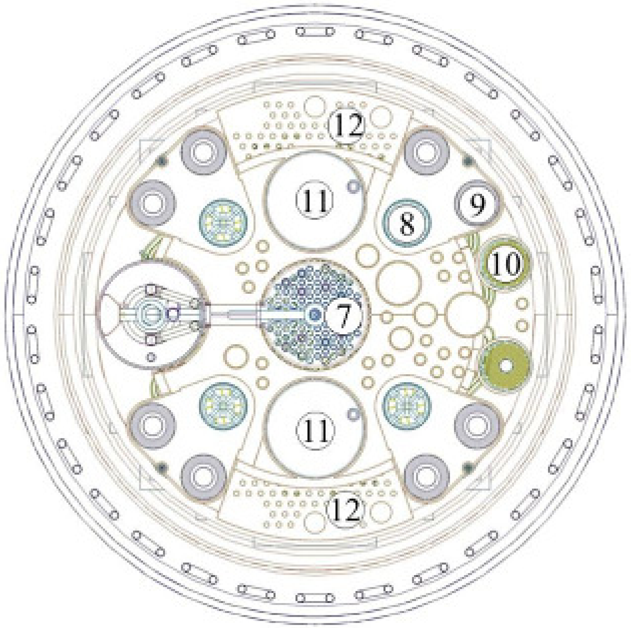
↓ Safety analysis

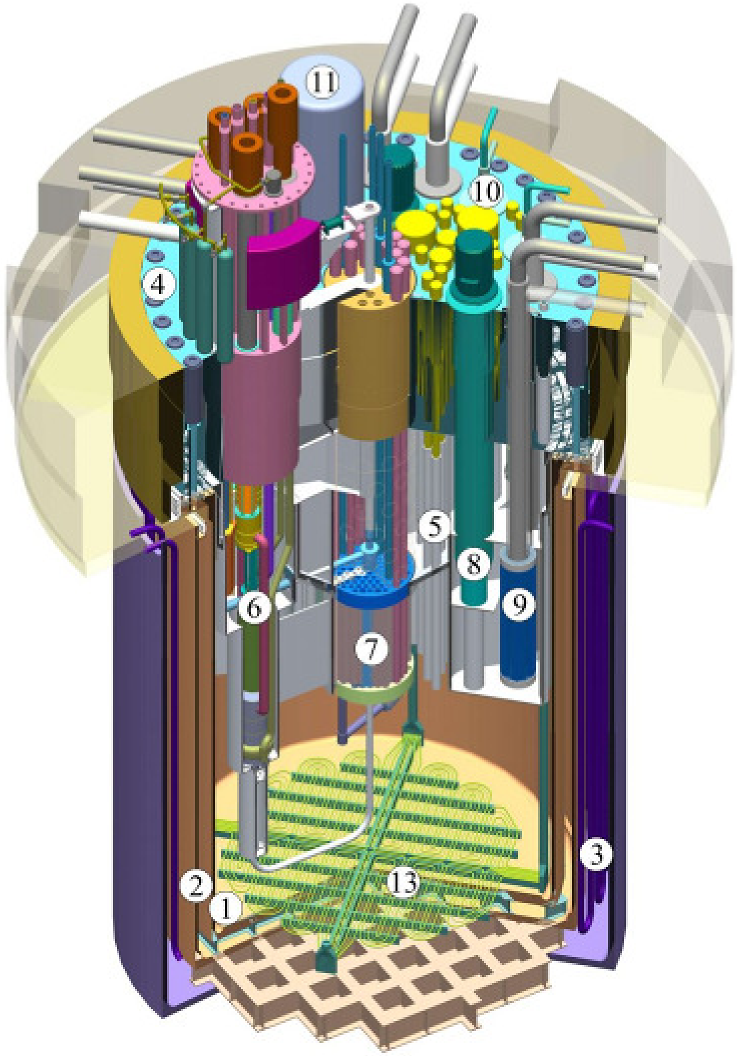
CDT (EC-FP7) — MYRRHA-FASTEF

Safety analysis

Interaction between design and safety goes beyond the framework of EUROTRANS. It is in fact an older and longer process that started with the MYRRHA-Draft2 design proposed in the PDS-XADS project and that will certainly stretch to the new CDT project

MYRRHA_Draft2 design





1. inner vessel
2. guard vessel
3. cooling tubes
4. cover
5. diaphragm
6. spallation loop
7. sub-critical core
8. primary pumps
9. primary heat exchangers
10. emergency heat exchangers
11. in-vessel fuel transfer machine
12. in-vessel fuel storage
13. coolant conditioning system

DHR system in MYRRHA_Draft2

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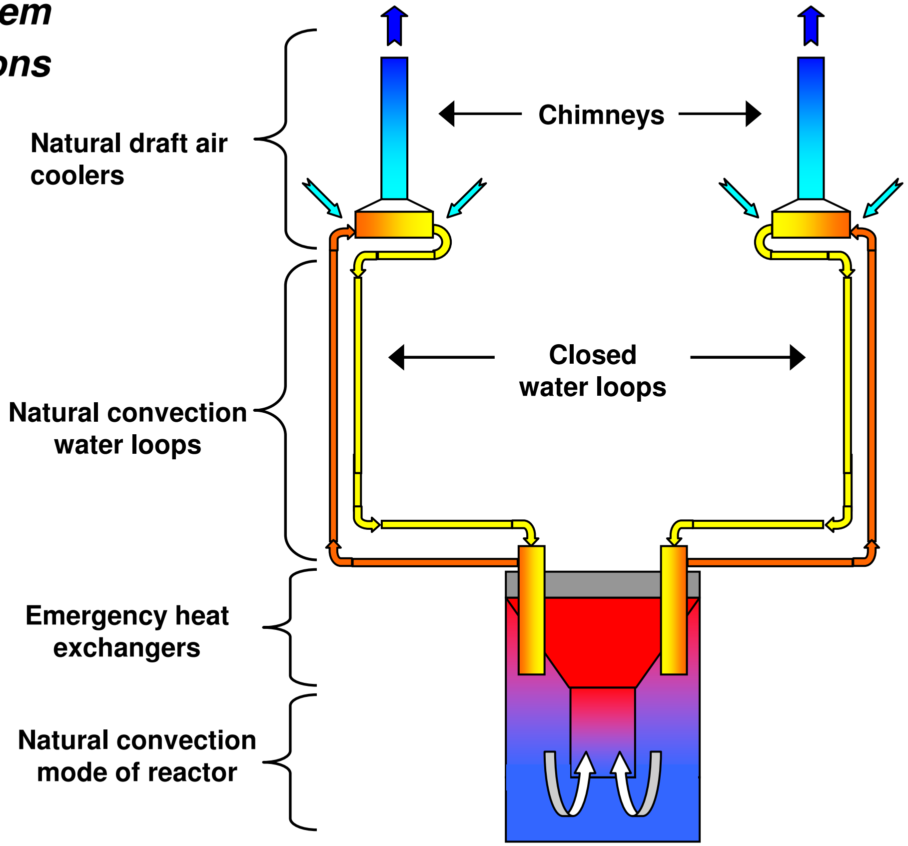
Within the safety analysis, particular attention was paid to the decay heat removal (DHR) system for the reactor protection in accidental conditions

- **Main focus on the decay heat removal (DHR)**
- **Only one DHR system with 2 independent emergency water loops**
- **Passive system: natural circulation**
- **Each loop dimensioned to remove the decay heat**
- **Natural convection in primary system**



MYRRHA_Draft2: safety analysis

- Main transients (taking into account bounding events):
  - LOF, LOH, LOF&LOH, T$_{ransient}$O$_{ver}$P$_{ower}$, S/A blockage, overcooling
  - Protected (DBC) and unprotected (DEC)
- Safety criteria:
  - Fuel (MOX): T < 2500°C
  - Cladding: T < 700°C
  - Coolant: T > 125°C (freezing)
- Main computation code: RELAP5 mod3.2 adapted to LBE by Ansaldo
- Results:
  - protected transients: OK
  - unprotected transients: not OK (e.g. grace time ≈ 10 s for ULOF)
- Main insights:
  - Capability of PHX and SCS not really used in LOF case (➔efficient EHX)
  - Natural convection in primary system to be enhanced
  - High pressure in DHR system (~100 bar)
  - Risk of freezing in EHX

ECS loop need improvement

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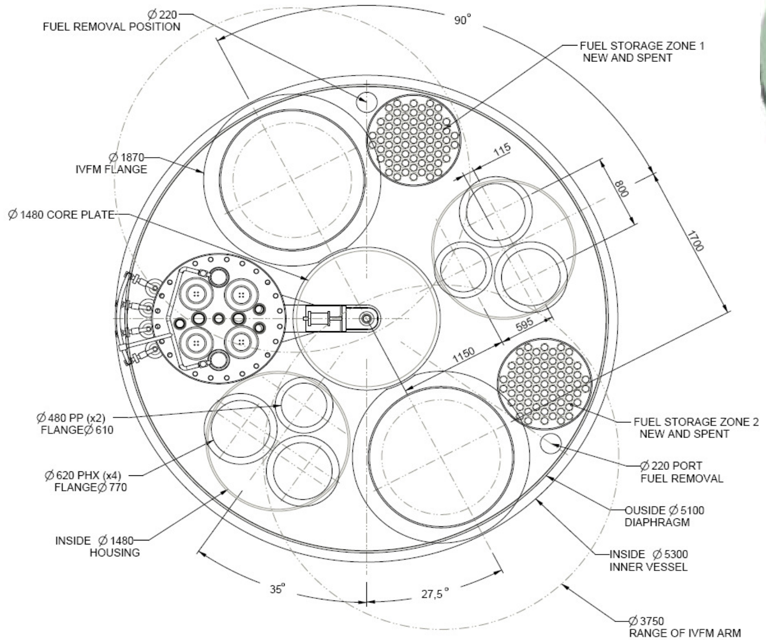
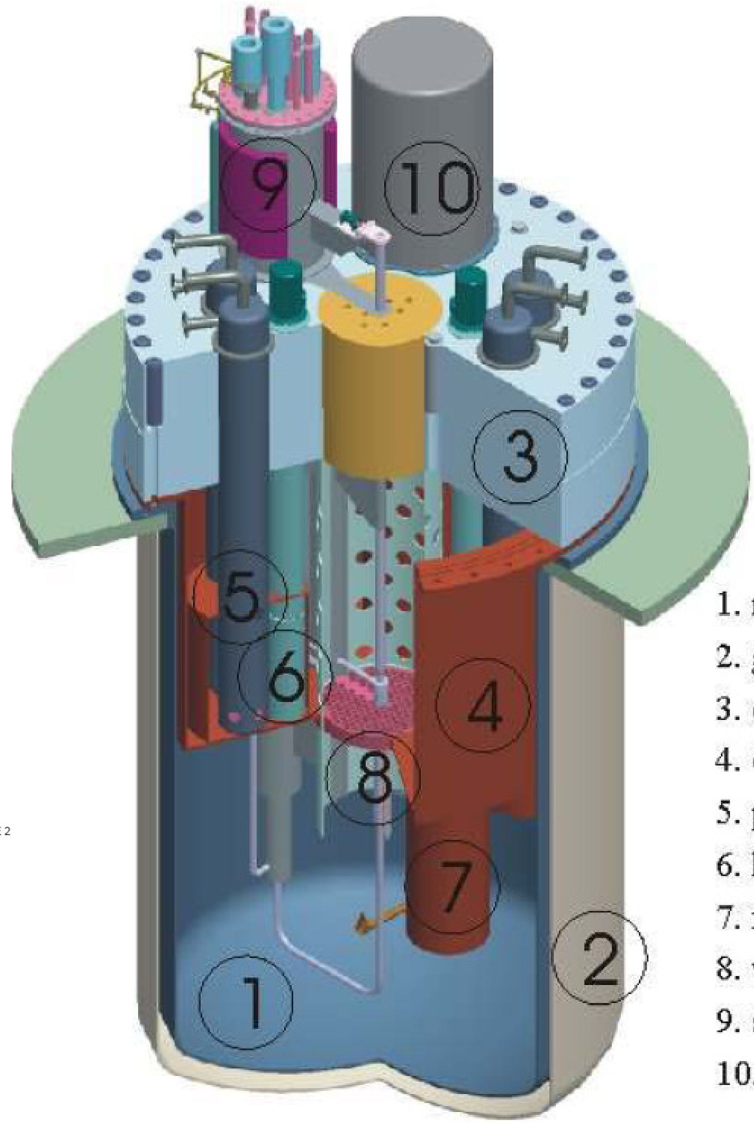
XT-ADS design





1. reactor vessel
2. guard vessel
3. cover
4. diaphragm
5. primary pumps
6. heat exchangers
7. fuel storage zone
8. windowless target and core
9. spallation loop
10. fuel manipulators

DHR Systems in XT-ADS

- Objective: grace time at least 30 min in unprotected accidents
- Two DHR systems:
  - Secondary cooling system (SCS) (2 independent loops)
  - RVACS (Reactor Vessel Air Cooling System)
- SCS is passive (natural circulation in any condition)
  - Independent of electrical supply
  - Dimensioned to remove nominal power
  - Use of full PHX capacity in LOF condition (protected and unprotected)
  - Natural convection capability in primary system enhanced by
    - Higher ΔH between PHX and core,
    - Smaller Δp in core
- RVACS
  - Passive system
  - Dimensioned for decay heat rate (not for nominal power)

XT-ADS: safety analysis

- Main transients (≡ MYRRHA_Draft2):
  - LOF, LOH, LOF&LOH, T$_{ransient}$O$_{ver}$P$_{ower}$, S/A blockage, overcooling
  - Protected (DBC) and unprotected (DEC)
- Safety criteria:
  - Fuel (MOX): T < 2707°C for fresh fuel, 2673°C for 100 MWd/kg burnup
  - Cladding: T < 800°C for max. 30 min
  - Coolant: T > 125°C (freezing)
- Main computation code: RELAP5 mod3.2 adapted to LBE by Ansaldo
- Preliminary results:
  - protected transients: OK
  - unprotected LOF: OK
- Full conclusions will be drawn at the end of the safety analysis and recommendations for the next project (CDT) will follow

Conclusions

- Up to now, the Accelerator Driven System design should comply with the requirements
- Nevertheless the technical solutions for achieving them remain to be confirmed since request additional R&D and/or qualifications, mainly:
  - Accelerator availability (need to operate over a long duration the prototype accelerator)
  - Qualification of core and primary circuit materials (under lead environment)
  - Lead oxidation stability and control, everywhere within the coolant circuit
  - Qualification of plant control system (especially control of sub-criticality level)
  - Qualification of design tools (computing codes, design standards)
  - ISIR qualification under non conventional liquid metal coolant
  - Qualification of remote handling and ISIR
- Significant analysis results are available to provide a noticeable confidence to pursue the development of ADS, but a demonstrator is requested to prove the transmutation performance, the reliability and the industrial feasibility