Fill in the title of your proposal below.

Title of Proposal

Innovative Approach to the Safety and Licensing of Small Modular Reactors

Acronym (**to be found; participants are asked to send proposals, in the meantime, we use ADSMR for Accelerator-Driven SMR**)

The consortium members are listed in part A of the proposal (administrative forms). A summary list should also be provided in the table below.

List of participants (to be put in systematic order, alphabetical? To be discussed)

Partic. No.	Participant organisation name	Short name	PIC	Country
1 (Coordinator)	European Organisation for Nuclear Research	CERN	999988133	IEIO*
2	Centro de Investigaciones Energeticas, Medioambientales y Tecyhnologicas	CIEMAT	999614877	ÈS
9	Kungliga Tekniska Högskolan	KTH	??	Se
4	Istituto Nazionale Fisica Nucleare	INFN	999992789	It
5	Hydromine Nuclear Energy S.a.r.l	HNE	917565681	L
6	Agenzia Nazionale per le Nuove Tecnologie, Energia e Sviluppo Economico	ENEA	999988521	It
7	international Thorium Energy Committee	iThEC	918008389	CH
8	Paul Scherrer Institut	PSI	999994923	CH
10	Centrum výzkumu Řež	CVR	996153820	Cz
11	**We must find a company to replace BelV**			

*International European Interest Organisation (IEIO)

* Please use the same participant numbering as that used in the administrative proposal forms.

1. Excellence

Your proposal must address a work programme topic for this call for proposals.

This proposal addresses the work programme 2019-2020 of EURATOM and more specifically NFRP-05: Support for safety research of Small Modular Reactors

This section of your proposal will be assessed only to the extent that it is relevant to that topic.

1.1 Objectives

- *Describe the overall and specific objectives for the project, which should be clear, measurable, realistic and achievable within the duration of the project. Objectives should be consistent with the expected exploitation and impact of the project (see section 2).*

In the general stagnation context of nuclear energy in Europe and in the Western world, Small Modular Reactors (SMR) have nonetheless gained a rising interest, as attested by the broad diversity of designs with very distinct characteristics, and the large number of countries involved (**Table 1**). Indeed, considering carbon emission concerns and fossil fuels availability in the medium term, nuclear energy is considered as one of the realistic portfolio solutions to the growing energy demand [1]. In this scenario, SMR may provide the possibility of deploying nuclear plants easier to install and less prone to severe accidents. The World Nuclear Association (WNA) foresees a large potential market for SMR, with many systems in operation by 2030. Hundreds of such systems could be deployed in China, according to WNA experts. However, as of today, the development and deployment of SMR is at a very early stage. The Korean 100 MWe SMART SMR is the only one to have received design approval from a regulatory body and it is only at the beginning of 2019, that Canada submitted a license application for its first SMR [2]. [**What about SVBR 100 in Russia?**]

The SMR definition used by IAEA is: "SMRs are newer generation reactors designed to generate electric power up to 300 MW, whose components and systems can be shop fabricated and then transported as modules to the sites for installation as demand arises."[3] This broad definition may be complemented by that of Micro Modular Reactor (MMR), limited to about 50 MWe. Since the late 1970s, MMR units have been deployed in remote areas of Siberia to produce affordable electricity in locations difficult to access.

A large scale commercial deployment of SMR is directly conditioned by the economics of the technology, its safety and consequently by the licensing process which is an important driver of the cost.

The high potential of SMR rests on a number of potential factors:

- Their small size combined with economy of series production lowers a main hurdle in the deployment of nuclear energy systems, namely, the high investment cost;
- Because of their small size and modularity, SMR could be built in a central factory setting and installed module per module, improving the level of construction quality and efficiency;
- Their small size and enhanced safety features make them suitable for countries in need of distributed energy sources and with less experience in nuclear power;
- Size, construction efficiency and safety advantages can lead to easier licensing compared to larger reactor plants.;
- SMR are proliferation resistant, as the fuel inventory is smaller than in conventional power plants and there is little or no access to the fuel.

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[1] International Energy Agency, Key World Energy Statistics 2018

[2] http://world-nuclear-news.org/Articles/First-Canadian-SMR-licence-application-submitted

[3] Advances in Small Modular Reactor Technology Developments, A Supplement to: IAEA Advanced Reactors Information System (ARIS) 2016 Edition, IAEA

However, to benefit from all the advances of nuclear technology, current regulations which are mainly tailored to light water reactors need to be adapted to these new technologies and in addition, the licensing process should be staged to provide applicants with a clear roadmap to facilitate the process, as pointed out by NIA[4]. In particular, as SMR have several innovative features in terms of fuel, cooling, control and safety, they are largely unstudied from a regulatory perspective, special attention must therefore be dedicated to the Licensing Process (LP), that was historically developed for larger Nuclear Power Plants (NPP).
The main SMR technologies developed so far are based on:

- Water-cooled reactor technology, both land-based and marine-based;
- High temperature gas-cooled reactors;
- Fast neutron spectrum, sodium- or other liquid metal-cooled reactors;
- Molten salt reactors.

SMRs in general, have not yet been licensed (except for the SMART 100 MWe SMR developed by KAERI, which received the first-ever Standard Design Approval (SDA) from Korean regulatory body, in 2012). Most designs have not yet been widely analyzed by regulators. [**What about SVBR 100?**]
All these technologies still have major issues to be resolved in order to make them convincingly safe:

- PWR SMR have to work at high pressure and with high enrichment of the fuel to compensate for the high neutron leakage;
- High-temperature gas-cooled SMR have cooling issues due to the small volume and the high-power density which requires high gas pressure, and they must be totally protected from water ingress;
- Fast neutron spectrum, sodium-cooled SMR have cooling issues due to the nature of sodium that requires rather broad cores, sodium leakage must be made impossible, and it is difficult to control the void coefficient while at the same time minimizing neutron leakage;
- Fast neutron spectrum, lead-bismuth- or pure lead-cooled SMR have mainly corrosion issues at high temperature, as well as polonium issue;
- Molten salt SMR require online extraction of the hot fuel with challenging chemistry online, and there are corrosion issues.

In addition, all these technologies have unresolved waste management issues. Dealing with its long-term radiotoxicity is a key challenge. In about 60 years of nuclear power plants activity, Europe has been accumulating a large stock of radioactive waste that may pose issues of safety, security, proliferation, environmental challenge and societal concern. According to IAEA Data Waste Counter [111], today over 400,000 tons of spent fuel have been discharged all over the world, out of which about one third in Europe. The problem will only increase in magnitude in the coming years, despite the decreasing number of nuclear plants in Europe. In the rest of the world, nuclear power is expanding, in particular in China and India. The most worrisome long-lived component of the waste, the TRU, now exceeds 3000 tons world-wide (Fig. 2).

[4] Enabling Nuclear Innovation, Strategies for Advanced Reactor Licensing, A Report by the Nuclear Innovation Alliance, Ashley E. Finan, et al., April 2016

Table 1: *Status of Deployment of SMR Designs and Technologies* (Source: Advances in Small Modular Reactor Technology Developments, A Supplement to IAEA Advanced Reactors Information System (ARIS) 2016 Edition, IAEA)

Design	Output	Type	Designers	Country	Status
KLT-40S	70	Floating NPP	OKBM Afrikantov	Russian Federation	Under construction
HTR-PM	210	HTGR	INET, Tsinghua University	China	Under construction
CAREM	30	PWR	CNEA	Argentina	Under construction
ACP100	100	PWR	CNNC	China	Conceptual Design
CAP150/200	150/200	PWR	CGNPC	China	Conceptual Design
AHWR-300	300	PHWR	BARC	India	Conceptual Design
IRIS	335	PWR	IRIS Consortium	Multi Countries	Conceptual Design
DMS	300	BWR	Hitachi GE	Japan	Conceptual Design
IMR	350	PWR	MHI	Japan	Conceptual Design
SMART	100	PWR	KAERI	Republic of Korea	Certified Design
UNITHERM	6.6	PWR	NIKIET	Russian Federation	Conceptual Design
KARAT-45/100	45/100	BWR	NIKIET	Russian Federation	Conceptual Design
ELENA	68 kW	PWR		Russian Federation	Conceptual Design
RUTA-70	70 MW(th)	PWR	NIKIET	United States of America	Conceptual Design
NuScale	50 × 12	PWR	NuScale Power	United States of America	Under Development
mPower	195 × 2	PWR	BWX Technologies	United States of America	Under Development
W-SMR	225	PWR	Westinghouse	United States of America	Conceptual design completed
SMR-160	160	PWR	Holtec International	United States of America	Conceptual Design
ACPR50S	60	PWR	CGNPC	China	Conceptual Design completed
Flexblue	165	Immersed NPP	DCNS	France	Conceptual Design
RITM-200	50 × 2	Floating NPP	OKBM Afrikantov	Russian Federation	Detailed Design
VBER-300	325	Floating NPP	OKBM Afrikantov	Russian Federation	Licensing Stage
ABV-6E	6	Floating NPP	OKBM Afrikantov	Russian Federation	Final design
SHELF	6.4	Immersed NPP	NIKIET	Russian Federation	Detailed Design Underway
GTHTR300	300	HTGR	JAEA	Japan	Basic Design
GT-MHR	285	HTGR	OKBM Afrikantov	Russian Federation	Preliminary Design completed
MHR-T	205.5x4	HTGR	OKBM Afrikantov	Russian Federation	Conceptual Design
MHR-100	25 – 87	HTGR	OKBM Afrikantov	Russian Federation	Conceptual Design
PBMR-400	165	HTGR	PBMR SOC Ltd	South Africa	Preliminary Design completed
HTMR-100	35	HTGR	Steenkampskraal Thorium Limited (STL)	South Africa	Advanced Conceptual Design phase

Design	Output	Type	Designers	Country	Status
SC-HTGR	272	HTGR	AREVA	United States of America	Conceptual Design
Xe-100	35	HTGR	X-energy LLC	United States of America	Conceptual Design
LEADIR-PS	39	LMFR	Northern Nuclear Industries Incorporated	Canada	Conceptual Design
4S	10	LMFR	Toshiba Corporation	Japan	Detailed Design
BREST-OD-300	300	LMFR	NIKIET	Russian Federation	Detailed Design
SVBR-100	100	LMFR	JSC AKME Engineering	Russian Federation	Detailed Design
G4M	25	LMFR	Gen4 Energy Inc.	United States of America	Conceptual Design
EM^2	265	GMFR	General Atomics	United States of America	Conceptual Design
IMSR	185-192	MSR	Terrestrial Energy	Canada	Conceptual Design
MSTW	100	MSR	Seaborg Technologies	Denmark	Conceptual Design
ThorCon	250	MSR	Martingale	International Consortium	Conceptual Design
FUJI	200	MSR	International Thorium Molten-Salt Forum: ITMSF	Japan	Conceptual Design Completed
Stable Salt Reactor	37.5×8	MSR	Moltex Energy	United Kingdom	Conceptual Design
SmAHTR	125 MW(th)	MSR	ORNL	United States of America	Pre-conceptual design
LFTR	250	MSR	Flibe Energy	United States of America	Conceptual Design
Mk1 PB-FHR	100	MSR	University of California, Berkeley	United States of America	Pre-Conceptual Design

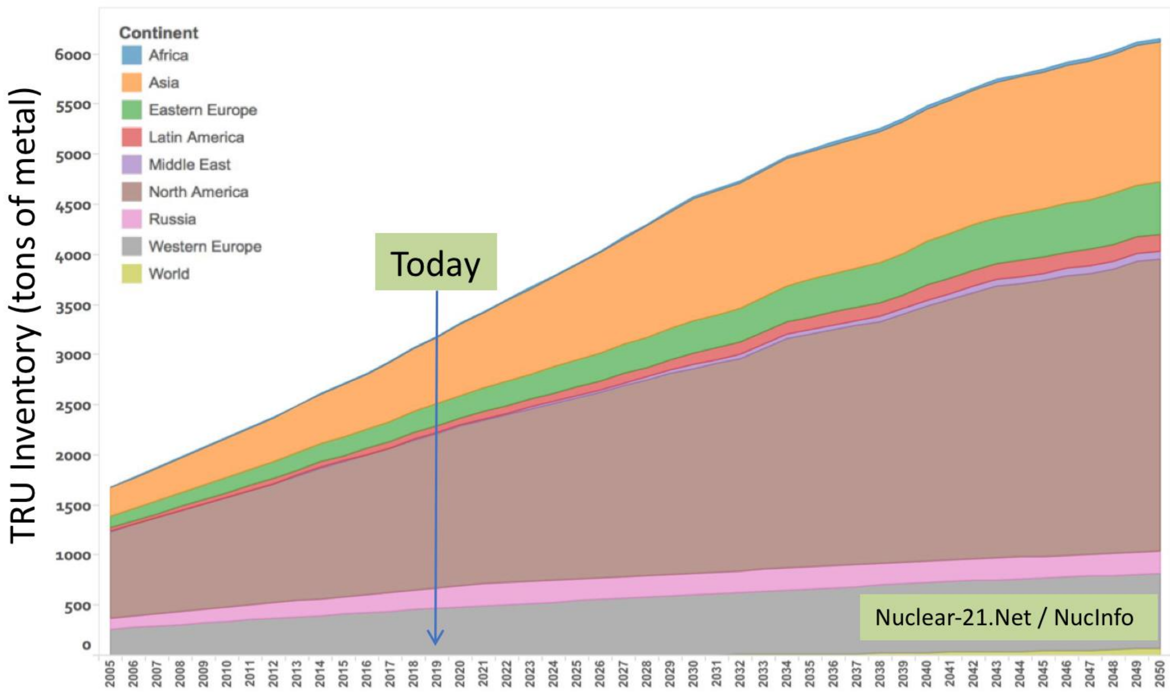

Figure 1: TRU represent the dominant part of the long-lived nuclear waste. This figure shows the evolution of the world inventory of TRU with extrapolation to 2050, assuming that only currently approved new power plants will be deployed. (Source: Nuclear-21.Net / NucInfo)

As is more apparent in the USA, the unduly long delay in providing definite management solutions to nuclear waste imposes financial risks to operators and governments, which renders nuclear energy less competitive and thus removes a significant CO_2-free emitting energy source for the future. Geological disposal is today's technological paradigm, as the only actively pursued option for spent fuel or High Level Waste (HLW) management. However, this option raises strong concerns in the public opinion on the ability to guarantee a safe and secured system for the extremely long period of time during which nuclear waste must be isolated (200,000 years or longer). Our political or social institutions have not even been stable over a period of only 1,000 years, therefore, it is not obvious how to ensure stable monitoring and safeguarding for the required long term. Moreover, geological disposal of radioactive waste requires careful analyses projecting the site geo-chemo-physical evolution into the future for millennia. In addition, several voices questioned whether it is ethically acceptable to burden future generations with the potential risks posed by nuclear waste.

We believe that the future of nuclear energy depends on the capability of the forthcoming systems to cope with the concurrent issues of safety, proliferation, waste production reprocessing and management, cost. Acceptability by the public is a requirement considered as a mandatory review step in the usual LPs and political decision is the normal initiation phase of all LP. A system layout that is not able to address convincingly all of the above-mentioned issues will not pass these barriers.

On the other hand, SMR, with their distributed deployment nature introduce a new situation both in terms of waste management, as more spent fuel transport might be necessary, and in terms of resistance to proliferation, as the number of sites increases.

For all these reasons, we believe that further innovation is required in the design of SMR in order to meet the most stringent requirements of safety, proliferation, waste management, and sustainability all together.

So far, most or all of SMR research was concentrated on critical SMR systems. However, the significant progress in accelerator technology in the past 20 years, makes it possible today to consider Accelerator-Driven SMR (ADSMR) (Fig. 2). The presence of an external neutron source provided by a proton accelerator allows an innovative approach to safety and waste management, which should lead to a much-simplified licensing process.

The ADS concept is not new, as it originates from the late 1940s with Lawrence in the USA and the beginning of the 1950's with Lewis in Canada. However, today progress in accelerator technology as well as in spallation target technology, makes the concept much more realistic.

Already in the 1990s at CERN, Nobel Prize Laureate Carlo Rubbia proposed the concept of Energy Amplifier (EA) [111], an Accelerator-Driven System (ADS) with a proton beam impinging on a spallation target enclosed within a subcritical core. Today, the ADS state-of-the-art project is MYRRHA [112]. However, there is also an ambitious ADS project in China, the Accelerator-Driven Advanced Energy System (ADANES) [113]. Furthermore, in the past 20 years EUROPE carried out a systematic R&D programs on transmutation and partitioning across several EU Framework Programs for Research and Technological Development, EUROTRANS [5]. EUROTRANS included a broad program of R&D on pure lead and lead-bismuth

[5] https://www.oecd-nea.org/pt/iempt9/Nimes_Presentations/KNEBEL.pdf

technologies, in particular, on corrosion which limits the output temperature, hence the energy efficiency of electricity production. A status of world efforts on ADS may be found in [114].

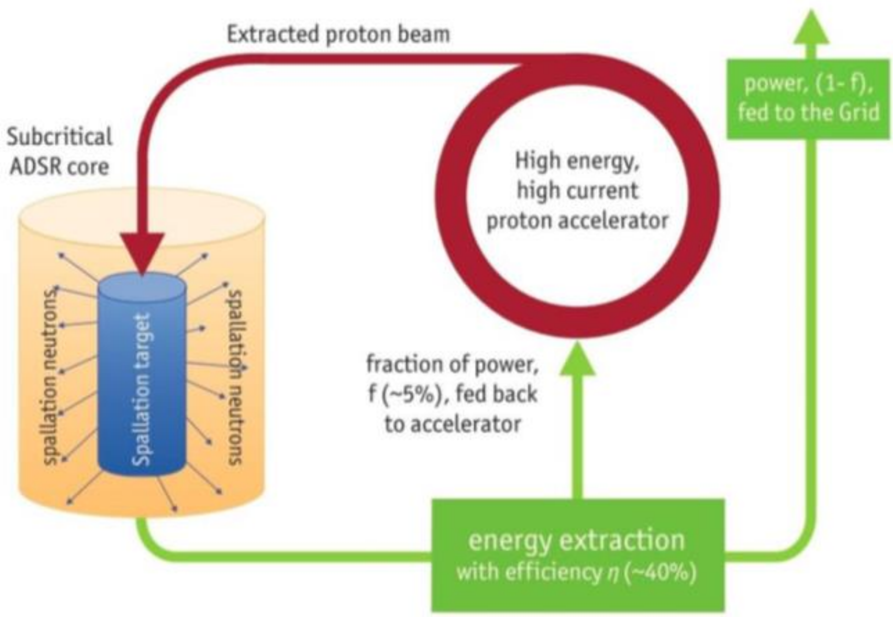

Figure 2: Schematic representation of the concept of Accelerator-Driven SMR (**Sketch to be remade without specific numbers**)

Today, all the elements of an ADS have been built and tested at a scale appropriate for significant power, but only separately:

- Proton accelerators have exceeded 1 MW of beam power, both for linacs (SNS in the USA) and for cyclotrons, the preferred option for ADSMR (PSI Cyclotron);
- Spallation target: MEGAPIE, a Pb-Bi eutectic spallation target of 1 MW was operated successfully at PSI for several months. A 5 MW proton beam is under construction at Lund, in Sweden, to drive the future European Neutron Spallation Source.;
- Heavy-metal-cooled reactor cores: For instance, Russia, which developed about 80 years of experience in the operation of lead-bismuth submarine reactors, obtained recently an export license from IAEA for its SVBR-75/100, a Lead-Bismuth critical core SMR, that could be readily adapted to an ADSMR.

The proposed ADSMR is a novel and innovative concept, that corresponds to a paradigm shift when the concepts of SMR and of ADS are combined. The main added advantages include:

- Sub-critical operation of the core;
- Possibility to work with a lower enrichment of the fuel;
- Higher flexibility in the choice of fuel;
- Simpler and more reliable control system through the accelerator, allowing load modulation, to follow demand;

- Enhanced safety features;
- Possibility of mitigating the issue of spent fuel management through the use of thorium fuel;
- Possibility to envisage economic competitiveness for power production units smaller that 300 MWe, because of the simpler passive safety characteristics of the system.

Our project consists of (1) a new SMR design, making use of ADS technology advances; (2) the development of tools for the assessment of improvement in safety, waste reduction, and cost; (3) a new licensing strategy including a set of safety specifications and requirements, in line with the EU directives and IAEA recommendations; and finally (3) a study of deployment scenarios, fuel cycle and economic aspects, including waste management.

A *Analysis of licensing process*: The main objective of the ADSMR proposal is to analyze the Licensing Process (LP) applied to a specific, innovative concept, the Accelerator-Driven Small Modular Reactor (ADSMR).

- o Conditions for achievement:

B *Conceptual design*: As the LP is layout-specific, because inherently linked to the specific project characteristics and to the targeted applications, we present a specific, innovative and safe ADSMR concept, with a view to define a generic ADSMR design, in order to advance toward standardized plant projects for authorization of construction and operation. The targeted applications of the concept we propose are including, but not limited to, energy production, hydrogen production, and nuclear waste transmutation.

- o Conditions for achievement:

C *Licensing process*: We want to demonstrate that harmonization of engineering aspects, manufacturing and accompanying certifications can standardize the LP, thereby, facilitating the licensing of ADSMR, which, together with its economies of scale, could make it more attractive for industry. The final aim of this study would be to facilitate efficient progression of regulatory activities for licensing general types of SMRs.

We want to define criteria that allow for ADSMR “generic site” prescriptions, and “generic engineering project”, in order to fully exploit the modularity concept applicable to critical SMR projects, identifying what factors would facilitate international licensing of SMR.

We want to define the authorizations for construction, operation, decommissioning for a generic ADSMR.

- o Conditions for achievement: ensure competence building and transfer of knowledge on ADS and SMR

D *Risk analysis*: We want to define the magnitude of risks embedded in the specific ADSMR, with the aim of applying a graded approach to determining the level of regulatory control.

- o Conditions for achievement: prepare a plan with harmonized methods for reviewing safety cases

E *Economic aspects*: We want to study deployments scenarios, including the management of spent fuel and compare their competiveness as a function of the energy scale.

F Education, training, communication and dissemination are additional objectives: We expect that the level of innovation combined with the importance of energy issues for the future of our civilization should motivate strongly a new generation of young researchers.

- a) Training of young researchers within the project through experiments carried out to validates concepts and elements of the system, as well as the overall system behavior, schools and workshops on specific topics
- b) Documentation, communication and dissemination of the results, addressing the directly concerned community involved in the nuclear waste disposal safety case and a broader scientific community.

Therefore, our vision, in a time horizon at the middle of this century, is that ADSMR can allow a new development of nuclear industry, by providing distributed energy supplies with load following capacity that would be a complement to fluctuating wind and solar energy systems. With a view of progressively replacing the retiring fossil-fuel power plants and to extend to other applications such as water desalinization, hydrogen production, etc. To help quantify the potentiality of the market, we note that Nuclear Energy Insider estimates that in the USA alone, replacing coal power plants (that shall have to be shut down sooner or later), offers a market opportunity of 30 B$.[6]

Once the concept engineering features (modularity, reactor / safety system integration, sub-grade installation, etc.) will have demonstrated technical and economic feasibility, the principle will be more easily scaled to multi-unit installations allowing for a cost-efficient deployment of SMR able in addition to cope with a vision that surpasses the current paradigm of “burying the waste”, by the use of a new technology that provides a workable contribution to solving a worldwide problem, and that at the same time helps increasing the social acceptability of nuclear power plants.

1.2 Relation to the work programme

- *Indicate the work programme topic to which your proposal relates, and explain how your proposal addresses the specific challenge and scope of that topic, as set out in the work programme.*

This proposal relates to the work program topic NFRP-05 which concerns the methodologies for performing safety evaluations and safety improvements fostering safety standards of SMR. We propose an innovative SMR which combines both critical SMR and ADS technologies, and we will show that ADSMR offer new safety features which represent a significant advance toward certification. For this we define a safe generic small modular ADS (ADSMR) as a case

[6] http://www.nuclearenergyinsider.com/smr/pdf/USSMRUtilityMarket5.pdf

study and make a systematic analysis of all safety related issues, taking both standard nuclear reactors and critical SMR for comparison.

Safety by design

For SMR, the safety-by-design can be enhanced by the subcriticality of the system, in addition to the use of proper passive safety systems activated by force of nature (gravity, conduction, convection, i.e.) represents the second level of safety. In ADS, the spallation technique is the efficient way to produce high neutron flux by externally supplying neutrons into the reactor. In this way, including the low inventory of radioactive materials with respect to larger NPP, as well as the capability of the accelerator to very rapidly shut the beam down, thereby interrupting the nuclear chain reaction, the ADSMR can set a benchmark in the nuclear safety standard. The safety-by-design, reducing the probability of accidents and mitigating the consequences, produces a system which is simpler, safer, cost effective and, in principle, easier to-be-licensed. The long operating experience (OPEX) accumulated singularly on the main components of the ADSMR reduces uncertainties and mitigate risks. In fact, accelerators technologies are deployed since almost a century, with operating data available in terms of safety, availability and reliability. Even if it is not obvious that a smaller reactor means a shorter technical assessment (the time to complete the review is influenced by the time needed to confirm that the proposed safety and control measures meet regulatory requirements), for the subcritical reactor the demonstration of safety in support to the application for authorization is expected to be easier, for example, because of the physical response to abnormal conditions.

Conditions for achievement

Requirements for SMRs may be site-specific and also legislation dependent, and therefore the regulatory and legal requirements in different countries can jeopardize one of the main features of SMR: exportability. Moreover, the precise legal authority and role of regulatory body is not the same in all countries. But even if requirements cannot be harmonized between different countries due to legal structure differences, acceptance of common methodologies can facilitate the use of one regulator’s conclusions to inform another’s technical assessment work, which would reflect into time and cost savings. This would include for example the use of common mechanical design codes, personnel and process qualifications, materials and analysis requirements, and a quality assessment (QA) system that includes design change management. Standardization is a key factor for SMR, because factory production is one of the distinctive features of this type of systems, differentiating it from the existing nuclear supply chain. Indeed, the SMR business model has been assimilated to the production of nuclear engines for ships. The ADSMR project should be highly standardized, which implies that the possible vendor must find an appropriate balance between standardization and customization demands. In addition, any rework should be avoided because it disturbs the assembly process. Finally, all components/parts/kits required for ongoing work should be available at due time because any delays will affect the production of the entire plant and not only one unit. An important challenge for the factory assembly of SMRs is nuclear regulation. While all of the safety features of SMRs could be addressed generally within the existing regulatory framework, there are issues that must be resolved. In particular, current regulatory practices might not be fully compatible with a factory assembly model, especially if the assembly process is automated. Regulators must adapt their methods of work to test the units to the greatest extent possible at the assembly stage and reduce the potential for rework. For the successful deployment of SMRs, a new approach to licensing should be developed to allow factory-based manufacturing and serial deployment. It might require strong co-ordination not only between regulators but also between manufacturers. On the other hand, full factory assembly of SMR units will allow large savings in manufacturing costs.

Market and other economic aspects

Many factors are influencing the SMR market. According to NEA [7], among the several factors influencing the SMR market need to be included the nuclear regulatory barriers and the public attitude towards nuclear power. In the case of ADS, we should add to the challenges the skeptic attitude towards this specific industrial application of accelerator technology, which is sometimes in our opinion wrongly perceived as a research domain-centered activity. We believe that ADSMR can deal with all these challenges at the same time, by targeting basic safety objectives able to support future SMR licensing processes. This will be done in particular by complementing the choice of the accelerator layout with a careful component and system reliability analysis. Moreover, the close interaction in the Consortium among designers, typical manufacturers of specific components (magnets for example, or spallation target) and regulators will allow examining various approaches and possibilities, providing more realistic results.

1.3 Concept and methodology

(a) Concept

- *Describe and explain the overall concept underpinning the project. Describe the main ideas, models or assumptions involved. Identify any inter-disciplinary considerations and, where relevant, use of stakeholder knowledge. Where relevant, include measures taken for public/societal engagement on issues related to the project. Describe the positioning of the project e.g. where it is situated in the spectrum from 'idea to application', or from 'lab to market'. Refer to Technology Readiness Levels where relevant. (See General Annex G of the work programme);*

- *Describe any national or international research and innovation activities which will be linked with the project, especially where the outputs from these will feed into the project;*

The conceptual and traditional scheme of an ADS is shown in fig. 2 (from [8]). The ADSMR concept stems from the combination of particle beam accelerator technology and compact nuclear reactor technology. The benefits of this combination multiply the advantages of the

[7] https://www.oecd-nea.org/ndd/pubs/2016/7213-smrs.pdf

8 R. Cywinski, A. Herrera-Martínez, G. Hodgson, et al., "Towards an Alternative Nuclear Future," The Thorium Energy Amplifier Association (ThorEA), 2009

single SMR in terms of safety, cost, and environmental impact. Because the LP has been individuated as a barrier to the deployment of SMRs in general, and therefore of ADSMR as a consequence, we want to analyze the LP specifically for the ADSMR system with the aim to advance the concept to a realistic approach.

Baseline design

The accelerator: We believes that a cyclotron is a better choice than a linac to power an ADSMR. Several innovative cyclotron concepts exist. The Institute Paul Scherrer in Switzerland operates a cyclotron which has exceeded 1 MW of beam power. An 800 MeV high-power cyclotron was proposed for the Daeδalus experiment, searching for CP violation in the neutrino sector (*J.M Conrad and M. H. Shaevitz, PRL 104, 141802 (2010)*). AIMA Developpement[9] proposed a superconducting high-power cyclotron (600 MeV, 6 mA), which is innovative and promising in terms of reliability, with its 3 external injections (Fig. 3). It should also have high beam power to grid power efficiency, significantly higher than a linac.

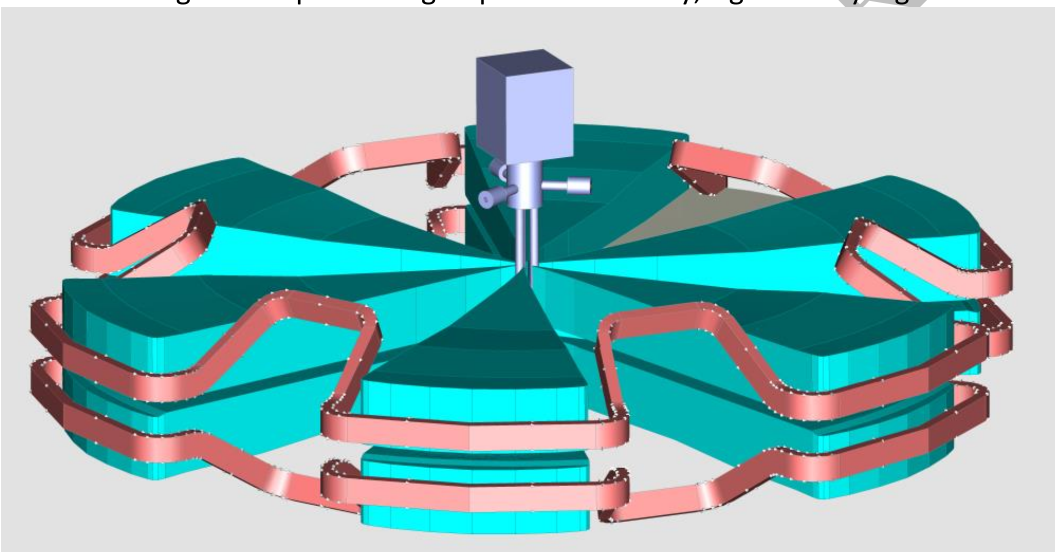

Figure 3: AIMA Developpement design of a high power, superconducting one stage cyclotron (**S2CD™**)

The subcritical core: One of the main strategic choices is the choice of coolant and moderator, between pure lead and lead/bismuth eutectic. Even though pure lead is obviously desirable for industrial ADS, a pure-lead core has not been built until now. The two main contributors to lead-cooled core technology so far are ROSATOM in Russia and HNE in Italy. Materials exist already that can resist corrosion up to lead temperatures of about 500 ˚C. At Oakridge National Laboratory, new alumina-forming austenitic stainless steel alloys have been developed for a temperature range 700 to 800 ˚C, that will, obviously be of interest for the future, as temperature increases the efficiency of conversion of heat into electricity. However, none of these materials were ever tested in a fast neutron flux, so the uncertainty on this approach is high, and the required R&D will certainly take a significant amount of time. Today, it would be safer to opt for a Lead-Bismuth Eutectic (LBE) core. There is experience in Russia over 80 years of operation of LBE reactors for submarines. A rather practical solution for the subcritical core, would be to adapt a SVBR 75/100 (Fig. 4) from Russia, and modify it to implement the coupling to a cyclotron.

[9] AIMA Developpement, Lacassagne lab du cyclotron, 227 Avenue Lanterne 06200 Nice France

HNE develops lead-cooled critical cores. For a subcritical core, they propose a fuel loading strategy different from that of MYRRHA, which clearly would distinguish them from MYRRHA. For what concerns ADANES we do not have information on their core strategy.

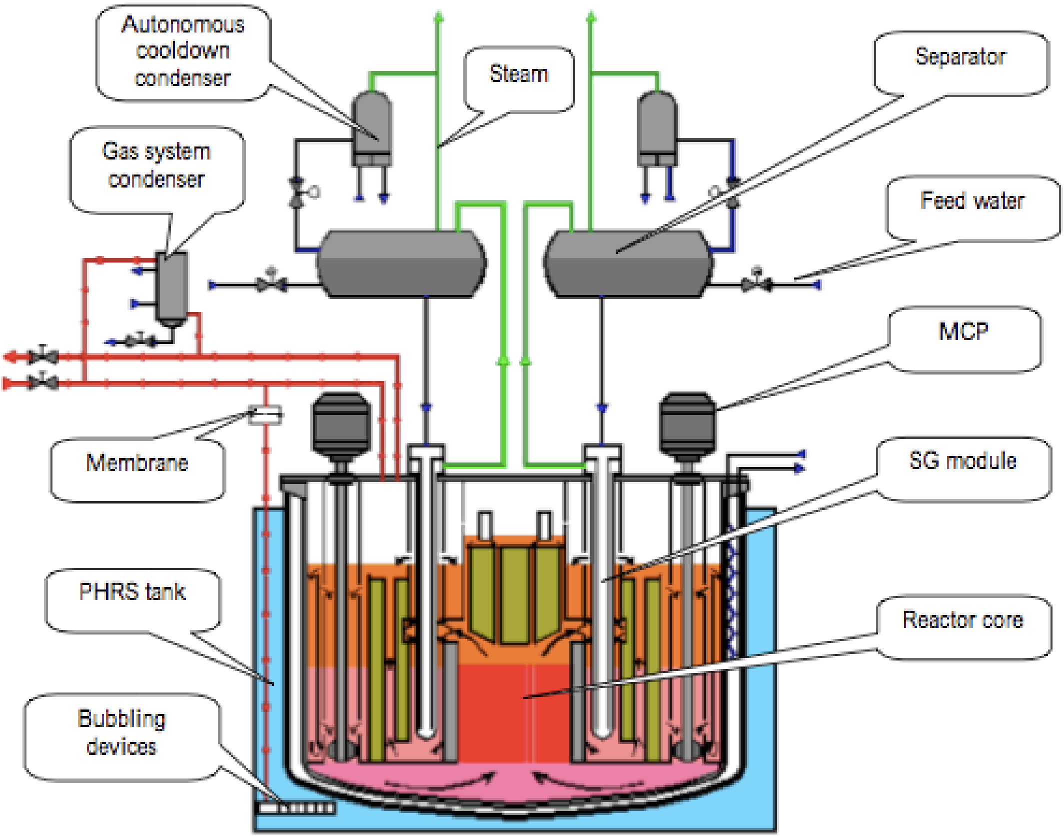

Figure 4: Schematics of a Russian SVBR 75/100, with a lead/bismuth core, showing all basic systems of the reactor installation. At a thermal power of 280 MW the SBBR produces 101.5 MW of electrical power.

For the spallation target, one could easily adapt the MEGAPIE design, a 1 MW target that operated successfully at PSI. The MEGAPIE design would have to be integrated into the subcritical core. This is a part of the project that requires coordination with both the accelerator and the subcritical core sectors.

Scale of the ADS-SMR to be considered

An economical critical SMR needs a power of order 300 MWe, however, the advantages of ADS in terms of safety might make a smaller system worth considering. In addition, if we want to avoid extrapolating existing elements of an ADS too far and also be representative of MYRRHA at the same time, then we should stay within a reasonable factor from these existing elements. In order to keep the accelerator within readily achievable performance it would be safe to aim for an ADSMR of 100 MWe. At least initially, which would correspond to order 300 MW of thermal power. Fixing an electric power goal defines essentially most of the system, within a range of parameters to be used for optimization.

The ADS parameters that are to be optimized in order to reach the required thermal power, are the operational temperature ($T_{op.}$), the level of sub-criticality (k), the target efficiency represented by the gain factor G_0, the beam energy (E_{beam}), and the beam current (I_{beam}).

The SVBR-75/100 works at a primary coolant temperature, of 482˚C at the core outlet and 320 ˚C at the core inlet, which results in an electric conversion efficiency of 36%. Using the

same thermal efficiency implies that the thermal power to be produced for an electric power of 100 MWe is 278 MW.
In order to ensure sub-criticality at all times, the k value should not exceed 0.975[10], which is therefore the highest value that should be considered. Figure 5 shows, under the above conditions, the beam intensity required as a function of beam energy in order to produce 100 MWe, as well as for a MMR od 55 MWe. Figure 6 shows the beam power under the same conditions. For instance, with a 600 MeV beam, the beam intensity required is 6.7 mA, corresponding to a beam powers of 4 MW.
Therefore, the task of the cyclotron designer, will be to optimize for beam losses and reliability, along the curve of figures 1 and 2, perhaps also in terms of cost (warm versus superconducting?).

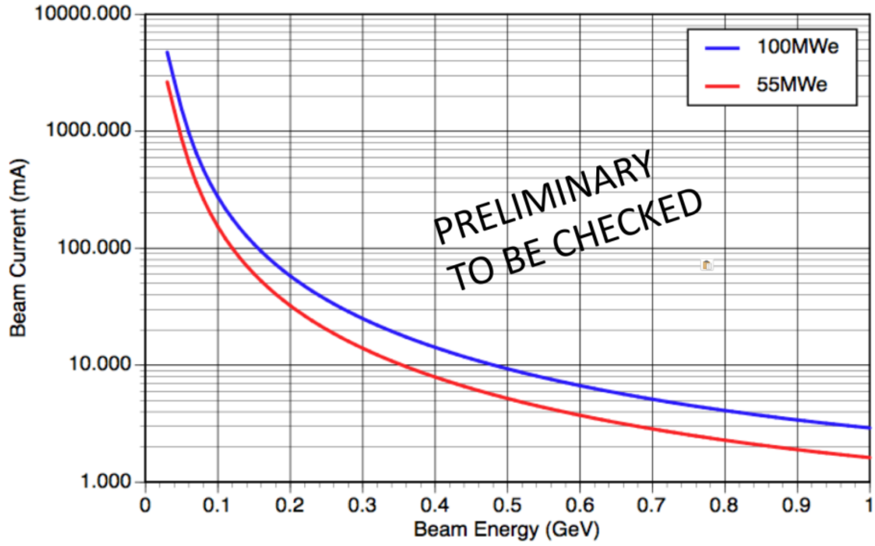

Figure 5: Beam current as a function of beam energy for two electric power output cases: 100 MWe and 55 MWe. The 100 MWe case corresponds to the option discussed in the text for NFRP-05, the 55 MWe case is given here for comparison.

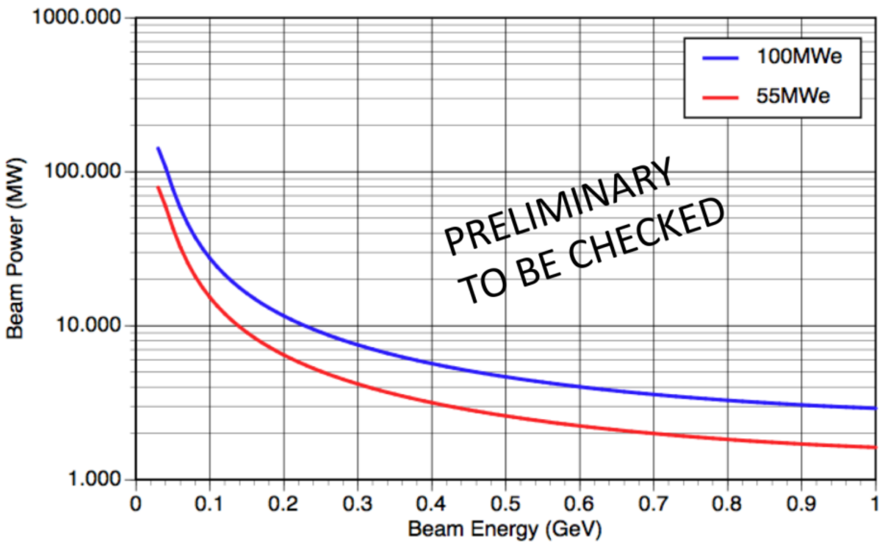

Figure 6: Beam power as a function of beam energy for two electric power output cases: 100 MWe and 55 MWe. The 100 MWe case corresponds to the option discussed in the text for NFRP-05, the 55 MWe case is given here for comparison.

[10] This is for the case of thorium based fuel

General description of ADS

The main components of the ADSMR system ar e: accelerator, subcritical core and spallation target. The requirement of subcriticality of the reactor implies that during operation the neutrons necessary to sustain the fission must be continually supplied to the core. This is done by the accelerator, producing proton impinging on the spallation target. For each of the system components technology benchmarks are available and diverse solutions for the layout exist. More than 40,000 accelerating machines are deployed today in the world, with applications as diverse as medical therapy and diagnosis, manufacturing processes (EB-welding, n implantation, radioisotope production…) and research (particle physics, synchrotron radiation, material science…).- Based on such widespread applications and the available long duration OPEX data, we can consider the corresponding technology scenario to be mature (although continuously and fast developing towards more and more innovative solutions). In the process of producing neutrons from an accelerator-based spallation neutron source, the accelerator plays an important part in the facility to achieve the maximum number of neutrons. ADSMR will investigate an accelerator of the cyclotron type, because its relative compactness enhances the characteristics of a SMR, which by definition needs to be size effective. The experience of operating for 50 years the PSI cyclotron, world record in its power class, and the experience of design, construction and operation of the Large Hadron Collider at CERN, the largest circular collider in the world, will be relevant to define requirements of safety and reliability for the ADSMR accelerator. The reactor core of a SMR can be considered a simplified, scaled version of the equivalent NNP. Spallation is the process of producing neutrons by causing particles from an accelerator to impact a heavy metal target. In order to achieve the highest rate of neutron production, the target material of the spallation process has to be composed of an element which has a high atomic number along with a reasonable thickness. Neutron multiplicity, defined as the number of neutrons produced by spallation per incident particle (n/p), is a crucial parameter for showing the performance of applications of an accelerator driven neutron source. Neutron multiplicity is a function of beam energy and target materials, linearly dependent on the target mass number (in the range $12 < A < 238$) and slowly increasing with incident proton energy (in the range $0.2 < E < 2$ GeV).

The average number of neutrons is approximately given by

$$\langle n \rangle = (0.0803+0.0336 \ln E)A$$

where E is the incident proton energy in GeV and A is the target mass number. This formula provides 10 % accuracy or better for $A \geq 40$ [11].

11 J. Cugnon, C. Volant, and S. Vuillier, “Nucleon and deuteron induced spallation reactions,” Nucl. Phys. A, vol. 625, no. 4, pp. 729–757, Nov. 1997.

The spallation target we will consider is based on liquid Lead Bismuth metal eutectic (????), for reason of experience and OPEX accumulated (MEGAPIE[12] was using the same technology, and MYRRHA will be adopting this technology as well).

For the ADSMRsystem, we will produce a reference layout and, at the same time, we will produce the requirements and safety documentation that are demanded for a full LP. It will be a sort of “dummy exercise” of licensing, calibrated and proof-checked on a valid layout, because the LP is concept-dependent, and because safety-by-design is part of the process. To get the most out of the project and making the exercise realistic and useful it is necessary to include all design aspects, from the starting point, that otherwise will be hidden in the folding of the documentation.

The ADSMR collaboration will interface with the MYRRHA community in SCK, as well as with the community of nuclear engineers and scientists in CERN, PSI, CIEMAT, ENEA and INFN.

The licensing process requires for the applicant to submit a detailed demonstration of safety, which is reviewed by independent regulators, according to nationally applicable laws. It should be the responsibility of the regulator to provide guidance, safety objectives, criteria and the format of the documents to be produced (generally a Safety Analysis Report, SAR). For this reason, and also in consideration of the innovative type of plant for which little regulatory experience exists, we deem necessary to work according to a well-defined stakeholders scheme, where the regulatory functions shall interface with the technical counterparts and with the implementing actors, and where the public and policy makers also have a definite role. An early involvement of regulators in a process like the one depicted here is critical to prevent delays. Our partner (Partner to be found to replace BelV) will mirror the regulator action, providing the guidance and steering the exercise process.

According to the hierarchy of safety standards for innovative reactors, prepared in the framework of the SARGEN-IV project, as reported in figue 7 [13], it will be necessary to ensure that the safety standard of LEVELS I, II and III are fulfilled already before submission of a safety analysis report (SAR).

[12] G. S. Bauer, M. Salvatores, and G. Heusener, “MEGAPIE, a 1 MW pilot experiment for a liquid metal spallation target,” J. Nucl. Mater., vol. 296, no. 1–3, pp. 17–33, 2001.

[13] Sargen-IV: Consideration on the possible content of the safety analysis report for innovative ESNII reactors – Nuclear Engineering and design 300 (2016) 453-466

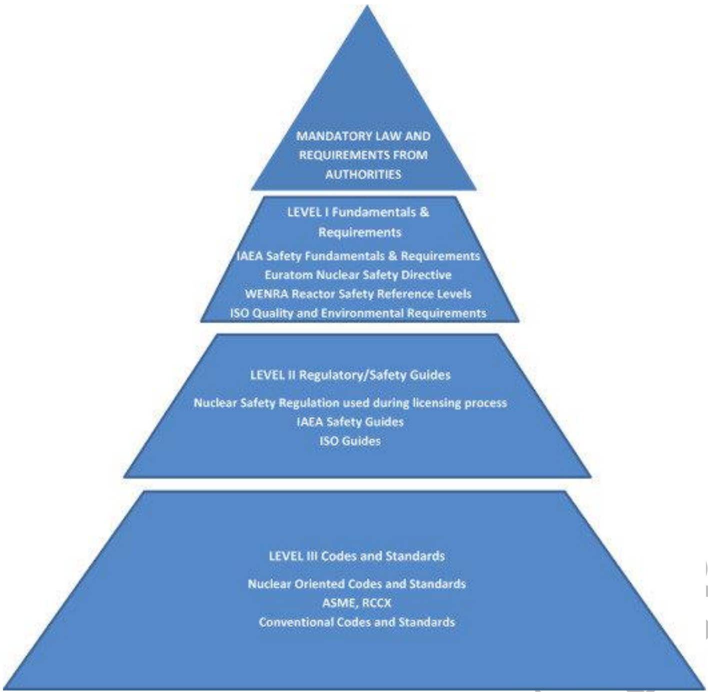

Figure 7: Hierarchy of safety standards for innovative reactors.

Well before the submission of the license application, it would be also requested for the regulators to meet with the licensees, the designer and with the prospected operator. The Consortium will prepare, under supervision of the partner to be found to replace BelV, our "internal regulator", the documentation according to the general structure of the SAR:

1- General Design Aspect, safety objectives and engineering design requirements
2- Simulation
3- Design of systems, structures and components
4- Reactor, reactor coolant and connected systems
5- Accelerator and beam losses
6- Spallation target and window, qualification and experimental data.
7- Safety features
8- Decay heat removal system
9- Containment system
10- Habitability system
11- Instrumentation & control
12- Electric power and power conversion system
13- Radioactive waste management and Radiation protection

Site characteristics, operational conditions, human factors engineering and management systems, which are also normally included in the SAR, will only be treated on general terms, because they are either geography dependent, or depending on the experience of the specific operator, that, at this moment, is not defined and not part of the work.

1.2 Ambition

2. Impact

2.1 Expected Impact

2.2 Measures to maximise impact

2.2.1 Dissemination and exploitation of results

2.2.2 Communication activities

3. Implementation

3.1 Description of work — Work packages, deliverables and milestones

3.2 Management capabilities

3.3 Management structure and procedures

3.4 Risk management

3.5 Consortium/ Clusters as a whole (where applicable)

3.6 Resources to be committed

PART B. I

⚠ **For a proposal to be considered as complete, the applicant(s) should fill in the following table templates:**

1. **Table 3.1.a – List of Work Packages**
2. **Table 3.1.b – Work Package Descriptions**
3. **Table 3.1.c – Work Package Effort**
   An excel template is provided in the "Partner(s) Application/Proposal Template" package made available to the applicant(s) via the submission system
4. **Table 3.2 – List of identified critical risks and the mitigating measures foreseen**
5. **Table 3.3 – Total Eligible Costs breakdown per Work Package**
   An excel template is provided in the "Partner(s) Application/Proposal Template" package made available to the applicant(s) via the submission system