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Small Modular Reactor Safety-in-Design and Perspectives

Nuclear Power is Dead, Long Live Nuclear Energy!

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Cover:
Site layout for the SMR nuclear site complex by MOLTEX Energy. A feasibility report for Canada with the MOLTEX concept under review has just been published.

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2020-year-in review –
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A Zero-power Facility as a Multi-fold Opportunity to Support Quick Progress in Innovative Reactor Development

Bruno Merk, Dzianis Litskevich, Anna Detkina, Greg Cartland-Glover, Seddon Atknison and Mark Bankhead

Introduction and history Nuclear has a very unique role to play in a sustainable energy future, since it is the only currently available technology which can assure 24/7 availability and controllability while delivering massive amounts of low carbon energy on demand for a net-zero future. However, in the recent decades there has not been any significant progress in the development of viable innovative nuclear technologies in comparison with the golden age of the nuclear development (1950's-1970's). Most new designs are iterative improvements of the nuclear technologies developed at that time (e. g. EPR in France, BN in Russia), or are more radical designs with little substantiation with an exception made for BREST-OD-300 [1], currently under development/construction [2]. Regardless of the different nuclear technologies studied and developed, the majority of the NPPs built around the world are still light water reactors. Unfortunately, light water reactor technologies have their limits due to their operational characteristics and cannot address major challenges which nuclear industry faces at the moment. Core points are: reducing nuclear waste, the availability of resources to manage assets over 100's years and the complexity systems leading to elevated cost. To be accepted by both, business and public, nuclear must deliver and be cost competitive compared to other flexible, on-demand producing, power plants with similar financial risks applied. Thus, nuclear needs innovations to be more sustainable, but even more importantly, we need to regrow the trust that nuclear can deliver these innovations. Finally, we need innovative approaches to reduce the risks associated with nuclear power plant construction becoming complex mega projects.

Looking back to the most recent western nuclear reactors put into operation as well as the current new build projects, the demand for risk reduction should be evident. The time since the last reactor being put into operation in the west indicates that we will have a problem when we intend to rely on experience.

Looking into innovative reactor development, the last building projects fall into the 1980ies, followed by very mixed levels of success on operation. The German THTR project to build an industrial demonstrator for high temperature reactor technology lasted from 1971 to 1985 with the permanent shutdown in 1988. The French SUPERPHENIX construction took from 1976 to 1985 and the reactor was permanently shutdown 1998 never delivering an Energy Availability Factor above 33 % and most of the time below 15 %. The UK fast reactor project in Dounreay indicates comparable dates and outcomes, construction started in 1966, first criticality in 1974 with a load factor of below 30 % and the shutdown in 1994 (all data from [3]).

Obviously, if we want to be successful in delivering innovative reactors, we need to learn again, and this should happen in a smart way. The key will be to receive timely feedback/quick response on the decisions made instead of the long lead times which results typically in high costs when late adaptions are required, see e. g. the Olkiluoto or the Vogtle project, where changes in the later construction phase have not only led to higher costs but also to massive time delays which is maybe even more important.

To support the required learning, we need an innovative and efficient approach, start smart and small – looking back to early reactor developments, zero/low power reactors have been used as a test bed for the next steps [5, 6] which seems to be highly promising. The main challenge will be to make the best out of the money and to use the time wisely.

Country	Western Reactors under construction	Reactor type	Construction start year	Grid connection
USA	Watts Bar-1	WH 4LP	1973	1996
USA	River Bend	GE BWR	1977	1985
France	Chooz B	N4	1984	1996
France	Civaux	N4	1988	1997
USA	Watts Bar-2	WH 4LP	1973/2007	2016

Table 1
The last constructed nuclear power plants and their grid connection [3].

- How is starting small possible in a highly complex multi-billion industry?
- How did we do this in the 50ies and 60ies? Can we repeat this? What do we need to do differently in the 21st century?
- How important are collaborative opportunities to support upskilling and engineering development?

The fundamental problem is, when building an innovative reactor there is no experience, no plan, so appropriate cost management is almost impossible because we don't know all the steps, the required technologies, and the challenges (unknown unknowns). Introducing a structured process to the R&D will be a key requirement and will help to define a structured approach to the first of a kind (FOAK) or the later serial build. Learning on a small real project and going in steps will allow us to achieve a more efficient cost reduction than just learning from experience which typically takes place at a very later stage of the project which leads to delays and cost over runs. These multiple arguments speak for starting a new, innovative reactor programme on a small scale using a zero-power reactor to reduce the risk of the whole development program.

Why do we need this program?

The last indigenous reactor in the UK was constructed 1980 and put into operation in 1988, while the design

The Dungeness disaster

Construction on the new AGR at Dungeness B started in January 1966. A later historian of the privatization of the British electricity industry described it as “the single most disastrous engineering project undertaken in Britain” [Henney (1994) p. 131]. Among a certain generation of people, Dungeness B is still a byword for failure of construction, design and project management on a heroic scale. The project was beset by delays, strikes and cost overruns.

Henney, A (1994). A Study of the Privatisation of the Electricity Supply Industry in England & Wales, London: Energy Economic Engineering

Figure 1
Simon Taylor (2016) The Fall and Rise of Nuclear Power in Britain: A history [8].

also occurred several decades earlier and the knowledge was not passed onto the next generation. This has led to a significant reduction in the number of the specialists in the nuclear sector. Looking deeper, the last indigenous development of a reactor has been delivered in the late 1960ies, see **Figure 1**. This development was pushed by an ambitious construction programme aiming to deliver five twin reactor stations and was quickly rolled out to support business since export orders were eagerly anticipated. Thus, the situation seems to be a bit like the todays nuclear renaissance supported by the BEIS (Department for Business, Energy & Industrial Strategy) nuclear innovation program (NIP) [7] with the aim to produce business opportunities for UK plc and to become a top table nation in nuclear latest in 2050 to support the green recovery.

The lead station of the AGR program was Dungeness B which could be seen as industrial demonstrator and a first of a kind and it was a direct step into a large station without real stepwise development. It was ordered in 1965 with a targeted completion date of 1970. The project did not progress as expected, being several times delayed after problems in many aspects of the reactor design, a bit comparable to today’s mega projects, see Figure 1. Finally, electricity generation began in 1983, 13 years late, while full power was reached for the first time in 2004, roughly 38 years after construction began [8]. Another, early example how costly and time consuming it can be to learn on a full power project. The last, more successful, reactor of the AGR fleet was connected to the grid in 1989, thus the last classical UK thermal reactor project finished construction more than 30 years ago. The last delivery in the innovative reactor program was the prototype fast reactor (PFR) which was announced in 1966 to be built at Dounreay. The PFR achieved first criticality in 1974 and grid connection 1975.

Thus, the design of the reactor system of the commercial fleet took place in the early 1960ies and the design of the innovative reactor system just shortly after, leading to the situation that the last experience of construction, commissioning, and connection to the grid took place in the late 1980ies [3]. This is a UK view, but only the dates will be slightly different in other western countries, while the introduction just shows that the situation is comparable. Maybe the length of time period will be slightly smaller, but in all cases, it is too far back in time to rely on the experience gained at that time.

The key questions to answer are:

- What should we learn from this history to avoid repetition of such a very costly disasters – costly in regards not only to money, but also with regards to time?
- How can we re-gain experience and quick response in the whole process?
- How can we reduce the risk in the project as mentioned at the end of the introduction?

A key point will be to learn and to re-educate experts for the nuclear renaissance since the historic expertise is obviously lost. In addition, we can neither afford massive delays which are predictable and costly when problems appear at the very late stage of a project, e.g. in the middle of construction, nor do we have time to waste if nuclear should make a real contribution to a future net-zero society. Luckily, the situation still allows us to deliver on these tasks if we start now and if we use time and resources wisely. Moreover, in comparison with the 1960ies we have more robust and efficient simulation tools which should speed up the R&D activities. Digitalisation will help the whole process via end to end support and by adopted working practices instead of simply sending more information to key stakeholders creating a decision-making bottleneck. To make this possible some tools require targeted validation for the innovative reactor designs to leverage their full potential and to reduce time of development and costs significantly.

The learning has to be supported by creating a structured programme from feasibility through to construction, see **Figure 2**, in combination with following the recently proposed 4 step process [6] consisting of preliminary studies, an experimental phase starting with the zero power reactor as the key steps towards feasibility. This will support the small-scale demonstrator providing information for the preliminary design with the first experience of nuclear power production in a new kind of reactor. However, in an innovative reactor development, FOAK is going all the way through this cycle in each step. We need to build a complete programme at sufficient detail encompassing all of the R&D and skills development required to effectively project manage the delivery of each step right-to-left (thus backwards) engaging all of the stakeholders at each level in the process.

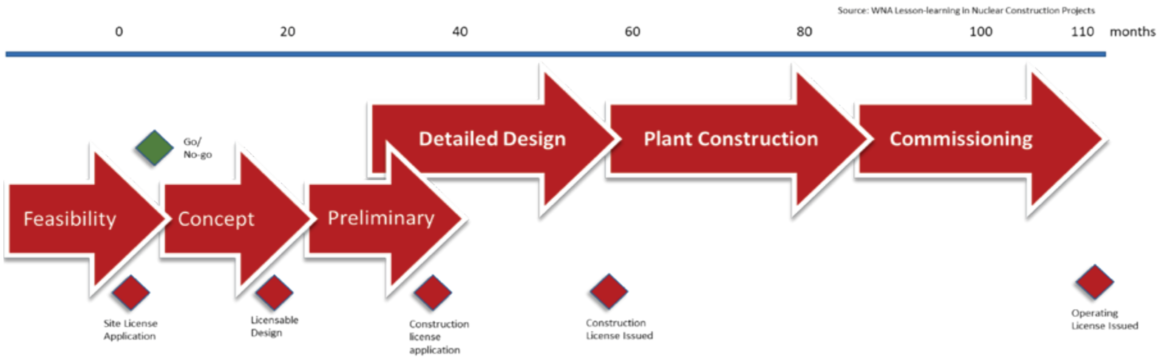

Figure 2
A structured program for the development of a nuclear reactor along the recommendations in a WNA white paper [9].

All mentioned points demonstrate that we need a new strategy to speed up learning by identifying strengths and weaknesses of the capabilities and the current capacities available to be able to deliver the end-to-end approach developed above. Key will be to work on the known unknowns and to identify early the unknown unknowns – areas where the community is weak, but where we are not aware of the weakness or the lack of knowledge. Testing procedures and technologies early and on smaller scale will be of high importance to avoid costly late failures.

Opportunities of a zero-power reactor as a first step

Developing and delivering an indigenous zero-power facility should be the most promising first step into any innovative reactor program as a part of an active risk limitation program for the whole nuclear reactor development. The zero-power facility has the potential to be used as a multi-fold opportunity, since it is more than a system that can be used for the validation of numerical models and their inherent approximations. It is a FOAK and the opportunity to go through the whole process from design to operation of an innovative reactor facility testing the feasibility, but in contrast to any larger reactor it is delivering a:

- low cost opportunity compared to a power reactor due to limited size and significantly reduced system complexity
- low risk opportunity in time, finance, and nuclear – it is not rocket science, GUINEVERE [15] has finally been successfully delivered – here the reduced complexity is key, it reduces the number of critical tasks and the required safety systems. However, all key components for the nuclear island and the fuel production have to be designed, regulated, and delivered
- less complex project, no heat transfer and no power conversion system are needed, no extensive multi-redundant and diverse safety systems are required as well as no expensive mitigation devices like a containment
- quick response opportunity, since such a project should not take more than 3 to 5 years, a quick turnaround and an accelerated learning curve will be seen. Knowledge and capacity gaps will be identified in short time creating less costly opportunities to close gaps and even change/adapt the final product in a comparably late project phase.
- High flexibility of the facility itself which could be equipped with a new core (as done in the GUINEVERE project) if another technology should be investigated

A zero-power facility for a new technology is a comparably small project, which still requires the whole production chain for a nuclear reactor, while it requests collaboration in an interdisciplinary team. Thus, it will be a perfect test case for the readiness for future, larger projects, assuring an accelerated learning curve in an innovative reactor technology on:

- designing,
- licensing,
- constructing,
- commissioning, and
- operation

Where can these advantages be delivered?

As previously mentioned, the zero-power facility is a low cost, low risk, quick response project which delivers opportunities on different levels, see **Figure 3.**

The opportunities of the facility are in detail:

- **Manufacturing**
  Manufacturing an innovative reactor of a new technology will help identifying weak points (unknown unknowns), upskilling demands, and already available pockets of expertise. It will allow developing and testing of new technological approaches and advanced manufacturing technologies on a small scale and support the creation of a core team of experts with real hands on experience for the following small scale demonstrator which would make the UK an attractive location to deploy these designs. Testing of new components, e. g. establishing a pre-industrial fuel production. It will help creating and educating the required supply chain for the technologies.
  All points will be essential for progressing into the next step of the development process – the small-scale demonstrator.
- **Experiment**
  On the one hand, the experiment will help in the education and the qualification of future reactor physics experts, which are highly demanded worldwide. On the other hand, it will help to improve the recognition of reactor physics and new reactor technologies. Thus, it will attract bright students of future generations into nuclear. The investment in an experiment will showcase the innovation potential in nuclear technologies and the drive to innovate to the public.
- **Leading Science**
  Taking the lead through an investment into advanced reactor technologies such as the proposed molten salt reactor technology. The investment into the zero-power facility will create a sustainable long term claim in an innovative reactor technology. The facility will create the opportunity to provide safety demonstrations and code validation and deliver an accelerated learning curve for the operating entity as well as the local academic community. The demonstration opportunity will help creating new IP for the country. The facility will attract top scientists to the country either in collaborations or through relocation while giving UK plc an advantageous position.

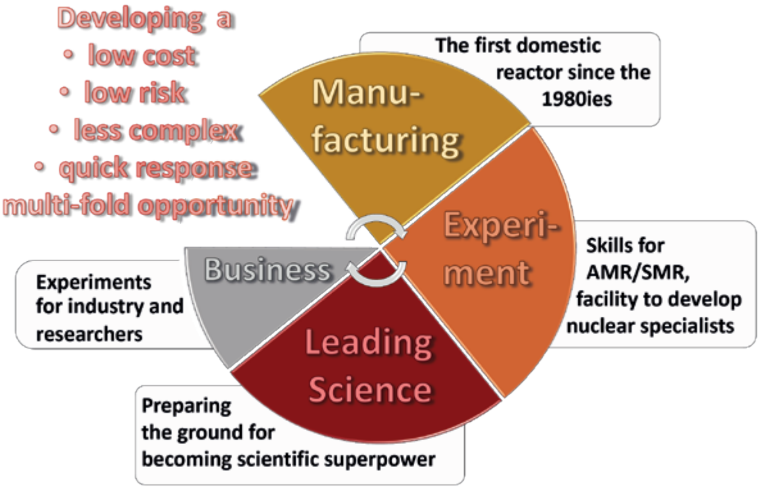

Figure 3
The multiple opportunities which can be delivered in a zero-power facility.

- **Business Opportunity**
  Finally, besides the leading science, the facility will allow experiments for international partners and for industrial developers who cannot afford to build their own zero-power system, as has been delivered for decades through the BFS at IPPE Obninsk for international sodium fast reactor development or through the new opportunities of GUINEVERE at SCK·CEN at Mol for lead cooled fast reactor technologies. The facility will serve industry to support the home-grown supply chain and link them to reactor developers while earning money through paid experiments.

How can these advantages be delivered?

The key for the success will be to make the most out of the money invested, as well as to use the time available wisely. The zero-power reactor project has to deliver much more than only results for code validation or safety demonstration, which would be the outcome of doing paid experiments at another facility. Possible opportunities are given above.

A zero-power reactor project can build on these first approaches delivered in project FAITH (see text box), but it can and has to go much further. The accelerated learning curve starts already with the design and manufacturing of a facility to study innovative reactor development and operation, not with the experiment. Creating, enabling, and educating the supply chain on a very small scale and reduced complexity system, as a basis for the next level of the small-scale power demonstrator. Key points will be to develop and test new approaches (modular manufacturing, advanced fuel production, and applying digital twin technology across the whole lifecycle of the asset), accept failure and be prepared for a quick for recovery to support rapid developments, but in all cases by using small steps. This approach reduces risk and promotes learning and solving problems at each step. Learning has to be seen as a process making progress based on UK capabilities and capacities instead of just buying a product. It is about involving all main suppliers into the development instead of having just suppliers delivering their parts. This also implies using the available nuclear chemistry expertise of academic partners to improve the available database for the pre-experiments required for the design, as well as upgrading of existing facilities to be able to deliver on the new challenges, e.g. salt based uranium fuels production. A further opportunity is refurbishing existing facilities and retaining the highly skilled employees at these facilities thus serving as a social-economic development to support a new facility as in the case of the VENUS facility at SCK. This will be complemented by linking with leading groups from outside nuclear energy to involve them in the project and attract available expertise from other areas, e. g. detector development for particle physics delivering UK's contribution to CERN experiments or modular manufacturing.

An already successful example:

A first demonstrator of this approach is Project FAITH (Fuel Assembly Incorporating Thermal Hydraulics) a multi-purpose project using new, highly innovative approaches to make better use out of the invested money. Main side purposes are: Educating new partners from outside of the nuclear industry how to deliver on nuclear standards while using already established innovations from other technologies, e. g. modular manufacturing established in ship building or application of tailored materials through additive manufacturing. "In FAITH we intend to demonstrate modular manufacturing on small scale with low cost and complexity to quickly evaluate a key technology for small modular reactors, while creating an opportunity for qualification and education of the strongly demanded workforce. This is delivered by a stepwise approach from easy to build and operate experiments into future cutting-edge science and technology with a complex and challenging fluid. All surrounded by digital design and development technologies from cradle to grave as well as the approach to deliver a project management integrated with the technical delivery. This will allow to include product quality management into the digital twin as well as thinking in terms of the whole project lifecycle using a common modelling environment." [9]

It is about using the experiment to deliver a hands on education to give the future experts a tier-one experience in building a new type of reactor as well as to operate the facility instead of completely relying on modelling & simulation as it has often become tradition in reactor physics. The facility will offer very effective accelerated learning to the next generation of engineers and scientists that comes with designing, developing and constructing the facility as well as running and analyzing the experiments. The facility will be at the centre of a user community and attracting international experts while growing an experimental program for a new type of zero-power experiment in collaboration with national and international partners. In addition, the facility will allow the testing of new detector technologies in a challenging environment and potentially invest into developing some tailored, innovative detector technology.

The development of zero-power experiments will proceed from easy to complex to support the learning process, a further example of learning from project FAITH. Most probably, the experimental campaign will be started with experiments based on a solid salt block operating at room temperature to learn how to apply experimental procedures from the ground, to test detector technologies and establish the data acquisition systems, while providing first code validation data, but keeping the commissioning process at a much lower risk than a full power system. This will be followed by the much more complex experiments using a liquid molten salt core to demonstrate the real operational behaviour of a liquid core including feedbacks, power distribution, and the effects of density changes which are typically hard to observe and demonstrate to the required accuracy with traditional modelling and simulation.

Besides the technical advantages, the investment into the development and delivery of a zero-power facility will demonstrate leadership in science in an innovative reactor technology. This is essential since "the start of a nuclear programme is often associated for with the first significant reactor experiment" [6], thus the project will create a major claim in innovative nuclear of the 21st century. It will mark a clear step for preparing to become a leading player in new nuclear in 2050 as it is expected in the BEIS nuclear innovation program [7].

The zero-power experiment marks a key crossroads for a technology, since this facility will allow the delivery of experiments which are essential for the progress of a new technology to accelerate the development process. On the one hand, it is the first time that codes can be evaluated on the real reactor behaviour of a critical system. On the other hand, it is the first time that safety demonstrations can be delivered which involve the neutronic behaviour of the system. If the zero-power facility is designed in a smart way, it will even allow to deliver first coupled safety demonstrations of a liquid core considering not only the neutronics but also thermodynamic effects and thermal feedback effects. Typical, essential safety demonstrations for a new, innovative technology, thus a broad range of proposed innovative reactor designs, are required to be delivered through experimental confirmation for licensing of a power operation system are:

- of core criticality;
- of neutron flux, energy, and power distribution;
- of reactivity coefficients;

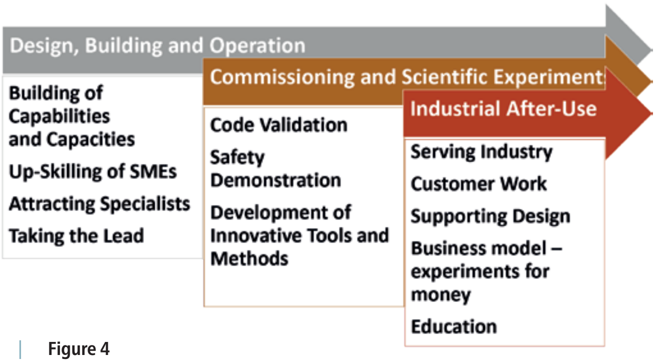

Figure 4
Opportunities in the different steps given by a zero-power facility at one glance.

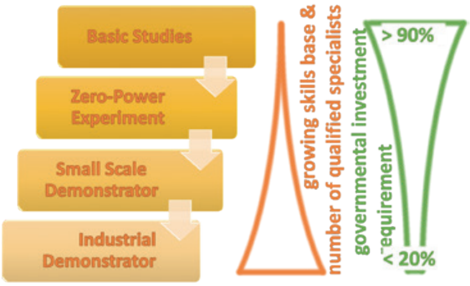

Figure 5
The process to develop an innovative, new reactor system, required governmental investment structure in a successful program and resulting skills development and growth.

- of changes in reactivity and flux as a function of salt density, temperature and composition change

Applying a smart design of a zero-power facility for molten salt technology will allow these demonstrations without the requirement for a considerable nuclear power production, which typically requires a powerful cooling system and strong radiation protection measures.

Delivering the zero-power facility will create a focal point for a longer-term game changer technology which will support the formation of the teams and educating the specialist for the next step in the process. The facility opens the opportunity for spin-offs of the technology already at a very early stage through paid experiments before achieving the industrial scale demonstrator, see **Figure 4.** The zero power experiments help accelerating the next steps and avoid potential mistakes (which can be really costly for a large-scale demonstrators) due to the availability of experience and expertise with a real project. The opportunity of quick studies in a safe setting to test technologies and to optimize new approaches will create very valuable experience and data. A role which has been described through the development of the German HTR program where the zero-power experiment KATHER was set up very late for the design phase of the industrial demonstrator [11].

However, it is important to keep in mind that the use of the facility will not be finished when the demonstration and validation experiments are finished. As described in the THTR program the facility will help to speed up the design process and reduce risks during the small scale and later the industrial demonstrator projects for the iMAGINE technology [6]. The facility has a strong potential to support the education of future reactor physics specialists through the access to real world experiments. In addition, zero-power reactors are a well-recognized tool to deliver experiments for money for start-ups around the globe (e. g. Seaborg, TerraPower, Moltex, Terrestrial Energy, etc.) to support their development and their interaction with the regulator as it is today delivered at the BfS facility in Obninsk [12, 13] and in the GUNIEVERE facility in Mol [14, 15]. **Figure 4** gives a collection of the opportunities delivered through the life of a future zero power facility.

How would the next steps look like?

As already discussed the zero power experiment is the first real world step in the process of the development of an innovative reactor program [6] which delivers technology specific hardware – thus it is often seen as the start in a new reactor program leading to the small scale and the industrial demonstrator, see **Figure 5.** The role of the facility for risk reduction has been recently described by a high-level expert, the general director of JSC "NIKIET", in the opening remarks for the Russian MSR project in Zheleznogorsk [6] in October 2019. "We all have to solve an extremely ambitious task – to create a research reactor here. There is no similar real facility anywhere in the world. I am convinced that we will succeed, we will be the first. … we will go in stages. First of all, the creation of a research reactor for testing technologies. Let's move on to a large reactor with more powerful parameters, having completely developed the underlying technology. The path is not fast, but it is new, and it is impossible to not take risks. At the same time, it is logical to build our work as parallel as possible in order to save time." Thus, reducing the risk is the key point even for the very experienced Russian specialists. For a country which has not delivered an indigenous reactor for decades, the other key point is creating a project tolerant for expected failure through developing methods to quickly recover with reasonably small risk in time and cost. This will assure an effective, accelerated learning opportunity which has to be delivered alongside a consequent stepwise learning process from one step to the other. Thus, the approach is to lead by applying as much testing and learning as possible in the smallest and least complex units as possible while using the experience of the last step to support the next one. This will assure the parallel development of capabilities and capacities where the core group of one step will form the seed for the much larger team required for the next step.

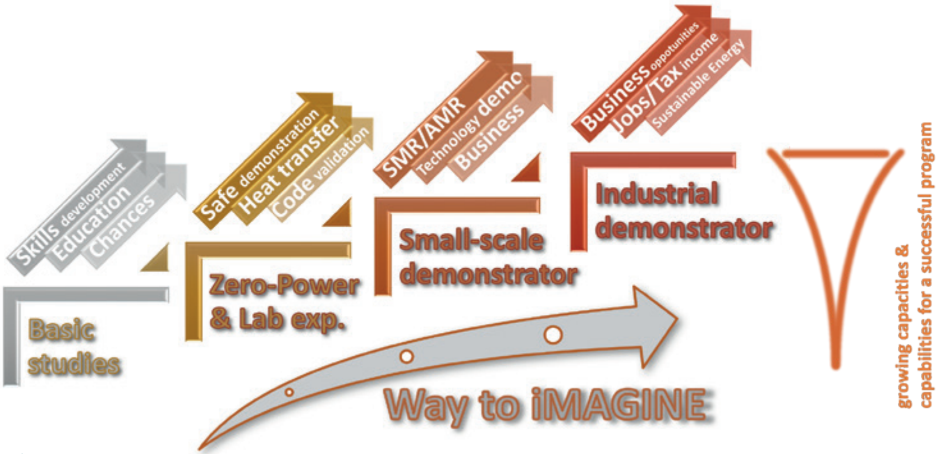

Figure 6
Possible spin-offs in the different development steps during the process to develop an innovative reactor system.

Considering all focus on the zero power reactor experiments, it must be clear it is only the first of the steps required on the way to delivering an innovative nuclear system, see **Figure 5** and **Figure 6.** For any kind of investment planning, the multi-fold opportunities of the zero-power facility are a perfect example of creating early wins on the way through the process by delivering more than just a facility to do the required experiments. These spin-offs are essential, due to the long timescales of nuclear programs, since they allow the investors to create some early revenues, even before the final step is delivered. These revenues can be financial like paid experiments, but in nuclear with the strong demand on highly qualified subject matter experts and complex manufacturing challenges the most valuable spin-offs are provided by growing capabilities and capacities. However, for investors into a successful new build program based on innovative reactors it seems that the risk reduction in cost and delivery schedules through the stepwise approach forms a key part for a successful program.

Conclusions

The last innovative reactor projects have been delivered more than 40 years ago, thus it will be almost impossible to rely on the experience from these projects. In addition, recent reactor projects have suffered from massive cost overruns and time delays due to changes in a very late project stage. Learning from this, for innovative projects we need much quicker feedback since the number of unknowns and thus the risk will be much larger than in LWR technology. Thus, a new, historically proven way to develop this industry is required. At the point entering into a new, innovative nuclear reactor technology, it is important to find a new way to reduce the project risks of each of the process steps as a first of a kind.

The first step is traditionally via zero power experiments. However, we have highlighted here that the experiments are only a small part of the opportunities given by a zero-power facility. Developing a zero-power facility will deliver on several levels starting with manufacturing of the facility and the components which demand the development of capabilities and capacities while delivering a strong learning process which is required after no innovative reactor has been built in the west and no native reactor has been designed and built within the last few generations within the UK. The next required opportunity will be provided by the experiment itself which will help to grow capabilities and capacities in operating a reactor and developing experiments which in turn will provide the chance for quick learning. Investing into a zero-power facility will demonstrate the willingness to lead and the operation will deliver leading science, providing unique results and the opportunity to deliver the very valuable scientific data for code validation, but also the chance to provide the essential experiments which will be demanded for the regulation process of a future small-scale demonstrator. Finally, after the most promising cutting-edge science feat of delivering the experiments for the countries own program, the zero-power facility will give a good business opportunity to deliver experiments on demand for national and international scientific and industrial partners.

On the one hand a zero-power facility requires the same steps as that of any full-scale reactor development which is required; designing, licensing, constructing, commissioning, and operating of a nuclear facility. On the other hand, such a facility is a low-cost opportunity with limited size and significantly reduced system complexity, being a low risk opportunity in time, finance, and nuclear – here the reduced complexity is very helpful since it reduces the number of critical tasks, while all key technologies for the nuclear island are required, but the consequences of potential accidents and the related mitigation measures are not needed. However, due to the reduced complexity, neither requiring heat transfer and no power conversion nor extensive multi redundant and diverse safety systems, the adventure is easier to overview and it will lead a quick response. Delivering such a facility should not take more than 3 to 5 years assuring a quick turnaround and a accelerated learning curve.

All points together demonstrate that a zero-power facility is a great, multi-fold opportunity which could deliver a quick and very efficient start into a new, innovative nuclear program.

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