The problems with innovation in the nuclear industry and how to solve them

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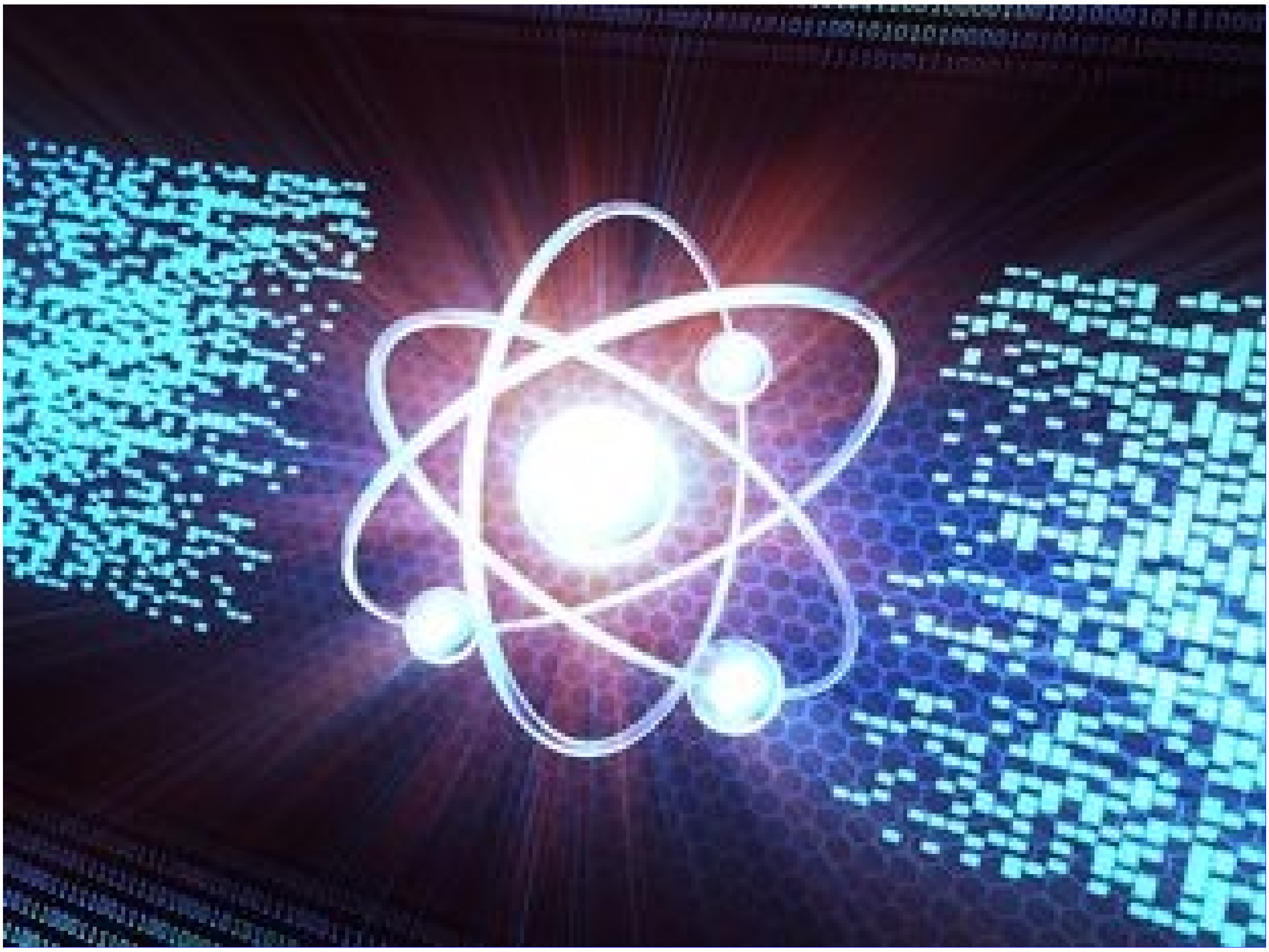

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1 Introduction

There is a global desire to "go green" and one of the ways in which this can be achieved is by adopting a nuclear power programme to replace fossil fuels. Similarly the current increase in energy prices is driving innovators to develop even cheaper reactors. The most common reactor types, Pressurised Water Reactor (PWR), Boiling Water Reactor (BWR) and Canadian Deuterium Uranium (CANDU) heavy water reactors, were all designed decades ago and most current nuclear vendors are proposing relatively small modifications to these overall designs.

However, there is also a move to consider more innovative designs of reactors especially Small Modular Reactors (SMRs) and to adopt so-called "advanced technologies". These new reactors would also lead to new fuel manufacturing facilities. In addition the pressure on the nuclear industry to "clean up" its existing facilities is leading to proposed innovations in decommissioning, waste treatment, waste storage and disposal.

2 Types of Regulator

It is a requirement of the International Atomic Energy Agency (IAEA) that countries appoint regulators to ensure the safety of nuclear installations within their country. The IAEA's international regulatory review service and the external scrutiny arising from the Joint Safety Convention result in the belief within the industry that it is currently safe. In support of the aim for continued safety the IAEA produces a number of safety guides to assist regulators (and operators) in judging the safety of their facilities. Despite these efforts different approaches in individual countries result in varying and in some cases differing requirements, e.g. how doses to individuals outside the site boundary are calculated.

The most fundamental difference between regulators is in their demands regarding safety cases. Many countries, of which the US Nuclear Regulatory Commission (NRC) is a prime example, have what is called a prescriptive regulatory regime whereby the regulator prescribes exactly how the safety of a facility should be demonstrated. The extent of this prescription varies from country to country with the opposite extreme being that in the UK which has a non-prescriptive goal setting regime. This form of regulation is where the regulators set numerical targets, e.g. in terms of doses to workers and probabilities of certain incidents taking place, but leaves it to the prerogative of the operator/designer to show how these goals are met.

In the case of the UK it would be very time consuming and inordinately expensive to set out prescriptive regulations for the broad range of facilities that the Office for Nuclear Regulation (ONR) regulates (i.e. various reactor designs, fuel manufacture, waste facilities and some defence sites), and this goal setting approach has served its purpose over the decades of the UK nuclear industry and has helped in establishing ONR as one of the foremost nuclear regulators in the world despite purportedly having less inspectors per site licensed than most other regulators.

As already stated, this non-prescriptive regulatory regime leaves it to the operator to decide how to demonstrate the safety of the facility it is planning to operate at the specific site at which it is located. As in all countries the resultant safety case and the operator's competence both to carry out the operation safely and to abide with all requisite legal requirements are all factors considered in granting a license to operate.

3 Innovation – The Problem

The problem facing true innovation in the nuclear industry (or any other high hazard/risk industry), rather than a development of an existing design, is there can never be as much evidence to support the innovation as already exists for current designs. Hence any requirement for relevant good practice (RGP) is always going to favour the past. Similarly any truly innovative design is unlikely to be supported by any Codes and Standards at this stage of its development.

A similar dilemma exists in trying to provide relevant operating experience (OPEX), modelling core or reactor behaviour or validating new materials, coolants and their compatibility in a nuclear environment. This problem is exacerbated by the absence of convenient material test reactors (MTRs), but even if these did exist, for most radical reactor innovations it is likely that the exact temperatures and neutron flux spectra would be impossible to replicate. A similar situation exists in long term disposal and in this case the situation is likely to be further complicated in that for each deep facility the geology is going to be unique.

Despite these difficulties one of the innovative SMRs recently received the "significant comments" from a safety regulator that there were no relevant OPEX, relevant test/experimental data or evidence of relevant good practice. Whilst these comments from the regulator were clearly valid comments, vendors/operators of innovative reactor designs are therefore faced with the classic 'Catch 22' situation of needing OPEX or relevant data but not being able to build a reactor to provide this experience/data until they have the OPEX and relevant data. To put it simply, *"to build an innovative nuclear facility you need relevant OPEX, relevant experimental data and evidence of RGP, but to get these at the required level you need to operate the facility".*

In the UK, the safety regulator ONR claims to be a facilitating regulator that welcomes innovation. In other countries, regulators whilst also ensuring safety, should ideally not impede progress either. Nevertheless no regulator should permit a reduction in safety and its safety requirements just to support innovation.

In the case of non-prescriptive regulators the safety case writers need to explore different approaches to justifying their facilities from those adopted in the past because the reliance on Codes, Standards, OPEX and RGP will necessarily play a lesser part in the justification argument. In the case of the prescriptive regulator, the regulator will need to decide what it will require in a safety case from an innovative design with reduced OPEX and RGP. Clearly regulators also have the problem that if they refuse to accept a safety case can be made without extensive RGP and OPEX, then no innovation is likely to be possible and no progress in the industry can ever be achieved.

Therefore how should vendors/operators proceed to overcome the deficiency in truly relevant data, RGP and OPEX that the regulators appear to expect, and what if any changes should regulators make to enable progress in the industry to take place. Indeed, in the UK the ONR has stated that it intends to provide an environment that will foster creative thinking and solutions by focusing its practices and behaviours on four principles:

- being enabling, accessible, open-minded and providing stimulating challenge
- working collaboratively
- being adaptable and responsive to our environment and the needs of others; and
- horizon scanning, so it better understands future demands and technologies.

In this respect it is interesting to examine what lessons can be learnt from other high risk industries where progress and innovation has been successfully achieved.

4 Innovation in Other Industries

4.1 Aviation

One of the best examples of an industry that welcomes innovation is the aviation industry. Classic examples of UK innovation in the aviation industry include the delta winged Vulcan bomber, the vertical take-off Harrier and the supersonic Concorde (in conjunction with France). Despite the aeronautical models that are used, the flight simulators and the numerous wind tunnel experiments, ultimately somebody (the test pilot) has to sit in a new plane, take off and (hopefully) land safely. Everything possible is done before a flight to ensure that the design will work as expected and the maiden flight involves the minimal number of people on board and very straightforward operation involving a very short flight over, as far as possible, relatively unpopulated areas. The test flights then progress in complexity to further examine the flight characteristics of the plane and to ensure that it is safe to get an airworthiness certificate. It should be noted that this testing is very analogous to the best nuclear practice of a gradual increase in risk as the new design is commissioned.

This progressive commissioning of the plane is one route whereby the nuclear industry can introduce innovation, i.e. by developing properly staged commissioning processes that would gradually increase risk but where the actual risk is reduced by benefitting from the confidence provided by the preceding stages in the commissioning process. This is particularly true for the staged commissioning of a nuclear plant, which is typically performed involving a number of “hold points” where the process is stopped to allow the preceding stages of the commissioning to be fully evaluated and where the initial stages of commissioning involve greater levels of instrumentation. This staged commissioning process could involve more arduous conditions to demonstrate safety, e.g. an overpressure test. The practice of initially involving inactive operation before active material is introduced on to waste treatment and fuel manufacturing facilities is one example of how commissioning can become an important part of the safety case.

Nevertheless, the aircraft industry also has cautionary tales regarding innovation. Not all safety issues manifest themselves immediately. The initial Comet jet passenger planes introduced new design features, most prominently rectangular windows supposedly to improve the view for the passengers. Several of the Comet jet passenger planes failed catastrophically with the resultant loss of life of all on board. In the investigations, high-level fatigue in pressure cabins was determined as the most probable cause. The designer consequently took measures to deal with this problem, especially the use of thicker gauge materials in the pressure cabin area as well as the strengthening and redesigning of the windows and cut-outs. The lesson here being that ageing effects cannot typically be justified by cautious staged commissioning and other measures are required.

Another cautionary tale relates to the recent Boeing crashes in Ethiopia and Indonesia. In this instance an innovation to the automatic pilot was introduced but for commercial reasons the commissioning was seemingly accelerated. Hence, allegedly, the testing was not carried out thoroughly and in particular the pilots had not all been trained in the necessary procedures should the required innovation fail and remedial action be required. The lesson here being that not only should any innovation be thoroughly tested including during fault conditions (a situation not always possible during commissioning) but that the operators also need to be fully trained in any changes resulting from the innovation.

With respect to ageing, assurance can often be gained by suitable in-service inspection, pre-ageing of components or even destructive examination of a prototype or first of a kind (FOAK) reactor. In the case of the delta winged Vulcan bomber, MoD actually cut a whole plane into pieces to examine for any signs of deterioration before extending its life.

4.2 Medical

A good recent example of innovation in the medical industry can be seen in the Covid pandemic. The science excelled itself in developing potential vaccines and presumably all the available models showed these would work. However, nothing was guaranteed and testing with animals then took place. Even having successfully done this nothing could be certain and eventually a live human (or to be exact several live humans) had to be vaccinated. Similarly new surgical procedures such as heart transplants needed to have their first human “guinea pig”. The risk was minimised as much as possible by prior testing and modelling, but eventually the only real way of progressing was to test the vaccine (or procedure) on a human and accept the risk. But why is this risk acceptable? In the case of the first heart transplant it was presumably because the patient would be terminally ill if not operated on, i.e. the risk of operating whilst still clearly high was less than that of not operating. Similarly in the Covid instance it would be because the overall benefit and risk of adopting the vaccine compared favourably with the risk to the population of not having it. However, there must still be risks regarding any long term effects that cannot have been tested within the timescales that the vaccine was introduced, albeit the science will have demonstrated that the likelihood of this will be very small.

The nuclear industry is in a different position. The existing reactors do not pose an unacceptable risk and therefore there is no significant reason (other than the sensible and moral driver to want to improve safety even further) to drive innovation from a risk reduction perspective. However, those vendors/operators of new designs clearly have reasons for their innovations, for example, either that their innovations result in even greater safety, very significant cost savings, produce less radioactive waste or less hazardous waste or that they assist in other areas such as burning plutonium as fuel. The onus is still on the vendor/operator to demonstrate adequate safety and as already discussed, staged commissioning can help. The question of ageing can be ameliorated by in service inspection, early potentially destructive decommissioning of a FOAK reactor or even the use of surveillance specimens such as those incorporated in PWR pressure vessels to confirm embrittlement rates. Nevertheless the FOAK still has to be licensed and as already stated, it would be morally incorrect for such a reactor to be licensed without sufficient assurances that it was safe according to current regulatory requirements. Furthermore the economics of an approach that builds a reactor to obtain data rather than for commercial gain would probably be prohibitively expensive except for instances where the FOAK may be the first of a fleet of such facilities, e.g. SMRs. This approach is probably also less applicable where the facility is a “one off” such as a fuel manufacturing facility or a Geological Disposal Facility (GDF), although Finland and Switzerland are exploring such an approach. Nevertheless there would be more scope for the FOAK “prototype” approach if evidence from such a facility could be utilised across to justify facilities world-wide in other countries.

4.3 Software Validation

The complexity of modern software is such that much of it can often no longer be verified in the traditional sense. In the UK, ONR currently requires a "validation report" for all new software but it is acknowledged that for some Specific, Measurable, Achievable, Relevant, and Time-bound (SMART) sensors and "off the shelf" components this cannot be demonstrated in the "traditional" manner. In these cases confidence in reliability is achieved by a mixture of quality assurance and the proven integrity of the software upon which the new software is based. This is a clear example of the regulator wanting all models to be validated, not being able to be fully complied with in the traditional sense, but safety is still acceptably achieved through other means of which progressive commissioning usually plays a big part. Amusement park rides are typically a good example of this form of validation in the non-nuclear field. It is also an example of a safety related component being accepted primarily due to the assurance that was provided during manufacture.

4.4 Prototypes

Regulators will obviously still seek to have as much validation of safety related models as is possible. Innovative chemical plant designs licensed in the UK include Mixed Oxide fuel (MOX) and Thermal Oxide Reprocessing Plant (THORP) where there was heavy reliance upon laboratory modelling, and in the case of MOX a prototypic demonstration plant. The Canadian Safety Regulator Chief Inspector has cited the need for a prototype reactor, followed by a FOAK and then further fleet reactors when justifying new reactor designs. This is consistent with the concept of preceding actions reducing what would normally be a staged increase in risk – BUT (as already stated) the prototype reactor also has to be shown to be adequately safe and licensed before it can be used to validate any models, and as previously discussed the economics of such an approach could be difficult.

It is useful to consider that ONR's deliberations here (especially in the light of the MOX experience which, although safe, never worked commercially) which require that it must have some confidence that not only is the design safe, but that it will work. If this is not ensured then a country is left, as is the case with the MOX facility, with a heavily contaminated facility that needs to be decommissioned, the radioactive waste managed and with significant resultant dose accruals to workers carrying out these tasks without any tangible benefit. The idea of a reactor design that successfully shows there will be no harm to the public and operators in the event of any accident will be unlikely to be accepted if it cannot also prove to be reliable and guarantee overall benefit, i.e. that it will be justifiable. It will work!

5 Methods to Reduce Risk

Another way of justifying safety is to remove the hazard, e.g. the use of unleaded petrol in cars. Of course this is difficult to achieve in a reactor where the radioactivity in the core represents most of the hazard. However innovative reactors that segregate the hazard and prevent single (or combined) failures that impact upon more than one of the segregated hazards could assist in improved safety. Gated, segregated fuel cooling ponds (that would have reduced the concerns at Fukushima) or waste/disposal facilities involving segregated cells are examples. A similar approach is being adopted with multiple co-joined SMRs. The current most common GDF disposal concept of multiple segregated containers in a series of isolated sealed tunnels is another such example.

Another way to improve safety is to either reduce the risk, e.g. by the introduction of dual circuit brakes in cars to prevent overall brake failure and minimise the effects of a single failure (the single failure criterion being well known in the nuclear industry). The latest automobile tyres, that do not instantly deflate when punctured, are an example of where the risk cannot be removed but the impact of the risk can be. Similarly the risk of hydrogen explosions in reactors can be avoided by not using water as a coolant, e.g. gas, sodium or molten salt. However, these coolants can then cause their own hazards, for example sodium fires or increased tendency for intergranular stress corrosion cracking.

Another alleged benefit that is being explored in the automobile industry is driverless cars. This is because one of the main risks with cars is that the driver makes a mistake, despite supposedly being capable (SQEP – suitably qualified experienced person) as shown by needing a license. The same thing could be a result of innovation in the nuclear industry, i.e. less reliance upon operators for example in PWRs to ensure that the reactor is warmed up within the appropriate temperature and pressure parameters and to take the correct remedial action, or the reactor scramming or partially scramming in the event of a potential problem being identified. In fact there are at least 2 SMR designs being proposed where there is either no operator proposed or the role of the operator is little more than that of a monitor. Having said that, how many of us will feel comfortable in our first ride in a driverless car especially if there was no way of overriding the “system” and stopping the car? Those who have sat at the front of driverless trains in airports or cities service will be able to testify what a disconcerting experience it is in the first instance. In that respect the days of the operator free reactor could still be some years off being accepted by regulators, even if such a reactor could be designed and if only because of the need for operators to be maintained to keep risks As Low As Reasonably Practicable (ALARP).

6 Model Validation

Fully validating innovative models can be very difficult as already discussed yet there are regulators that insist upon a "full understanding" of degradation mechanisms. Clearly a situation such as that which occurred at the Windscale reactor fire in the UK where a lack of understanding of Wigner energy build up in graphite was a prime cause of the accident, must be avoided. Nevertheless there is precedent in the nuclear industry itself of proceeding without full knowledge of the degradation mechanism. In the early days of the PWR Westinghouse discovered apparently very much accelerated stress corrosion cracking rates in PWR environments and these rates were totally unexplained. Nevertheless the industry was able to proceed by a mixture of in-service inspection, surveillance specimens and fracture analyses demonstrating the damage tolerance of the affected components (primarily the reactor pressure vessel).

Another approach that has not yet been discussed is to design the innovative reactor/facility such that the safety significance of the model is less. For example, models demonstrating core behaviour become less significant if it can be shown that the core is damage tolerant.

Similarly models involving heat transfer can also become less important from a safety perspective if the reactor can be shown to be tolerant to extremes of temperature. Another example would be structural degradation mechanisms that could become less important if the facility is leak tolerant.

There is a strong case for classifying models according to their safety significance in the same way that safety related components need to be classified. This classification could then determine the extent of validation required. For inherently safe designs this could significantly reduce the supporting data that would be required.

7 Relevant Good Practice

In a similar way reactor designs should be capable of indicating a reduced need on RGP if the mode of operation being justified by RGP can be demonstrated to be safe by alternative means, e.g. modelling, commissioning, inherent safety (damage tolerant). Indeed the requirement for relevant good practice should only be a requirement if the practice is actually relevant. RGP should (as the title implies) be relevant to the situation being justified, e.g. the need to avoid fuel melting should clearly not apply to reactor designs involving liquid fuels. Vented fuel pins could be safer than sealed fuel pins if the risk posed by pressurised pins failing is greater than the loss of containment that the pins normally provide.

However, if there is no relevant RGP then confidence has to be obtained by other means, and if the design is so truly innovative that no RGP exists, then as already discussed OPEX will also be unlikely. In these situations alternative methods for demonstrating safety need to be found, but similarly regulators should not be demanding RGP when none is feasible and they should be looking for other means to obtain the necessary confidence in the safety of the proposed facility.

8 Benefits of Innovation

Innovation can improve safety, assuming that the hazard will always be present in some form and operator interaction has been minimised, is by addressing risks. In conventional reactor designs this can be:

- By removing the potential for missiles
- Minimising the potential for radioactive spread by avoiding significant
- pressurisation
- Damage tolerant containments that guarantee no radiation release and spread
- Ensuring materials are fully compatible with each other
- Reducing the number of safety components that are required
- Conversely having many independent shutdown safety systems (the belt and braces approach)
- Ensuring full inspectability of safety components that could be subject to ageing
- Either minimising the potential for core damage or designing a core that is damage tolerant
- Ensuring designs produce little radioactive waste and that such waste as is produced is compatible with proposed waste treatment and/or disposal concepts
- Designing facilities that are amenable to decommissioning.

However, none of these may actually involve radically new designs of core that are potentially safer and that is where the true ability to innovate is currently very difficult.

As mentioned earlier one reason for innovation could simply be to be cheaper and therefore make nuclear power more affordable compared to its competitors. This is potentially an even more difficult concept for vendors/operators to convince regulators especially where this innovation relates to changes to existing designs or manufacturing processes. In this case regulators would need to be convinced that any cost savings either:

- Still provide adequate assurance that the design and its safe manufacture is maintained
- Do not result in any reduction in safety, and/or
- That the reduction of safety still results in acceptable safety AND that the increased cost of reverting to the old design is grossly disproportionate to the increased safety that may arise.

9 International Cooperation

New reactor concepts will only be economically viable if they find a sufficiently large market. Hence, acceptance in different countries will be needed. However, for innovative designs this condition is likely to be difficult to meet when each regulator performs its own, time consuming detailed analyses.

Therefore, improved international cooperation will be necessary. On the other hand, each regulator is fully responsible to the people of its country to maintain adequate safety. International cooperation must not hamper the ability of the regulator to comply with its responsibility.

The concept of informed adoption of the results of foreign regulators by the regulator of the host country, especially of safety assessments or design approvals by well-established regulatory bodies is a possible means by which regulators could facilitate innovation. With informed adoption:

- An informed decision by the regulatory body of the host country whether the regulatory body of the country of origin will be accepted ("recognized regulatory body")
- Evaluation of the applicability of the existing safety assessment / design approval under the specific conditions of the host country.

For an informed adoption of safety assessments or design approvals, various requirements have to be fulfilled. Especially, to acknowledge a regulatory body as "recognized", the host regulatory body has to verify its

- competence and experience
- transparency
- strict independence from the economic interests of the vendor as well as political interests of the government
- willingness to cooperate honestly.

In fact the host regulator has to be an „intelligent customer" for the work carried out by the other regulator.

Futhermore, for the applicability of the existing safety assessment under the conditions of the host country, the host regulatory body has to perform

- a qualified analysis of the applicability of the assessment, e.g. by using an experienced, independent TSO
- an assessment of identified gaps, e.g. due to different environmental conditions or different radiological requirements for accident scenarios.

These assessments can result in additional requirements to be met by the vendor to prove the applicability of the design for the host country.

Finally, the regulatory body has to decide on the overall acceptance of the design.

This suggested approach could significantly assist in the necessary acceleration of innovation through reducing and accelerating the regulatory processes in the nuclear industry.

10 Discussion

There appears to have been little true innovation in reactor design over last decades, just development of existing designs. An insistence by regulators upon OPEX, representative experimental data, relevant good practice and fully validated models is unlikely to be achievable for truly innovative reactor designs and hence regulators need to consider what their expectations are in the face of these absences and what alternative safety arguments can be used to justify novel and innovative designs.

Recognising that regulators must ensure adequate safety and cannot “sacrifice” their safety requirements for the sake of permitting innovation, the vendors/operators are left with a variety of safety arguments to attempt to persuade the regulator of the safety of their designs:

- Minimising or segregating the hazard: For most designs this will not be achievable as even an SMR would contain sufficient hazard to warrant full regulatory scrutiny and it is unlikely that any core could be designed so that only a small hazard could be affected by any fault, e.g. a CANDU pressure tube is an example of where this could be argued such that any fault is limited to one tube
- Designing the reactor such that many of the existing risks prevailing in current reactors no longer exist, e.g. the avoidance of potential hydrogen explosions
- Demonstrating that even where risks still exist, their impact upon overall safety is minimised, e.g. by demonstrating that loss of core integrity does not lead to radioactive release
- Having a staged commissioning process that would normally gradually increase risk whilst relying on each previous stage of the commissioning process to partially justify the next step and actually reduce the risk, and the possible adoption of a prototype philosophy
- Making provision to demonstrate that ageing is not an issue by inspection, the use of surveillance specimens or even premature destructive testing
- Minimising the need for operator interaction
- Ensuring that any radioactive waste produced is minimised and compatible with treatment, storage and disposal methods

- Any cost savings not resulting in safety improvements can be justified on ALARP grounds.

On the other hand, what can regulators do to prevent themselves impeding progress? As already stated they cannot reduce their standards. Nevertheless, one of the problems facing vendors and operators is that regulators can have differing standards/requirements. Whilst it would be unrealistic to expect regulators to fully unify their approaches and requirements, there should be scope for better collaboration. Regulators are, and must remain responsible for ensuring safety in their individual countries but should be able to act as intelligent customers for work done by other regulators, e.g. the assessment of some technical areas where there are common standards. Similarly, as touched upon earlier in this paper, there might be scope for regulators to collaborate in using data from FOAK facilities to justify more extensive operation of similar facilities worldwide.

Conclusions

a. A requirement for relevant good practice, relevant OPEX, and fully validated models will not be achievable for many radical reactor innovations

b. Regulators cannot reduce their safety requirements for the sake of encouraging innovation. Similarly regulators should be open minded to assessing safety cases that do not include RGP and OPEX including the degree to which some models are validated

c. Potential innovators must therefore be innovative in how they justify the safety of their innovations and experience from other high risk industries can be helpful in indicating strategies that may be helpful

d. Regulators should potentially accept judgements from other regulators as long as the basis for any regulatory decision is well known.

Acronyms

ALARP	As Low As Reasonably Practicable
BWR	Boiling Water Reactor
CANDU	Canadian Deuterium Uranium
FOAK	First Of A Kind
GDF	Geological Disposal Facility
IAEA	International Atomic Energy Agency
MOX	Mixed Oxide fuel
MTR	Material Test Reactor
NRC	Nuclear Regulatory Commission
ONR	Office for Nuclear Regulation
OPEX	Operating Experience
PWR	Pressurised Water Reactor
RGP	Relevant Good Practice
SMART	Specific, Measurable, Achievable, Relevant and Time-bound
SMR	Small Modular Reactor
SQEP	Suitably Qualified and Experienced Person
THORP	Thermal Oxide Reprocessing Plant

Biographies

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Sue Hewish (FRSC) is the Director-Nuclear for TÜV UK Ltd. As a Chartered Chemist with over 30 years' experience, she initially specialised in research and development of innovative decontamination technologies for the nuclear industry from first concept through to field pilot demonstration, and ultimately commercialisation.

Dr Thomas Riekert has over 30 years' experience in nuclear safety in Germany and in international projects. After holding various management positions within TÜV NORD GROUP, he is now Head of Nuclear Safety at TÜV NORD EnSys GmbH&Co.KG, Germany. In addition, he is vice-chairman of the German Reactor Safety Commission (RSK).