Small Modular Reactor Safety-in-Design and Perspectives

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Across the public, nuclear power and global energy sectors, there are various degrees of interest in next and near-generation micro- to small, modular reactors (MMR, SMR)[1]. The ongoing interests, here defined in terms of commercial and national technology developments, policy documents (roadmaps, action plans, etc.), various levels and means of "investments", are intended to support and facilitate development of select advanced reactor concepts and demonstration units. The current portfolio of SMRs and MMRs is relative to the current, global fleet; mostly larger scale nuclear plants (Generation III and III+ designs) currently under construction and/or operating. These legacy designs largely meet the electricity demand in nations with robust socio-economic development rates. Both the operating plants and those in various stages of development are included in a "pan-global, nuclear portfolio", touted (in the "24/7/365" social media) to address and mitigate the negative impacts of climate change. While there are reasons to "worry" about the lack of foresight, preventative preparedness and response to address the cliff-edge impacts of climate change, the goal here is not to argue climate change nor policies/developments in national commitments to a lower or net-zero carbon economies of scale. If anything, climate change can be construed as human society's inability to exercise a paradigm shift – in effect, a linear extrapolation from 150+ years of industrialization based on fossil fuels and release of effluents without consequences. Along the way, we forgot to ask what can happen and how can it happen. The consequences are here and imminent ("urgent"), as expressed by climate change leaders, Greta Thunberg, and others. Nature is suffering in our age of our Anthropocene.

With this in mind, the article here will review a number of ongoing micro- to small, modular reactors concepts, but from the perspective of engineering and design development so that the design is completed. While engineered and designed features hold much interest to those with engineering and R&D backgrounds, one might argue that if nuclear energy is to serve in transition and/or as a solution to aspirational economies of scale that mitigate and reduce the negative impacts of climate change, nuclear reactor designs need to be complete, prudently financed and "constructable", because ultimately they serve to generate electricity that the public expects and demands. Some 70 years ago in nuclear history, then U.S. President Dwight Eisenhower appeared at the United Nations (1953) and spoke on, "Atoms for Peace". Subsequently, in the then short list of post-WWII developed and developing nations, there was rapid development, and selection process of Generation I and II nuclear concepts. Many of these are part of the 440 or so nuclear power plants operating today.

1 Designs, Legacy and Processes

A few words about the design and engineering process of new/advanced reactor concepts is in order. Perhaps owing to the lead author's educational legacy, it is not something that I remember explicitly learning during my nuclear engineering education. That said, there are established processes within nuclear vendors (manufacturers) that remain proprietary. These practices do not necessarily make it into university classrooms. My observation has been that seasoned professionals from the nuclear sector do not transition late in their career, to university nuclear engineering programs/classrooms. There can thus be a knowledge transfer gap, from the reactor vendor to the classroom.

The article here on advanced reactor concepts and SMRs/MMRs, is based on the assumption that completing the design is of utmost importance, and that the design process takes time and requires sufficient and sustained funding because the key high-level task is, iterative system design. That is, engineering system design, wherein systems and subsystems are coupled, require iterative design optimization. This is certainly the case in nuclear reactor design.

So, we note that SMRs, like many nuclear reactors are generally designed from the reactor core, outward in terms of various essential and supporting systems; that is, the primary, secondary systems and beyond. In fact, one could say for SMRs, the design regions of interest extend all the way to the emergency planning zone (EPZ), since in principle, a SMR's EPZ should be related to, "very small probability (keep reading) but a high consequence", hypothetical accidents. One can say that increasingly Generation IV (or advanced) reactor concepts are expected to have very small hypothetical probability with respect to design basis and beyond design basis accidents (DBA, BDBA), and features that substantiate means to address Fukushima (Daichi) type situations. In fact, the design itself is expected to have a number of safety-in-design features so that the commonly cited metrics such as, "core damage frequency" (CDF) and/or "early release frequency" (ERF), are typically, smaller than 1E-06[2], if not 1E-08. (We note here that probabilities – less than say, 1E-09, 1E-10 or smaller may not hold regulatory meaning or significance.) Further, other than these small probabilities, observance or adherence to safety-in-design philosophies/principles as described in INSAG-10 [14], and "goodness" in design such that no human intervention is required for durations of time beyond "event" initiation (i.e. first 24, 48, 72 hours, etc.), detailed information on accident progression/evolution, may appear as aspirational or embedded in the design features and functions, without open access to the technical details. Open access of detailed technical information may not be possible; thus, it is not current practice.

With the above design engineering process and metrics in mind, let us look at the micro- to small modular reactor

1 The term, SMR, is used to be inclusive of Small and Micro Modular Reactor concepts and designs.
2 This notation is used instead of a superscript that may appear visibly small (1×10^{-6}).

concepts currently under various states of development. We note that since a number of overview articles on SMR/MMR reactor concepts exist, this article is not intended to be such. Instead we thought to reveal some of the not so obvious aspects of safety-in-design, that various advanced reactor designers may adopt to varying degrees. First for brevity and utility, we cite some of the key documents below as a starting point into the various aspects surrounding SMRs as follows:

- On safety-in-design, references [1, 7, 14, 17(US only), 23, 24, 30]
- On licensing and regulatory aspects of SMRs, reference [3, 15, 19, 22]
- Overview and advances of SMR, reference [2, 6, 9, 16, 31, 33, 36, 40]
- Specifically passive safety systems within safety-in-design, references [8, 20, 32]
- Nuscale, SMART, IRIS, CAREM, ESBWR, AP1000 specific starting documents, reference [10, 11, 12, 13, 21 (NuScale EPZ), 28, 29]. Note that the ESBWR and AP1000 are Generation III/III+, large-scale plant designs from which lessons learned are realized in SMR designs.
- General principles in nuclear design and economics, references [4 (economics),18, 25, 26]

2 Back to the future with nuclear energy?

In a manner similar to many early nuclear reactor concepts in the late 1950s, early 1960s, there are many micro- to small, modular reactor concepts. However, with approximately 60 years of complete design experience, operational experience, lessons learned from three major severe accidents, (along with other recorded events), unrestrained cost increases, regulatory compliance burdens, anti-nuclear sentiments and advances in computer-based engineering, recent advanced reactor designs hold consensus expectations in safety, non-proliferation and economics. It goes without much declaration that nuclear energy is often questioned and compared to other forms of energy (including renewable energy sources) and as a matter of regional to national energy policy. In recent years, public acceptance of any risk-inherent technology, processes, production and consumption – a composite portfolio of social license, advocacy and questionable objectivity issues, are fiercely fought with fervent banter in social media domains. Everyone has an opinion.

Nuclear energy and new micro- to small, modular reactor concepts are not benign from socio-technical scrutiny, most recently in the global debate on whether nuclear energy is a partial to full solution to counter the increasingly emerging evidence on the negative impacts of climate change.

2.1 The micro- to small, modular reactor concepts

Nuclear reactors are traditionally classified in terms of the following technical features. These features are high-level decisions made by its originators. They are: 1) neutron spectrum, 2) related type of neutron moderation, 3) type of coolant, 4) fuel type and core configuration. We will use the same approach for consistency. We note Hussein [40] review that used an expanded classification based on 200+ cited references.

We limit our coverage below to SMR design concepts of thermal power (output) magnitude that feature conventional or unique energy conversion system design, utilizing a liquid-based energy transport system from a defined core configuration. The core and energy transport system should fulfill the basic functions as follows: startup (to criticality), (transition to) steady-state operation at a targeted power, transition up or down from a given power setting to another, intended shutdown, emergency shutdown and post-shutdown decay heat energy removal (to cold shutdown state).

In this regard, micro-modular reactor concepts (MMR) are even simpler in design than many SMR concepts because the thermal power output is approximately an order of magnitude smaller than SMR (i.e. ~O (5 MWth) per reactor core vs. ~O (50 MWth)) per reactor core] and as such, the corresponding means of reactivity control are reduced accordingly. With respect to MMR safety-in-design, post-shutdown energy removal mechanisms are predominantly passive such that air or a large volume of water, serves as the ultimate heat sink for decay heat. Energy conversion systems are correspondingly modular in design and may feature reduced coupling to reactor core control (and thus operations) such that the sole output is electricity and/or thermal energy. With such simple design and limited functions, the thermal-hydraulic "parameter space" is correspondingly small, such that conventional means of control (analog and/or digital) can be used for monitoring, prognostics and diagnostics. The 2020 release of the IAEA "book" on SMRs/MMRs contains 6 MMR concepts. A concise, descriptive summary of the announced MMR concepts is given below.

1) Energy Well (Rez, Czech Republic) – is a high temperature (core inlet, 650 °C; outlet, 700 °C) molten salt FLiBe cooled and moderated, with targeted thermal and electrical power output, 20MWt/8 MWe. The once through core design features 15 % enriched TRISO fuel and operational reactivity control via Y-shaped control rods. Energy conversion is a 3-loop (FLiBe, $NaBF_4$, supercritical CO_2) design so as to avail production of electricity, hydrogen and energy storage, juxtaposed against the Czech national energy portfolio. Common to many national nuclear conceptual design engineering studies (here at nuclear R&D centre, Rez), while development details may be ongoing, a path toward commercialized deployment is unknown.
2) MoveLuX (Toshiba, Japan) – is a sodium heat-pipe cooled and calcium hydride moderated, natural convection (air-based primary circuit) driven MMR with thermal/electrical power output, targeted at 10 MWt/3-4 MWe. The core design uses uranium silicide (U_3Si_2) fuel housed in hexagonal "cans" with lithium expansion system reactivity control. With a sodium heat pipe based higher temperature conversion system coupled to helium gas, electricity and hydrogen production are possible, as well as a fuel cycle adapted to the national fuel cycle practice. This MMR concept is a Toshiba internal conceptual design study.
3) U-Battery (Urenco, UK) – is a high-temperature, helium gas-cooled, graphite-moderated MMR with targeted thermal/electrical output, 10 MWt/4 MWe. The core design uses TRISO fuel, enriched up to 20 %, in hexagonal blocks with control rods, fixed burnable poisons and shut-down absorber spheres. A 5-year full power year and 30-year design life are targeted. Energy conversion is via indirect secondary nitrogen circuit with applications both for heat applications or closed gas-turbine technology (no combustion stage). Regulatory approval of its detailed design and commercialization partners have been announced by its developer, URENCO – UK.

4) AURORA – (Oklo, USA) – with a targeted thermal/electric power output, 4 MWt/1.5 MWe, this compact, liquid-metal cooled fast reactor MMR using metal fuel, a 20-year refueling cyle, Oklo has applied for a USNRC combined license application. The plant features low power output, low power density and low decay heat output, and correspondingly has low fuel burnup, small fuel inventory, simplicity in energy removal by inherent and passive means, and overall takes advantage of thermal capacity via use of higher conductivity material selection. Oklo has an existing agreement to access the Idaho National Lab site and some aspects of their technology know-how under a partnership agreement.
5) eVinci Micro Reactor (Westinghouse, USA) – this conceptual design MMR with a targeted thermal/electrical power output, 7-12 MWt/2-3.5 MWe, uses (sodium) heat pipes and metal hydride moderator in a stand-alone, transportable reactor and energy conversion system unit. Instrumentation and controls are provided via a separate, integrated (second) unit. The core is based on TRISO or similarly encapsulated fuel, in a monolithic core with reactivity control realized via ex-core (moving) control drums. Onsite refueling or whole reactor replacement are envisioned. Energy conversion is via open-air Brayton and single shaft gas turbomachinery. The core is designed with negative reactivity, and decay heat removal is via intended conduction and natural convective heat dissipation to air. The design integrates many elements and simplifications based on lessons learned by Westinghouse in overall plant "island" design. The design concept is under Vendor Design Review, Canadian Nuclear Safety Commission (CNSC), and preliminary discussions with the USNRC.
6) MMR (Ultra Safe Nuclear, USA) – this MMR with a (Canadian) national laboratory site partnership permit, has a targeted thermal/electrical power ouput, 15 MWt/greater than 5MWe. This MMR is a high-temperature, (helium) gas-cooled, graphite-moderated, solar salt energy stored integral design. The core will use TRISO for fully ceramic micro-encapsulated (FCM) fuel pellets, HALEU enriched to just under 20 %, in hexagonal blocks with control rods. Its inherent core negative temperature feedback and low power density, dissipates heat radiatively and via natural convection. Energy conversion is via a 3-loop system with a molten salt intermediate (heat exchanger) loop that also stores thermal energy. This loop connected to a steam generator unit. The concept, under Global First Power, has submitted a license to prepare site initial application at CNL Chalk River site, and with the CNSC.

2.2 Water-cooled, moderated, thermal spectrum designs

Due to the large number of light water-cooled, thermal spectrum reactor designs in the history of nuclear energy, SMRs based on the similar light water moderation, reflection and cooling concepts comprise the largest grouping of SMR concepts and designs at present. In fact, one of the most complete, if not the only completed design is that by NuScale Power. Not surprisingly, many aspects of the design, engineering, system design and overall, design methodology are proprietary. That said, based on a survey of various SMR designs of integral Pressurized Water Reactor type (iPWR) by Zeliang, Mi and co-workers [32], if the selected core design is conventional (primarily to reduce overall cost), but smaller, then differences in various designs are most clearly revealed in the thermal-hydraulic design that minimize and/or eliminate potential initiating events may be linked to DBA and certainly BDBA scenarios. In the latter case, the DBA/BDBA can then be claimed as impossible. Reflection of this approach then begs the question of prudent integration of the following practices: probabilistic risk assessment (PRA), system analysis (RELAP and similar), accident analysis (MELCOR and similar) and dispersion analysis. The work by Williams et al. [34] describes the safety-in-design, including foremost, defense-in-depth and putting into (design) practice, the INSAG-10 explicit levels.

2.3 Gas-cooled, graphite-moderated

Large scale gas-cooled, often graphite-moderated reactors have a history as long as water-cooled, thermal spectrum reactors. As such, there have been generational reactor concepts paralleling that of LWRs. Much of the generational development can be traced to the 1950s to 1970s, and is associated with the prismatic (block) type Magnox and AGR in the UK [41, 42]. The pre-commercial, experimental Dragon reactor introduced the TRISO (tristructral-isotropic) fuel type. Soon thereafter, the German constructed and operated the AVR (Arbeitsgemeinschaft Versuchsreaktor), with a pebble bed fuel and moderator (spheres) core configuration, demonstrated high-termperature operation using gas as coolant. This reactor concept is often attributed to Daniels and Schulten, and following the AVR saw incremental developments via the following: German THTR-300, the Japanese High

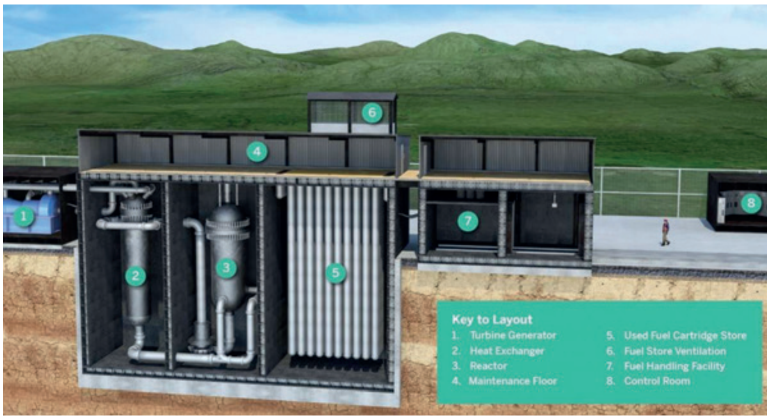

Figure 1
U-Battery Design (Source: www.u-battery.com/design-and-technology).

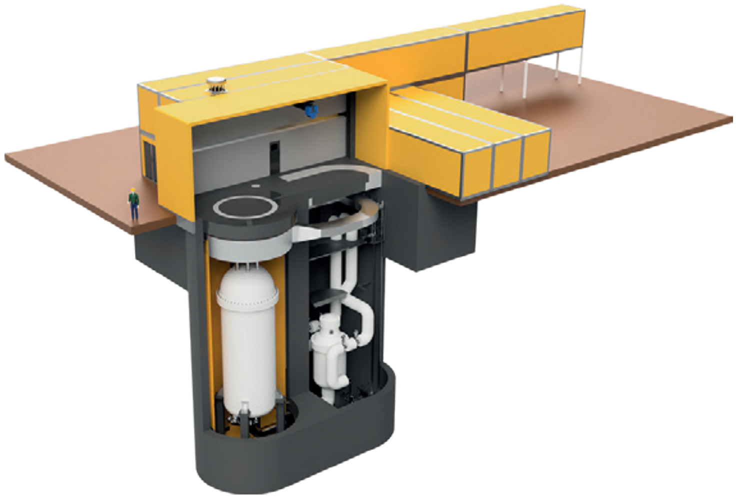

Figure 2
The Micro Modular Reactor (MMR™) system (Source: www.usnc.com/mmr-energy-system/).

Figure 3
Westinghouse eVinci™ Micro Reactor
(Source: www.westinghousenuclear.com/new-plants/evinci-micro-reactor).

Temperature Test Reactor (HTTR) and Chinese High Temperature Reactor, HTR-10. X-Energy's Xe-100 is the current pebble-bed, high temperature, gas-cooled nuclear reactor (SMR) design, using TRISO fuel and with targeted output at 200 MWth/76 MWe. Consistent with many light water based SMR designs, the current day gas-cooled, graphite based concepts feature active or passive safety features.

2.4 Unique Reactor Designs

There are and can be other unique types of SMRs and MMRs designs and concepts, differing in selection of fuel type, fuel form (solid vs. liquid), neutron energy spectrum, the combination of coolant, moderator and reflector, thermal/electrical output, safety-in-design and deployment strategies, including aspects of modularity, manufactureability, cost savings per advance manufacturing methods, and "add-on" benefits such as medical isotope, hydrogen and district heating production. It may be reasonable to say that, assuming that there is (sovereign) regulatory review with inclusion of public consultation of any particular SMR design, aspects of technical innovation and interest, has to prevail against public sentiment and skepticism. Thus, innovative concepts rarely have a chance, even in demonstration, and in today's social media driven, multi-national climate, consensus acceptance may be needed for certain. In other words, new technology solutions have to overcome a daily battle of disinformation and misinformation to garner and secure sustainable investments and developments. In other words, "the odds are not very good, even if the technology (the goods) are very innovative (not odd)".

2.5 Molten salt-fueled and cooled, and fast spectrum, liquid metal designs

As noted, finishing the SMR design and submitting this for regulatory review and approval, as well as commitment to construction via sufficient and satisfactory investments, are the most important in current SMR efforts. These linked objectives also apply to novel SMR/MMR concepts based on molten-salt fueled and cooled concepts as well as fast spectrum concepts. Historically and technically, fast spectrum concepts are often associated with liquid metal (sodium, lead, eutectic alloys, etc.) thermal-hydraulic system designs. Most notably, large thermal diffusivity (and conductivity, relative to water) and selection of materials with small neutron cross section, provide design advantages in fast spectrum concepts. A succinct summary of the sodium-cooled fast reactor is contained in [43]. The IAEA "2020 booklet" provides technical specification of the Terrestrial Energy's [39] and Kairos Power's (fluoride salt-cooled, high temperature, pebble bed), [40] designs, as well as the fast spectrum designs of the ARC-100 (sodium-cooled) and Oklo (MMR, HALEU fuel, supercritical CO_2 with heat pipe) concepts. Additional information of technical interest can be found via ongoing regulatory review processes (examples: US, Canada) and open access publications and news releases. Of importance, relative to and in contrast to thermal spectrum SMR/MMRs with safety-in-design, is the inherently passive safety system feature (including reactivity control) corresponding to a defense-in-depth approach, that provides competitive, if not advantageous benefit, in the eyes of the stakeholders. Because these reactor concepts are or can be significantly different than thermal spectrum, water-based SMR/MMR designs (example, flowing in-solution liquid fuel and coolant), they provide important regulatory opportunity to confirm technology "neutrality" when that objective is sought.

There are 11 fast spectrum SMR concepts noted in the IAEA – 2020 book. Of these, the Siberian Chemical Combine's, BREST-OD-300, with declared thermal and electrical power output, 700 MWt/300 MWe, recently received license (from Rostechnadzor) to be constructed in Seversk. This, a lead (Pb-cooled and moderated, pool type fast reactor, is both a test and demonstration plant. It is thus an evolutionary design similar in design to French and Japanese one-off SFR designs (Super Phenix, Joyo, Monju), but incorporating lessons learned using lead and lead-bismuth within the Russian Federation. The core consists of mixed uranium-plutonium nitride fuel, enriched up to 14.5 %, in hexagonal configuration with chromium ferritic-martensitic steel cladding and capability for fuel breeding. Reactivity control is via shim and automatic control roads, while the 2-loop energy conversion system features a lead to water steam generator system. The emergency core cooling system is passive, and consists of pipes immersed directly into the primary system, thus serving as a natural circulation driven lead-to-air heat exchanger. Completion of construction is scheduled to be as early as 2026.

It is worth noting that in terms of safety-in-design of liquid-metal cooled fast reactors, the key safety feature is a prompt, negative temperature feedback from Doppler broadening of the cross section. In simple terms, because of the combination of higher fuel enrichment (relative to water-cooled reactors), liquid metal as coolant and subsequent compactness of the overall core design, the power density of a fast reactor is larger than water-cooled reactors. Thus, the probability of an initiating event developing into an energetic event has to be considered. The safety-in-design of the EBR-II test/demonstration plant considered many of these aspects and demonstrated its inherent safety. In brief, historically documented (accident) phenomena specifically for sodium-cooled designs include the following: transient overpower, loss-of-flow, fuel-vapor explosion, sodium vapor explosion, containment response under short and sustained loads. For specific liquid metal cooled, SMR-scale fast spectrum designs, these specific issues have to be addressed.

It remains to be seen how the ARC-100 SFR will develop as a scaled-down, updated version of EBR-II [44], with some of the original EBR-II lead principals. The ARC-100 is a forced circulation SFR, thermally projected to be 286 MWt/100 MWe, and featuring U-Zr metallic fuel, enriched on average to 13.1 %, such that it has a 20-year refueling service life. Beyond the primary circuit, it features a 2-loop IHX to SG design, supported by four submersed EM pumps. The SG is a vertically oriented, helical coil, single-walled, counter-flow sodium-to-water, shell-in-tube design. Reactivity control is via a redundant system of 6 control rods (3 x 2). Besides the core, many of the major energy conversion system components are integrated into the reactor vessel and defining building. The ARC-100 is undergoing CNSC Vendor Design Review and has Provincial support from New Brunswick (Canada). Generational knowledge preservation and transfer, as well as workforce capability to understand the SFR remains to be seen.

Finally, we would be remiss if the long-standing promise of fast reactors as part of national energy self-sufficiency strategy via closing of the nuclear fuel cycle, is not noted. Unfortunately, no nuclear nation today completely practices a fully closed (commercial) nuclear fuel cycle and thus, with fast reactors of a SMR "kind", we have to again maintain a sensible view to technology readiness of fuel reprocessing aspects for those fast SMR concepts that use existing supplies of spent fuel. Except possibly in China and the Russian Federation, openly competitive global markets have eroded the promise of fast reactors and closed fuel cycle.

3 Lesson learned, evolution of safety-in-design, getting to the end

One can look at the 70+-year history of nuclear power generation of electricity, and relative to other public use/acceptance of other risk-inherent technologies such as the automobile and travel via commercial airlines (approximately 100 years), begin to understand the development of social license/public acceptance of technologies. Once could state that unfortunately, nuclear power developed alongside environmental consciousness and a spectrum of "anti" movements that continue to this day. This paper is not intended to argue rightful acceptance of nuclear power. However, not preserving the options presented by nuclear generated electricity would be testimony to lack of foresight in the world we live in today, with the issues and challenges that we have.

The ongoing "nuclear renaissance" of recent years can be summarized in terms of the following trends: 1) conceptual designs followed by various states of engineering design development of many types of SMRs and MMRs, 2) a broad discussion of the socio-technological importance of addressing (the emerging, negative impacts of) climate change, and thus, transitioning away from a carbon-based (fossil fueled) to low carbon or net zero carbon economies of scale using nuclear energy, and 3) unbeknownst to many but integration of lessons learned, evolution in safety-in-design thinking, and advancements in modeling and simulation (using high performance computing) for advanced reactor designs. Recent advancements in accident tolerant fuels, and advanced manufacturing are noted but perhaps years away from being inherent in SMR/MMR design.

4 Emerging drivers in SMR and advanced reactor concept design

The ongoing global interest and enthusiasm for SMR/MMR has generated many concepts but equally revealed uncoordinated global gaps, including regulatory review of the safety-in-design of various concepts. This is to be expected, given that regulatory mandate is at the national level. That said, there are a few bi-/tri-lateral collaboration agreements to share regulatory practices. It remains to be seen whether such collaborations will facilitate review and thus reduce the overall time to realizing any particular SMR/MMR concept. We further note that global institutions, such as the IAEA, WNA, OECD-NEA, WANO

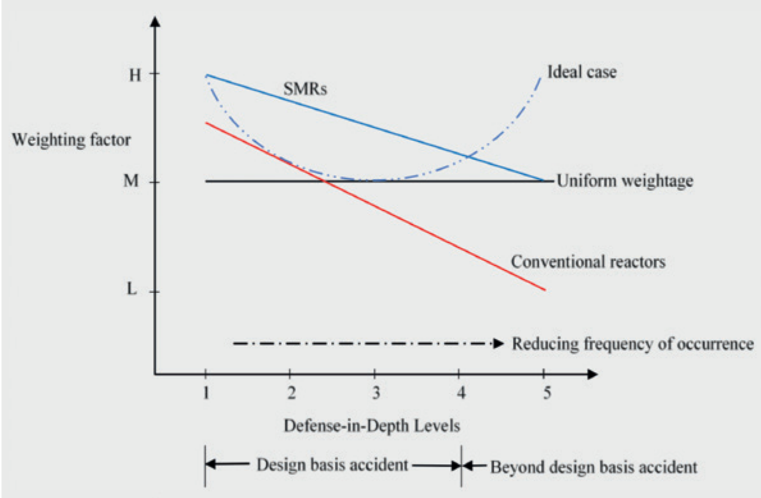

Figure 4
Conceptual sketch of weighting factor assignment.

and related promote common understanding – here with respect to safety-in-design of SMRs/MMRs and other advanced reactor concepts. The authors herein describe emerging drivers or influences, based on many lessons learned in reactor concepts and designs. We offer this account since, design methods and approaches often remain proprietary and as such, not openly discussed. We thus offer for contemplation and discussion, high-level aspects of safety-in-design of SMRs.

Figure 4 first shows a qualitative "high, medium or low" weighting in importance versus the INSAG-10 levels (1 to 5), meant to reflect historial perspective on defence-in-depth. The figure compares conventional reactors (larger plants) versus SMRs currently proposed. We note that the weigthing for convential reactors may sensibly decrease incremental manner if level "1, 4, 5", for example, loosely correspond to AOOs, DBA an BDBA respectively. That is, convential reactors have largely been designed so that safety systems can respond to and counter consequences of the postulated DBA. However, history has taught us that human operational error can generate BDBA-type situations; that is, leading to core meltdown (degradation) and (unintended) release of radioactivity beyond the plant boundary. Thus, for older generation reactor designs (Generation II), one could imagine a higher weighting for levels 1-to-3, relative to levels 4-to-5 event. Since, the authors anticipate arguments under such qualitative perspectives, an uniform, medium weighting across levels, 1-to-5, is also shown. It is conceivable that a particular, recent design (Generation III, III+) could feature uniform weighting as depicted.

In contrast, the designs of current SMRs are generally expected to reflect generational improvements in safety-in-design, overall. Thus, at minimum, the SMR may feature inherent, passive safety system/s in its design, and thus reflect a safety-in-design philosophy, that may emphasize at least "M" weighting for unlikely, level "4 or 5" scenarios. In so doing, the design eliminates the need for immediate (human) emergency response. This latter philosophy may not always be apparent by studying the design itself, but depicted through an integration of a number of safety-in-design aspects. In reality and with operational excellence taken into consideration, the relationship may be something similar to the (non-linear) dotted trend with high imporance placed on both low and higher level scenarios. Any difference in magnitude or slope comparing conventional reactors to SMRs, thus reflects historical

DiD Level	SMR target frequency (/yr)*	Attributes	PRA Levels	Current regulatory requirements (/yr)
Level 1	< 10^{-2}	Initiating event frequency	Level 1	< 1 x 10^{-5} and < 1 x 10^{-4} (depending on regulator)
Level 2	< 10^{-5}	Failure detection capability and control action (automatic or manual)		
Level 3	< 10^{-8}	Core damage frequency (CDF)		
Level 4	< 10^{-10}	Conditional containment failure probability	Level 2	< 0.1 (depending on regulator)
Level 5	< 10^{-12}	Large early release frequency (LERF)	Level 3	< 1 x 10^{-6} (depending on regulator)

Table 1
Relationship among DiD, PRA, existing requirements and expectations. *small values can be argued, conservatively

No.	Generic eliminated scenarios	Contributing innovative features
1.	Large Break Loss of Coolant Accidents (LB-LOCAs)	Integrated Reactor Cooling System
2.	Elimination of control rod ejection/injection accidents	Integrated Control Rod Drive Mechanisms (CRDMs)
3.	Exclusion of inadvertent reactivity insertion as a result of boron dilution	Eliminated liquid boron reactivity control system
4.	Elimination of loss of flow accidents and failures/scenarios related to reactor coolant pumps	Naturally circulated primary system
5.	Elimination of the need for external power under accident conditions	Fail-safe passive safety features on loss of power

Table 2
SMR design features that challenge conventional safety analysis.

Design characteristics	Facilitating factors in (SMR) passive safety systems (PSSs) start-up/operation
Integral reactor coolant system (RCS)-design-reduced accident initiators	Minimizes accident initiators, thus consider use of PSS. Results in a simplified design
Lower core power capacity	Less (magnitude) decay heat to be removed 30)
Larger surface to volume ratio	Facilitates decay heat removal due to large surface area, particularly for single phase flow
Larger primary coolant inventory per MW(th)	Larger heat sink for natural circulation; larger buoyancy-driven flows/regioins; reduces requirements for heat removal systems 31)
Smaller reactor core power density	Larger thermal-hydraulics margins; favourable in long term decay heat removal, in particular via PSSs
Large secondary coolant inventory, e.g., NuScale reactor pool	Facilitates passive decay heat removal and containment cooling 10)
Taller and broader reactor pressure vessel or vessel containing core	Facilitates decay heat removal via natural circulation, i.e., higher elevation difference between heat source and sink 30)

Table 3
SMR design features that challenge conventional safety analysis.

lessons learned and competing philosophies in safety-in-design of nuclear reactors.

Continuing, **Table1** below provides a semi-quantitative equivalent to **Figure 4** but compares INSAG-10 levels, against the possible SMR target frequencies (a design merit), short descriptors of the corresponding attributes of an event or accident, the commonly noted PRA levels, and the currently known regulatory values for existing plants. This table is qualitative and simply contrasts different perspectives that may be used by a SMR designer. We recognize that small frequency values, say less than 1E-08, may not hold regulatory meaning and as such, higher frequencies for levels 1-5 may apply, depending on the practicality of such values in regulatory review of submitted SMR/MMR designs and concepts. Finally, as a measure of confidence in its design, a vendor may assume a probability 3 orders of magnitude smaller at each level, except at level 4-and-5.

Table 2 provides five representative, generic events for which design features and/or design concepts of recent SMRs (also MMRs), have either greately reduced or eliminated all together the likelihood of such vulnerabilities, most often associated with conventional reactor designs. Here again, through gradual advancements in conventional reactor safety-in-design, further facilated by ongoing development in SMRs, safety-in-design and defence-in-depth have both been embodied in various SMR designs. The rightmost column gives an example of the SMR design feature that eliminated the generic scenarios.

Finally, **Table 3** representative design characteristics or features observed in recent iPWR-type SMRs (left column), relative to their phenomenolgical impact in assuring energy removal under many severe accident scenarios and design vulnerabilties associated with conventionl reactor designs. Further, for a given SMR design encompassing a mulitple number of design characteristics as above, operator intervention is greatly reduced or eliminated for substantial durations of time, starting from the initiating event and possibly linked to an additional sequence of unlikely events. In other words, current SMR designs anticipate BDBA and catastrophic, external events.

5 Uphill costs and getting to the end

It is no secret there are major milestones on the path to realizing any new commercial nuclear power plant. Some major milestones that come to mind are first criticality and connection to the electricity grid. New conventional builds have however become too expensive, relative to other large infrastructure projects and public spending that address regional to national priorities. As ramification of the Fukushima Daiichi earthquake-tsunami-nuclear plant accident, and examples of cost overruns and delays associated with large nuclear plant projects persist, "opportunist" have taken sides – to either support or not support nuclear energy as a valued energy source option. It is well known that the merits of nuclear power (as zero to low carbon) in addressing the negative impacts of climate change, continue to be argued in public and social media spaces. Pragmatism regarding public infrastructure need can become easily mired and disconnected to those elected and engaged in media. If the authors may inject opinion, nuclear energy is an energy technology that we have today and it provides, at minimum, the time needed for society to reach consensus via change in mindsets, values and beliefs. This lead author is of the opinion that addressing climate change is just as much a matter of change needed in how we live and consume. Energy consumption and its sources are very much part of the anthropocene.

While various perspective on developments in SMRs/MMRs can be taken, the authors' position here is that getting to the "end" may be the most important.

6 Conclusion

Development of various Small- and Micro-Modular Reactor concepts, regardless of its point of origin depends on alignment of both timely and prudent engineering and design efforts, sustained financial backing during this effort and, public and/or private stakeholder investments so that a first-of-a-kind reactor (FOAK) is constructed on time and at cost, post timely regulatory safety-in-design approval. Beyond the FOAK plant, expectations are such that sustained investments and commitments, parallel reduction in cost with each additional unit constructed in modular manner.

Here the authors have elaborated on a holistic safety-in-design perspectives wherein technical features make design and beyond design basis accidents nearly impossible (or eliminated), and even under improbable initiating events, decay heat removal is passive such that it does not require operator intervention for a defined length of time. The article also emphasized that completion of the design and (time) efficient regulatory review of the submitted design, are of tantamount importance with respect to the sustained investments, and can determine the fate of any given SMR/MMR design. It is clear that regional to national support of nuclear energy, an existing history of reactor design development, a skilled nuclear and energy sector workforce, and an existing supply chain are increasingly expected conditions when considering new nuclear plants. Finally, early public engagement and confirmation of gradual public acceptance and social license (nominal acceptance of nuclear energy) must exist, as identified via fleeting social media platforms. This is the reality of the world that we live in today. Let us brave the future of nuclear energy.

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