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Small-sized Reactors of Different Types: Regulatory Framework to Be Re-Thought?

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Abstract: All types of large reactors, subject of intensive development, are represented in SMR lines. A study of evolutionary (mostly water cooled), revolutionary (sodium or gas cooled), and exotic (salt or lead cooled) designs is performed, focusing on safety characteristics and assessment against tightened-up requirements; notably robustness against malicious interventions and instability of societies. In general, lower power and operating pressure reduce the potential of catastrophic releases; increased safety margins and special design characteristics almost eliminate risk of severe core damage, triggered by Reactivity Induced Accidents or Station Blackout. Active systems and early operator actions are avoided; the need for a tight containment, and emergency planning is often negated.

However, concept-specific accident scenarios such as fierce chemical reactions, flawed fuel addition, overcooling/freezing or air/water ingress deserve attention. Most developers claim that classical regulatory approaches to safety are inappropriate. However, relying on "one line of defense" and replacing active systems by passive, inherent mechanisms result in a shift of safety proofs to material properties, validity of experiments and computer codes, completeness of scenarios — under constraints of increased uncertainties. Furthermore, some reactor concepts are closely linked to elements of the fuel cycle, introducing new challenges. It seems evident that new regulatory concepts need to be developed — aiming to avoid unnecessary safety measures, while ensuring exceedingly high standards - and regulators to be educated, both in parallel with technological developments.

Key words: novel reactor concepts, tightened safety requirements, regulatory framework

1. Introduction

A thorough assessment of past operating experience, based on a comprehensive nuclear events with database [1], emphasizes that severe nuclear accidents are rare in absolute and relative terms due to disproportional, far-reaching design and operational measures, provided they are diligently followed and implemented. Nevertheless, the physical process (surplus of fission neutrons, radio-toxic fission products, decay heat production) and current technology (high power density and size, meltable fuel claddings and structural materials, high operating pressure, etc.) make today's uranium fuelled reactors highly vulnerable to perturbations and deficits of the operational context; although substantially low in frequency, the potential of large radioactive releases and associated frightening consequences cannot be ignored.

2. Key Requirements for Less Vulnerable Designs and Means to Achieve Them

As a way out, we suggest that future nuclear power reactors should be less dependent on: properly designed safety systems and security measures as well as protection against external events of both natural and malicious/intentional origin, the adequacy of broader infrastructure, safety culture, operational modes and, *last but not least,* on the stability of our societies [2]. For this the following technical requirements are put forward:

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- Elimination of potential reactivity induced accidents by reactor core design or at least controllability by passive means. This can be achieved by:

a) sub-critical systems (receiving additional neutrons from accelerator driven systems);

b) weak, negative reactivity coefficients (graceful reaction on increasing fuel temperature, power, void fraction, burn up);

c) small reactivity surplus at start up with fresh fuel;

d) fail-safe design of shutdown absorber rods.

- Forgiveness against loss of active core cooling, including total loss of power by reactor design and inherent/passive means. This can be done by:

a) low power density and power size (to avoid exceeding critical temperature limits);

b) strategies to avoid high fission product inventory, e.g., by dispersed fuel;

c) temperature resistant fuel cladding and structural materials;

d) sufficient heat storage capability and inherent/passive heat transfer mechanisms in case of loss of normal (forced) cooling/loss of coolant (de-pressurization)/total loss of power;

e) passive decay heat removal systems.

- Securing structural integrity to avoid geometric disorders (losing core cooling capability) or loss of confinement of radioactive inventory. This can be obtained by:

a) low primary circuit pressure or leak/rupture proof components (notably pressure vessel);

b) radiation resistant and robust core structures;

c) underground siting for protection against extreme external impact.

- Use of chemically non-reactive, non-toxic materials and fluids, or avoiding direct contact of reacting substances, e.g., by intermediate cycles.
- Avoidance/incineration of long-lived radioisotopes (actinides) by fuel cycle designs allowing for reduced long-term stewardship. This can be achieved by:

a) switching to fuel cycles (thorium) with drastically smaller generation of long-lived minor actinides, or waste burner core designs;

b) striving for enhanced closed fuel cycles or for long-term stable, high burn-up spent fuel as an open fuel cycle option.

- Intrinsic proliferation resistance characteristics of the fuel, fuel cycle and related processes, inter alia by:

a) avoiding the use of highly enriched uranium (HEU);

b) striving for online reprocessing, or facilities/ processes including fuel fabrication at reactor location.

3. SMR Concepts and Associated Principal Safety Characteristics

All types of large reactors, presently in operation, under construction or subject of intensive development, are represented in SMR (small modular reactor) lines. We have carried a comprehensive study of evolutionary (mostly water cooled), innovative/ revolutionary (sodium or gas-cooled), and highly innovative/exotic (molten salt or lead cooled) designs, focusing on safety characteristics and their assessment against the strengthened key requirements outlined before. Key characteristics and design specific features are depicted in Table 1 for selected concepts.

All selected SMR concepts — varying by coolant, neutron spectrum (thermal-fast), purpose, power size (typically below 250 MW thermal, with roughly proportionally reduced fission product inventory compared to large a PWR up to 5 000 MW thermal) and operating pressure (most concepts are not pressurized) — lower the potential of catastrophic releases and related driving forces, significantly; increased safety margins and rugged design characteristics (like a fully ceramic core or an accident tolerant fuel) can almost eliminate the risk of severe core damage, triggered by loss of active heat removal accidents (including station blackout). Active systems and the need for early operator actions are largely avoided; the need for enforced containment structure, emergency planning and even remote siting are often negated. However, some fast reactor concepts deserve special attention regarding reactivity-induced accidents (RIA). Furthermore concept-specific accident scenarios (such as fierce chemical reactions (sodium), flawed fuel addition, over-cooling/freezing (molten salt, lead/lead bismuth) or air/water ingress (graphite) call for thorough analysis.

Based on mostly preliminary information, a more specific assessment of selected SMR concepts has been made by evaluation against strengthened technical requirements/design criteria. The results (see Table 2) indicate a high potential for far-reaching improvements compared to most advanced light water reactors like

Table 1 Characterization of basic design approaches, distinguished by coolant, and with specific SMR concepts taken into consideration

Design Approach	Evolutionary	Innovative-revolutionary		Highly innovative-exotic	
Characteristics/ Design Features	Water	Sodium	Gas (Helium)	Molten Salt	Lead
Selected concepts	mPower|NuScale	PRISM	HTR-PM	SaWB	BREST-OD-300
- Neutron spectrum	thermal	fast	thermal	semi-thermal, fast	fast
- power density [MW/m^3]	< 80	290 (?)	8	70	150
- pressure [MPa]	14.1| ?	unpressurized	80	unpressurized	unpressurized
- type	pool	pool; IHX	loop	pool, overflow tank; IHX	loop
- purpose	burner	waste burner	burner	waste burner	converter
- fuel (enrichment)	UO_2 (5%)	$(U,TRU)O_2$ (15%)	$(U,Th)O_2$ (8.5%)	U, Th, TRU dissolved in salt	(U+Pu)N
- power size	180|50 MWe	311 MWe	100 MWe	50 MWt	300 MWe
-basic safety approach	integral design passive	passive	inherent/passive	inherent/passive	inherent/passive
-cladding/structural material	metallic	metallic	ceramic	salt-metallic	metallic
- construction	factory	factory	on-site/factory	factory	on-site
- siting issues (reactor)	underground	underground	underground	underground	above ground

Table 2 Assessing selected SMR concepts against strengthened requirements - ranking from excellent (++), medium to very poor (--)

Key requirements	*Candidate reactor concepts – varying coolant, selected designs in brackets*				
	Water-thermal (large EPR)	Sodium- fast (PRISM)	Molten Salt-fast (SaWB)	Helium-thermal (HTR-PM)	Lead-fast (BREST-OD-300)
Elimination of Reactivity Induced Accidents	+	-	--	++	-/~
Forgiveness against Loss of Active Core Cooling	--	-	~	++	-/~
- avoid exceeding critical temperatures	--	n.a.	n.a.	++	
- avoid high fission product inventory	--	+[1]	++[2]	+[1]	+[1]
- provide sufficient heat storage & transfer capacity	+	++	+	+	++
Structural Integrity	-	+	+	++	+
- avoid high operating pressure	--	+[3]	++	+	+[3]
[suitability of underground siting]	[-]	[?]	[++][4]	[++][4]	[+]
Use Non-chemically Reactive/Non Toxic Materials	+	--[5]	-[5](non-stable)	++	+
Avoid Long-lived Radioisotopes	--	+	++	+	++
Enhance Proliferation Resistance	+	-	-	~	-
- avoid high enriched uranium	++	-[6]	-[6]	-[6]	-[6]

[1] due to small power size; [2] in case of dispersed fuel & due to small power size;[3] not pressurized but high static load; [4] foreseen; [5]intermediate cycle (IHX) foreseen; [6] close to HEU lower limit; n.a.: not assessable

the European Pressurized water Reactor (EPR), which here serves as a benchmark, and that may finally achieve very ambitious and challenging specifications. However none of the selected candidate concepts, small sized in general, fulfils all of them yet, and may prove less proliferation resistant. Thermal helium cooled reactors (HTR-PM) comes closest, promising inherent robustness against "classical severe accidents" and largely avoiding long-lived radioisotopes when using thorium[1] fuel but currently not being capable of burning radioactive waste. In this respect molten salt fast reactors promise to do best but appear to be most susceptible to reactivity induced accidents (--) as all liquid metal cooled fast reactors are, albeit to different degrees.

4. Regulatory Approach and Need for Modernization

Most developers pretend to basically apply well-established safety objectives and fundamental principles for their concepts, notably the defence in depth principle. However they claim that classical approaches are inappropriate, too burdensome, need to be adapted to the characteristics of the particular SMR concept, and need to become more efficient [2] 2), although the need for this is less for the small water cooled reactors.

To come up with an independent appraisal, we made reference to the technical safety objective and the strategy of defence in depth as one of the fundamental principles, all developed within the IAEA-INSAG framework [4] and widely accepted as the regulatory basis for existing plants. Then we contrasted key safety characteristics of large water-cooled nuclear power plants (EPR as an example) with those of highly innovative revolutionary — exotic SMR concepts, highlighted before. Obviously to prevent, with high confidence, accidents in nuclear plants, and to pay special attention to severe accidents with serious radiological consequences are objectives, commonly shared by all plant designers. However, for current designs it has been assumed that the prevention of accidents cannot be totally successful and additional protection has to be achieved by the incorporation of many engineered features into the plant to cope with design basis accidents [4], paragraph 21; the likelihood of even multiple failures of provided redundant active safety systems, and resulting serious accidents, has to be proven small as one of the key requirements within the regulatory process. Most of the SMR designers argue that, due to favourable physical properties and inherent safety features or at least passive rather than active safety systems, such failures can be excluded. And, to exaggerate, severe core damage accidents and serious releases of radioactive substances, triggered by "classical" accident scenarios, in particular loss of core cooling accidents, e.g., following station blackout conditions, can be deterministically excluded.

Along these lines the defence in depth principle (which centred on several levels of protection including successive release barriers) has been applied in existing plants to compensate for potential human and mechanical failures. Most SMR designers do not question the relevance of this concept, but claim to re-assess the vulnerability of barriers and the necessary lines of defence, e.g., whether (i) the failure of the primary circuit/pressure vessels must be assumed in case of unpressurization and (ii) the loss of the first barriers, i.e., the fuel and fuel cladding, must be assumed in case of temperature resistant fuel elements (i.e., coated particles and ceramic fuel balls of HTR-PM). Most SMR do not deny the need for secondary safety containment, in principle, but discuss the adequacy of current design requirements such as leak tightness, though the HTR-PM safety concept relies on "one line of defence".

In general, we largely share this reasoning. Also in our view there is clear evidence that a pure application

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[1] As foreseen in the second phase of the Chinese HTR-PM program.

[2] In the USA, the Nuclear Energy Innovation and Modernization Act aims to modernize the NRC "to bring increased efficiency and fiscal accountability…".

of current regulatory requirements and best practices is not meaningful and poses unnecessary (economic) barriers to the deployment of most of the SMR concepts. However their adaptation to the innovative safety features of most of the considered designs poses challenges, that are hard to achieve: Relying on other/reduced lines of defence, replacing active safety systems by inherent/passive mechanisms, claiming reduced or no emergency planning zones, etc. result in a shift of safety proofs to material properties (often at extreme conditions), demonstration of sufficient quality/validity of small and large-scale experiments and computer codes. Eliminating "classical" accident scenarios and design base accidents raises the question of sufficient completeness of accident scenarios taken into consideration including new, concept-specific accident scenarios, etc. — all under constraints of lack of sufficient knowledge and experience, and under increased uncertainties and ambiguities.

For most fast reactor concepts, reactivity induced accidents deserve special attention and measures. Furthermore, some concepts are closely linked to elements of the fuel cycle (e.g., the molten salt reactors with on-line chemical reprocessing) and use highly enriched fuel, foresee below ground siting and off-site fabrication, introducing new conditions and challenges, respectively.

5. Conclusions

Our investigations into selected SMR concepts in general, and highly innovative concepts in particular [5], have indicated a high potential to meet extremely ambitious safety requirements. They also highlighted and confirmed safety features, which are significantly different from those of large power plants currently in operation or under construction. Therefore the regulatory framework for very promising SMR concepts must be re-thought to avoid unnecessary burden and obstacles for the development and commercial deployment, for water-cooled bridging technologies the least decisive.

The adaptation of basic safety principles and regulatory requirements as well as education and training of the respective staff may turn out to be a huge technical and organizational challenge and need to be taken up in a timely fashion, provided that the interest in SMR is real and continuous.

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