Progress in Design and Technology Development for Innovative Small and Medium Sized Reactors

A. Introduction

1. There is continuing interest in Member States in the development and application of small and medium sized reactors (SMRs). "Small" reactors are defined as those with an equivalent electric power less than 300 MW(e). "Medium sized" reactors are those with an equivalent electric power between 300 and 700 MW(e).

2. In the near term, most new nuclear power plants (NPPs) are likely to be evolutionary water cooled reactor designs building on proven systems while incorporating technological advances and often taking advantage of economics of scale. Currently such designs range up to 1600 MW(e). For the longer term, there is interest in innovative designs that promise improvements in safety, security, non-proliferation, waste management, resource utilization, economics, product variety (e.g. desalinated seawater, process heat, district heat and hydrogen) and flexibility in siting and fuel cycles. Many innovative reactor designs have been proposed in the small-to-medium sized range. In most cases, they are intended for markets different from those in which large nuclear power plants currently operate, i.e. markets that value more distributed electrical supplies, a better match between supply increments and demand growth, more flexible siting or greater product variety.

B. Current status: design and technology development

3. In 2006, more than 50 innovative SMR concepts and designs have been, or are being, developed by national or international programmes involving Argentina, Brazil, China, Croatia, France, India, Indonesia, Italy, Japan, Republic of Korea, Lithuania, Morocco, Russian Federation, South Africa, Turkey, USA, and Vietnam [1, 2]. Innovative SMRs are under development for all principal reactor lines and for some non-conventional combinations [2]. The target dates when they would be ready for deployment range from 2010 to 2030. Many of the designs share common design approaches as summarized in the following sections.

B.1. Safety

4. In SMR designs, as in large reactor designs, defence in depth strategies are used to protect the public and environment from accidental radiation releases [2]. However, nearly all SMR designs seek to strengthen the first and, to the extent possible, subsequent levels of defence by incorporating inherent and passive safety features as well as active safety systems. Certain common characteristics of smaller reactors lend themselves to passive safety features, such as larger reactor surface-to-volume ratios, which facilitate passive decay heat removal and lower core power densities. The first goal is to eliminate or prevent, by design, as many accident initiators and accident consequences as possible. Remaining plausible accident initiators and consequences are then addressed by appropriate

combinations of active and passive systems. The intended outcome is greater plant simplicity with higher safety levels that, in turn, might allow reduced emergency requirements offsite.

5. For innovative water cooled SMRs, design approaches to reduce accident-initiating failures include the integration of steam generators and pressurizers within the reactor pressure vessel. This eliminates large-diameter pipes and large-diameter penetrations in the reactor vessel, thereby eliminating 'large-break' loss of coolant accidents (LOCAs). Figure 1 shows the example of the 330 MW(e) SMART design. Some designs also apply in-vessel control rod drives, which both eliminates inadvertent control rod ejections leading to reactivity insertion accidents and reduces the number of reactor vessel penetrations [2]. A second approach to preventing loss of coolant accidents uses compact loop designs with short piping and fewer connections between components. The approach is based on operating experience with submarine reactors. Figure 2 shows the example of the KLT-40S design.

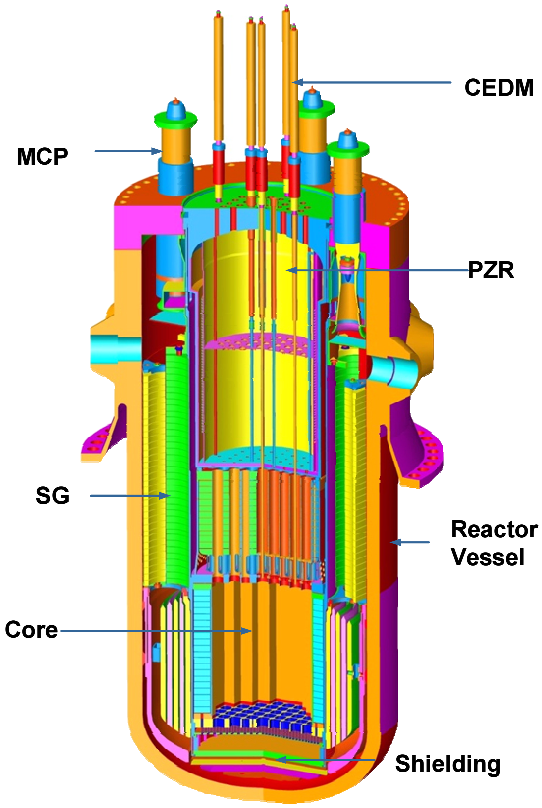

FIG. 1. Layout of the SMART integral primary coolant system. MCP = main circulating pump; CEDM = control element drive mechanism; PZR = pressurizer; SG = steam generator. (Source: KAERI-MOST, the Republic of Korea).

6. All high temperature gas cooled reactor (HTGRs) designs fall in the SMR size range. Figure 3 shows the example of the 165 MW(e) pebble bed modular reactor (PBMR). HTGRs use tristructural-isotropic (TRISO) coated fuel particles, each or which consists of a fuel kernel coated with, among other layers, a ceramic layer of SiC that retains fission products at high temperatures. The PBMR design uses graphite spheres (pebbles) in which thousands of TRISO fuel particles are embedded, but other HTGR designs use pin-in-block type fuel with graphite TRISO particles incorporated in graphite pins. The ability of TRISO fuel particles to contain fission products at high temperatures creates additional opportunities, relative to established practices in light water reactors, in designing safety systems and mitigation measures and essentially makes it possible to eliminate adverse consequences of many severe accidents by design. Passive decay heat removal in HTGRs is accomplished by heat

conduction through the graphite holding the TRISO particles, followed by convection and radiation in the structures and other media. Also, due to the large heat capacity of the graphite in the HTGR core, HTGRs have a slow and stable response to transients caused by initiating events.

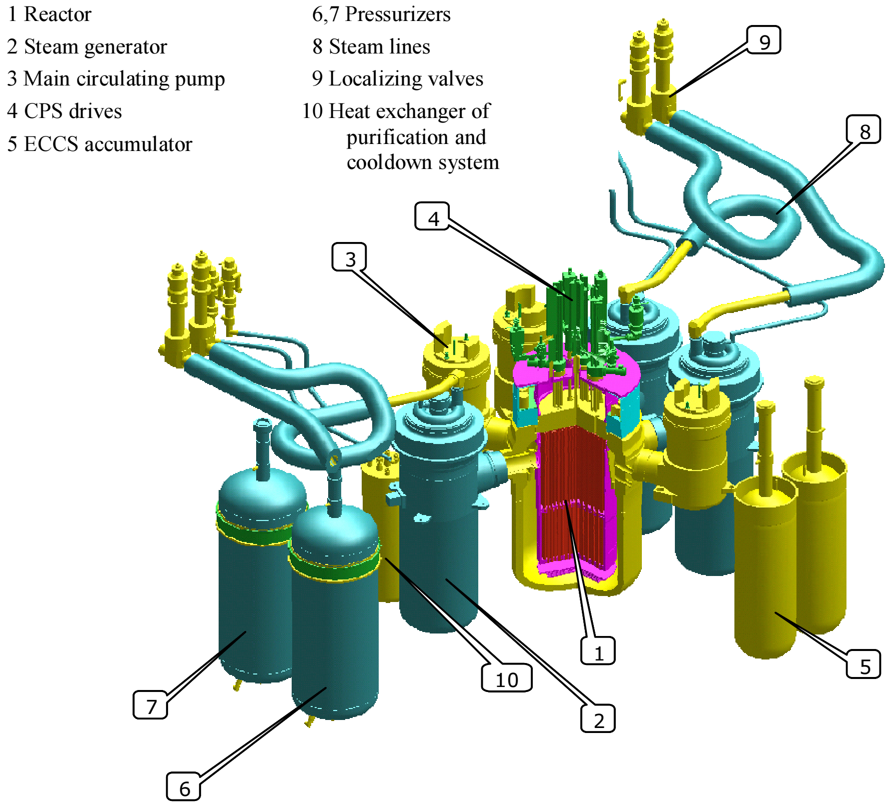

FIG. 2. Modular layout of the KLT-40S reactor plant (Source: OKBM, Russian Federation).

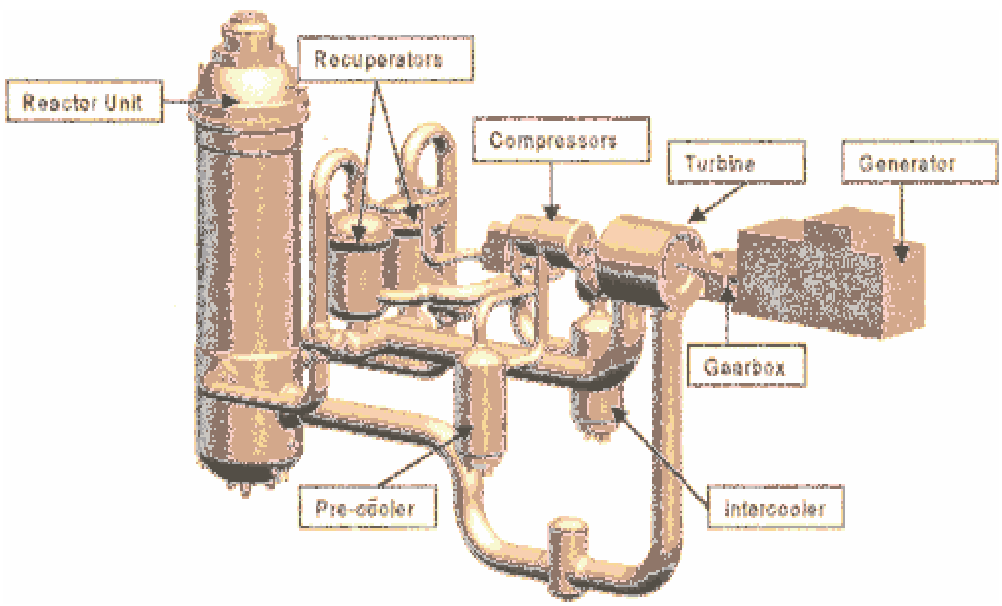

FIG. 3. Conceptual layout of the PBMR primary system, offering >41% energy conversion efficiency with direct gas turbine cycle (Source: PBMR Ltd., South Africa).

7. All fast reactor designs in the SMR family offer greater design flexibility in setting desired combinations of reactivity coefficients and effects. This is due to the larger leakage rate of fast neutrons and the high core conversion ratio. The resulting design flexibility creates the potential to eliminate transient overpower accidents by design, to ensure reactor self-control in a variety of other anticipated transients without scram, to enable passive load following capabilities for a plant, and to allow for the power to be controlled solely by adjusting the feedwater flow rate in the steam-turbine circuit [2].

B.2. Economics

8. The most common design approaches to improve the economic performance of SMRs are [1, 2]:

- to reduce plant complexity and reduce, as much as possible, by design, both accident initiators and their potential consequences;
- to reduce the construction time and cost, to enable a more rapid return on investment, by:
  - sizing the reactor for transportability (or at least transportability of modules) and
  - targeting a standardized design with no site specific modifications;
- to take advantage of cost reductions through factory mass production associated with serial manufacture of standardized plants or equipment modules incorporating unified structures, systems and components; and
- to build into the design the option of cost-saving ‘just-in-time’ incremental capacity additions and to take advantage of small module sizes to:
  - accelerate learning curve effects and
  - reduce interest costs and investment risks.

9. In order to facilitate just-in-time incremental capacity additions, design approaches include:

- setting aside space for future incremental additions,
- sizing the switchyard, water and district heat distribution pipelines, etc. for growth,
- sharing railroad, road and sea access facilities among future increment plants, and
- multi-module plant configurations with shared components (see Figure 4).

10. To reduce operation and maintenance (O&M) costs, SMR designs generally reduce the number of structures, systems and components that require maintenance and, in some case, design for passive load following or autonomous operation. Examples discussed below include small reactors without on-site refuelling: these require neither refuelling equipment nor storage capacity for fresh or spent fuel.

11. Almost all water cooled SMR concepts use a Rankine steam cycle with saturated or slightly superheated steam for energy conversion. The maximum energy conversion efficiency is approximately 33% based on reactor core outlet temperatures between 270 and 345°C. In contrast, most HTGRs achieve higher energy conversion efficiencies of 41–50% using direct Brayton cycles or re-using otherwise rejected heat. Several prospective liquid metal cooled, gas cooled and molten-salt cooled SMR designs may also use higher core outlet temperatures and gas turbine Brayton cycles.

12. Bottoming co-generation cycles, which are incorporated in many SMR designs to produce potable water, district heat or process heat, can, in some cases, recycle heat that would otherwise be rejected to increase overall plant efficiency.

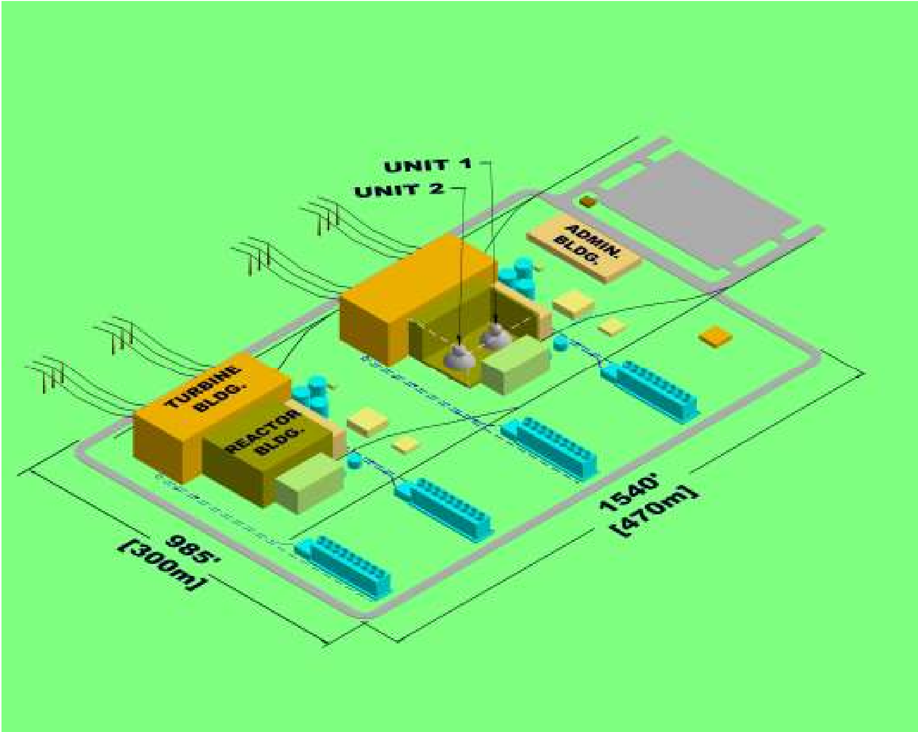

FIG. 4. Perspective view of IRIS multiple twin-unit site layout (Source: Westinghouse, USA)

B.3. Proliferation resistance

13. Being small or medium sized does not, by itself, make a design more proliferation resistant. Proliferation resistance depends on the incorporation of specific technical features and operational options, coupled with extrinsic features. As with large scale designs, SMR designers seek to include features that impede the diversion or undeclared production of nuclear material, or the misuse of technology [2].

14. Intrinsic proliferation resistance features common to HTGRs include high fuel burn-up (which leaves a low residual inventory of plutonium, but with a high share of plutonium-240); a fuel matrix that is difficult to reprocess; high radiation barriers; and a low ratio of fissile material to fuel-block/fuel-pebble material. Although several HTGR designs allow for the future possibility of reprocessing TRISO fuel, the technology is not yet established, and until it is, its absence is considered to provide enhanced proliferation resistance. TRISO fuel is also being considered for some innovative water cooled, molten salt cooled and lead-bismuth cooled SMRs. To the extent it is used in such designs, they also would benefit from the proliferation resistant features described here for HTGRs.

15. Small reactors without on-site refuelling, a category that includes more than half of all innovative SMR concepts, offer additional proliferation resistance features. These are summarized in the general description of such reactors in the section below.

B.4. Small reactors without on-site refuelling

16. Small reactors without on-site refuelling are designed for infrequent replacement of well-contained fuel cassette(s) in a manner that impedes clandestine diversion of nuclear fuel material [1, 2]. Figure 5 shows the example of Toshiba's 4S design. Such designs aim for refuelling intervals that are much longer than those of today's operating reactors (5–30 years or more), but still achieve design

objectives for economics and energy security. Small reactors without on-site refuelling are either factory fabricated and fuelled, or design for whole-core reloads performed at the site by a dedicated service team provided by the vendor, which would bring in its own refuelling equipment and fresh fuel and take away when it leaves both the equipment and the spent fuel.

17. About 30 concepts for small reactors without on-site refuelling are being developed within national and international programmes in Brazil, India, Indonesia, Japan, Morocco, Russian Federation, Turkey, USA and Vietnam [1, 2]. Small reactor designs without on-site refuelling are being considered, for both the near term and the longer term, for water cooled, liquid metal cooled and molten salt cooled reactor lines and some non-conventional fuel/coolant combinations.

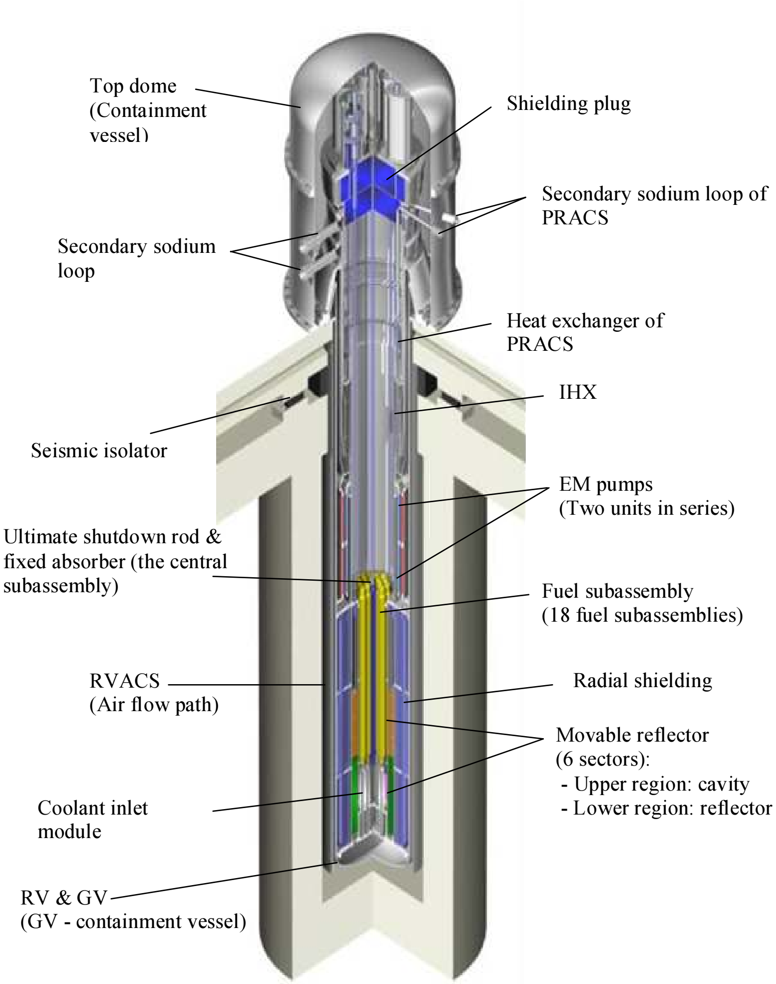

FIG. 5. General view of the 4S sodium cooled reactor with a 10 – 30-year refuelling interval for a 50 MW(e) plant (Toshiba – CRIEPI, Japan)

18. For both fast and thermal neutron spectrum concepts, the fuel discharge burn-up and the irradiation of core structures are not intended to exceed standard practices for conventional or anticipated designs. The refuelling interval is extended by decreasing core specific power; power densities in such designs never significantly exceed 100 kW(th)/litre and often are much lower. To compensate for excess reactivity and burn-up reactivity loss burnable poisons and active control rods are used in thermal systems and fast systems are designed for internal breeding. Although the specific inventories of fissile material (per unit of power and energy produced) are higher than for reactors

with conventional refuelling schedules, some concepts for fast reactors without on-site refuelling are capable of self-sustained operation with a breeding ratio of approximately one. This means that the fissile mass in the core is effectively constant throughout its full extended lifetime, while the amount of fertile material decreases and the amount of fission products grows.

C. Opportunities for SMRs

19. Because SMRs will likely continue to have higher specific costs than large nuclear power plants that benefit from economies of scale, prospects for innovative SMRs depend on their ability to serve several categories of users whose needs are not met by larger plants, such as:

- countries with small and medium sized electricity grids or limited energy demand growth;
- villages, towns and energy intensive industrial sites that are remote from existing grids;
- rapidly growing cities in developing countries with limited investment capability; and
- future merchant plants in liberalized electricity markets, in both developed and developing countries, that might value the reduced investment risk associated with incremental small capacity additions.

20. The first category includes users in small and medium sized countries where overall targeted energy production is limited, as well as countries with large territories but relatively small and sparse populations.

21. The second category includes the many areas in the world with remote centres of power consumption unsupportable by electricity grids [4]. Some island countries face a particular challenge in delivering electricity to widely dispersed population centres on scattered islands separated by miles of ocean [5]. Some continental countries include hinterlands with low population densities where grid extension may be not cost effective, or where the cooling water necessary for large plants may be in short supply. The location of many remote settlements is dictated by the location of the natural resources on which they depend, for example, for mining, drilling, logging, fishing, etc. Such remote demand centres may not have sufficient demand for a large nuclear power plant, but may find an SMR cheaper than particularly non-nuclear alternatives with high fuel delivery costs.

22. The third category is expected to grow, particularly if economic growth in developing countries accelerates in the coming decades [7]. Growing populations, plus increasing urbanization and growing per capita energy use driven by development, may create a market for SMRs because of limited grids in many countries and limited investment capabilities. By 2015, more than 370 cities in Asia, Africa, and Latin America are expected to have more than one million people each; collectively, these cities would account for 1.5–2 billion people. To accommodate rapid demand growth where initial grids and financing are limited, a 'just-in-time' capacity growth plan might be appropriate, with incremental capacity additions as the population grows, as per capita energy use increases, and as a city becomes wealthier. SMRs could meet the needs of these emerging energy markets where the industrial and technical infrastructure is generally poor, if they are designed to be easily expandable into clusters comprising ever-larger power installations.

23. The fourth category anticipates future situations in which incremental SMR additions matched to demand growth might be attractive to utilities operating in deregulated competitive markets. In these situations, the lower investment risk and shorter payback period associated with SMRs may outweigh their higher capital cost per kilowatt. These advantages may become even more important if nuclear energy broadly enters non-electric markets for seawater desalination, district heating, low temperature process heat, and high temperature here for, among others things, thermochemical hydrogen production.

24. Prospects for SMRs also depend partly on how well various SMR designs complement the future evolution of large nuclear power plants. Well over a third of current innovative SMR concepts are fast spectrum nuclear reactors that can achieve high conversion or self-sustainable operation with breeding ratio slightly greater than one [1, 2]. Several medium sized concepts go even higher, to breeding ratios of 1.1–1.3. This raises the possibility of breeding fissile materials to feed thermal-spectrum reactors and SMRs fitting well in any transition, at a global or national level, from a once-through to a closed nuclear fuel cycle.

25. Prospects for SMRs may also depend on the future of current initiatives to limit the global spread of sensitive fuel cycle facilities without constraining the expansion of nuclear power in interested countries [10]. SMRs with long refuelling intervals that are designed specifically to outsource front-end and back-end fuel cycle services, and SMRs without on-site refuelling, could contribute to any of the institutional approaches currently proposed. Some proposals are designed specifically to lessen the risks associated with dependence on outsourced suppliers in a world with continuing political tensions and conflicts between countries (although long refuelling intervals are, in themselves, one way to increase supply security for those outsourcing front-end and back-end fuel cycle services). Such proposals would thus benefit SMR designs that imply a greater dependence on outsourcing. To the extent SMR designs, particularly those without on-site refuelling, are considered more proliferation resistant than alternatives, they will benefit from any incentives developed to favour more proliferation resistant designs. Factory fabricated and fuelled reactors may also be judged more environmentally clean, simple, safe and secure simply because the reactor is effectively a long-life ‘battery’, welded shut and requiring no nuclear fuel handling during its whole operational life at the site.

26. Potential customers in developing countries are often interested in possibilities for local participation and gradual technology transfer. Nuclear power plants are viewed not only as energy sources but also as vehicles for overall national economic development. Design features responsive to such interests could also contribute to better plant economics, e.g., if certain parts are built to local standards by local firms using local labour and financed in the local currency. However several developing countries, such as Argentina, India and Republic of Korea, are potential sellers of SMRs, with sufficiently mature nuclear industries to offer domestically designed and produced SMRs in the very near term.

D. Challenges for SMRs

27. Figure 6 summarizes the challenges facing SMR development to the extent that some SMR designs may compete directly with large reactors, which benefit from economies of scale. The curve shows schematically the economies of scale (Item 1 in the figure): the greater the size, the lower the specific costs. Items 2-6 summarize factors in SMR design that might contribute to closing the gap between SMRs and large reactors. Although most SMR designs are not intended to compete with large

reactors, but with other alternatives in markets for which large reactors are unsuitable, Items 2-6 in Figure 6 still provide a useful conceptual summary of the approaches described above to reduce costs, independent of the intended competition.

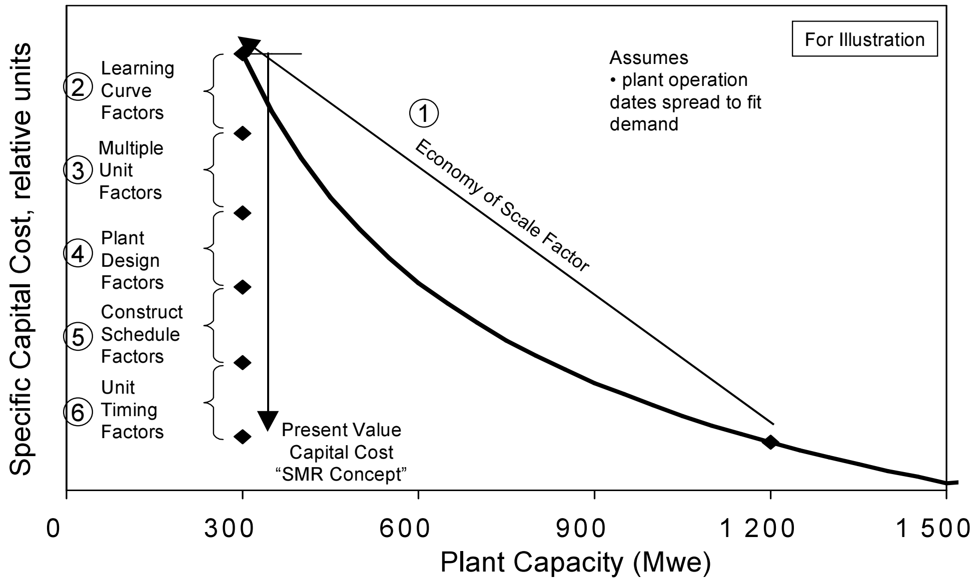

FIG. 6. A generic scheme illustrating potential SMR economic factor advantages (courtesy of Westinghouse, USA).

28. In addition to cost reduction challenges, SMR designs face a number of licensing challenges. Many SMR concepts incorporate design approaches and system configurations that do not have proven operating records in the civilian nuclear power sector. Because many innovative SMRs are not water cooled, licensing approaches focussed on current light water reactors may need adjustments toward a more technology-neutral risk-informed approach [1, 2]. And some innovative SMR concepts rely on passive systems, the reliability of which needs to be proven to enable risk-informed qualification and licensing.

29. In addition, many potential applications of SMRs may require them to be located close to customers. Thus an important goal for many SMR designers is a reduction or elimination of a plant's emergency planning zone. This would, again, require a departure from conventional licensing requirements established for LWRs. Examples of such situations include the following.

- In industrial cogeneration applications, such as hydrogen production, SMRs would need to be located near industrial sites if they are to provide process heat.
- SMRs might be sited close to cities that they power in regions where only local electricity grids exist.
- SMRs that produce products such as potable water and district heat, which cannot be transported long distances, would need to be sited near their customers.

30. Moreover, co-locating a nuclear plant and a chemical plant on a single site would also require new safety rules and regulations to be applied to both.

31. For small reactors with long core lifetimes and no on-site refuelling, operating experience for such long refuelling intervals is generally unavailable for civilian nuclear power [1], although experience with small marine reactors confirms the possibility of 7-8 years of continuous operation.

32. Finally, some innovative designs may need validation through testing on prototype reactors, also a lengthy process, to enable series production of a standardized plant.

33. As SMR designs move forward, and as discussions between possible customers, vendors, governments and regulators continue, the development of common criteria for assessing the suitability of different SMRs in different situations would be useful. Such criteria could be developed using examples of national analyses of the needs for SMRs in member states where the experience with SMRs is positive. They should incorporate all cost components (hardware and services) that are influenced by localization or optimum outsourcing. The criteria could also reflect customer demands for vendor support services (such as licensing issues for innovative NPPs) where there is limited operating experience, operational reliability issues for novel equipment, training of domestic operational personnel, use of local sub-contractors, and other relevant factors.

E. Progress towards deployment

34. For about a dozen innovative SMR designs, current progress in developing the technology and finalizing the design suggests possible deployment within the next decade [1, 2]. Construction began in April 2007 in the Russian Federation on a pilot floating cogeneration plant of 400 MW(th)/70 MW(e) with two water cooled KLT-40S reactors. Deployment is scheduled for 2010. In July 2006, the Russian Federation and Kazakhstan created a joint venture to complete design development for a 300 MW(e) VBER-300 reactor (basically a scaled-up version of the KLT-40S) for use in either floating or land-based co-generation plants. They also agreed to promote nuclear power plants using such reactors in both domestic markets and on the global market. Three integral PWR designs are in advanced design stages and commercialization could start around 2015: the 335 MW(e) IRIS design developed by International consortium led by Westinghouse, USA; the 330 MW(e) SMART design developed in the Republic of Korea; and the prototype 27 MW(e) CAREM developed in Argentina, for which construction in scheduled to be complete by 2011. The 165 MW(e) PBMR, developed in South Africa, is scheduled for demonstration at full size by 2012. Additional designs from France, India, Japan and the Russian Federation may also be demonstrated and proven on similar timescales, thus providing several potential choices to interested countries in the intermediate term. In India, licensing and construction activities are scheduled to start in 2008 for an advanced heavy water reactor (AHWR) designed to co-generate 300 MW(e) and 500 m^3/day of potable water. The AHWR is also designed to eventually accommodate Pu-Th and ^{233}U-Th fuel.

35. In contrast, only a few small reactors without on-site refuelling might be ready for deployment within the next ten years. The only concept that has reached the detailed design stage is the Russian 101.5 MW(e) lead-bismuth cooled SVBR-75/100 with a refuelling interval of 6-9 years. This design benefits from 80 reactor-years of operating experience with reactors of this type in the Russian submarine fleet and is relatively flexible in terms of both applications and fuel cycle options. Russia's

Federal Agency for Atomic Energy (Rosatom) is supporting further development for deployment in 2014. The Russian Federation could also develop within a few years, if requested by potential customers, the VBER-150 and KLT-20, which are smaller versions of the KT-40S and VBER-300 respectively, with refuelling intervals of 6 and 8 years. The ABV integral water cooled design is at the basic design stage; it is an 11 MW(e) reactor suitable for a floating nuclear power plant, with a refuelling interval of 8 years.

36. In Japan, the Toshiba Corporation, in cooperation with the Central Research Institute of Electric Power Industry (CRIEPI) and several other organizations, is developing the 4S sodium cooled reactor. It has a design power of 10-50 MW(e), a refuelling interval of 30 years, and a design that allows the power to be controlled by adjusting the feedwater flow rate in the steam-turbine circuit. The conceptual design and major parts of the system design have been completed. A pre-application review by the US NRC is anticipated in the near future. Construction of a demonstration reactor and safety tests are planned for early next decade.

F. Conclusion

37. Of the world's 442 operating nuclear power plants, 28 are small, 111 are medium sized and 303 are large. Of the 31 reactors under construction seven are small, four are medium sized and 20 are large. In the near term, most new nuclear power reactors are likely to be evolutionary large units. But particularly in the event of a shift towards the increasing use of nuclear power in national energy mixes, the nuclear industry can expect an increasing diversity of customers, and thus an increasing number of customers with needs potentially best met by one or more of the innovative SMR designs now under development.

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