PRELIMINARY NUCLEAR POWER REACTOR TECHNOLOGY QUALITATIVE ASSESSMENT FOR MALAYSIA

Shamsul Amri Sulaiman[a]

[a]*Senior Engineer, Tenaga Nasional Berhad (TNB), Malaysia*

Nuclear Energy Unit, Tenaga Nasional Berhad (TNB),

A-05-02, Block A, PJ8 Building, No. 23, Jalan Barat, Seksyen 8

46050 Petaling Jaya, Selangor D.E., Malaysia. shamsulamri@tnb.com.my

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ABSTRACT

Since the world's first nuclear reactor major breakthrough in December 02, 1942, the nuclear power industry has undergone tremendous development and evolution for more than half a century. After surpassing moratorium of nuclear power plant construction caused by catastrophic accidents at Three-Mile Island (1979) and Chernobyl (1986), today, nuclear energy is back on the policy agendas of many states, both developed and developing nations, signaling nuclear revival or nuclear renaissance. Selection of suitable nuclear power technology has thus been subjected to primary attention. This short paper attempts to draw preliminary technology assessment for the first nuclear power reactor technology for Malaysia. Methodology employed is qualitative analysis collating recent finding of TNB-KEPCO Preliminary Feasibility Study for Nuclear Power Program in Peninsular Malaysia and other published presentations and/or papers by multiple experts. The results suggested that the pressurized water reactor (PWR) is the prevailing technology in terms of numbers and plant performances, and while the commercialization of Gen IV reactors is remote (e.g. not until 2030), Generation III/III+ NPP models are commercially available on the market today. Five (5) major steps involved in reactor technology selection were introduced with a focus on introducing important aspects of selection criteria. Three (3) categories for the of reactor technology selection were used for the cursory evaluation. The outcome of these analyses shall constitute deeper and full review analyses of the recommended reactor technologies for the intended full feasibility study in the near future. Recommendations for reactor technology option were also provided for both strategic and technical recommendations. The paper shall also postulate or rather implore what could be the best way for Malaysian and also other aspiring new entrant nations to select systematically their first civilian nuclear power reactor.

ABSTRAK

Sejak penerobosan utama reaktor nuklear pertama dunia pada Disember 02, 1942, industri tenaga nuklear telah mengalami pembangunan hebat dan evolusi untuk lebih daripada separuh abad. Selepas mengatasi moratorium pembinaan loji kuasa nuklear disebabkan oleh kemalangan-kemalangan membawa bencana di Island Three Mile (1979) dan Chernobyl (1986), hari ini, tenaga nuklear kembali ke agenda dasar banyak negeri, kedua-dua negara maju dan negara membangun, memberi isyarat pemulihan nuklear atau kelahiran semula nuklear. Pemilihan teknologi kuasa nuklear sesuai mempunyai maka pernah bawah perhatian utama. Akhbar ringkas ini cuba untuk menarik penilaian teknologi awal untuk teknologi reaktor kuasa nuklear pertama itu untuk Malaysia. Kaedah berpekerjaan ialah analisis kualitatif mengumpul penemuan baru-baru ini Preliminary Feasibility Study for Nuclear Power Program TNB KEPCO di Semenanjung Malaysia dan persembahan-persembahan bercetak lain dan / atau kertas-kertas oleh pakar-pakar berbilang. Keputusan-keputusan mencadangkan yang reaktor air tekan (PWR) ialah teknologi lazim dari segi nombor dan menanam persembahan , dan manakala pengkomersialan reaktor GEN IV jauh (contohnya bukan sehingga 2030), Generasi III / model-model III+ NPP secara komersial boleh didapati pada pasaran hari ini. Lima (5) langkah-langkah utama melibatkan dalam pemilihan teknologi reaktor telah diperkenalkan dengan satu tumpuan pada memperkenalkan aspek-aspek penting kriteria pemilihan. Tiga (3) kategori-kategori untuk pemilihan teknologi reaktor digunakan untuk penilaian sepintas lalu. Hasil analisis ini akan membentuk kajian semula penuh dan lebih dalam menganalisis teknologi-teknologi reaktor dicadangkan untuk kajian kebolehlaksanaan penuh bakal dalam masa terdekat. Cadangan-cadangan untuk pilihan teknologi reaktor juga disediakan untuk kedua-dua cadangan-cadangan strategik dan teknikal. Kertas juga akan mempostulatkan atau agak merayu apa mungkin jalan terbaik terhadap rakyat Malaysia dan juga negara-negara kemasukan baru bercita-cita lain memilih secara sistematik reaktor kuasa nuklear orang awam pertama mereka.

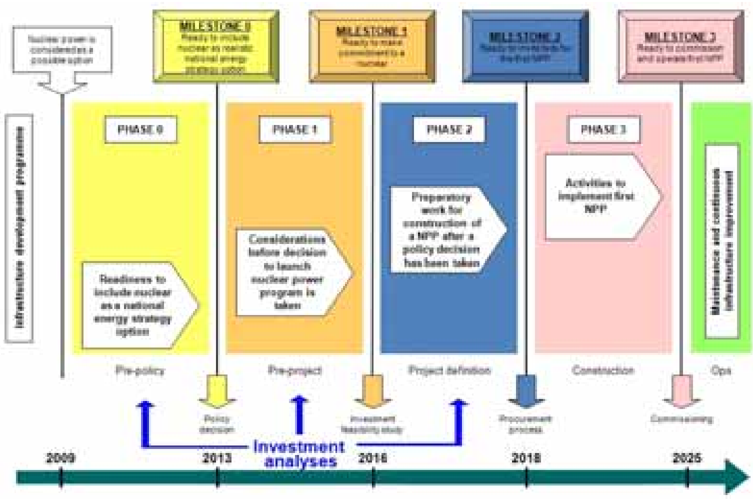
Keywords: reactor technology selection, screening criteria, candidate reactor technologies

INTRODUCTION

Developing a nuclear energy program is a complex and lengthy process; usually 10-15 years are required, involving many interrelated activities [1]. These activities involve planning, preparation and investment to build sustainable infrastructures to provide legal, regulatory, technological, human resources and industrial support. It is known that the effort required for building nuclear power infrastructures may vary significantly among countries, depending on their existing infrastructure. Special measures are necessary to ensure that the nuclear program is used exclusively for peaceful purposes, in a safe and secure manner.

Malaysia has never had a nuclear power plant (NPP). Malaysia experience with nuclear energy is primarily with a small Triga Mark-II 1.0 MWt research reactor commissioned in 1982. The present initiative of Tenaga Nasional Berhad (TNB) nuclear power planning and preparatory activities is the 3rd attempt of convincing the Government on the need to embark on a nuclear power program [2]. The ultimate objective is to be well-prepared and be ready to carry all necessary tasks leading to the eventual transmission of nuclear generated electricity to TNB power grid.

In light of this, TNB has embarked on its systematic program to produce nuclear energy for electricity generation in Malaysia by establishment of Nuclear Energy Unit (NEU) in June 2008 for planning and preparatory activities of nuclear power project. TNB NEU is also responsible for being a single-stop centre to coordinate with TNB internal Departments and collaborate with other external parties (international and domestic) on nuclear related matters [3]. Together with a cross-divisional, multi-disciplinary Nuclear Pre-Project team, TNB NEU has been actively pursuing multiple preparatory activities. The first major task of TNB NEU was engagement with CRA International to prepare a White Paper on Nuclear Roadmap for Malaysia. This 2nd White Paper complemented the 1st White Paper prepared by TNB Planning Division, in collaboration with CRA International on TNB's way forward with respect to future energy scenarios and requirements [4]. The 2nd White Paper primary outcome was a nuclear roadmap for activities to be carried by TNB, taking into account IAEA recommended nuclear power planning phases and milestones (stepwise approach), experiences and lessons from some selected countries, as well as planned activities to be conducted by Atomic Energy Licensing Board (AELB), Malaysia Nuclear Agency (Nuclear Malaysia) and TNB (Figure 1-1) [5]. The study was completed in February 2009.



Source: CRA, 2009

Fig.1. Nuclear Roadmap for Malaysia

The Consultancy Agreement for *Preliminary Feasibility Study of Nuclear Power Program in Peninsular Malaysia* ("Pre-FS") between TNB of Malaysia and Korea Electric Power

Corporation (KEPCO) of Korea in June 2009 based on the earlier memorandum of understanding (MoU) between the (KEPCO) of the Republic of Korea and the TNB of Malaysia which was signed on March 2008. KEPCO team (KEPCO, KOPEC, KHNP, Doosan, Hyosung and KNF) and TNB team (TNB, TNB Research, Nuclear Malaysia, and AELB) jointly implemented the Pre-FS for twelve (12) months, from July 2009 to June 2010. Topic of Reactor Technology Options was one of the central parts of the study [6].

METHODOLOGY

General Overview

The nuclear power industry has been developing constantly for more than five (5) decades as evidenced by the production of improved reactor design and technology. These days, the industry is undergoing nuclear renaissance or renewed interest in the construction of new build for the next generation of nuclear power reactors, with particular emphasis is given to Generation III /III+ advanced reactors (Figure 2.1-1).

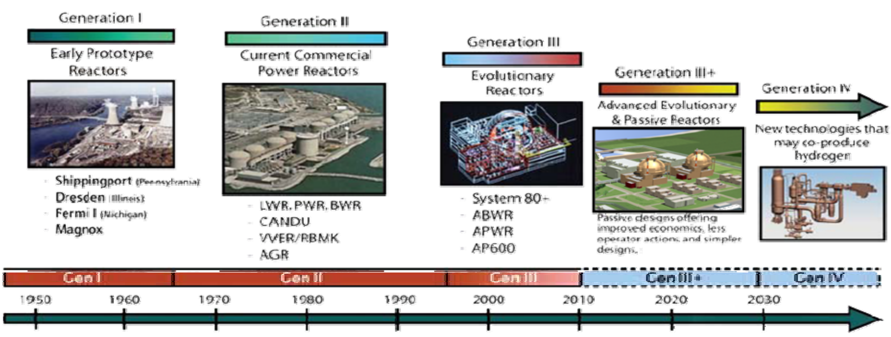


Fig.2. Evolution of nuclear reactors

The Generation III/III+ reactors in which many designs incorporate passive or inherent safety features, i.e. require no active controls or operational intervention to avoid accidents in the event of malfunction, and may rely on gravity, natural convection or resistance to high temperatures, are under serious attention and central target for many nations as candidates for their new build (Table 2.1-1).

Table 1: Generation III/III+ Thermal Reactors Available in the Market

Country (Developer)	Reactor Type	Size (MWe)	Status	Key Features (Improved Safety in All)
US-Japan (GE-Hitachi, Toshiba)	ABWR	1,300	Commercial operation in Japan since 1996-7. In US: NRC certified 1997, FOAKE.	▪ Evolutionary design. ▪ More efficient, less waste. ▪ Simplified construction (48 months) and operation.
USA (WH)	AP-600 AP-1000 (PWR)	600 1,100	AP-600: NRC certified 1999, FOAKE. AP-1000 NRC certification 2005, first units being built in China, many more planned	▪ Simplified construction and operation. ▪ 3 years to build. ▪ 60-year plant life.
France-Germany (Areva NP)	EPR US-EPR (PWR)	1,600	French design approval. Being built in Finland and France, planned for China. US version developed.	▪ Evolutionary design. ▪ High fuel efficiency. ▪ Flexible operation.
USA (GE-Hitachi)	ESBWR	1,550	Developed from ABWR, under certification in USA, likely construction there.	▪ Evolutionary design. ▪ Short construction time.
Japan (utilities, Mitsubishi)	APWR US-APWR EU-APWR	1,530 1,700 1,700	Basic design in progress, planned for Tsuruga US DC application 2008.	▪ Hybrid safety features. ▪ Simplified Construction and operation.
Korea (KEPCO)	APR-1400 (PWR)	1,450	Design certification 2002, First units expected to be operating in 2013.	▪ Evolutionary design. ▪ Increased reliability. ▪ Simplified construction and operation.
Russia (Gidropress)	VVER-1200 (PWR)	1,200	Replacement under construction for Leningrad and Novovoronezh plants	▪ Evolutionary design. ▪ High fuel efficiency. ▪ 50-year plant life
Canada (AECL)	CANDU-6 CANDU-9	750 925+	Enhanced model Licensing approval 1997	▪ Evolutionary design. ▪ Flexible fuel requirements. ▪ C-9: Single stand-

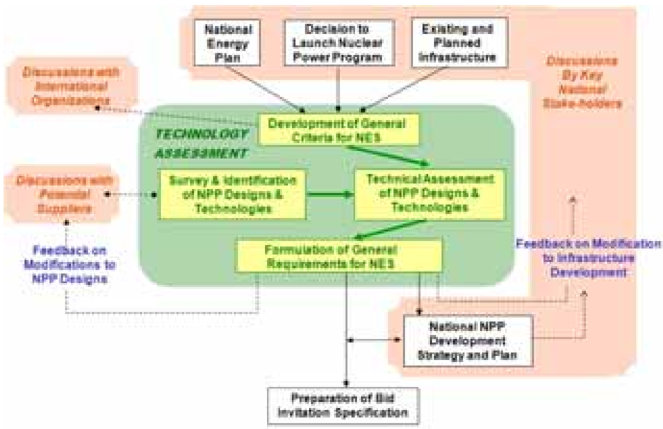
Country (Developer)	Reactor Type	Size (MWe)	Status	Key Features (Improved Safety in All)
				alone unit.
Canada (AECL)	ACR	700 1,000	Undergoing certification in Canada	▪ Evolutionary design. ▪ Light water cooling. ▪ Low-enriched fuel.
South Africa (Eskom, WH)	PBMR	170 (module)	Prototype due to start building (Chinese 200 MWe counterpart under const.)	▪ Modular plant, low cost. ▪ High fuel efficiency. ▪ Direct cycle gas turbine.
USA-Russia et. Al. (GA- OKBM)	GT-MHR	285 (module)	Under development in Russia by multinational joint venture	▪ Modular plant, low cost. ▪ High fuel efficiency. ▪ Direct cycle gas turbine.

General Considerations

The technology assessment for the implementation of nuclear power plants (NPPs) is a part of Nuclear Energy System (NES) development (which include NPP designs and associated fuel-cycle and supporting technologies) **based on the national energy plan and existing and planned national infrastructure (Figure 2.2-1).** In broad terms, technology assessment is defined as an exercise conducted by a country to determine, which NPP designs and associated NES technologies may meet the needs and requirements of the country [7] [8].

Ideally, technology assessment activity should start prior to the decision to embark on a nuclear power program is made and the activity continues during the planning and preparatory phases, i.e. pre-project award activities together with other activities such assessment of national capabilities and the definition of the degree of national participation in the nuclear power program, identification of appropriate sites for the NPP, establishment of a fuel cycle policy, formulation of national NES deployment strategy and plan, and selection of NPP designs and associated NES technology including preparation of bid documents and bid evaluation. The next step is survey and identification of potential NPP designs and associated NES technologies that are commercially being marketed and may potentially meet the General Criteria. Then the assessment of the selected NPP designs against the General Criteria will be carried out and finally the expansion of the General Criteria with additional details and its formulation into the General Requirements for NES. All of these activities are closely related and cross-functional to each other in which they may result in high likelihood of establishing conflicts among the important national stakeholders. Creation of well-balanced selection criteria is of paramount importance in compromising the conflicts among the stakeholders. The cursory evaluation of reactor selection presented here is not intended to develop the entire selection criteria to be used for actual and detailed comparison of reactor technologies which would be under the scope of one of primary pre-project award activities, i.e. full feasibility study ("Full FS") to be carried out by developer of NPP, however, only the primary technical aspects in establishing the selection criteria with their significances are briefly discussed.

A sound strategy and plan to produce a set of comprehensive, unequivocal selection criteria to distinguish variations of design characteristics with regards to safety, performance, functions and purposes of reactor technologies is necessary to be harnessed for variety of power generation capacities ranging from a few MWt to 1700 MWe. Among those characteristics, the initial decision that requires immediate attention is selection of a type of fuel and its associated reactor technology to use (which of course tied-in with national nuclear fuel cycle policy). This decision making can be accomplished through a systematic comparative study among the available reactor and fuel cycle technologies. In general, the major steps outlining reactor technology selection are divided into two (2) stages; namely pre-bid and bid activities (Figure 2.2-2).



Source: IAEA, 2009

Fig.3. Typical process of selecting reactor technology

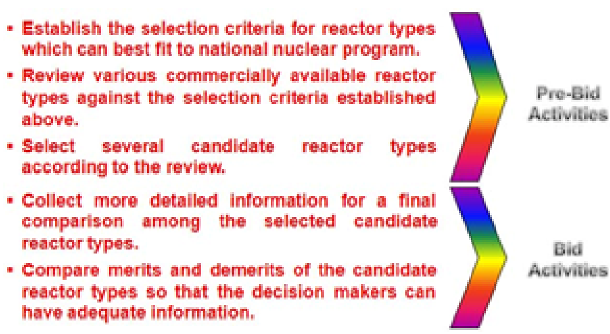


Fig.4. Five (5) steps of reactor technology selection

Establishment of Selection Criteria

The key objective for the selection criteria establishment is to systematically choose the candidate reactor types for a detailed comparison considering both technical and commercial aspects. Therefore, a formation of a group of national experts from multiple backgrounds is necessary for the establishment of the selection criteria since many aspects of the selection criteria are interrelated and may influence others. It is reasonable that aspects such as national strategic, socio-economical, or infrastructural importance are given higher weighting factors than others. Nevertheless, careful attention is necessary for the distribution of weighting factors to avoid some aspects to become more dominant than other aspects which are also critical in the reactor technology selection. In this study, the reactor evaluation is based on three (3) categories; namely (1) national strategic or top-tier decision making aspects, (2) intermediate or techno-economic aspects and (3) detailed technical aspects (Figure 2.3-1). The 1st aspect deals with reactor type selection (including size) which having strong influence on the national plans and/or strategies. The 2nd aspect provides generic evidences which provide acceptability of a certain type of reactor in both technical and commercial viewpoints. The 3rd aspect includes in-depth technical information focusing on the design characteristics. The prime focus of this evaluation is on the technical side on the available Generation II/III+ reactors (Table 2.1-1) by comparing merits and demerits and finally cost-benefit analysis which is partially involved with the commercial or economic analyses.

National Strategic or Top-Tier Decision Making Aspects

The Purpose of NPP

The selection of reactor type varies depending on the objective of NPP construction in Malaysia, e.g. water desalination or electricity generation. Economy-of-scale is one of the most important factors to be considered should the reactor is meant to be utilized as electricity generation and small reactor options may deem to be unsuitable.

National Energy Development Plan and Infrastructure (Plant Power Rating)

Depending on the economic circumstances in the country, should the demand of electricity require grow rapidly, the higher capacity NPPs are the preferred option. Economically, economy-of-scale favors the selection of the highest electrical output (MW), i.e. larger unit size translates to lower engineering, procurement and construction (EPC) or investment cost ($/kW), partly due various mandatory and costly activities, e.g. licensing, infrastructure development and human resources, which are practically independent from the size. In more advanced nations which embark new NPP construction, e.g. Finland, relatively larger units are adopted to take advantage of economy-of-scale. Nevertheless, due consideration must be given for the electrical grid augmentation and reinforcement particularly for new entrant nations to maintain performance and quality as a consequence of integration of such a large unit of NPP.

Fig.5. Reactor evaluation categories

In large number of countries (excluding France), NPP is designed to operate efficiently as base load generation without load following capabilities. Transients operation of NPP should not jeopardize the grid stability. A rule of thumb is no single NPP unit should take into account for more than 10% of the installed capacity of the entire grid network to avoid any stability failure [9] or maximum 5% of peak demand [10]. Therefore, a comprehensive system study and grid stability analysis is thus required to determine the maximum plant power rating to be installed.

National Natural Resource Utilization Strategy

In the event Malaysia is blessed with significant reasonably assured resources of natural uranium or thorium that can be exploited commercially together with utilization of back end fuel cycle technology, i.e. spent fuel reprocessing as part nuclear fuel policy or strategy, the adoption of pressurized heavy water reactor (PHWR) or CANDU, graphite moderated reactor technology or molten salt cooled reactor technology needs a considerable attention than others. Nevertheless, should Malaysia wish to avoid any unnecessary concern on proliferation or safeguards related issues, particularly with activities in the nuclear fuel cycle that are associated with sensitive technologies such as fuel enrichment and spent fuel reprocessing, the selection for the reactor technology is wide open (including reactor technologies that utilize enriched fuel to all currently available in the international market).

Technology Self-Reliance Strategy

Should Malaysia inspire to be a technology self-reliance nation, the strategy to select the nuclear vendor which offers the best package of technology transfer program using the most advanced and proven Generation II/III+ reactor is a top priority. It is prudent for Malaysia to have at least partial technology self-reliance program in its quest to become a high-income country. Through wealth-creating initiatives, nuclear could create the competitive leap forward by creating demand for high-skilled knowledge workers with high safety culture, strong integrity and full of discipline which may result a stronger stance of Malaysia in the eyes of the world industry. It is also anticipated that the introduction of this cutting-edge technology shall also spur spin-off technologies in various industries and thus resulting in green growth and thus qualifies the country as a future green economy. The success story of Korea nuclear industry can be a good reference for Malaysia policy maker towards Malaysia version of technology self-reliance program.

Intermediate or Techno-Economics Aspects

Plant Economics

Several key technical aspects with high potential to affect overall plant economics such as radioactive waste management and decommissioning issues need to be given serious consideration in the Full FS. Care must be taken to say that certain reactor technologies which produce less waste per unit electricity generation are superior to others (Table 2.3-1).

Table 2: Waste classification in relation to reactor technology

Waste Classification	Remark
Low Level Waste (LLW)	Amount is not directly related to reactor technology. The amount may be strongly influenced by the health physics procedures a NPP adopts and the maintenance procedures.
Intermediate Level Waste (ILW)	Amount depends strongly on the radioactive waste management system (RMS) design. It may indicate RMS performance but it is not a direct indication to be used for the superiority comparison of different reactor technologies.
High Level Waste (HLW)	Amount depends primarily on the reactor technology and electrical output of a NPP, i.e. almost similar within PWR but differs between different reactor types. For instance, a CANDU reactor produces a lot more HLW than most PWRs since CANDU is fuelled by natural uranium. However, one has consider merits and demerits of using natural uranium fuel prior to make any statement that CANDU technology is less superior to other reactor types.

Note that spent fuel which requires special storage facilities is a valuable energy resource (the actual usage of ^{235}U of the present LWR technology is 0.6% [11]) which could be reprocessed to make MOX for future reactors generation, particularly to those operated under fast neutron spectrum.

All reactors are designed for commissioning and operation. Therefore, the ease of decommissioning shall not be a prime factor to be considered in reactor technology selection since no reactor is designed for decommissioning.. Nevertheless, it is noteworthy to know the ranges of decommissioning cost of different reactor type (Table 2.3-2). Generally, nuclear vendors these days have taken into account the ease of decommissioning in their latest Generation III/III+ designs.

Table 3: Decommissioning cost for different reactor types

Reactor Type	Decommissioning Cost (US$/kWe)
Western PWR	200-500
VVER (Russian PWR)	$330
BWR	300-550
CANDU	270-430
GCR	2600

Source: OECD, 2003

Generic Safety

It is prudent to exclude those reactor types with previous accident history (unless significant efforts to mitigate the causes of the accidents) and those which are not complying with international standards of safety requirements. Typical safety measurements include core damage frequency (CDF) and containment failure frequency (CFF) values which are computed using probabilistic safety assessment (PSA). Advanced Light Water Reactor Utility Requirement Documents (ALWR URD) specifies the design goal for CDF and CFF to be less than 10^{-5}/reactor-year and 10^{-6}/reactor-year, respectively.

Licensability

In the Pre-FS, the recommended licensing principles are:

- In accordance to IAEA guidance, even if a similar NPP design has been authorized in another country, the national regulatory body should still perform its own independent review and assessment.

- It may take into account the review and assessment made in other country, and also new experience and knowledge that have been gained since that review and assessment.
- The owner/operator (licensee) is responsible for the licensing. Depending on contractual approach, the supplier may be responsible for the licensability.

The first point stresses that for a NPP to be constructed in Malaysia, it should be licensable in accordance to the Malaysian rules and regulations that need to be established in advance. It is normal for those new entrants that have less established rules and regulations to adopt those of vendor country for licensing purposes or IAEA's safety guides. Therefore, since licensability is one of the important factors to be considered in decision making and it is important for the candidate reactor design to have required level of safety by the rules and regulations in accordance with the most up-to-date safety culture prevailing in the international community, the licensability of a reactor technology may be declared high, intermediate and low by the order of "proven by operation", "evolutionary design" and "revolutionary design".

Proven Technology

Proven technology of NPP can be substantiated by several years of commercial operation of similar NPP complete with good operational records, full or part scale testing facilities, and also by several years of operation in other applicable industries such as conventional power plant and process industries. Proven technology increases the level of confidence that the design will not require major modifications prior to or during construction and the overall NPP systems will function as designed. However, too stringent requirements for proven technology may lead to adoption of obsolete design and theoretically, new advanced design should be the improved version of its predecessor.

Standardization

At present, utilities and vendors are in consensus to adopt plant standardization as compared with customized designs used by Generation II reactors in the past. Most reactor vendors have developed a standard plant design. Advantages of plant standardization are as follows:

- Early definition of requirements ensures regulatory stability and eliminates unnecessary changes.
- Design optimization into improve constructability, operability and maintainability.
- More simple and uniform designs easier to construct and operate.
- Maximize experience feedback from units in each family of standard plants.
- Standard plants designed to comply with an envelope of site conditions:
  - Plant design will be transferable without major changes, to any site with design conditions within the envelope of design parameters.

- Design drawings identical except for changes due to equipment sourcing and site-unique conditions.

However, there are several important issues related to the standardized design:

- Licensability of a standard plant design may not be assured in the countries different from the country of origin where it was certified (as demonstrated by the EPR design which does not satisfy stringent Finland licensing requirements particularly matters related to severe accidents even though EPR design is believed to meet requirements in the EUR documents), and
- Construction in different sites may breach the standardized design
  - Minimizing changes to the standard plant design minimizes costs to the investor and facilitates licensing

Site Considerations

With regard to site considerations, the concerns are not directly related to the reactor technology with the exception of the power rating in order to provide adequate cooling water requirement and availability of medium for ultimate heat sink (sea, lake, river, and atmosphere). Several other specific siting requirements are generic for many types of reactor and shall not direct influence in the reactor technology selection.

Plant Performance

The performance parameters of reactor technology which have direct relationship with the plant economy and safety such as the plant capacity factor, plant energy availability factors (EAF), unplanned shutdown, and operational can be assessed easily in the world's nuclear data bases provided by IAEA Power Reactor Information System (PRIS), reference data series annual editions of Nuclear Power Reactors in the World, World Nuclear Association, EPRI and/or nuclear magazines, e.g. Nucleonics Week, Nuclear Engineering International, etc. It is prudent review thoroughly all the above parameters during the Full FS.

Constructability

Constructability is closely related to project schedule and the EPRI URD stated that the constructability policy is to achieve a substantially improved construction schedule compared to what was the experience with existing plants.

Technological Monopoly

Technological monopoly is probably the least discussed issue by the reactor vendors simply because the nuclear power technology is in the hand of a few advanced nations and no driving factors and direct benefits for them to discuss about this matter publicly. In case of BWR and CANDU, the reactor technologies are derived from GE-Hitachi and AECL, respectively. As a consequence, the plant owners will depend solely on the monopolized technology owners in getting after services support particularly in the area of operation and maintenance related activities. Technological monopoly is not only limited to BWR and CANDU but it is also applicable to PWR despite having multiple vendors capable of manufacturing and operating PWR. For instance, a recent PWR type NPP developed by Areva is using RCC-M codes which have been developed in reference to the ASME codes but many aspects thereof are unique especially the material specifications in section-2 of RCC-M code. As such, it is hard to find a credible number of component vendors satisfying the specifications and to form a competitive environment. This is of course will result in more expensive component costs which will affect plant economy in the long run.

DETAIL TECHNICAL ASPECTS

The design characteristics of a reactor technology are rather general which require considerable efforts for evaluation. The IAEA Unit Design Characteristics included in PRIS database [12] combined with the Top-Tier design requirements [13] could form a solid fundamental for the detailed reactor technology evaluation and determination of the selection criteria. The followings are some highlights on essential areas for reactor technologies comparison.

Design Life

Most of present operating NPPs fleet (Generation II) has been designed for 30-40 year operation. Currently, many utilities in advanced nuclear countries have taken a step forward for plant lifetime extension (20 more years) and power up-rate. For instance, in the US, 59 license renewals approved by NRC to operate for an additional 20 years and 20 license renewal applications in US NRC review [11]. Since 1977, 5,726 MWe have been added to existing fleet through power up-rate activities and additional 1,145 MWe applications have been submitted [11].

Particular attention needs to be given to design life of expensive major equipment and components such as reactor pressure vessel, reactor coolant piping, reactor coolant pump (primary heat transport pump in case of CANDU), steam generators, turbine generators, and containment building, etc. For PWR, steam generators are the most expensive equipment which normally being replaced after 30 years base-load operation (or 20 years for load following plant [14]) whereas the reactor pressure vessel is designed for 60 years. In CANDU reactors, replacement of pressure tubes is necessary after 30 year operation [15]. It is also prudent to check whether the candidate reactor technology has sufficiently long design life of expensive instruments such as ex-core neutron flux monitoring instruments and in-core instrumentations that are necessary to be replaced during the plant life.

Seismic Design Conditions

As stated in 10 CFR 50 Appendix S of US NRC Regulation, portions of plant systems and equipment performing and/or important to perform safety function and those to support safety systems and equipment are designed to withstand a certain seismic design condition such as the operating basis earthquake ground motion (OBE) and safe-shutdown earthquake ground motion (SSE). Therefore, it is wise to check seismic design conditions of all reactor technologies. Typical Generation III/III+ peak ground acceleration (PGA) value for SSE is 0.3g.

Performance Warranty

It is extremely important to examine at which conditions the design capacity is warranted. For instance, if a certain reactor technology has a rated capacity of 1100 MWe at the beginning of plant life, e.g. clean core (without cruds generated in the primary loop) and no steam generator tube plugging condition; in which both events may trigger the increase of flow resistance in the primary loop thereby reducing the mass flow rate and the plant performance, the plant performance will be significantly degraded by the end of plant life (i.e. 60 years after the commercial operation). It is clear that the bigger steam generator plugging margin implies more room for the steam generator to reach the warranted condition.

Refueling Cycle

Typical refueling cycle interval for LWR is between 12 to 24 months (normally 18 months). The longer refueling cycle may be achieved by using the higher enrichment fuel thereby resulting in the higher fuel cost. For PWR, the duration of the refueling outage is in between 15 to 40 days depending on the relevant design and the outage management strategy. Longer refueling cycle interval means high likelihood of better plant availability and capacity factor. In fact, the refueling cycle interval is one of the primary factors that affect plant economy and the longer refueling cycle is being pursued.

Thermal Efficiency

In the nutshell, higher thermal efficiency translated to better plant economy. At present, thermal efficiency of the LWR is thermodynamically limited in between 33% to 37% [16] due to the low pressure and temperature of the steam produced to drive turbine generator in the Rankine cycle. In contrast, state-of-the-art coal power plant with reheat cycles can reach 47% thermal efficiency and latest combined cycle gas turbine plants can attain up to 60% thermal efficiency.

Simplicity

Great understanding of design concept of all reactor technology including their detail designs is a key to evaluate whether a certain reactor technology has reached an acceptable level of simplicity. Primary design considerations for simplification include utilization of minimum number of system and components for the function; reduction of the number of components, site work and cost, e.g. less pipes and valves, fewer pumps, less cables, etc.; and also ability to ease construction by design. It was noted that customized designs in the past have somewhat establishing complexity in project implementation. Care also needs to be taken on difficulty to have access on proprietary detail design information which may mislead simplicity evaluation. Claim of some vendors that their design is simplified by reducing some number (or percentage) of components as compared with their predecessor may provide wrong picture for comparison with different designs from different vendors.

Safety Features

NPP design shall achieve safety excellence via integrated design approach implementation using deterministic analysis framework supplemented by Probabilistic Safety Assessment (PSA) for accident resistance, core damage prevention and mitigation. Accident resistance shall be incorporated into NPP to minimize the frequency and severity of initiating events which could confront safety. EPRI ALWR URD clearly indicates that design simplicity, diverse design margins, prudent selection of materials and water chemistry control, enhanced diagnostic monitoring and negative reactivity coefficients are essential to amplify accident resistance. Buffer for NPP for non-diversion from normal operating conditions to abnormal and/or accident conditions is achieved through design margins. Compliance with stringent regulatory requirements by prudent designs is also served as resistances against various accidents. Core damage prevention incorporates systems and features which furnish high assurance that occurrence of initiating events will not progress to the point leading to core damage. For the core damage prevention, EPRI ALWR URD highlighted the significance of sufficiency of Licensing Design Bases (LDB) analyses meeting regulatory criteria and design features to protect plant owner's investment. Amongst important safety features of NPP's are containment system (CS) and containment spray system (CSS), reactor protection system, emergency core cooling system (ECCS), emergency/auxiliary feedwater supply system, emergency power supply system, main control room heat, ventilation and air conditioning (HVAC) system, engineered safety feature actuation system (ESFAS) and related monitoring and control systems. Careful review of design concept, configuration, functions and modes of operation of all these systems are highly required.

Maneuverability

Power maneuvering capabilities include daily load following, house load operation and rapid reactor power reduction. Daily load following capability is not required for a NPP designed for base load. Daily load following is only required in France where 78% of electricity generation are derived from nuclear power. The house operation is the event of grid failure islanding mode of operation of the electric generation unit. Under this condition, turbine generator produces only auxiliary load which is required to keep electric power plant unit alive and prevents reactor trip. After restoration of grid the unit can be quickly synchronized back & load could be increased. The ability of a nuclear reactor to operate lower than its full power is depending on its time during 18- 24 month refueling cycle and also provision of special control rods which function to reduce power levels throughout the core without reactor shutdown. Therefore, even though the ability on any individual reactor to operate on a sustainable basis at low power decreases significantly as it is moving closer towards its refueling cycle, there is considerable scope for running a fleet of reactors in load-following mode. In the event where the grid stability is a concern, the rapid reactor power reduction capability during a grid anomaly shall be given a higher priority than daily load following capability. All requirements for ALWR maneuvering and non-accident transient response shall be checked during the Full FS evaluation for the reactor technology selection.

Inspection and Testing

It is prudent to review completeness of Inspection, Test and Analysis Acceptance Criteria (ITAAC) document (which is a part of Design Certificate process) furnished by the plant designer in order to ensure a certain reactor design satisfies inspection and test requirements. In conducting review of inspection and testing for a certain reactor technology, it might not be an effective way to review on how each one of the systems, subsystems and components meet relevant requirements. Perhaps examination of which codes and standards applied for the plant design for inspection and testing, e.g. ASME section XI might be better approach in carrying review of inspection and testing activity.

Man-Machine Interface System

Man-Machine Interface System (MMIS) design shall be one of key factors for evaluation of reactor technology selection since NPP is operated by plant personnel. All aspects of plant design which require interfacing with plant personnel shall incorporate human factors considerations. Human factors driven design features shall be applied consistently plant-wide. Amongst top-level requirements for MMIS include:

- Use of modern digital technology, including multiplexing and fiber optics, for monitoring, control, and protection functions.
- Segmentation and separation on safety and protection systems.
- Use of compact, redundant, operator work stations with multiple display and control devices that provide organized, hierarchical access to alarms, displays, and controls.
- Incorporate modern, computer-driven displays to provide enhanced trending information, validated data, and alarm prioritization and supervision, as well as diagrammatic normal, abnormal, and emergency operating procedures with embedded dynamic indication and alarm information.

- Include large, upright, spatially dedicated panels which provide an integrated plant mimic, indicating equipment status, plant parameters, and high level alarms.
- Lighting levels, HVAC, sound levels, colors, etc., shall provide a comfortable, professional atmosphere that enhances operator effectiveness and alertness.
- Local and stand-alone control systems shall be designed in the same rigorous way as the main control stations and will use consistent labeling, nomenclature, etc. Particular attention is to be paid to visibility, color coding, use of mimics, access, lighting, and communication.
- An integrated, plant wide communications system shall be provided for construction and operations.

Operability, Maintainability and Testing

Important aspects for operability, maintainability, and testing of NPP design are as follows:

- Ease of operation shall be achieved through (1) the use of modem digital technology for monitoring, control, and protection functions, (2) a forgiving plant response to upset conditions, (3) design margins, and (4) consideration on the operating environment.
- Experience feedback of O&M problems which exist in current plants.
- Minimize the number of different types of equipment by standardization except for those limited applications where diversification is adopted to protect against common mode failure (CMF).
- Design to facilitate replacement of major components such as steam generators, within design availability limits.
- Equipment design to have minimal, simple maintenance needs, and be designed to facilitate needed maintenance.
- Consideration of the maintenance access, pull and laydown space, and heavy lifts.
- Environmental design to provide satisfactory working conditions, including temperature, dose, ventilation, and illumination.
- Design to facilitate the use of robots addressing arrangements to accommodate movement, access ports, communication, and robot storage and decontamination.
- The surveillance tests shall be designed to measure the systems design basis performance parameters, preferably with the plant at power in order to avoid adding tasks to the planned outage time. Mechanical and electrical systems shall be designed to avoid plant trips, and plant equipment and layout shall be designed to facilitate and simplify surveillance testing. The allowable interval between tasks should be increased where justified. Where surveillance tasks must be performed during an outage, the design should assure that the tests will not be critical path for the outage.
- The protection system and control systems for the engineered safety systems shall be designed so that: (a) the plant can be safely operated indefinitely at full power with one protection channel in test or bypassed (because of failure or other reasons), (b) one subsequent single failure will not cause a plant trip.

- The MMIS shall be such that testing and maintenance is greatly simplified with respect to current plants. For example, self-testing shall be included and the testing automated to the degree practical.

Physical Protection

Amongst primary concerns for physical concerns (but not limited to) are:

- Meteorological, hydrological, geological and seismological characteristics; ,
- Protection against natural phenomena, such as earthquakes, tornados, hurricanes, floods and tsunamis; and
- Protection against man-induced events, such as dam ruptures, aircraft crashes, chemical explosions and malicious acts;
- Others.

Specific Symptoms and/or Occasions

It is prudent that specific symptoms and/or occasions involved with a specific reactor type need to be identified and evaluated in the Full FS. For instance, phenomenon peculiar to gas cooled reactor such as graphite dust and graphite brick failure shall be considered seriously in the reactor technology selection [17].

RESULTS AND DISCUSSIONS

Preliminary Evaluation

In performing the qualitative reactor technology evaluation for Malaysia, the following six (6) screening criteria and rationales are applied (Table 3.1-1).

- C1: The purpose of NPP to be introduced in Malaysia is for the electricity generation and the economy-of-scale calls for large capacity NPP's with power rating greater than 500 MWe (the IAEA definition of small and medium reactor (SMR) as under 300 MWe but these days, 500 MWe is considered the upper limit for SMR);
- C2: By the virtue of not more than 10% maximum NPP single unit capacity, the maximum power rating of the first NPP to be constructed in Malaysia is 2,000 MWe (based on the study by TNB Planning Division in the Pre-FS, the system size in 2020/21 is about 20,000 MW based on low long term growth rate of 3% from 2009 to 2030);

- C3: The national natural resource utilization strategy of Malaysia does not preclude the use of enriched uranium fuels available in the world market, i.e. both natural and enriched fuels are considered.
- C4: Proven of operation is the concrete evidence of proven technology and in most of the countries the NPP could be constructed only after the design obtained the construction permit or combined construction and operation license through licensing review by the regulatory authority. The DC process assumes the design is standardized;
- C5: The reactor technology is proven and standardized if the technology satisfies one of the followings; the similar design is in operation or under construction, and/or the similar design is design certified by the regulatory authority of the country of origin. Proven by operation is the concrete proof of proven technology and in most of the countries the NPP could be constructed only after the design obtained the construction permit or combined construction and operation license through licensing review by the regulatory authority. On the other hand, US NRC design certification process assumes the design is standardized;
- C6: The selected reactor technology must comply with the safety and performance goals are set to be equal or equivalent to those of the US EPRI ALWR URD [13] since those goals are reasonably achievable and very well-accepted in the world nuclear industry.

By the virtue of the economy-of-scale, the nuclear vendors will promote the largest capacity, i.e. the most competitive and latest design available in the present international market.

As a result of the reactor evaluation based on the above six (6) screening criteria, seven (7) candidates for reactor technologies are proposed for Malaysia (Table 3.1-2). Nonetheless, there are three (3) points of concern in relation to each VVER-1200 (PWR), ACR-1000 (PHWR) and ESBWR.

- The design of VVER probably is the least known to the world and the design life of the VVER-1200 is 50 years while 60 years is warranted by the other ALWR models. In addition, VVER design has many derivatives and it was noted that the safety systems of some versions did not satisfy international safety standards. It is recommended to perform in-depth review on the system design during the Full FS or during the bid process. The average energy availability factor (EAF) values of the 1000 MWe rating VVER in Ukraine and Russia are not seemed to be quite as competitive as other PWRs and this necessitates careful investigation on the model performance.
- For the ACR, AECL applied for UK generic design assessment (pre-licensing approval) in 2007 but then withdrew after the first stage. Present news indicated that AECL's CANDU engineering division for is open for bidding [18] and of course this development will trigger uncertainty for the existing and potential customers. This movement may also cause discontinuation of existing models and after service supports in the form of operation and maintenance from the technology holder.
- For BWR, the overall EAF is about 77% which is far less than the performance goal of design availability value of 87% as designated in the ALWR design requirements [13] and hence a further review seems necessary for the performance of the ABWR which is the base technology for the ESBWR. Consideration on the technology monopoly issue is also need to be taken into account when discussing about BWR related technologies.

Table 4: Reactor evaluation based on six (6) screening criteria

Country (developer)	Reactor	Size Mwe	C1	C2	C3	C4	C5	C6	Remarks
US-Japan (GE-Hitachi, Toshiba)	ABWR	1300	√	√	√	√	√	×	
USA (WH)	AP-600	600	√	√	√	√	√	√	
	AP-1000	1100	√	√	√	√	√	×	
France-Germany (Areva NP)	EPR	1600	√	√	√	√	√	√	
	US-EPR	1600	√	√	√	√	√	√	
USA (GE-Hitachi)	ESBWR	1550	√	√	√	√	√	√	Focus of attention in the international market
Japan (utilities, Mitsubishi)	APWR	1530	√	√	√	√	√	×	
	US-APWR	1700	√	√	√	√	√	√	Focus of attention in the international market
	EU-APWR	1700	√	√	√	√	√	√	
Korea (KEPCO)	APR-1400	1450	√	√	√	√	√	√	
Russia (Gidropress)	VVER-1200	1200	√	√	√	√	×	√	50 year life
Canada (AECL)	CANDU-6	750	√	√	√	√	×	×	

Country (developer)	Reactor	Size Mwe	C1	C2	C3	C4	C5	C6	Remarks
	CANDU-9	925+	√	√	√	√	×	×	
	ACR	700	√	√	√	×	√	×	
	ACR	1000	√	√	√	×	√	√	Focus of attention in the international market, even not satisfy C4, the choice of ACR is based on C5) and spent fuel is reduced by about 30% by using slightly enriched uranium (1.5~2% U235) or MOX fuel and the small positive void reactivity problem is avoided
S. Africa (Eskom, WH)	PBMR	170 (module)	×	√	√	×	×	√	
USA-Russia et al (GA- OKBM)	GT-MHR	285 (module)	×	√	√	×	×	√	

Legend:

√ : in-compliance; × : non-compliance

Until further clarifications above issues are compromised in favor of the models for future marketing, it would be prudent to reside within the PWR technologies offered by Westinghouse, Areva NP, Mitsubishi and KEPCO Consortium.

Table 5: Candidate Reactor Technologies for Malaysia

Country	Vendor	Reactor	Size (MWe)
USA	Westinghouse	AP-1000 (PWR)	1100
France-Germany	Areva NP	EPR (PWR)	1600
USA-Japan	GE- Hitachi	ESBWR (BWR)	1550
Japan	Mitsubishi	US-APWR (PWR)	1700
Korea	KEPCO Consortium	APR-1400 (PWR)	1450
Russia	Gidropress	VVER-1200 (PWR)	1200
Canada	Canada (AECL)	ACR-1000 (PHWR)	1000

RECENT ANALYSES BY OTHERS

Analysis by independent consultant, Excel Services Inc.[19] based upon major features of each reactor such as plant efficiency, plant design life, construction time, containment type, safety system, etc. (Table 3.2-1) and also each reactor associated risk factors (certification, completed engineering, licensing certainty, operating certainty, construction certainty, etc.) (Table 3.2-2) is a very useful reference for reactor technology selection exercise. The value of CDF (Figure 3.2-1) is also important to determine the level of safety of each reactor. Another analysis by NERA Consulting [20] on status of reactor in operation, under construction, planned and proposed inside the USA (Figures 3.2-2 and 3.2-3) and outside USA (Figures 3.2-4 and 3.2-5) has provided some insight on the popularity on each reactor available in the commercial market.

Table 6: Major features of selected reactor technology

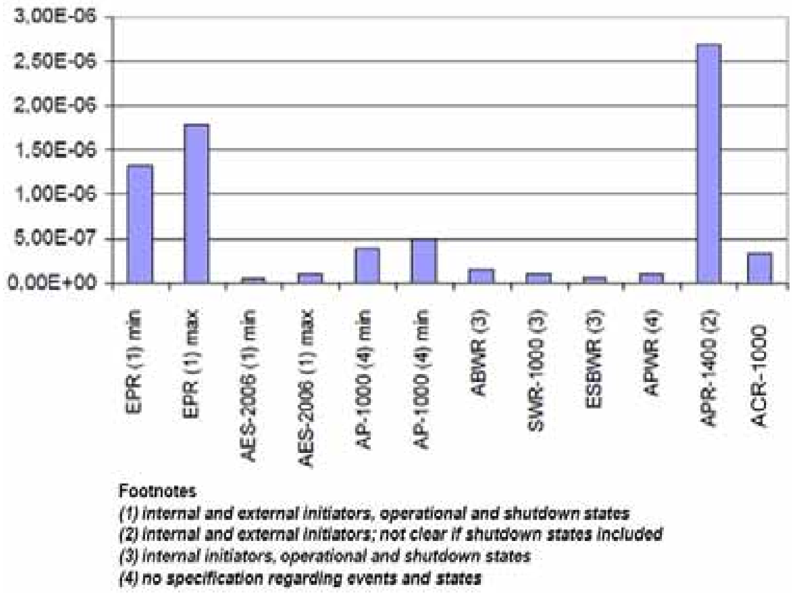
Major Features	ABWR	EPR	AP1000	APR1400	APWR	AES 2006 VVER1200	ESBWR	ACR1000
Vendor	GE-Hitachi Toshiba	AREVA	Westinghouse	KHNP	Mitsubishi	Rosatom	GE-Hitachi	AECL
Output, MWe	1370	1600 (Finland) 1700 (USA)	1117	1400	1538 (Japan) 1700 (USA)	1160	1535	1165
Plant Efficiency, %	35	37	34	35	35 (Japan) 39 (USA)	36	35	36
Design Life, years	60	60	60	60	60	50	60	60
Construction, months from 1st Concrete to COD	48 44 (in Japan)	51	42	48	46	54	42 estimate	42
First Unit COD	1996 (Japan) 2016 (USA)	2012 (Finland)	2014 (China)	2014 (S. Korea)	2015 (Japan)	2012 (Russia)	No order	No order
Extensive use of PreFab modules	Yes	No	Yes	Yes	Yes	No	Yes	Yes
Digital I&C	GE	Siemens TELEPERM-XS	ABB ADVANTAGE	Korean	MHI	Siemens TELEPERM-XS	GE	Dual computer
Containment	Single	Double	Single	Single	Single	Double	Single	Single
Safety Systems	4-train active	4-train active	4-train passive	4-train active	4-train active	4-train active	4-train passive	4-train active
Core Catcher function	Partially	Yes	In vessel	No	No	Yes	Partially	Partially
Fuel Lattice type	10x10	17x17XL	17x17XL	16x16	17x17XL	Hexagonal	10x10 short	43-rod
Discharge Burnup, MWd/kg	60	62	62	62	62	49 (VVER1000) 55 (VVER1200)	60	20 40 (future)
Steam Generators	n/a	4 U-tube	2 U-tube	2 U-tube largest in world	4 U-tube	4 horizontal	n/a	4 U-tube

Source: Excel Corp., 2009

Table 7: Risk factors of selected reactor technology

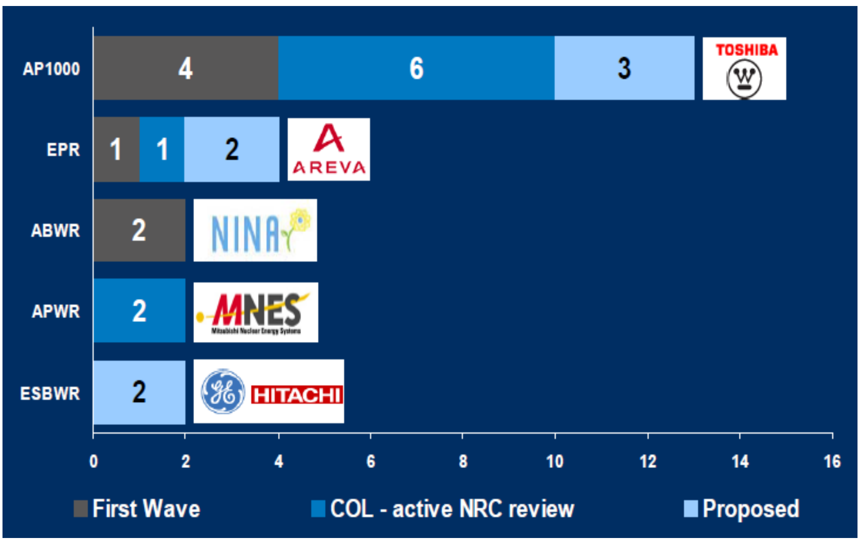
Risk Factors	ABWR	EPR	AP1000	APR1400	APWR	AES2006 VVER1200	ESBWR	ACR1000
Output, MWe	1370	1600 (Finland) 1700 (USA)	1117	1400	1538 (Japan) 1700 (USA)	1160	1535	1165
Certification	EUR NRC	EUR NRC ongoing	EUR NRC on going		EUR ongoing NRC ongoing	EUR	NRC ongoing	
Status	In operation in Japan	Under construction in Finland, France	Under construction in China	Under construction in South Korea	Under construction in Japan	VVER1000 in Operation. Not accepted in Western countries		
Completed Engineering	A	A	D	A	N	A	D	D
Licensing Certainty	N	N	N	N	N	D	D	D
Operating Certainty	A	N	N	A	A	A	D	N
Construction Certainty	A	N	N	A	N	N	N	A
Cost Certainty	A	D	D	A	N	D	D	D
Manufacturing Capability	A	A	A	A	A	D	D	A
Labor Supply	N	N	N	N	N	N	N	N
Life-cycle cost	N	A	N	A	A	N	A	N

Source: Excel Corp., 2009



Source: IAEA, 2008

Fig. 6. Core damage frequency of selected reactor technology



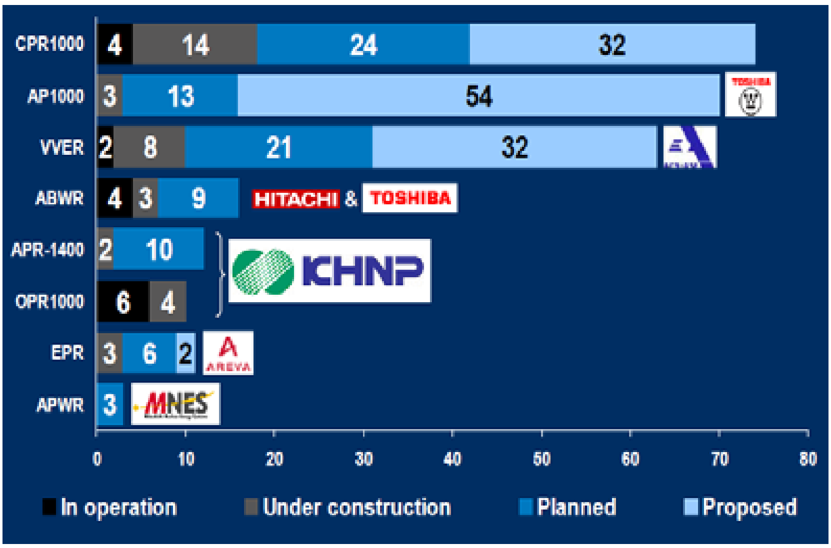
Source: NERA Consulting, 2010

Fig. 7. Nuclear vendor share for selected reactor technology (inside the USA)

Design	First Wave	Active COL review	Proposed
AP1000	4 - Vogtle (2), Summer (2)	6 - Lee/Duke (2), Levy County (2), Harris (2)	3 - Turkey Point/FPL (2), Bellefonte (1)
EPR	1 - Calvert Cliffs	1 - Bell Bend	2 - Callaway, Nine Mile Point
ABWR	2 - STP		
APWR		2 - Comanche Peak	
ESBWR			2 - Dominion, DTE

Source: NERA Consulting, 2010

Fig. 8. League table of selected reactor technology (inside the USA)



Source: NERA Consulting, 2010

Fig. 9. Nuclear vendors share for selected reactor technology (outside the USA)

Design	Op.	Construction	Planned	Proposed
CPR1000	4 - China	14 - China	24 - China	32 - China
AP1000		3 - China	13 - China	54 - China (48), India (6)
VVER	2 - China	8 - Russia (3), India (2), Bulgaria (2), Iran (1)	21 - India (8), Russia (7), China (4), Belarus (2)	32 - Russia (28), China (2), Iran (2)
ABWR	4 - Japan	3 - Japan (1), Taiwan (2)	9 - Japan	
APR1400		2 - Korea	10 - Korea (6), UAE (4)	
OPR1000	6 - Korea	4 - Korea		
EPR		3 - Finland, France, China	6 - India (4), China, France	2 - India
APWR			3 - Japan	

Source: NERA Consulting, 2010

Fig. 10. League table of selected reactor technology (outside the USA)

CONCLUSIONS

Reactor technology selection is a complex process which requires enormous information database review prior to make any decision. There is no silver bullet in reactor technology selection. There are various concepts and methodologies for assessment of available reactor technologies depending on priority, strategy and need of each country. For Malaysia, the qualitative assessment presented in here can be further enhanced for deeper and more systematic approach during Full FS with the assistance of credible and experienced consultants. It is necessary to keep abreast on the latest development of new build all over the world. More due diligence, fact findings plus careful and comprehensive analyses are required to augment and substantiate all reasoning. At present stage, it is premature to conclude which reactor is the best for the nation. For other inspiring new entrant nations, the study shall constitute additional information in their quest to devise their own reactor technology selection process systematically.

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