Comparing Boiling and Pressurized Water Reactors versus Novel Variants for Deployment in GCC Countries

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ABSTRACT

A broad comparison between the two main Light Water Reactor types, Boiling and Pressurized Water Reactors, is made in order to provide a background for the decision making on the nascent nuclear power industry in the Gulf Cooperation Council states. The comparison leads to the natural choice of a novel reactor concept based on proven Light Water Reactor technology and experience and especially suited to the GCC environment.

1. INTRODUCTION

A casual observer of the nuclear power landscape is quick to conclude that Light Water Reactors (LWR) have been proven not only technically but also through the test with fire in the marketplace. The main LWR types are the Boiling Water Reactor (BWR) and the Pressurized Water Reactor (PWR). The casual observer, turned judge, failing to discern a clear advantage of one over the other, will attribute the bigger market share of the PWR over BWR types to the accidents of fortune and blind fate – not an alien occurrence in the world of technology with the example of PC versus MAC jumping to the fore. The casual judge, aided by nothing more than a two-sided coin, with everything else being more or less equal, will decide on which reactor type to adopt: BWR or PWR, and he will not be totally wrong. Questions remain: is he totally right, is something else missing, a third alternative or a hybrid one? That is what we are set out to explore, in order to find the optimal path to founding a successful program leading to a world class nuclear power plant fleet in Saudi Arabia and the GCC countries.

2. A METHODOLOGY FOR NUCLEAR DECISION

Navigating the decision making plane is a rather difficult art because between point A, where we are, and point B where we wish to go, there exist numerous possibilities and paths. The optimal path to nuclear power is not unique and the quest is dynamic in the sense that what was workable and obvious a few years or even months ago is no longer even an option today. Questions of energy have become central to global economy and domestic and international politics as well as the protection of our plant against climate change. A decision to go nuclear is taking on a sense of urgency that is unprecedented; the next step is deciding how to go nuclear, not whether to go nuclear.

Navigating the decision making plane by exploring each possible path is not what really happens, rather the reverse. An insight comes first and defines points A and B and the path in between with crisp clarity, and it seeks to justify itself *a posteriori* by contrasting with other viable alternatives. Our methodology therefore accepts the intuitive insight as its basis, but is subjected to the scrutiny of systematic and disciplined study in order to arrive not only at the best decision but more importantly to arrive at a buy in, i.e. the unifying consensus that makes things happen on the ground.

To define the decision making methodology regarding how to introduce nuclear power, a few elements will need to be mentioned briefly. These elements include the time constraints, the implied assumptions, and a brief note on the evolution of nuclear technology and alternative power generation reactor systems. This will place our proposed entry point to join the nuclear stream in clearer perspective.

Constraints of Time

An ancient Greek philosopher encountered a good looking maiden and contemplated getting married. Given the seriousness of the matter, he gave it the most thorough consideration and deepest thoughts. By the time he decided to propose, it turned out she already became a grandmother of several children. The obvious constraint in our decision making is governed by a kind of uncertainty principle: the value of a decision multiplied by the time it takes to arrive at it is finite. The casual observer/judge will beat the philosopher every time. But it was the moderate decision maker, not the casual and not the philosopher, who actually married the beautiful maiden.

The time-versus-detail constraint will serve our immediate purpose by justifying oversimplifications when such is not justifiable elsewhere, and provide an excuse for stating the obvious when under different circumstances it is a mere waste of time. It is only in this spirit that we propose the first guiding principle: "It is better to make any decision on the selection of which available reactor system to adopt and make that decision now, than make an elaborate and time wasting one only to find that the opportunity is gone." A quick review of which systems are really available is addressed next.

Some Implied Assumptions

There are assumptions, or conclusions from previous experience, that seem to go unstated and unchallenged. For the sake of completeness and clarity, some of these will be identified and singled out for a quick mention.

Coolants other than light water, and reactor systems with plutonium breeding potential, are excluded.

- Heavy water reactors (HWR) are successfully operated particularly in Canada where the technology of producing it is well developed. HW allows operating a thermal reactor with no or minor uranium enrichment which generates a larger volume of radioactive waste compared with a LWR of the same power. HWRs produce plutonium, a controversial substance!
- Liquid metal cooled reactors such as Super Phoenix in France prove that the challenges of sodium coolant can be overcome and controlled. However, plutonium breeding reactors are feasible only in countries where reprocessing capacity is well developed, and even then a large power capacity from breeder reactors is a concept for the future not the present. Their most attractive feature may prove to be their capacity to incinerate the radioactive actinides from accumulating radioactive waste, not an immediate problem for a start up nuclear power program.
- The power capacity of operational gas cooled reactors is small, while new designs are promising. The new designs, among other objectives, offer advantages due to high temperature such as higher thermal efficiency and the potential for hydrogen production, and in other instances plutonium breeding. They are worthy of consideration where a well established nuclear industry can take full advantage of their yet to be demonstrated potential.

Other considerations beyond the purely technical ones are also important. The LWR market is rich with well established companies with long standing competence in designing, constructing, and operating power plants with a diversity of management structures as private or government owned and controlled. There is also a vast engineering pool to draw on with experience in licensing and operating LWR. We will therefore focus on LWR based technology as our optimal entry point.

A Quick Comparison of the Main Features of Boiling and Pressurized Water Reactors

The BWR and PWR types are so well known it is hard to justify a section dedicated to describing them. It is also impossible to give justice to the details in their respective design and operational attributes even in a large book. For our purpose here, the main features showing similarities and differences suffice in order to demonstrate that there is room for further optimization and simplification for reactors of the LWR type. Instead of referring to different aspects of design as advantages or disadvantages, we will chose the milder terms, pluses and minuses, to be clear that these have been dealt with successfully as part of an evolving optimization for each design concept.

PWR evolved from the military development of naval propulsion in the US. In such specific environment it is not easy to control nuclear reactions under boiling conditions where the entire system is moving. Another important consideration is the tight space aboard a ship or submarine and the need to protect personnel from radiation exposure. These considerations lead to the pressurized water concept where boiling is not allowed, and also the indirect cycle design where the pressurized coolant remains in the so-called primary circulation side isolated from the turbine side. The nuclear heat transfer to the working steam is accomplished through several heat exchangers (steam generators). This separation between the primary and secondary cycles allows adjustable concentration of boric acid in the primary coolant for reactivity control. The main pluses of this design are the relative simplicity and smaller size of the reactor pressure vessel and the compact core allowing high energy density. Not everyone considers high core energy density as a plus, in case of a loss-of-coolant accident.

By contrast, BWR development is rooted in commercial application lead by General Electric (GE), with early participation of Argonne National Laboratory. All mature BWR design lines employ the direct cycle where the working steam is generated by boiling in the reactor core. While this eliminates the costly steam generators, the pressure vessel itself is larger compared with the PWR vessel and has to include steam separation and drying equipment inside the costly pressurized space. A definite plus for the BWR is the simplicity of reactor control through the negative reactivity feedback of the boiling process.

The primary coolant pressure of ~140 bars allows relatively high temperature at the primary side of a PWR, but this advantage is lost by the thermal barrier across the steam generators operating at ~70 bars and reducing the thermal efficiency of the plant. The BWR operates at nearly the same pressure as the PWR steam generators, which is selected as a design trade off between the desire for higher pressure which allows higher temperature and thermal efficiency, and on the other hand the desire to reduce condensation in the steam turbine which would occur if the pressure is set at a high level. This optimal pressure is mandated by the unfortunate constraint on the generated steam which does not allow any significant superheat above the saturation conditions. Attempts at solving this problem by considering nuclear superheating, mostly by GE for variants of its BWR designs, have failed to produce economically working solutions (see Cohen and Zebroski 1959, and Fennern 1992).

Generations of Nuclear Plants and the Evolution of Operating Temperature

Nuclear plant classifications were made with regard to several attributes. These include the coolant type (water, gas, liquid metals), neutron moderator type (often the coolant itself, heavy water, or solid graphite, or no moderator for fast reactors), fuel type, breeding capability, etc. A broader look divides the nuclear plants to 4 generations.

- Generation I include the early prototypes of the commercial plants that were developed in the 1950s and 60s.
- Generation II include the commercial fleets that operate today, mostly of the PWR and BWR types and the CANDU heavy water reactors, that were constructed in the 1970s to 90s.
- Generation III which is an evolutionary, not revolutionary, extension of the generation II designs. Key features are simplifications in design and controls and passive safety systems and modular standardized designs that would allow expediting the licensing processes. Examples of these designs include EPR (evolved from PWR) and SWR1000 (evolved from BWR), both designed by AREVA, ESBWR (evolved from BWR by GE), and APWR (evolved from

PWR by Westinghouse), etc. These designs are at different stages of maturity and several are being marketed by major nuclear companies in the US, Europe, and Japan. An EPR is currently under construction in Finland.

- Generation IV includes major advances in nuclear cycle and innovative concepts. These include molten salt reactors, liquid metal cooled plutonium breeding reactors, thorium-based reactors, very high temperature gas cooled reactors, and hydrogen generating reactors. None of these revolutionary concepts are currently used for power generation, with the exception of the Super-Phoenix sodium cooled fast breeder reactor prototype in France.

It is important to notice that a radical transition in the evolution of nuclear plants, common to all concepts regardless of the design details, is the markedly higher operating temperature envisioned for generation IV. Currently deployed fleets and marketed designs of generations II and III are all operating at relatively low temperatures which limit the thermal efficiency of the electricity generating cycles. It appears as if the limitations of nuclear suitable materials (low neutron absorbing metals) to withstand high temperatures have been accepted for the generation III candidates which are envisioned to carry the 21st century nuclear renaissance. Can this limitation be challenged without prematurely transitioning into generation IV? The answer to this question is yes, and the promise is explored briefly in the next section.

3. A GAS-CYCLE-COUPLED LWR DESIGN

Advances in conventional power plant technology did not go through the dormancy suffered by the nuclear side over the past 30 years. The major advance in natural gas-fired power plants is the development of the combined cycle, where a gas turbine/generator operates at high temperature, and the hot exhaust gasses are used to power a conventional steam cycle by providing heat to a boiler which in turn feeds a steam turbine/generator. Thermal efficiencies up to ~60% can be reached which far exceeds the LWR thermal efficiencies of ~35%.

In a power generation cycle, the working fluid must be heated from a low to a high temperature, and the cycle's efficiency is limited mainly by the high temperature end. A synergistic combination of the natural gas and nuclear technologies is advantageous: natural gas is capable of achieving high temperature and would be wasteful to use it for heating condenser return, while nuclear heating is limited in currently available technologies to relatively low temperatures. A serial system with nuclear reactor supplying the low temperature heat and natural gas supplying the high temperature heat is an optimal arrangement that is workable with current technology (for recent publications see Forsberg and Conklin 2007, and Jeong and Kazimi 2007).

The basic feature of the proposed reactor design takes advantage of the potential of the combined cycle technology on top of a nuclear base. Starting from a typical BWR design, the modifications would include the following:

1. One (or more) natural-gas turbine/generators which produce electric power and hot exhaust gasses.
2. The exhaust gasses are used to power two heat exchangers. The first one is used to superheat the steam output of the BWR, and the second is used to augment the feedwater heating.
3. With superheating capability accomplished, the reactor vessel pressure can be increased above the conventional 70 bars. The extent of pressure increase is an optimization exercise which must take into account the cost of the pressure vessel and the effect of the higher pressure on the thermo-mechanical performance of the fuel rods. It is also important to consider the effects of the operating pressure on the critical power ratio and other thermal limits. A rough estimate of approximately 100 bars would result in considerable thermal efficiency improvement and yet well within the pressure environment of PWR supported by considerable experience.
4. With the superheating availability, there is an opportunity to simplify the internals of the pressure vessel with regard to steam separation equipment. For example, steam dryers can be eliminated, and simpler steam separator set can be used to trade the no longer needed steam separation efficiency with reduction in pressure drop which allows improvement in natural circulation flow and improved system stability. Instead of the generation III trend to enlarge the pressure vessel of a BWR as illustrated in Figure (1), the proposed reactor vessel volume is reduced as shown in Figure (2).
5. The availability of exhaust gas feedwater heating provides significant advantages in controlling the reactor inlet subcooling and improves thermal efficiency. More importantly, as feedwater heating is essential in mitigating accidental transients combined with the loss of the ability to scram the reactor, transients leading to loss of steam feedwater heating, such as turbine trip with steam bypassing the turbine directly to the condenser, can be mitigated by the availability of exhaust gas feedwater heaters.
6. Secondary advantages of this design include the availability of electric power from the gas turbines which could substitute the emergency diesel and battery power, further simplifying the plant management.

The combined-cycle approach can be also used to modify a PWR, but the advantages are not as far reaching as in the case of a BWR. For example, the steam generators of a PWR will not be eliminated. To take advantage of the possibility to increase the secondary system pressure, the primary system pressure must be also increased, which would reach values beyond current PWR operational experience.

4. CONCLUDING REMARKS

The nuclear power decision from the perspective of the casual observer is frozen in time, where other's past success is a guaranteed guide to ours if we just duplicate their steps. The dynamic resembles more a wave surfer who gains energy by leading the wave not by trailing it. The advantages of being there first and being prepared cannot be exactly duplicated for a newcomer to the nuclear scene. However, a new wave of nuclear

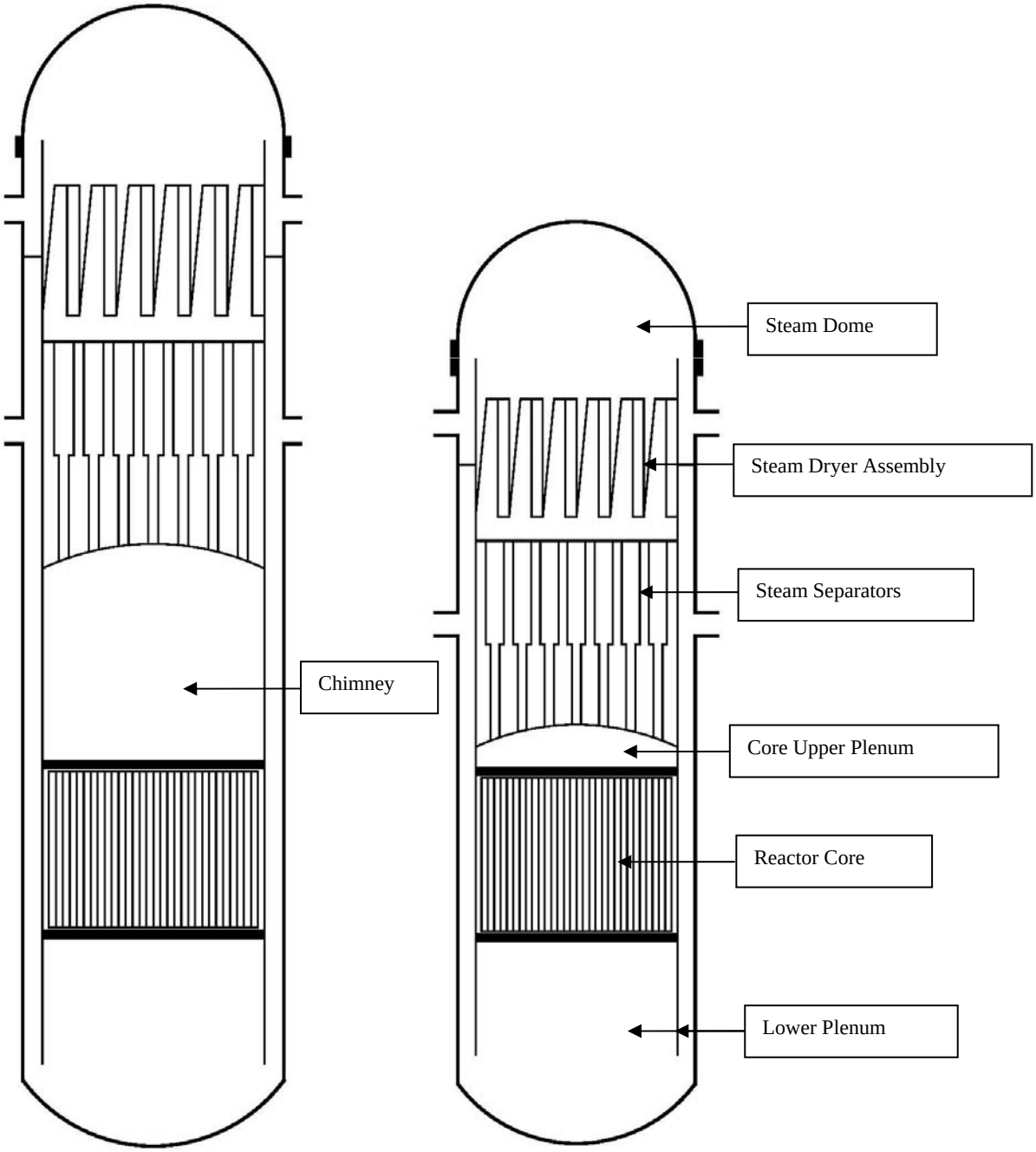

Figure 1: A sketch of a typical BWR pressure vessel showing various important internal components (right), and a sketch representing a recent generation III design (left) showing the main change features as a chimney structure used to increase the natural circulation pressure head at the expense of increasing the overall height of the pressure vessel.

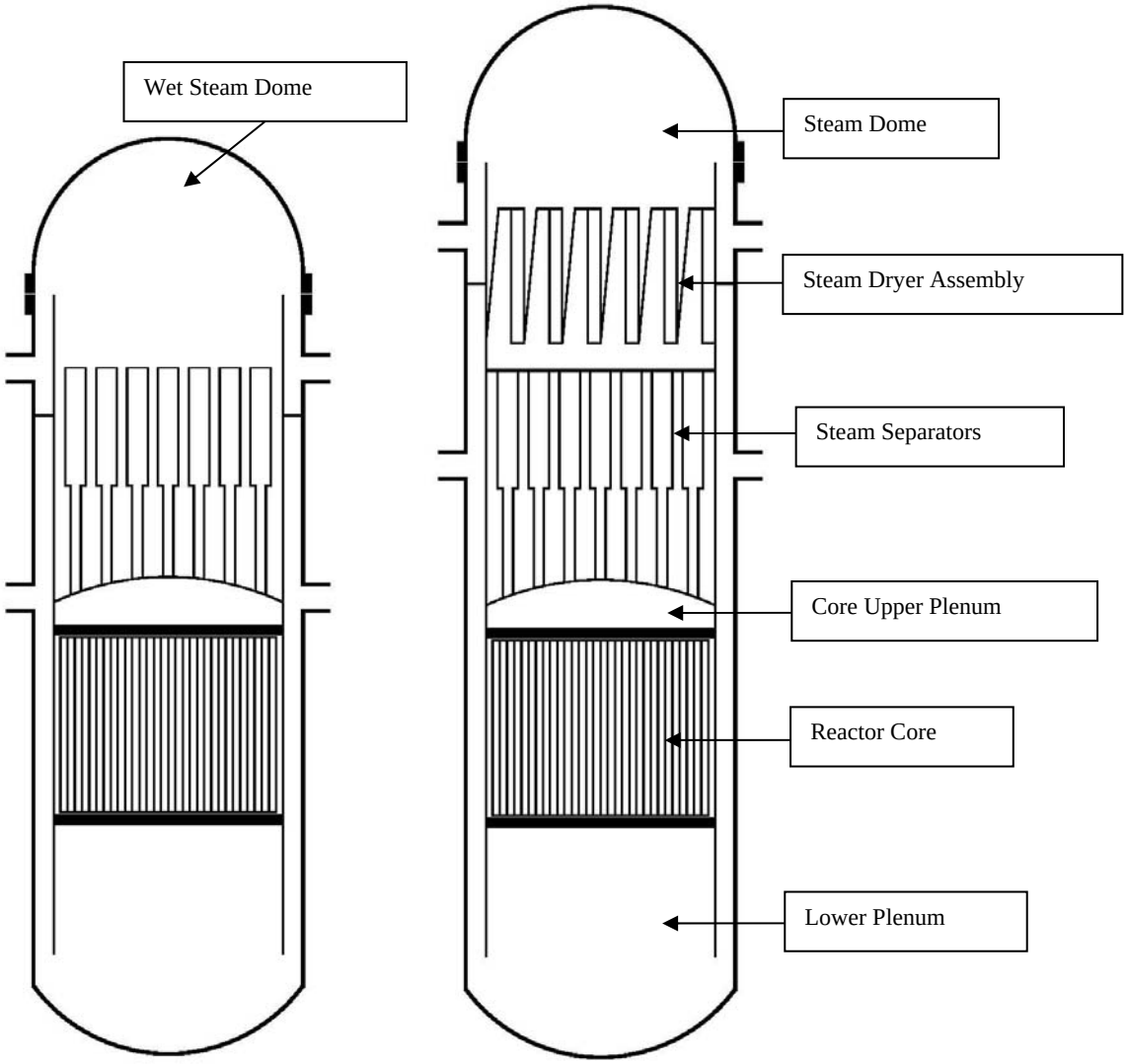

Figure 2: A sketch of a typical BWR pressure vessel showing various important internal components (right), and a sketch of the design of the proposed design (left) showing the main change features as eliminating the steam dryer assembly which permits wet steam to exit the pressure vessel with the advantage of decreasing the overall height of the pressure vessel which is a contrary trend to the recent design shown in the left side of Figure (1).

renaissance is approaching and it deserves a fresh look with the dynamics in mind.

A Decision Point: Let it be a LWR fleet, but not necessarily the BWR or PWR we know today. A moderate shift is the optimum point, where the new reactor is sufficiently related to the current designs and shares proven components such that the past experience remains relevant and the reactor safety is assured. On the other hand, the new reactor needs to be sufficiently different from current LWRs with design improvement in efficiency and simplicity as to place the newcomer in a leading position on the nuclear wave.

The GCC-BWR, Gas Coupled Cycle Boiling Water Reactor, or Gas Combined Cycle Boiling Water Reactor, or also fortuitously Gulf Cooperation Council Boiling Water Reactor, is introduced. It takes advantage of the LWR long and successful operational experience and the simultaneously the modern combined cycle, and is uniquely suited for the GCC and other Middle Eastern countries where natural gas is abundant. The resulting design offers significant advantages in basic design simplifications to reduce the initial capital cost for construction. It also offers significant economic advantage by increasing the thermal efficiency, which is directly proportional to the electric power output, and tolerant of projected increase in uranium prices, beyond the nuclear state of the art.

5. REFERENCES

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