Safety and Economical Requirements of Conceptual Fusion Power Reactors in Co-existing Advanced Fission Plants

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Abstract. An EPR fission plant is expected to operate from 2010 to 2070. In this time range a new generation of advanced fission reactors and several stages of fusion reactors from ITER to DEMO will emerge. Their viability in the competitive socio-economic environment and also their possible synergy benefits are discussed in this paper. The studied cases involve the Finnish EPR, Generation IV, and the EFDA Conceptual power plant study Models A-D. The main concentration is on economic and safety assessments. Some cross-cutting issues of technologies are discussed. Concerning the economic potential of both conceptual fusion power plants and those of Generation IV candidates, we have applied the present Finnish EPR as a reference. Comparisons using various pricing methods are being studied for fusion and Generation IV: the mass flow analyzes together with engineering, construction and financial margins exhibit one method and another one on simple scaling relations between components or structures with common technology level. In all these studies fusion competitiveness has to be improved in terms of plant availability and internal power recirculation. Present best fission plants have plant availability close to 95 % and internal power circulation of the order of 3-4%. The operation and maintenance solutions of Model C and D show the right way for fusion. A remarkable rise of the fuel costs of present LWRs would make at first the Generation IV breeder options more competitive and thereafter fusion plants. The costs of safety related components, like containment and equipment for severe accident mitigation such as the core catcher in a LWR, should be accounted for and to what extent the inherent fusion safety features could compensate such expenses. For an overall assessment of the various nuclear options both internal and external costs are considered.

1. Introduction

Nuclear fusion and fission are among the very few alternatives which can widely solve near- and long-term global energy problems. Fusion energy is amply abundant and inherently safe, but requires extensive technical development and innovations to achieve its economical viability. Advanced fission reactor concepts are, perhaps, closer to their commercial feasibility, but their political acceptance has to be improved. The recent decisions concerning ITER and the dawn of renaissance of fission reactors has generally advanced the interest of nuclear energy, and several genres of fission and fusion reactors are simultaneously evolving. Due to the long life-constants of nuclear energy various nuclear power plants will coexist and they have to meet common, global boundary conditions. This paper discusses some of the economical and safety requirements and the competition and synergies between such reactor genres.

For fusion we have adopted the EFDA studies of conceptual power plants [1] which outline the main economic and safety features of the four model designs. The alternatives with successively advanced features include: Model A and B use water-cooled lithium-lead and helium cooled pebble bed blanket, respectively, and they are based on presently anticipated plasma performance and on near-term technology choices. The more advanced Models C and D assume considerable improvement of plasma performance and involve double coolant loops and long term technology. Combinations of helium and lithium-lead cooling and structural parts of silicon carbide are assumed. As a manifestation, to obtain a reasonable plant availability factor, 75-80 %, the internal parts of the reactor are segmented and modularized to speed-up maintenance. The plant performance, efficiency, re-circulating power, life-time of plasma facing components, etc., are successively improving from Models A to D. In our comparative study between fusion and fission power plants we have used firstly evolutionary fission reactors of Generation III+ presenting the most modern light water reactors like the EPR under construction in Olkiluoto, Finland, and secondly the more revolutionary concepts of Generation IV [2] and INPRO [3].

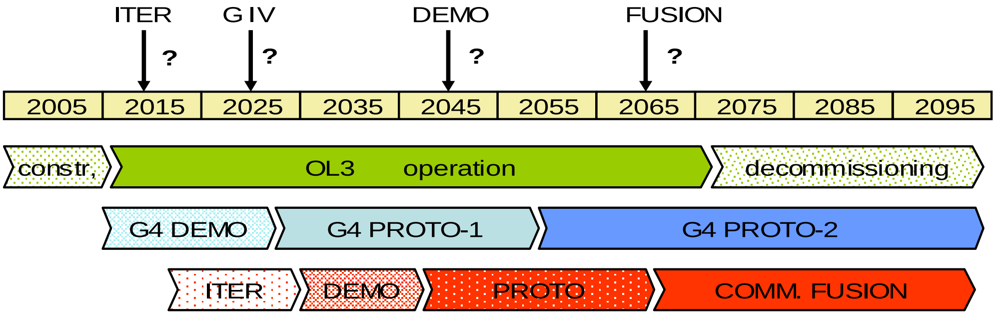
The main issues are: 1) The newest LWR reactors have a very long life-time during which ITER, DEMO and even the first commercial fusion power plants and the Generation IV options could co-exist. 2) The performance of present fission power plants will guide for all reactor types the safety and economical reference goals which will vary with competition and changing socio-economic environment. 3) Many of the technology problems share common R&D between fusion concepts and those of Generation IV: for instance, EFDA fusion Models C and D and candidates, such as lead or helium cooled fast reactors, and helium cooled very high temperature reactors face the same cooling technology problems. As a case study we have previously considered also the use of supercritical water for cooling in fusion reactor thermal hydraulic components which provides an interesting cross-cutting area for both fusion and fission. 4) In a long-run the different alternative lines could evolve into symbiotic fusion-fission systems.

2. The Long Term Commitment in Nuclear

To elucidate the long time evolution we note that the new Finnish NPP unit Olkiluoto 3 is planned to start its commercial operation at the turn of 2010. Its design life-time is 60 years which implies permanent shut-down earliest by 2070 and its final decommissioning would not take place before the next century. The closing of the spent fuel repository would - according to our present plans based on once-through cycle and deep-rock disposal concepts - take place only at 2130. The different Generation IV scenarios predict that their phases of viability, performance and demonstration would take about 5-10 and 10-15 years, respectively, which would imply the appearance of the first Generation IV commercial prototypes from 2025-2030 onwards. In fusion, including ITER and DEMO, the reasonably predictable time range covers already to 2040, involving ELE and the Fast Track. In this time frame, economical feasibility of fusion could rather reliably be assessed already during the life-time of present fission NPPs. Of course, the uncertainties of scenarios covering the whole century are huge and assume a scenario with a stable business-as-usual political development. Figure 1 elucidates the extreme long life-span of various nuclear reactor genres.

To exemplify some possible variations of the view shown in Fig. 1, we note that the economic life-time used of our fission plant studies assumes 40. The technical life is designed for 60 a. On the other hand, the pay-back time of Olkiluoto 3 can be only 10-15 a. The investment risk of the utility is thus already largely over the emerging times of fusion or Generation IV candidates and with appropriate policy nuclear waste management the liabilities can be kept in a reasonable time. It appears almost impossible to beat present fission reactors. Only a severe U^{235} shortage will change the situation and modify the economical expectations. The conclusion is that in the co-existence shown in Fig. 1 the global nuclear world can house only a rather limited number of the population of Generation III+ fission reactors. The situation is similar to the hydro power situation in most countries. The predicted increase in the nuclear energy scenarios must be covered by new reactor types.

Fig. 1: During the life time of the newest Gen III+ fission power plants completely new types of nuclear reactors will emerge. The actual timing is only indicative



3. Economic Viability Considerations

The newest Finnish unit, Olkiluoto 3 (a 1600 MWe European Pressurized Water Reactor, EPR) under construction provides a reference case for present economic assumptions on nuclear energy. The estimated cost of electricity clearly less than 30 €/MWh is comprised of capital, operation and maintenance, and fuel costs of about 58 %, 30 %, and 12 %, respectively. The uranium price is currently from one sixth to one third of the fuel costs. The capital cost estimates are based on a 40 a economic life-time (technically the EPR is designed for 60a), 5 % real interest rate, and about 8000 h of full power operation. Nuclear waste costs depend on the fuel cycle and adopted disposal method. In Finland, the primary solution is once-through cycle with deep-rock repositories and the waste funds collected are already by now expected to cover the liabilities. A rough estimate is that waste costs are about 2.5 €/MWh. The exact amount will depend on the cumulative production of Olkiluoto and Loviisa plants. Nuclear fission energy is in Finland clearly cheaper electricity source than coal, gas, peat, wood or wind, even when accounting for the CO_2 – emission trade.

The cost of electricity, COE, is estimated in the usual way:

$$COE = (FCR * TCC + OMF + REV)/E + FUEL + OMV$$

where TCC is the total construction cost, FRC the fixed charge rate, OMF and OMV fixed and variable O&M costs, respectively, REV annual revision cost and FUEL variable fuel cost. The total construction costs TCC include total overnight construction costs, escalation during construction and interest during construction. The direct total overnight costs on the other hand consists of total direct costs, construction services and equipment, home and field office engineering and services, owners costs and provisions&contingency. Typically these items multiply the direct overnight costs by a factor of two. We calculate FRC with the annuity method, i.e. $FRC = i / [1-(1+ i)^{-n}]$ where i is the real interest rate and n the number of economic life in years. E stands for the annual electricity production, i.e. the effective operation time multiplied by the rated maximum gross power.

Comparisons using various pricing methods are being studied for fusion and Generation IV in which the technical details are only sketchy. A mass balance analyzes together with engineering, construction and financial margins exhibit one method and another one can be done by simple scaling between components or structures with common technology level.

In all nuclear reactor types the capital costs dominate the electricity costs. The share between capital, operation & maintenance and fuel costs are similar in fission plants. In fusion plants the fuel cost due to lithium and heavy water are marginal and will be neglected here. The breeding cost and tritium processing are included into capital investments. Assuming O&M costs of fusion plants similar to those of fission plants, but with 2-3 times higher investment costs, the COE distribution would rise to 80-90 % of capital costs and even the rest, 20-10%, would mainly be fixed costs.

The highly intensive COE-structure of fusion emphasizes the need for improving the plant availability and internal power recirculation. Present best fission plants have plant availability well above 95 % and their internal power circulation (mainly the primary pumps) of the order of 3-4 %. Their shortest fuelling and maintenance shutdowns may be down to 10-15 days. The largest revisions needed in a fusion plant are the change of divertor casettes and the first wall modules. The divertor is expected to last two full power years and the first wall 5 full power years. Additionally sophisticated and time-consuming equipment testing and refurbishment is needed. Initial estimates were that the plant availability would drop down to an unexceptionally low value of about 50%. The operation and maintenance solutions of Model C and D, however, show the right goal to obtain availability 75-82 %. The internal circulation power of fusion reactors include the heat transfer which is similar to that of fission plants but in addition current drive and heating which are necessarily needed for fusion burn control. The re-circulating power, about 30% for the Models A and B, is too large, but the values 11-13 % of Models D and C, respectively, look more promising.

In fusion, and also partly in the Generation IV candidates some cost reductions might be obtained because of the passive safety features of the advanced systems. The EPR is equipped with a double wall containment able to survive a full-scale airplane crash and with a core catcher which and would mitigate core melting in a fully controlled fashion. The safety redundancy and diversity requirements, leak-before-break principles etc. give further cost increases due to the active safety measures. Suggestions have been made that in a pebble bed reactor a full containment would not be necessary. Also for instance, the fusion reactor Model A can manage full strength containment, but it must have suppression system and drain tanks, i.e. similar safety measures as in a typical BWR.

All of the considered nuclear reactors cause health and environmental risks. Quantitative measures for them can be obtained by the external costs [4] and by the life cycle analysis. As shown in Section 4 the external costs, however, play a negligible role in comparison to the uncertainties in the internal costs. External costs evaluations turn out to be useful for ranking between fully different types of energy sources, say e.g. nuclear and coal, in particular if the internal prices are very close to each other. The main advantage of fusion would be the lack of spent fission fuel burden and probably the inherent safety against severe reactor accidents.

Besides the dominant capital costs, the variable fuel price costs due to U_3O_8 have to be accounted. A remarkable rise of the fuel costs of present light water reactors would improve the competitiveness of first the Generation IV breeder options more competitive and later on that of fusion plants.

In Figures 2 and 3 we illustrate the sensitivity of COE as a function of the economical plant life time and investment costs. The basic parameters are given in Table 1.

Table 1: Estimates for performance parameters of various types of nuclear power reactors

	EPR	PBMR	SCWR	Model A	Model B	Model C	Model D
Thermal power [MWth]	4300	350	2200	5000	3600	3410	2530
Gross electric power [MWe]	1650	165	1000	2066	2105	1716	1640
Net electric power [MWe]	1600	n.a.	960	1546	1280	1517	1527
Plant efficiency	0,38	0,47	0,44	0,31	0,36	0,44	0,6
Availability factor	>0,9	0,95	0,9	0,50…0,80			
Direct costs [€/kWe]	1800	1700	900 [2]	2000…10000			
COE [€/MWh]	25	25	< 20	30…90			

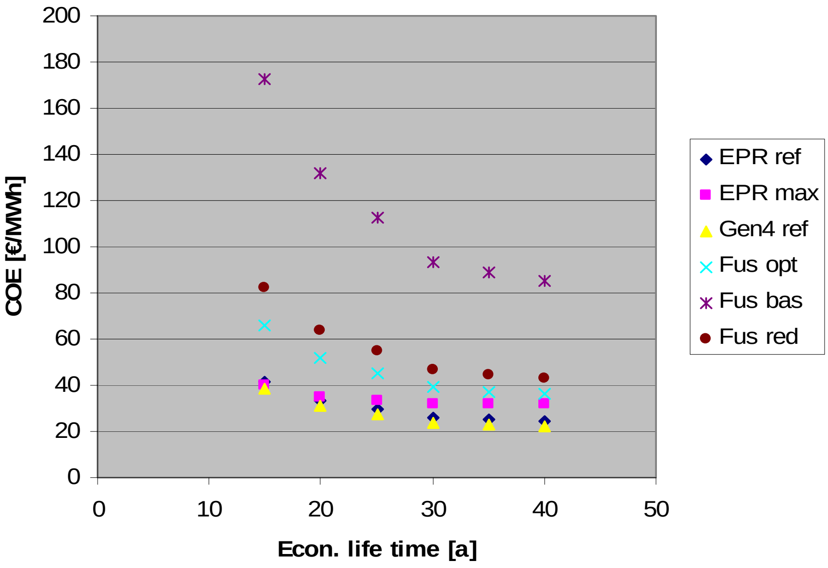


Figure 2: Effect of economical life time for fission reference scenario “EPR ref”, “EPR max” includes gradual increases in fuel costs, “Gen4” is stands for a fictious reference case. The fusion alternatives “Fus bas”, “Fus red”, and “Fus opt” represent a base case, a model with reduced investment costs and an optimistic goal, respectively.

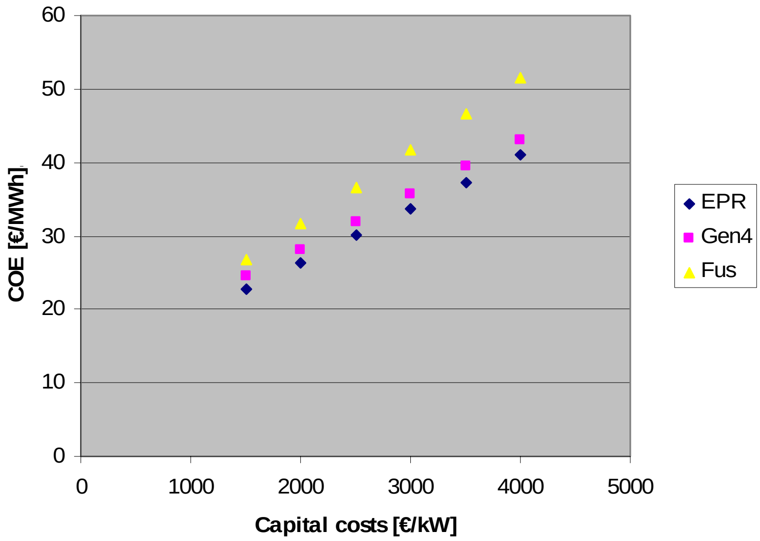


Figure 3: COE as a function of specific investment costs for EPR, Gen4 and fusion reactors. The fusion case assumes 1400 MWe net power, 15% recirculation and 80% availability. EPR and Gen4 (1000 MWe net power) both assume an availability factor of 95%.

The base fission scenario “EPR ref” in Fig. 2 assumes the present EPR design with 1 €/MWh as variable fuel cost and 90% availability. In “EPR max” the average uranium costs are escalated by a factor of five as the lifetime is increased from 10 years to 40 years. The “Gen4 ref” assumes the same investment costs as the reference EPR, but with an un-escalated fuel price (a breeder option). For the basic fusion case we have conservatively assumed a 10 billion € investment costs for 1400MWe (net), 18% power recirculation ratio and an availability of 70%. In the reduced cost option the investments are 6 billion €, recirculation is 15% and availability of 90%. In “Fus opt” the investments are 4.5 billion - only 50% higher than EPR. The circulation ratio has been cut to 6% (total of 100MWe for C&D and heat transport) and the availability is 80%. In Figure 3 all the options have the same economic lifetime. For fusion the recirculation ratio and availability factors are 15% and 80%, respectively.

Figures 2 and 3 demonstrate the importance of capital costs for all nuclear reactors. If uranium shortage becomes severe the thermal fission reactors must have shorter economic life times. As breeders and fusion reactors are not so much affected the parallel coexistence of various reactor genres may turn to a more sequential development. That would make smoother price jumps but with large demand restrictions.

4. Safety Issues

Nuclear safety involves both direct capital costs related to safety equipments and to possible indirect external costs due to health effects. The defence-in-depth philosophy has turned very successful and can be applied to many different kinds of systems. The barriers keeping the dangerous substances are both material and functional. A deterministic safety analysis appears to be most promising for systems with prototype systems like Generation 4 or fusion reactors. The operation of safety is usually sufficiently transparent. Probability based Risk Analysis (PRA) is excellent for balancing the risk spectrum and the operational risks of (individual) power units. PRA is very successful for complicated systems which are consisting of simple building blocks like pumps, pipes, valves, etc. A tokamak reactor is not a typical case for such.

In the conceptual power plant studies defence-in-depth has been fully applied. The methods for isolation of tritium and activation products form the barriers. The fusion reactor Model A is based on light water reactor technology and consequently its safety analysis, too. The main safety related systems have a one-to-one counterpart in BWR. The adoption of safety solutions for first fusion power plant studies is motivated by present for first studies of

The more advanced fusion reactor candidates, Models C and D are economically more promising, but their safety analysis is less developed. Their structural complications and insufficient data base put future challenges. If the inherent fusion safety can be “proved” convincingly enough considerable cost reductions could be found. The present ideas of safety systems is predominated by present fission reactors and could be re-considered. The first Generation 4 candidates are already close to facing these problems their licensing still requiring a lot of work.

The question of achieving a sufficient level of safety is an unsolved problem. All present commercial fission reactors must have equipment to survive their design basis accidents. Most of them have also been refurbished to handle intricate core-melt situations. Typical probabilities for a severe reactor accident range from close to 10^{-4}/a to 10^{-7}/a or even lower. In most of the plants the retrofits are not fully capable of surviving all possible scenarios. The EPR has a core catcher and it is designed against airplane crash. Further improvements of safety and their more transparent demonstration may call, e.g., underground containment.

The safety risks have been quantified by their external costs [5]. It turns out not to be a significant COE cost item. With the newest fission plants the burden of external costs to environment are the same order as wind, circa 0.5 €/MWh. From the COE point of view the external costs of 0.9 and 0.6 €/MWh of Model A and Model D play a smaller role only. For the moment the political acceptability plays a central role, but perhaps the situation changes as the energy of clean energy becomes more acute.

5. Cross-cutting Issues

The more advanced fusion reactor models share, in particular in thermal hydraulic features and materials, many similar problems as in Generation 4 reactors. The neutron spectrum gets harder and the radiation damage problems become more difficult as one moves from thermal fission reactors to fast breeders and to fusion. On the other hand, fusion reactors do not suffer from the nuclear fuel degradation.

In Model C and D of EFDA/PPCS the size of the plasma core has been drastically reduced from that of Model D approaching the current ITER design. The blanket cooling is based on helium and liquid LiPb alloy; the assumed temperatures are similar to those in Generation IV candidates. Some common problems of fission and fusion reactors are listed in Table I. The considered cases are: gas-cooled (GFR) and lead-cooled (LFR) fast reactors, supercritical water cooled reactors (SCWR) and very high temperature reactors.

Table 2. Cross-cutting issues of advanced fusion and Generation IV reactors

	GFR	LFR	SCWR	VHTR
Model A	n.a.	n.a.	Acc. assess. Rankine cycle	n.a.
Model B	He	n.a.	n.a.	He
Model C	He	LiPb-cooling Supercr. CO_2 Nat. convection Materials	n.a.	He-cooling Brayton cycle Materials
Model D	He	LiPb-cooling Materials	n.a.	Brayton cycle Materials

The choice between the Generation 4 candidates is just to exemplify the most obvious synergy effects that we see between present and future reactor technology. Thermal hydraulic simulation codes enlarge their range of applications and validation. We have extended the initially for fission reactor studies used, APROS code [6] for fusion reactor modeling and also for the interests in Generation IV activities related to SCWR. SCWR has interesting potential synergy with present nuclear power plants and with fusion technology research programs. SCWR has major economic advantages, high efficiency, possibilities for direct and indirect hydrogen production and also a reasonable deployment time in respect to predicted launch of detailed fusion DEMO projects.

Today, SCWR and fusion research are mainly motivated as mid-term technology projects. Candidate materials for SCWR are known and the considerable spin-offs are already now available in fossil fuel plants. The Technical Research Centre of Finland has previously participated in the HPWLR project [9] and has the technology for materials testing in an autoclave of 45MPa/695C for supercritical water.

6. Conclusions

To improve the economic potential of various new nuclear power plants:

- direct construction costs must be lowered (optimal thermal size),
- construction times must be minimized,
- efficiency improved (high temperatures),
- longer economical lifetime (40 a or more) if compatible with variable costs,
- maximum plant availability
- lower re-circulation factor

Fusion R&D is facing huge challenges in these features. Internal use of C&D power should be cut to less than 100 MWe for GWe-level plants and new O&M methods has to be developed to keep the plant availability acceptable. Some of the safety systems of present fission power plants could have a lighter and less expensive design in fusion reactors provided their safety case will be shown.

The various nuclear generations may appear simultaneously but their economic environment may lead to a natural sequential development instead of full parallel competition. All alternatives have also many cross-cutting features concerning safety and technology. In a longer run the species might coalesce to hybrid reactors or to symbiotic systems.

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