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The Economics of Fast Breeder Reactors [and Discussion]

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The economics of fast breeder reactors

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The overall status of the fast breeder reactor (FBR) system is periodically reviewed in France. In 1983, a report was prepared on the status and prospects of the FBR system at the request of the then Minister of Industry. Five years later, Electricité de France (EdF) and the French Atomic Energy Commission (CEA) jointly updated this report. The FBR reactor system economic considerations mentioned here are taken from the work performed in 1987–88 for this updating. The position in 1983 is reviewed to highlight concrete developments. Developments that have occurred since then are presented, along with the prospects that today enable us to define better the technical and economic potential of the FBR system. In conclusion, the effects of these findings on desirable directions are discussed, in particular with regard to European FBR cooperation.

1. FBRs in France in 1983

In 1983, the crude oil market had eased considerably, but cautious attitudes remained in the face of the possibility of new crises. OECD forecast yet further growth of nuclear power until the year 2000. On balance, it seemed reasonable to be ready to introduce FBRs at the beginning of the 21st century.

However, in this transition period it seemed that the introduction of FBRs, would be dependent upon the ability of this reactor system to compete with light water reactors (LWRs). The possibility of a uranium crisis was becoming more remote, and was not by itself sufficient to warrant FBR introduction. Therefore, everything was done in France to make FBRs competitive with LWRs.

This was the context in which the 1983 economic evaluation of future FBRs was performed. The following technical bases were used for the estimates.

Reactors

Phénix had been in operation for 10 years and the system has been proved sound.

The burn-up achieved was *ca.* 100000 MW d t^{-1}. Construction of SPX 1 continued apace. More than 80% of the facilities had been completed. No particular problems were revealed in the safety reports.

New orientations for a more advanced reactor, the '1500 MW_e project', had been almost completely defined and thought was being given to even more basic possible evolutions.

Fuel cycle

To accompany Phénix operation, 25 t of fuel were manufactured and 12 t reprocessed, half in the Marcoule pilot plant and the other half in dilution at the UP2 plant in La Hague. The economic evaluations based on these technical data are summarized in table 1.

TABLE 1. EVOLUTION OF BASE-LOAD FBR KILOWATTHOUR COSTS

(Figures are in French cents per kilowatthour under the economic conditions prevailing on 1 January 1982, including interest paid during construction and excluding taxes on operating costs. After Lorino (1984).)

	reference PWR (P'4)	Creys-Malville	1500 project (1986–92) SPX 2	first of a kind
investment	8.5	22.6	16.9	11.0
operation	3.2	5.0	4.7	4.0
fuel	5.3	10.0	8.7	4.7
total	17.0	37.6	30.3	19.7
ratio FBR:PWR P4	—	2.21	1.78	1.15

2. FBR PROSPECTS EVALUATED IN 1987–88

Studies in the 1980s had essentially been oriented toward lowering costs while respecting safety requirements at least equivalent to those of LWRS. To ensure that the evaluations were as credible as possible, they had to be based on data backed by as many nuclear industrial partners as possible. This matter was continually borne in mind for the technical and economic approach.

2.1. *Bases for establishing cost*

What were the new technical and economic bases used for economic evaluation updating?

Reactors

Phénix. In addition to an average load factor of 62% over 15 years guaranteeing the viability of options, the main demonstration concerned the achieving of high burn-up. In 1988 the burn-up for 1200–1500 MW_e cores was set at 120000 MW d t^{-1}. In 1993 qualification underway should guarantee a burn-up of 150000 MW d t^{-1}. PFR results confirm these values.

Creys-Malville. Nominal power was reached in December 1986 after a long set of scheduled tests that confirmed the performances expected from the NSSS. However, the fuel storage drum incident delayed start-up and, as a result, experience of operating behaviour. The real cost of the power plant is now well established and its various components have been analysed.

The '1500 MW_e *project*'. In the prospect of building an FBR series by 2000, NOVATOME was asked in 1983 by EdF to carry out preliminary studies for the design of a new 1500 MW_e reactor. This reactor was to benefit from Creys-Malville design and construction experience and would take into account new results from advanced option studies. An official recommendation from the safety authorities set out the safety goals to be obtained. Finally, the rules for the design and construction of FBRS were drawn up to guarantee stringent quality.

This project was completed at the end of 1987. The design was accompanied by a price estimate gleaned from industrial consultations for the main power plant components. In 1987–88, examination of the safety report by the competent authorities concluded that such a project was feasible in France provided that some modifications were made.

An advanced FBR. To achieve competitiveness, parallel to the 1500 MW_e project the CEA and EdF, in association with industry, set up an organization to propose new technical orientations for the next step, aimed at lowering the cost of future projects. The conclusions of this work, accompanied by industrial price consultations, were submitted in 1985. Development activities ensued.

Transition from construction of an isolated reactor to a reactor series. All the above-mentioned analyses were aimed at defining an economic nuclear power plant model. To this had to be added the effect of power plant construction in series. This effect is taken into account here, as drawn from a 1986 study commissioned by the Commission of European Communities. This study allowed collection of the opinions of representatives of European nuclear industry on series effect evaluation on the basis of the Creys-Malville project.

Fuel cycle

Concrete data are available from Phénix core operating experience and fabrication of the first two cores for Creys-Malville. For Phénix, 37 t of fuel were manufactured and 15 t reprocessed. Some of the plutonium has already been through the core and the reprocessing and fabrication plants four successive times. Similar experience exists for PFR. For Creys-Malville, 77 t of fuel were manufactured in the Cadarache complex.

These experiences allowed CEA to undertake with Cogema, on a precise basis, preliminary projects for facilities dedicated to fabrication and reprocessing of FBR fuel. Two projects were successively implemented: first, MAR 600 in 1984–85, a medium-sized fuel reprocessing plant (50 t a^{-1}); second, in 1986–87, a large plant able to manufacture and reprocess fuel from 15 or 30 FBRS.

Each of these projects was the subject of a precise analysis of capital and production costs. Design and construction experience from the La Hague plants, including UP3, provided a suitable framework for these projects.

Finally, the introduction of MOX fuel in PWRS owned by EdF led Cogema to examine in detail the conditions for reprocessing this type of fuel in dilution with standard fuel in the planned UP2 800 plant. This examination also enabled, within the framework of this dilution procedure, an estimate to be made of reprocessing costs during the initial phase of FBR introduction.

The bases for establishing costs are thus founded on results sanctioned by extensive experience in pilot facilities operating on an almost industrial scale and backed by nuclear industry companies both for the reactor and the fuel cycle.

2.2. *Cost presentation rules*

To evaluate the future of FBRS, we have chosen to assess costs for reactors commissioned in series in 2010. This date corresponds to a time when EdF should begin to replace its nuclear plants, and is thus of great interest to France. The justifications mentioned previously for establishing these costs cover work performed in the past few years. Projecting ahead to 2010, new advances in technology between now and then should also be taken into account. This is obviously difficult. The progress coefficients used here have been evaluated on the basis of partly studied new technical options that have not been fully qualified yet.

Since the goal to make FBRS competitive with LWRS, we also had to take into account probable developments concerning LWR investment and fuel costs by the year 2010. We thus assumed that capital costs would fall by a few percent while a greater decrease is expected in terms of fuel cycle costs because of higher burn-up, improved reloading schedules and a probable decrease in the cost of services, particularly enrichment.

To permit comparison between FBRS and LWRS, we also had to make assumptions on uranium price trends. For this, we used the French official hypothesis. As a result, the comparisons will be presented for two uranium price scenarios, a low one assuming an increase of 1 % per year and a high one assuming a revival of the nuclear option by 2000.

The economic lifetimes adopted are 25 years for power plants and 40 years for fuel cycle facilities. The discount rate is the official French rate of 8 %. The data selected to establish reference costs are obviously questionable. Thus a sensitivity study will complete this economic evaluation. The cost calculation method used is that of levelled costs, which is now commonly used by official authorities such as the OECD-NEA, UNIPEDE, etc.

2.3. *Investment costs*

The comparative investment costs for the NSSS are given on the above-mentioned bases for different phases of reactor development, i.e. Creys-Malville, the 1500 MW_e project, a European Commercial Prototype Reactor (RPCE), and European Commercial Reactor (RCE) that would begin to be commissioned in series in 2010. We also present the reference PWR for the same period. (See table 2.)

Table 2. Investment costs[a] NSSS and auxiliaries (FF_{86}/kW_e net)

one unit on the Creys-Malville site commissioned in 1995			series reactor on a new site commissioned in 2010	
SPX 1	1500 project	RPCE	RCE	PWR
9100	5700	5000	3400	2200

[a] These costs (rounded-off) are construction costs excluding prime contractor expenses, interest paid during construction, pre-operation costs and provisions for decommissioning.

Another approach to measuring technical and economic progress was made by evaluating the weight of special steels used in the construction of the NSSS for each model. This lends additional credibility to the construction costs. (See table 3.)

Table 3

	SPX 1	1500 project	RPCE
mass of special steels/(kg kW_e^{-1})	12.5	6.8	5.5

2.4. *Electricity generating cost*

To determine the kilowatthour cost, operation and fuel cycle costs had to be added to power plant capital costs (NSSS with, in addition, the conventional part of the facility, which is not detailed here). The operation costs are based upon current power plant operating experience and are a function of capital investment.

To determine the fuel cycle cost, we have to set the specific costs of fuel cycle services and natural uranium for FBR and PWR fuel cycles at the horizon considered. The values used here are given in tables 4 and 5.

Price of fissile materials

Natural uranium. Low assumption: 36 \$/Lb U308 in 1995 + 1 % by year thereafter; high assumption: 39 \$/Lb U308 in 1995 + 2 to 5 % by year, depending upon the periods.

Plutonium. We have given plutonium an equivalence value inferred from the price of uranium, assuming equivalent energy use in PWRs. This hypothesis relies upon the assumption

Table 4. Specific fbr fuel cycle costs for commissioning in 2010 with technical progress

FF$_{86}$(kg heavy metal (HM))$^{-1}$	hypothesis[a]	hypothesis[b]
fabrication	3900	2800
reprocessing	21000	14000
transportation and waste management	1400	1400

[a] Fuel cycle facilities adapted to feed 15 reactors.
[b] Fuel cycle facilities adapted to feed 30 reactors.

Table 5. Specific pwr fuel cycle costs for commissioning in 2010 with technical progress

enrichment	(FF$_{86}$/SWU)	850 in 2005 500 in 2020
fabrication	(FF$_{86}$/kg HM)	1400
reprocessing	(FF$_{86}$/kg HM)	4550
transportation and waste management	(FF$_{86}$/kg HM)	900

Table 6. Electricity generating costs for series reactors commissioned in 2010

cF$_{86}$/(kW h cost)	RCE[a]		PWR[a]	
capital	13.5		10.7	
ratio RCE:PWR	1.26		—	
operation	4.4		3.9	
	LH[c]	HH[c]	LH[c]	HH[c]
fuel cycle[b]	4.0	4.4	5.0	6.3
total cost/kWh	21.9	22.3	19.6	20.9
ratio RCE:PWR	1.12	1.07		

[a] For RCE, burn-up is 150000 MW d t^{-1} and breeding gain 0.2. For PWR, burn-up is 45000 MW d t^{-1}.
[b] Fuel cycle facilities adapted to 15 reactors feeding.
[c] LH, low hypothesis; HH, high hypothesis, for uranium prices.

Table 7. Electricity generating costs for prototype reactors commissioned in 1995

cF$_{86}$/(kW h cost)	Creys-Malville	RPCE	PWR-N4
capital	35.3	18.6	11.8
operation	7.6	5.3	4.3
fuel cycle[a]	8.5	4.2	5.5
total	51.4	28.1	21.6
FBR–PWR	2.4	1.3	

[a] With plutonium value established on the basis of low uranium price hypothesis.

that a plutonium market will exist at the horizon considered. On the basis of this set of assumptions, we have the figures given in table 6.

It is also interesting to estimate what the cost of the kilowatthour would be in the transition period preceding the launching of a series. This cost is given in table 7 for a prototype reactor preceding the RPCE series and in comparison to Creys-Malville and the PWR N4. It was evaluated on the above-mentioned bases, but takes into account the fact that the FBR model would not be at its optimum and that fuel fabrication and reprocessing would be performed in existing plants.

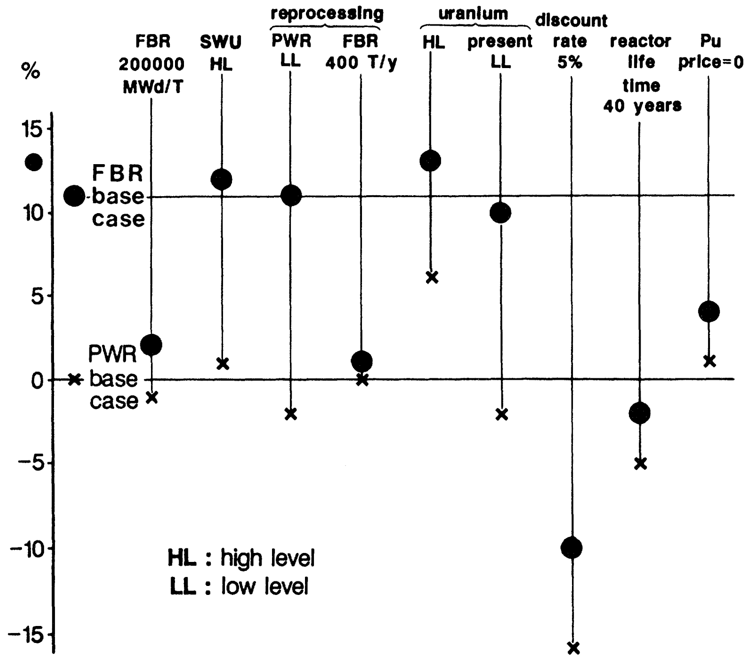

FIGURE 1. Effect of various sensitivities on generating costs.

Finally, given the uncertainties attached to the reference values used for each component of overall costs, we have indicated the sensitivity of these costs to fluctuations in several of its components (see figure 1). From this figure can be pointed out the full weight of certain technical parameters, such as the burn-up and the size of reprocessing plants for FBR. Taking into account the isolated or cumulative effect of certain parameters, it shows that it would be possible to reduce the margin between FBR and PWR kilowatthour, and even to achieve competitiveness.

3. COMMENTS UPON FBR ECONOMIC ASSESSMENT

We have entered a new phase of FBR economic evaluation. Its bases lie in experimental reality at a large enough scale and industrial studies devoted to projects that clearly and accurately outline reactor and fuel cycle data. The largest step for reactors has been taken through system simplification, compactness, analysis of value at all levels, and the series effect.

For the fuel cycle, the main points are high burn-up rates and effect of scale obtained in large specific plants. However, it would be appropriate to examine whether multipurpose reprocessing plants might not lead to similar results, especially since they would be better suited to the transition phases from one reactor system to another.

In the French context, the challenge of FBR competitiveness is very hard to meet. In fact, it means rivalling a large number of highly standardized PWRs (close to 50) with extensive operating experience. Nuclear kilowatthour costs for several large countries are given in table 8 to illustrate this point.

Despite the very low relative cost of the French nuclear kilowatthour, it should be possible for FBRs to meet this challenge if an overcost of some 10 % is accepted in the event that the price of uranium remains low. Some further qualitative advantages of the FBR should also be taken

TABLE 8. LEVELLED NUCLEAR ELECTRICITY GENERATING COSTS

(In U.S. mills 1987/kWh (OECD 1989) discount rate 5%, plant commissioned in 1995, lifetimes 25 years of service life.)

Belgium	30.8
Spain	45
F.R.G.	42.2
U.K.	38.2
France	28.6
U.S.A.	40.1
Japan	45.6

into consideration: conservation of the fissile material, security of supply, less radioactive release and lower personnel radiation exposure, less thermal effluents, etc.

The main economic trends foreseen at the beginning of the 1960s for this reactor system are thus confirmed: higher reactor capital investment, cheaper fuel cycle and, in all, a cost close to competitiveness. Reference to French estimates from 1983 mentioned earlier shows that, despite several differences in the analysis, the overcost per kilowatthour tends to decrease.

The comparative FBR–PWR results are applicable to two reactor systems that are assumed to have reached maturity and represented by at least a dozen reactors. This will be difficult to achieve because of the need for large reprocessing plants to obtain reasonable costs. This leads to more detailed examination of the probable benefits of a reprocessing plant able to handle standard MOX and FBR fuel.

It should again be noted that these results fall within the assumption of a safety equivalent to that of PWRS. New requirements in this field would increase the kilowatthour cost for both reactor systems, but could give FBRS an edge because of integrated design of the system benefitting from high thermal inertia and facilitating use of natural convection.

None the less, comparison of FBR and PWR reactor systems remains surrounded by uncertainty at this time. Between now and 2010, PWRS will evolve in directions that are hard to predict. Several possibilities are also foreseeable for FBRS. In the same way, the fissile material procurement situation which currently does not cause tensions on the natural uranium market may change completely, and the best use of the plutonium available from spent fuel may become one or even the main criterion of reactor type selection. Corrections would have to be made to the above economic comparison if this were to occur.

4. FBR ECONOMIC PROSPECTS AS SEEN BY OTHER COUNTRIES

The economic evaluations presented above are mainly based on French experience. Other countries have also carried out such evaluations. It is interesting to refer to them and examine how the various results compare. We have decided to look at work done in two countries, the U.K. and Japan, that have recently expressed their point of view on this subject.

In 1989 joint studies by UKAEA, CEGB, NNC and nuclear industry participants were published (Hall *et al.* 1989). Table 9 gives reference values for the kilowatthour cost for FBRS and PWRS, corresponding to post-2000 period.

The French and British evaluations of overall FBR kilowatthour costs are very similar. However, there are marked differences between the components of these costs: capital and fuel cycle costs are higher for the British while operating costs are lower. A more detailed analysis

TABLE 9. EVALUATION OF ELECTRICITY GENERATING COSTS IN U.K.

cost U.K. pence/kWh	follow-on FBRS 1450 MW_e	PWR 1175 MW_e
capital	1.5	1.45
operating	0.2	0.2
fuel cycle	0.32	0.43
generating cost	2.02	2.03

would probably reveal other differences, in particular for the fuel cycle. This is why these two countries have previously expressed two different points of view on the effect of scale on FBR reprocessing plants.

French and British evaluations also produced similar results with regard to the ratio between FBR and PWR kilowatthour reference costs. These two reactor systems should enable to generate electricity at very similar costs. Here again, more in-depth analysis would probably bring to light some differences, if only because of the great difference in the PWRS systems of both countries.

At JAIF in April 1989, Sazaki (1989) presented an assessment of FBR economic prospects. Table 10 gives the figures corresponding to the Japanese evaluation.

TABLE 10. EVALUATION OF ELECTRICITY GENERATING COSTS IN JAPAN

		LWR	
costs yen/kWh	FBR	current	next generation
construction	3.3	3.6	
operation	1.8	1.8	
fuel cycle	1.2	2.3	
generating cost	6.3	7.7	6.2

It is difficult, for reasons related to the difference in the economies of each country, to compare the cost of FBR kilowatthour as evaluated in Japan to those given by European countries. The Japanese results, however, confirm the feasibility of FBRS becoming competitive with PWRS.

CONCLUSION

Each new FBR status and prospect evaluation shows that achieving FBR–PWR competitiveness is increasingly feasible. The evaluations just given by U.K. and Japan on this point confirm the French approach.

As far as the European project EFR is concerned, all the needed efforts to minimize the kilowatthour cost should be done and investments as well as fuel cycle costs have to be lowered. While FBRS will be progressively deployed over a rather long period, adapted reprocessing equipment should be used bearing in mind the economic optimum.

The kilowatthour cost corresponding to competitiveness differs from country to country. The EFR goal must be the kilowatthour cost of the least expensive European partner.

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Discussion

F. J. Barclay (*Energy Consultant, London, U.K.*). Has Mr Rapin any comparison of the generating cost of a British 1175 MW_e PWR and that of a French N4 1500 MW_e PWR?

M. Rapin. I have no direct comparison between these types, but some idea of the benefits from series construction and advanced designs can be gained from the relative nuclear generation costs quoted in my paper: 38.2 mills kWh^{-1} for U.K. against 28.6 mills kWh^{-1} in France. Of course both these costs include those for gas-cooled reactors.

R. H. Allardice (*BNFL, Risley, U.K.*). In Mr Rapin's assessments of PWR costs have you included a MOX fuel cycle option?

M. Rapin. This assessment has only used a uranium-fuelled PWR. Other assessments we have done show there is a small benefit if MOX fuels are used in PWRs.