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Spallation in a Nuclear Energy System

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Abstract

There is a prospect that intense spallation neutron sources may become an efficient tool in alleviating some crucial problems troubling the fission reactor economy. However, the recent concept promotion seems to be based on fragmentary design and engineering considerations and inadequate system characterization. Premature claims may serve short term interests, but may also increase the chance that spallation research be eventually hit by public acceptance problems, if perceived as closely associated with the deployment of fission reactors. Therefore, a careful investigation of the actual benefits of associating fission reactors with intense spallation neutron sources is required. As an illustrative example for a static and dynamic impact assessment, the merits of intense spallation neutron sources as fissile fuel factories for fission converter reactors are investigated and numerical results are presented for typical design proposals.

Spallation in a Nuclear Energy System

M. Heindler

I. Introduction

While most contributions to ICANS meetings view spallation as a neutron source to be developed to serve fundamental research, there is a renewed interest in the potential role of spallation neutron sources in a nuclear energy economy (see Refs. 1 to 8 and papers quoted therein).

To a great extent this interest is motivated by the increasing recognition that external intense neutron sources could potentially represent a solution to those fission related problems which call in question both the public acceptance and the long-term prospect of the fission reactor economy. Also the accelerator community partly joins in the promotion of this new field of application for their technology, and weapons programs (Ref.9) as well as the initial fuel requirements for a DT-based fusion energy program may call for spallation as a future source for tritium.

This interest is also based on the promise that intense spallation neutron sources can be developed as a straight-forward extension of present spallation neutron source projects, such as those discussed at this and previous ICANS meetings; it has been claimed that there is no technological quantum jump required for the transition to high power designs as a result of the experience with advanced accelerators accumulated in high energy physics research (Ref.4) and of the benefit that can be taken from proven fission reactor technology. However, some requirements are recognized to be beyond the present experience in thermal and fast fission reactors (Ref.3) and may be closer to those associated with a fusion reactor (Ref.1o).

In a time period in which the fission reactor industry of important countries suffers from an unprecedented stalemate, there seems to be only modest tendency to be critical with respect to the apparent tension between "vision" and "realism" in dealing with emerging concepts. Hence, the ICANS community may wish to consider seriously the proper assessment of the spallation-fission synergism ideas,even if the near-term application of spallation neutron sources as research tool dominates its interest.

II. Spallation-Fission Synergetics

The idea to link spallation and fission goes back to the post-World War II period when fissile material needed for the US weapons program was thought to be in short supply. The MTA project was established in the US with the goal of producing spallation neutrons via the high-energy proton induced reaction

$$p + (\text{high Z nuclei}) \rightarrow \nu_{sp} n + (\text{residual nuclei}) \qquad (1)$$

and to use the emerging ν_{sp} neutrons to transmute fertile into fissile fuel,

$$^{232}\text{Th} + n \rightarrow \ldots . \rightarrow {}^{233}\text{U}$$

$$^{238}\text{U} + n \rightarrow \ldots . \rightarrow {}^{239}\text{Pu} \qquad (2)$$

With the discovery of ample resources of natural uranium and the successful development of the fission reactor technology, the MTA project was terminated.

Until recently, no need for non-fission neutron sources was perceived for the civilian application of nuclear power. This resulted from the firm belief in the early market penetration of fast fission breeder reactors and of the associated fuel cycle which would make full use of the natural fissile and fertile fuel resources. Only Canada has been showing a continued interest in spallation neutron induced fertile-to-fissile conversion for their CANDU program (Ref.8).

This situation has significantly changed in view of the actual development of the nuclear energy technology and economy which is far from meeting original expectations. Problems plaguing the fission reactor community are, amongst others, (i) the broadened insight into the consequences of a large scale deployment of nuclear energy based on low-converter reactors such as the LWR, showing the threat of local or even global unvailability of cheap fissile fuel as a consequence of the delayed market introduction, the economy and the marginal breeding capacity of fast breeder reactors; (ii) the growing concern regarding the link between nuclear weapons proliferation and the civilian nuclear fuel cycle, which motivated the International Nuclear Fuel Cycle (INFCE) studies and the Nonproliferation Alternative Systems Assessment Program (NASAP); (iii) the lack of public acceptance of specific aspects of the nuclear energy program, such as fission reactor safety and the nuclear waste management program.

To a great extent these problems can be seen as symptoms of the scarcity of neutrons in the fission cycle. This scarcity has been defining by and large the current nuclear energy program, which aims at stand-alone fission reactors. Therefore intense external neutron sources -- such as spallation or fusion -- may offer an answer to the above problems, as they potentially offer the following novel options:

(i) Intense spallation neutron sources as an alternative to the introduction of fast breeder reactors, or as a means to accelerate their introduction by providing for the initial fissile fuel requirement. In both cases this is based on the extension of the fissile fuel resources by neutron induced transmutation of plentiful fertile material into fissile fuel, Eq. (2).

(ii) Intense spallation neutron sources as enricher and rejuvenator of fuel contained in fission reactor fuel elements. These novel options for the nuclear fuel cycle are based on the in situ enrichment of fresh fuel elements and the rejuvenation, or re-enrichment, of spent fuel elements respectively, in high-flux neutron fields with appropriately tailored spectral distribution (Refs. 11,12,13). Thus the proliferation resistance may be increased by reduction or even elimination of the need for fissile enrichment in isotopic separation plants and for reprocessing of spent fuel elements.

(iii) Intense spallation neutron sources also offer novel options for the nuclear waste management by their potential to reduce the amount of radioactive waste by neutron induced transmutation of hazardous radioisotopes into less hazardous, or even stable ones in high-flux neutron fiels (Ref.4). With respect to nuclear waste incineration, the spallation source seems to be unrivaled as very high neutron fluxes are essential to its successful application.

(iv) The availability of external neutron sources could change the design requirements for advanced fission reactors by shifting the emphasis from neutron balance to safety considerations. This may point to a long-term deployment of fission power with high-converter reactors, offering safety features that may be superior to those achievable with fast breeder reactors.

III. Towards a World of Neutron Abundance ?!

This potential beneficial role of intense external neutron sources in a fission reactor economy gave rise to a wealth of ideas on how to combine various nuclear processes -- such as fission, spallation, fusion, breeding, transmutation, etc. -- in novel ways to yield a synergetic nuclear energy system that might be more acceptabele than current stand-alone fission reactors (Refs. 14,15).

However, many of the ideas promoted have enjoyed limited or only fragmentary investigation. A number of crucial factors remain to be demonstrated under realistic conditions and technical feasibility as well as engineering practicality has not yet been tackled seriously for various systems components, such as the high power target/blanket unit of an intense spallation neutron source, to name one example of interest here (Refs. 3,1o). It seems therefore important to note that the traditional approach in selecting crucial design parameter -- such as beam power and intensity, target power multiplication, etc. -- is to "adjust" these data within "reasonable" limits to yield an overall spallation source performance which seems desirable.

Scepticism is occasionally expressed with respect to the question whether intense spallation neutron sources should be and could be developed for integration into the fission reactor economy. However, little attention has been paid to a realistic examination of the impact of spallation-fission systems on the future nuclear power market in the event that the various system components can eventually be built and operated as proposed. This criticism equally applies to other emerging energy concepts such as fusion-fission systems (Ref.17).

In our analyses (Refs. 18 to 21) we take the following approach:
We assume the feasibility of intense spallation neutron sources as described in various design proposals and evaluate the actual impact which such spallation sources would have on the fuel and power market. Clearly this impact will not only depend on the performance of the spallation neutron source, but also on the performance of the companion fission reactors, on the associated fuel cycle and on the rate at which the energy system is assumed to grow. The impact is evaluated in terms of appropriately chosen system merit parameters which directly reflect the "price" to pay for the introduction of spallation sources into a fission reactor economy per unit energy supplied to external costumers, depending on their use as fuel producer, enricher, rejuvenator and/or waste incinerator. This price will here be expressed in physical units such as energy efficiency of the system, beam power requirement per unit net power to the grid, etc. Based on these results an economic analysis can be undertaken, translating our physical units into any currency, such as constant Dollars. This then can be used to define cost break-even points (e.g. mined vs. spallation produced fissile fuel), but also to formulate requirements which spallation neutron sources will have to meet in any nuclear energy scenario.

In particular we emphasize here the role of spallation neutrons in breeding fissile fuel for use in fission converter reactors such as LWRs, HTGRs, HWRs. The possible role of spallation neutrons for the incineration of nuclear waste and for the full of partial replacement of chemical reprocessing by rejuvenation of spent fuel elements in a spallation neutron field will be touched upon only qualitatively in this paper.

IV. Static Analysis of Spallation Breeders

We first consider a zero growth nuclear energy system in its operational equilibrium. This system is conceived to consist of fission converter (FC) reactors which receive their fuel requirement from an associated spallation breeder (SB). In some cases only "topping enrichment" will be provided by the spallation breeder with some fissile fuel supplied from external sources, e.g. in the form of natural uranium (Ref. 8). It is common practice to characterize the breeding performance of the spallation breeder in terms of static support ratios, such as (i) the "number" support ratio defined as the number of fission reactors supported by one spallation breeder, or (ii) the "electrical" support ratio, that is the number of GWe fission power supported per GW beam power, etc.

In order to evaluate these support ratios, we need to know the specific fissile fuel requirement of a fission converter reactor described in tons of fissile fuel per year per GWe installed capacity; typical values found in the literature are

$$y_{FC} = \begin{cases} 1.2 \; ; & \text{LWR-OT (Pu)} \\ 0.8 \; ; & \text{LWR-OT, HWR-OT (U3,U5)} \\ 0.48 \; ; & \text{LWR (U5,Pu)} \\ 0.3 \; ; & \text{LWR, HTGR (U3)} \\ 0.1 \; ; & \text{HWR, advanced HTGR (U3)} \end{cases} \quad ; \quad [\text{t/a/GWe}] \tag{3}$$

As indicated these values apply to various fuel cycles -- reprocessing and full recycle in general, once through if labeled "OT" -- and to various types of fissile fuel. Some of the above combinations of reactor types, fuel types and fuel cycles are being deployed, such as LWR-OT (U5,Pu) and HWR-OT (U5), others are more or less remote options envisaged for the future.

Concurrently, the breeding performance of a spallation source is here characterized by the specific breeding capacity in tons per year per GW beam power. Typical values for lead-bismuth targets are

$$y_{SB} = \begin{cases} 2.5 \; ; & \text{(Pu)} \\ 1.5 \; ; & \text{(U3)} \end{cases} \quad ; \quad [\text{t/a/GW beam}] \tag{4}$$

This fissile fuel yield is quite insensitive to the proton energy, but may considerably vary depending on the blanket and target design. Recently, considerably higher breeding capacities have been predicted for uranium targets (Ref. 4). Note, however, that the data available for y_{SB} result generally from one-dimensional calculations with computational models and data files that have yet to be checked against experimental results. Therefore this parameter is still subject to much uncertainty; it will eventually have to be established from space and time dependent isotopic built-up and burn-up calculations, which account for the spectral and density variation with space and time of the neutron flux and of the isotopic concentrations, and for the actual fuel management scheme.

The steady state fissile fuel balance equation

$$y_{SB}P_p - (1-f_{ext})y_{FC}P_{FC,e} = 0 \tag{5}$$

then provides the coupling condition between the spallation and the fission component of the synergetic system. In Eq.(5) f_{ext} is taken to be the fraction of fuel provided from sources external to the synergetic spallation-fission system, P_p and $P_{FC,e}$ is the nameplate power of the accelerator beam and of the fission converter reactor, respectively.

The electrical support ratio results immediately from Eq.(5):

$$P_{FC,e}/P_p = (1-f_{ext})^{-1} y_{SB}/y_{FC} \tag{6}$$

As an illustrative example let us consider two proposals by the Brookhaven National Laboratory, the LAFER (Linear Accelerator Fuel Enricher and Regenerator, Ref.13) and the most recent design proposal, the ASR (Accelerator Spallation Reactor, Ref.4). The former has a liquid lead-bismuth target, the latter a metallic uranium target making the ASR power-self-sufficient. The reported and derived characteristics of these two spallation breeder proposals are listed in Table I.

Reported Data		LAFER	ASR
Parameter	Unit		
proton energy	GeV	1.5	2.0
beam power	GW	0.45	0.60
beam current	A	0.3	0.3
accelerator efficiency	-	0.5	0.5
Pu production	t/a	1.2	3.7
thermal power generated	GWt	1.35	3.6
net thermal-to-electric eff'y	-	0.33	0.33
power required for acc.	GWe	0.9	1.2
Derived Parameters			
specific breeding capacity	t/a/GW	2.67	6.17
Q-value (electric-to-electr.)	-	0.50	1.00

Table I: Spallation breeder parameters

The number of fission reactors that can be supported with one LAFER and one ASR, resp., is calculated from these data and shown in Table II.

Fission Converter Reactor	Fuel	Fuel Cycle	Number Support Ratios LAFER	ASR
LWR	Pu	OT	1.0	3.1
LWR, HWR	U3	OT	0.9	2.8
LWR	Pu	rec.	2.5	7.7
LWR, HTGR	U3	rec.	2.4	7.4
HWR, adv. HTGR	U3	rec.	7.2	22.2

Table II: Number support ratios obtained with two typical spallation breeder designs.

As can be seen, one spallation breeder supports one to three LWRs if reprocessing is prohibited, and two to eight LWRs if fissile fuel contained in spent fuel elements is fully recycled.

As is evident from Eq.(5), the support ratio can be considerably increased if one does not impose the condition of complete fuel self-sufficiency, $f_{ext} > 0$; this then explains the higher support ratios abtained in Ref.4. Clearly this "improvement" severely reduces the fuel resource utilization, that is the fission power that can ultimately be achieved from existing fissile and fertile fuel resources.

At this point in the analysis, the physics assessment of a spallation breeder design proposal typically ends, followed by an economic assessment yielding, for example, the break even price for yellow cake (U_3O_8), for which the spallation breeder starts to be competitive.

V. The Power Cycle of Spallation Breeders

The analysis in the previous section yields a characterization of the performance of the breeder in terms of tons of Pu or U3 bred per year. However, it does not respond to the question for the impact of a synergetic spallation-fission system on the external fuel and power market.

As an illustrative example let us consider one LAFER-type spallation breeder, Table I, supporting 2.5 Pu-fulled 1 GWe-LWRs, Table II. Out of the 2.5 GWe produced in these fission reactors, only 2 GWe reach external customers; the rest is required as make-up power for the accelerator and for operation and control of the spallation breeder. Since the quantity of interest is clearly the electric power available to the consumers rather than the power produced in the system, the conventional support ratios should be replaced by system parameters which describe the system-consumer interface rather than system components. For instance we may define a "net" support ratio by

$$\frac{P_{o,e}}{P_p} = \frac{\text{electric power to the grid}}{\text{beam power}} \qquad (7)$$

Table III shows this parameter for a synergetic system in which a LAFER-type spallation breeder supports various fission reactors and compares it to the corresponding conventional support ratio, Eq.(6). Only for self-powered breeders -- such as the ASR -- do the two support ratios merge. This illustrates that the power going to the grid may be considerably smaller than the power produced in the supported fission reactors; the difference will increase with decreasing breeding capacity, decreasing reliance on natural fissile fuel resources and increasing power requirement of the accelerator.

It is a particular feature of spallation neutron sources -- in which

Fission Converter Reactor	Fuel	Fuel Cycle	Electrical Support Ratio conventional $\frac{(GWe)_{FC}}{(GW\ beam)}$	Electrical Support Ratio net $\frac{(GWe)_{grid}}{(GW\ beam)}$
LWR	Pu	OT	2.2	1.1
LWR, HWR	U3	OT	2.0	0.8
LWR	Pu	rec.	5.6	4.4
LWR, HTGR	U3	rec.	5.3	4.2
HWR, adv. HTGR	U3	rec.	16.0	14.8

Table III: Conventional and net electrical support ratios for LAFER-type spallation breeders.

they contrast with fusion neutron sources -- that the circulating energy invariably proceeds via the thermal conversion cycle (electrical to rf to kinetic to thermal to electrical) and that the basic nuclear reaction itself is endoergic. Thus the spallation source is inherently an energy sink unless an exoergic reaction is concurring. By choosing a fissionable target material (Th, U8, Unat,...) and/or by admitting an appreciable fissile concentration in the blanket, the proton and neutron induced fission reactions will improve the overall energy balance of the spallation breeder. In principle the breeder can be made energy self-sufficient or even a net energy producer, just by allowing enough fission reactions to occur, e.g. in a near-critical blanket, in which case the spallation breeder would be better described as spallation neutron driven fission reactor (Ref.22), or an Accelerator Spallation Reactor (Ref.4).

However, the problems anticipated for fissionable targets (power density, radioactive load, structural integrity,...) and for high-power blankets (high peak average power ratio, non-uniform fuel built-up, complex fuel management, ...) are considered to be far beyond currently existing engineering and operating experience from fission power reactors, including that with the liquid metal cooled fast breeder. Furthermore a serious deficiency of definitive design calculations and engineering considerations concerning the power cycle is recognized by the authors of breeder proposals (e.g.Ref.23).

This suggests that power-cycle-related design data, in particular the thermal power deposition in the target and the blanket, reflect the wish of their authors to minimize the net power requirement of the breeder, rather than thorough engineering studies. It is worth noting in this context that blanket studies performed for fusion-fission hybrids have recently been tending to minimize the power production in the blanket for technological reasons; this lead to the so-called fission-suppressed blankets (Ref.24). Since many more blanket design studies have been performed for fusion breeders than for spallation breeders, there is reason to believe that more thorough spallation blanket studies will point in the same direction. Thus we consider power self-sufficient spallation breeders to be very remote options.

In view of these tremendous power cycle uncertainties we will characterize the power cycle associated with the spallation breeder by a set of parameters identified in Fig. 1 for which values may be chosen, in a specific analysis, according to one's preference:

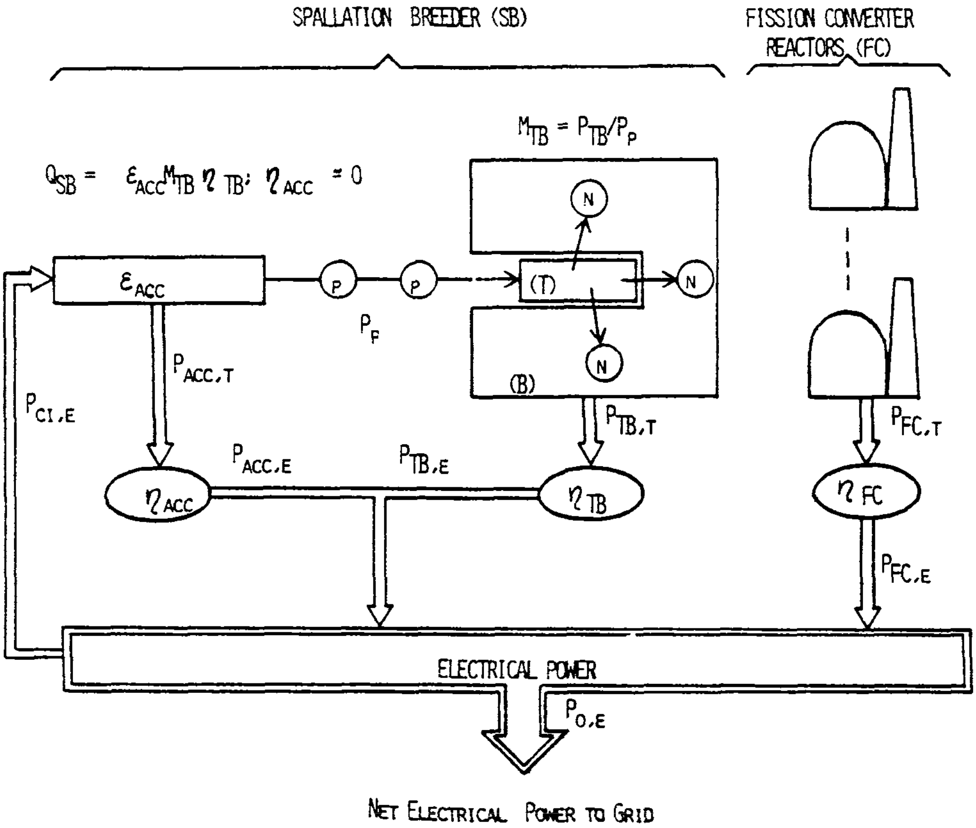

Fig. 1: Power flow in a synergetic spallation-fission system.

(i) Accelerator efficiency ε_{acc} (electric to beam). Typical values are

$$\varepsilon_{acc} = \begin{cases} 0.2 \text{ to } 0.3; & \text{current proposals for next generation of spallation sources for fundamental research;} \\ 0.5 & \text{current proposals for high-intensity spallation sources for energy systems;} \\ 0.7 \text{ to } 0.8; & \text{optimistic estimates based on novel technology.} \end{cases} \qquad (8)$$

It is assumed that the lost power fraction is rejected as low grade heat, which will not be converted into electricity.

(ii) Thermal-to-electrical conversion efficiency of the heat deposited in the target and blanket of the breeder. The similarity to fission power reactors suggests

$$\eta_{TB} \simeq 0.3 \text{ to } 0.35. \qquad (9)$$

Just as the anlogous efficiency η_{FC} for the fission power conversion, η_{TB} is taken to be a net efficiency, accounting for the power requirement for operation and control of the breeder.

(iii) The power multiplication of the target/blanket station, M_{TB}, defined as the amount of thermal power deposited in the target and blanket per unit beam power; this parameter depends on the target material and on the power production in the blanket which, in turn, is determined by the blanket design and the fission fuel concentration. Reasonable values seem to be

$$M_{TB} = \begin{cases} 2\ ; & \text{non-fissionable target, fission-suppressed blanket;} \\ 3\ ; & \text{non-fissionable target, blanket with moderate enrichment;} \\ 6\ ; & \text{fissionable target and for near-critical blanket.} \end{cases} \qquad (1o)$$

This results in an overall electric-to-electric Q value of the breeder,

$$Q_{SB} = \varepsilon_{acc} M_{TB}\, \eta_{TB} \qquad (11)$$

of the order of

$$Q_{SB} = \begin{cases} 0.1 \text{ ; low-efficiency accelerator, non-fissionable target,} \\ \quad\quad \text{fission-suppressed blanked;} \\ 0.3 \text{ ; average design value;} \\ 0.5 \text{ ; high-efficiency accelerator, non-fissionable target,} \\ \quad\quad \text{blanket with moderate fissile concentration.} \end{cases} \tag{12}$$

The value $Q_{SB} = 1$ may be used as an upper bound characterizing a breeder with fissionable target and near-critical blanket. The heat production associated with power self-sufficiency,

$$P_{TB,t} \simeq \begin{cases} 2.7 \text{ GWt ; LAFER-type breeder} \\ 3.6 \text{ GWt ; ASR-type breeder} \end{cases} \tag{13}$$

compares to that achieved in the most recent generation of LWRs, yet it presents an incomparable challenge, due to the considerably higher power densities in the target and to the higher peak-to-average power ratios in the blanket.

VI. Static Impact Analysis of Synergetic Spallation-Fission Systems

We have identified two fundamental system merit parameters, the electrical energy efficiency ε_E and the overall energy conversion efficiency η_o of the system. Another fundamental merit parameter not considered here is the fuel efficiency defined as the fraction of nuclear energy content of natural fertile and fissile fuel transformed, by a given system into useful energy.

The energy efficiency was originally introduced by R.W. Hardie (Ref.25) and is defined as that fraction of the electric power generated in the system which ultimately becomes available to exernal consumers:

$$\varepsilon_E = \frac{\text{electric power to grid}}{\text{electric power generated in the system}} \tag{14}$$

Note that $\varepsilon_E = 0$ indicates that the synergetic system circulates internally all the electric power generated in the system; this apparently constitutes a lower bound for a system which may be termed an "energy" system. On the other hand $\varepsilon_E = 1$ constitutes the theoretical upper bound, which is approached as Q_{SB} and/or y_{SB} approach infinity.

Other merit parameters can be easily derived from ε_E to characterize the size of various system components on a per-unit-power-to-the-grid basis, such as the specific beam power requirement,

$$P_p/P_{o,e} = \varepsilon_{acc}(1-\varepsilon_E)\varepsilon_E^{-1} \tag{15}$$

and the specific circulating power,

$$P_{ci,e}/P_{o,e} = (1-\varepsilon_E)\varepsilon_E^{-1} \tag{16}$$

The second fundamental system-merit-parameter is the overall energy conversion efficiency, defined by

$$\eta_o = \frac{\text{electric power to grid}}{\text{thermal power generated in system}} \tag{17}$$

The inverse of this parameter characterizes the amount of thermal energy that must be handled and, consequently, the amount of fissionable nuclei consumed and of nuclear waste produced per unit electric energy supplied to the grid.

Both system merit parameters can be described in terms of the previously defined fuel and power flow parameters,

$$\varepsilon_E = 1 - \left(\frac{\varepsilon_{acc}}{1-f_{ext}}\,\frac{y_{SB}}{y_{FC}} + Q_{SB}\right)^{-1} \tag{18}$$

and

$$\eta_o = \eta_{FC}\,\varepsilon_E\,\{1+(1-\varepsilon_E)[\,Q_{SB}(\eta_{FC}/\eta_{TB}-1)-(1-\varepsilon_{acc})\eta_{FC}]\} \tag{19}$$

As can be seen from these equations, the energy efficiency of a system with self-powered spallation breeders does not reach unity. In fact, this corrects the common viewpoint that a self-powered system component is energetically "free"; apparently ε_E, η_o and all derived parameters correctly account for the fact that circulating energy is never "free", neither fuel-wise, nor with respect to the associated thermal and radioactive waste.

For our previously discussed examples, LAFER and ASR assisted fission reactors, Table IV displays a few results which clearly show the effect of the spallation breeder on the overall system performance. Note that ASR-type breeders are taken to be power self-sufficient.

Fission Converter Reactor	Fuel	Fuel Cycle	LAFER			ASR		
			ε_E	η_o	$\frac{P_{ci}}{P_{o,e}}$	ε_E	η_o	$\frac{P_{ci}}{P_{o,e}}$
LWR	Pu	OT	0.38	0.10	1.63	0.72	0.21	0.39
LWR, HWR	U3	OT	0.33	0.08	2.00	0.70	0.20	0.43
LWR	Pu	rec.	0.70	0.20	0.44	0.87	0.27	0.16
LWR, HTGR	U3	rec.	0.68	0.20	0.46	0.86	0.27	0.16
HWR, adv. HTGR	U3	rec.	0.88	0.28	0.13	0.95	0.31	0.05
Stand-alone FC	any	any	1.0	0.33	0.0	1.0	0.33	0.0

Table IV: System merit parameters for a LAFER and ASR supported fission reactor economy, resp.; for comparison the last row gives the corresponding values for stand-alone fission reactors.

It becomes apparent that any type of fission reactor associated with a once-through fuel management yields unsatisfactory system performance, even if combined with high-yield self-powered ASR-type spallation breeders. With LAFER-type breeders, only high converting reactors in a closed fuel cycle display attractive features, whereas ASR-type spallation breeders may also favourably combine with moderately-converting fission reactors if the fuel cycle is closed.

As previously noted, there is much uncertainty about the eventual power multiplication of the target/blanket unit of spallation breeders. In order to evaluate the sensitivity of power cycle parameters, we elaborate in Fig. 2 on a medium gain LAFER-type breeder associated with various fission reactors; we take the electrical-out to electrical-in power-ratio Q_{SB} as variable, with the accelerator efficiency being constant. In the case of a system based on LWRs or HTGRs with closed fuel cycles, the sensitivity to the accelerator efficiency is also indicated. Note that a breeder with a low-efficiency accelerator requires a high power multiplication M_{TB} in the target/blanket unit to yield the same Q_{SB} as a breeder with a more efficient accelerator. The achievable limit in Q_{SB} is indicated for $M_{TB} = 3$ and 6 by asterisks and crosses respectively. The description of the energy system by the merit-parameters defined in this section constitutes an essential improvement with respect to the conventional support-ratio-parameters, as they give information that is relevant to the assessment of the system-consumer interface rather than of internal performance parameters.

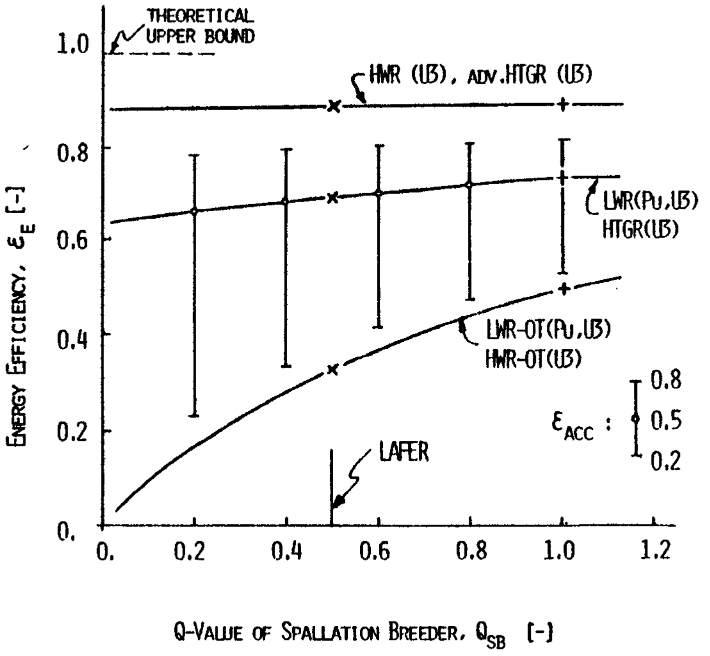

Fig. 2: The energy efficiency of a LAFER-type spallation breeder supporting various types of fission reactors as a function of the electric-to-electric Q value of the breeder. For details see the text.

VII. Dynamic Impact Analysis of Synergetic Spallation-Fission Systems

So far we have considered energy systems in their operational equilibrium, with all fuel flows to be taken constant with time. However both the past development and future expectations show nuclear energy in expansion. Growth rates of the installed nuclear capacity were of the order of 27.5 % from 1968 to 1978 and only little less between then and now (Ref.26). In this case, not only the operating, but also the embodied energy and fuel requirements are of importance; for high expansion rates, the latter may even dominate.

By embodied energy we here mean the energy that has been required to build the energy system. Information on this subject (e.g. Refs.27 and 28 and references therein) is both scarce and vague, in particular in as far as the quality profile of the invested energy compared to that of the energy supplied by the system is concerned. Much uncertainty also surrounds the definition of the system boundary,e.g. whether the power transmission is included or not, whether today's high-grade or tomorrow's low grade ore should be considered, etc. It is also to be noted that the net thermal-to-electrical energy conversion efficiencies η_{TB} and η_{FC} should not only account for operational and control power requirements but also for the energy annually invested into the fuel cycle from mining to reprocessing and disposal, except for initial inventories. In the same realm the embodied fuel is taken here to represent that amount of fissile fuel which has to be accumulated in a device to make it operational.

In a detailed analysis the net amount of fuel and energy made available to or required by each component of the expanding nuclear energy system has to be described as a function of time, accounting for the energy investment during construction, for initial fuel inventories due at time of startup, for pre-equilibrium and eventually equilibrium characteristics. To each of the system components a fuel trajectory $M_i(t)$ (Refs. 29 to 31) and an energy trajectory $E_i(t)$ can be associated, describing the cumulative amount of fuel and energy, resp., that has been made available to or has been required by this system component up to the point in time t. The expanding nuclear energy system -- consisting of an increasing number of fission reactors, accelerator breeders etc. -- may then be described by a system fuel trajectory

$$M_o(t) = \sum M_i(t) = \sum \int y_i(t-t_i)P_i(t-t_i)dt \qquad (2o)$$

and a system energy trajectory

$$E_o(t) = \sum E_i(t) = \sum \int P_i(t-t_i)dt \qquad (21)$$

where y_i is the specific fuel yield (>0) or requirement (<0), Eqs.(3) and (4), P_i represent the respective power terms and t_i the time of startup of the i-th system component. The time-dependence of y_i and P_i accounts for pre-startup and pre-equilibrium features. As has been shown in Ref.3o, these trajectories are "functions-of-merit" which replace, in a non--steady-state analysis, the usual single-valued merit parameters and yield a compact and adequate system description.

In order to simplify the analysis of an expanding spallation-fission system in a first approach, we here replace the exact trajectory by the following quasi-dynamic model:
(i) At time of startup the asymptotic -- rather than the initial -- fuel inventory is loaded, defining the specific fuel inventory.
(ii) The energy required for construction and lower-than-asymptotic thermal energy production during pre-equilibrium operation (e.g. during fissile fuel build-up in the blanket) is accounted for in a single energy investment at time of startup, defining the specific energy inventory.

With these approximations, both the fuel and the energy yield/requirement of a system component can be taken to assume its constant equilibrium value from the very beginning of its operation, as all pre-startup and pre-equilibrium features are embodied in the fuel and energy investments taken to occur at time of startup.

Note that in this model no distinction is made between fuel that is externally supplied and fuel that is breed in situ. As a matter of fact, we have shown in Ref. 3o, taking the fast fission breeder reactor with its loaded core-inventory and its in-situ bred blanket-inventory as an illustrative example, that the cumulative fuel yield/requirement is independent of the way the fuel was originally provided for, as soon as the associated fuel flow reaches its equilibrium.

Let us assume an exponentially growing system taken to consist of spallation breeders and partially or fully supported fission converter reactors. Let us also smooth out the discontinuities due to the actual size of each unit going into operation. This then translates into a growing installed proton beam and electric fission power as described by

$$\frac{d}{dt}P_i = GP_i \quad ; \quad i = p \text{ and } FC,e \qquad (22)$$

Here G is the fractional annual system growth rate, with the associated doubling time $\tau = \ln 2/G$.

As previously indicated, we define specific fuel inventories of fission converter reactors and spallation breeders, in units of tons per GW of electric fission power and beam power, respectively. Again taking typical design values from the literature, we find for the various fission reactors

$$\mu_{FC} = (1+Z_{FC})\cdot\begin{cases} 3.5 \ ; \ \text{HWR(U5),LWR(Pu)} \\ 2.4 \ ; \ \text{LWR(U3,U5)} \\ 1.8 \ ; \ \text{HTGR(U3),HWR(U3)} \end{cases} ; \quad [\text{t/GWe}] \qquad (23)$$

and for spallation breeders

$$\mu_{SB} = (1+Z_{SB})(m_B Q_{SB} \varepsilon_{acc}^{-1} \varepsilon_{SB}) \quad ; \quad [\text{t/GW beam}] \qquad (24)$$

Here Z is the amount of fuel accumulated in the fuel cycle, expressed in units of the asymptotic inventory of the fission reactor and breeder respectively, with $Z_{FC} = 0$ for OT-cycles; otherwise we assume $Z_{SB} = 0.5$ and, perhaps too optimistically, $Z_{FC} = 0.5$. Furthermore, m_B is the specific blanket inventory per percent enrichment in the blanket and per GWe power obtained from the target/blanket unit; clearly, this value is strongly design dependent, with typically $m_B = 0.9$ [t/GWe] .

In addition, we define a specific energy requirement for the fission reactors, π_{FC}, in units of equivalent GWe years per GWe fission power, and for the spallation breeders, π_{SB}, in units of equivalent GWe per GW beam power. The term "equivalent" here alludes to the quality profile of the invested vs. supplied power. We here take $\pi_{FC} = 0.3$ [GWe-years per GWe] corresponding to an energy pay-back time of 0.3 years; we will also assume that, for the same electric power generated, the spallation breeder requires twice as much embodied energy as does the fission reactor, $\lambda_{SB/FC} = 2$:

$$\pi_{SB} = \lambda_{SB/FC}\cdot Q_{SB}\varepsilon_{acc}^{-1}\pi_{FC} \qquad \text{[GWe per GW beam]} \qquad (25)$$

In the quasi-dynamic model, the coupling equation which replaces Eq.(5) now reads

$$(y_{SB}-G\mu_{SB})\; P_p(t) = (1-f_{ext})(y_{FC}+G\mu_{FC})P_{FC,e}(t) \qquad (26)$$

This then defines, in turn, the exponentially growing power which the system makes available to external customers:

$$P_{o,e}(t) = P_{FC,e}(t)(1-G\pi_{FC})-P_p(t)\{\,\varepsilon_{acc}^{-1}(1-Q_{SB})+G\pi_{SB}\} \qquad (27)$$

From these equations, the electrical energy efficiency, Eq.(14), can again be calculated:

$$\varepsilon_E(G) = (1-G\pi_{FC}) - \frac{1+G\pi_{FC}Q_{SB}(\lambda_{SB/FC}-1)}{\varepsilon_{acc}(1-f_{ext})^{-1}(y_{SB}-G\mu_{SB})(y_{FC}+G\mu_{FC})^{-1}+Q_{SB}} \qquad (28)$$

Again for the design proposals for LAFER and ASR as typical examples, we show in Table V the dependence of the energy efficiency on the growth rate for the various reactor types and fuel cycles. Throughout these calculations we have used the design parameters displayed in Table I; furthermore we have assumed an asymptotic fuel enrichment in the breeding blanket of 2 % for LAFER and 4 % for the self-powered ASR, independently of the type of fuel.

Fission Component	LAFER				ASR			
	G =0.	.05	.10	.20	0.	.05	.10	.20
LWR-OT(Pu)	.38	.28	.17	<0	.72	.65	.58	.42
LWR-OT(U3)	.33	.21	.08	<0	.70	.61	.51	.28
LWR-rec.(Pu)	.70	.53	.37	.08	.87	.77	.68	.48
LWR-rec.(U3)	.68	.49	.30	<0	.86	.75	.62	.34
HTGR-rec.(U3)	.68	.52	.36	.03	.86	.77	.66	.39
HWR-rec.(U3)	.88	.71	.53	.16	.95	.85	.74	.46

Table V: Growth dependence of the electrical energy efficiency of the spallation-fission system.

From these results it becomes obvious that even for low-inventory high-converting fission reactors, such as the HWR(U3) with full fissile fuel recycle, the energy efficiency drops considerably with increasing growth rate. For growth rates as low as 10 %, LAFER-type spallation breeders yield energy efficiencies below 5o % -- corresponding to specific circulating power fractions, Eq.(17), of more than 5o % -- with one single exception, that is if they are associated with U-233 fuelled HWRs; for self-powered high-yield ASR-type breeders the energy efficiency ranges from 5o to 75 % for the various fission reactors and fuel cycles, dropping well below 5o % in all cases for growth rates in excess of 2o %.

It is interesting to study the sensitivity of the results to parameters which describe the various fuel cycles and system components. Figure 3 illustrates, for Pu-239 fuelled LWRs with full fissile recycle in association with LAFER-type spallation breeders, the sensitivity of the growth rate dependence of the energy efficiency on the accelerator efficiency, the specific embodied energy, the fissile inventory of the breeding blanket and the fuel cycle inventory fraction; upper and/or lower bounds of the respective parameters are thereby considered, all the other parameters taken to assume the standard values in each case. It becomes obvious that the single most important parameter is the accelerator efficiency which will determine to a great extent the attractiveness of spallation-fission synergetic systems.

VII. Nuclear Fission Waste Incineration and Rejuvenation

Without attempting a numerical analysis of the spallation breeder as nuclear waste incinerator and spent fuel rejuvenator, we may readily gain a qualitative appraisal of the effect of these fuel cycle options on the system merit parameters such as the energy efficiency.

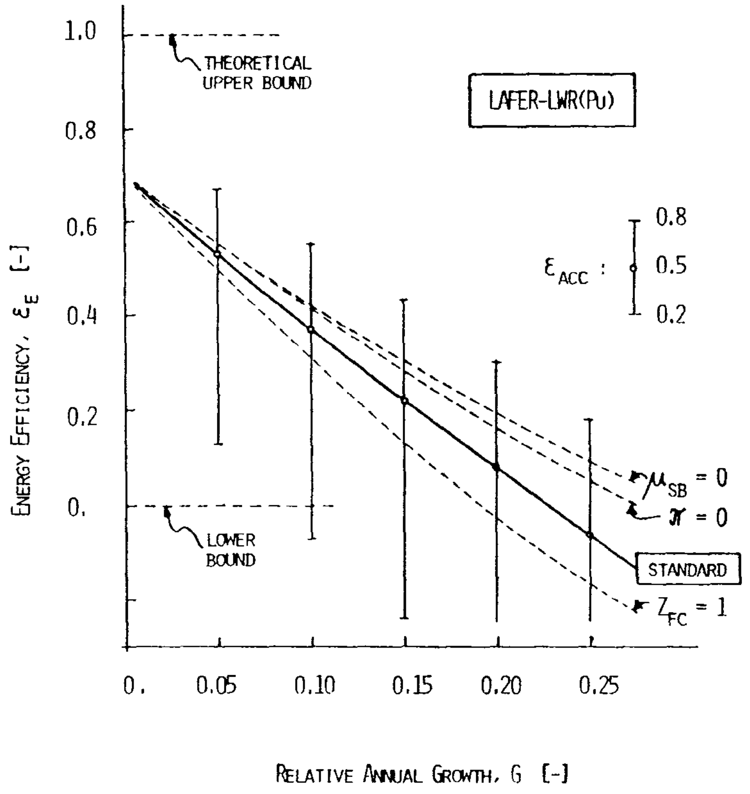

Fig.3: Growth dependence of the energy efficiency of Pu-fuelled LWRs supported by LAFER-type accelerator breeders. For details see text.

The incineration of hazardous radioisotopes produced in fission reactors can be envisaged through beam and spallation proton induced as well as through spallation neutron induced reactions. In particular the latter case, which will invariably occur in the presence of absorbing waste isotopes, will reduce the number of neutrons available for breeding purposes. Also side reactions, reactions with transmuted waste nuclei and the appearance of unstable spallation reaction products will counteract the incineration process, increasing the energy cost of the radiological hazard-reduction of nuclear waste. To include nuclear waste incineration via spallation induced reactions, therefore means necessarily to reduce further the energy efficiency of the synergetic system. The question therefore arises to what extent nuclear waste incineration can be performed before an intolerable fraction of the fission energy is reinvested therein.

The same is true for the rejuvenation of spent fuel as an alternative to chemical reprocessing. The accumulation of fission products in the fuel elements will necessarily have a deteriorating effect on the neutron balance, resulting both in parasitic neutron absorptions and the necessity to achieve increasingly high enrichment in order to compensate for the adverse reactivity effect of the fission and activation products. Preliminary studies show that the fissile fuel breeding requirement will be close to that for a once-through fuel management starting from purely fertile fuel.

In addition, the breeding requirement per unit net power output will clearly increase -- and the energy efficiency accordingly decrease -- with an increasing number of rejuvenation cycles.

Thus the previously discussed use of the spallation neutron sources as fissile fuel factory only, combined with spent fuel reprocessing, definitively yields the most favourable merit parameters for a spallation fission system. The deployment of any supplementary option offered by the physics of spallation processes will invariably tend to adversely affect the system performance and may be justified for reasons other than energy-physics related ones only.

VIII. Conclusions and Implications

This analysis reveals the invariable role of energy and fissile mass as "endowments" towards more secure and complete nuclear energy options. For example, the consideration of the initial fuel requirement of a fission reactor and of the complementary initial power requirement of a spallation breeder, makes fissile fuel and energy sustainability the limits to growth of a spallation-fission based nuclear economy.

The electric-energy efficiency and the energy conversion efficiency of a synergetic system have been shown to describe adequately the system performance with respect to the system-consumer interface, that is with respect to its actual impact on external fuel and power markets. It accounts for all fuel and power flows occuring from the beginning of construction to equilibrium operation of each of the system components, while simultaneously incorporating the effect of a system expansion. A straightforward extension to economic analyses is possible.

The implications of this analysis identify the parameter ranges and system options of interest. The results demonstrate that there is no clear-cut answer to the question of the desirability of the various spallation-fission synergism options. They indicate that, in any event, only high-performance accelerators associated with fuel-efficient fission converter reactors and with a closed fuel cycle show the prospect of an attractive systems performance.

In a steady state operation, the power requirement of a spallation breeder is of minor concern if the breeder is associated with high-converter low-inventory fission reactors.

This aspect changes drastically for an expanding economy, even for expansion rates well below historical growth rates for installed nuclear capacities. In this case there are growth rate dependent trade-offs between the effect of increasing power production and decreasing fuel availibility with increasing blanket enrichment, between invested vs. annual fuel requirements of the associated fission reactors, etc., which require a careful analysis before the question of the feasibility of spallation-fission synergisms can be answered.

The implications of this analysis point also strongly to the fact that a fundamental and engineering analysis needs to be undertaken in order to identify the actual fuel breeding and power amplification potentials of spallation breeders and to realistically estimate the duty factor and the efficiency of high power high-intensity proton accelerators. Only then will a full appraisal of the potential of spallation-fission synergisms be possible.

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Bibliography

1. H.J.C.Kouts, Ed., Proc. of an Information Meeting on Accelerator Breeding, Upton, Jan. 1977, CONF-770107.
2. G.Kessler and P.J.Jansen: Accelerator Breeders and Fission Converter Reactors, Proc. IIASA Conf., Ref. 16.
3. J.S.Fraser: Accelerator Breeder Applications, Proc. IIASA Conf., Ref. 16.
4. M.Steinberg: Accelerator Spallation Reactors for Breeding of Fissile Fuel and Transmuting Fission Products, Proc. IIASA Conf., Ref. 16.
5. Special Session on the Physics of Accelerator Breeding, Transactions of the American Nuclear Society 28 (1978) 754 - 6o.
6. A.A.Harms and C.W.Gordon: A Parametric Analysis of the Spallation Breeder, Nucl.Sci.Eng. 63 (1977) 336 - 41.
7. T.J.Burns, D.E.Bartine and J.P.Renier: Concept Evaluation of a Nuclear Design for Electronuclear Fuel Production; ORNL/TM-6828 (1979).
8. G.A.Bartholomew: Research Opportunities with Prototype Accelerators for an Accelerator Breeder. Proceedings of this Meeting, ICANS-V (1981).

9. Nucleonics Week 22, No. 8, Feb. 26 (1981).

1o. S.O.Schriber: Electronuclear Fuel Production using High-Intensity Accelerators; Proc. First Int. Conf. Advanced Nuclear Energy Systems, Graz, March 1978, Atomkernenergie 32 (1978) 49 - 55.

11. A.A.Harms, W.J.Hartmann: Spent Nuclear Fuel Re-enrichment without Reprocessing; Annals of Nuclear Energy 5 (1978) 213 - 4.

12. J.Dorning and F.Gunnison: On the Feasibility of an Accelerator-Driven Rejuvenator for Light-Water-Reactor Fuel; Transactions of the A.N.S. 32 (1979) 799 - 8oo.

13. P.Grand, H.J.Kouts, J.R.Powell, M.Steinberg and H.Takahashi: Conceptual Design and Economic Analysis of a Light-Water-Reactor Fuel Enricher/Regenerator; Brookhaven National Laboratory, USA, Report BNL 5o838 (1978).

14. A.A.Harms: The Nuclear Energy Continuum and its Spectrum of Choices, Proc. IIASA Conf., Ref. 16.

15. A.A.Harms, W.Haefele: Nuclear Synergism: An Emerging Framework for Energy Systems; American Scientist 69 (1981) 1 - 8.

16. A Perspective on Adaptive Nuclear Energy Evolutions: Towards a World of Neutron Abundance; Workshop of the International Institute for Applied Systems Analysis, Laxenburg, Austria, May 25-27, 1981; Proceedings to be published by IIASA.

17. S.I.Abdel-Khalik, P.Jansen, G.Kessler, P.Klumpp: Impact of Fusion-Fission Hybrids on World Nuclear Future; University of Wisconsin Report UWFDM-333 (198o), Kernforschungszentrum Karlsruhe, Report KfK 2998 (198o).

18. K.F.Schöpf, M.Heindler and A.A.Harms: Energy Production in Stand-Alone and Interactive Fission and Fusion Systems: Proceedings Jahrestagung Kerntechnik, Düsseldorf, March 1981, pp. 621 - 624.

19. M.Heindler, K.F.Schöpf, A.A.Harms: The Effective Breeding Capacity of Spallation Breeders; Proceedings Jahrestagung Kerntechnik, Düsseldorf, March 1981, pp. 625 - 628.

2o. M.Heindler, A.A.Harms: Efficiency Merit Assessment of Emerging Synergetic Nuclear Energy Systems; Proc. 2nd Int. Conf. Emerging Nuclear Energy Systems, Lausanne, April 198o, Atomkernenergie-Kerntechnik 36 (198o) 7 - 12.

21. M.Heindler, K.F.Schöpf: A Dynamic Analysis of the Breeding and Expansion Capacity of Spallation Breeders; in preparation (1981).

22. E.Greenspan: Preliminary Report on the Promise of Accelerator-Driven Natural-Uranium-Fueled Light-Water-Moderated Breeding Power Reactors; Oak Ridge National Laboratory, ORNL/TM-6138.

23. M.Steinberg, J.R.Powell, H.Takahashi, P.Grand, H.J.C.Kouts: The Linear Accelerator Fuel Enricher Regenerator (LAFER) and Fission Product Transmuter (APEX); Proc. 2nd Int.Conf. Emerging Nuclear Energy Systems, Lausanne, April 198o, Atomkernenergie-Kerntechnik 36 (198o) 42 - 46.

24. R.W.Moir: Hybrid Reactors; Lawrence Livermore Laboratory, UCRL-84826 (1981), presented at Jahrestagung Kerntechnik '81, Düsseldorf, March 1981.

25. R.W.Hardie, R.J.Barrett, J.G.Freiwald: Comparative Assessment of Nuclear Fuel Cycles; Los Alamos Scientific Laboratory, LA-8291-MS, June 198o.

26. Another Year of Lost Opportunities, Nuclear News, Aug. 198o, p.73.

27. H.J.Wagner: Der Energieaufwand zum Bau und Betrieb ausgewählter Energieversorgungstechnologien, eine nettoenergetische Analyse; Kernforschungsanlage Jülich, Jül-1561 (1978).

28. C.Held, G.Moraw, M.Schneeberger, A.Szeless: Energy Analysis of Nuclear Power Plants and Their Fuel Cycle; Proc.Int.Conf. on Nuclear Power and its Fuel Cycle, IAEA, Salzburg, May 1977, paper IAEA-CN-36/145, Vol.I, 723 - 29.

29. A.A.Harms, M.Heindler: Life-Time Fuel Trajectories for Fission Reactors, Transactions of the A.N.S. 33 (1979) 125 - 7.

3o. A.A.Harms, M.Heindler: Theory and Application of the Nuclear Fuel Trajectory Concept, Nuclear Technology 53 (1981) 267 - 79.

31. J.K.Presley, A.A.Harms, M.Heindler: Nuclear Fuel Trajectories of Fusion-Fission Symbionts, Nucl.Sci.Eng. 74 (198o) 193 - 8.