SAFETY CONSIDERATIONS IN DESIGN OF FAST SPECTRUM ADS FOR TRANSURANIC OR MINOR ACTINIDE BURNING: A STATUS REPORT ON ACTIVITIES OF THE OECD/NEA EXPERT GROUP

OVERVIEW PAPER

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Abstract

The Nuclear Development Committee of the OECD/NEA convened an expert group for a "Comparative Study of Accelerator Driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles". The expert group has studied complexes (i.e. energy parks) of fission-based energy production and associated waste management facilities comprised of thermal and fast reactors, and ADS. With a goal to minimise transuranic (TRU) flows to the repository per unit of useful energy provided by the complex, the expert group has studied homogenous and heterogeneous recycle of TRU and minor actinides (MA) in the facilities of the complex using aqueous or dry recycle in single and double strata architectures. In the complexes considered by the expert group the ADS is always assigned a TRU or MA (and sometimes a LLFP) incineration mission – with useful energy production only as a secondary ADS goal to partially offset the cost of its construction and operation.

Ancillary issues have also been considered – including ADS safety challenges and strategies for resolving them. This paper reports on the status of the expert group's considerations of ADS safety strategy.

1. Introduction

The term ADS comprehensively includes all non-self sustaining fissioning neutron multiplying assemblies which are driven by an external neutron source provided by a charged particle accelerator and a neutron producing target. ADS systems under current study worldwide include both thermal and fast neutron multiplying media comprised of either liquid or solid (lattice) fuel and driven by either cyclotron or linear proton accelerators and spallation targets (liquid and solid) of various heavy metals. The underlying missions targeted for ADS systems span the range from nuclear waste incineration with ancillary power production through power production with integral waste self-incineration to finally, excess neutron production for the purpose of isotope production via neutron capture reactions on targets.

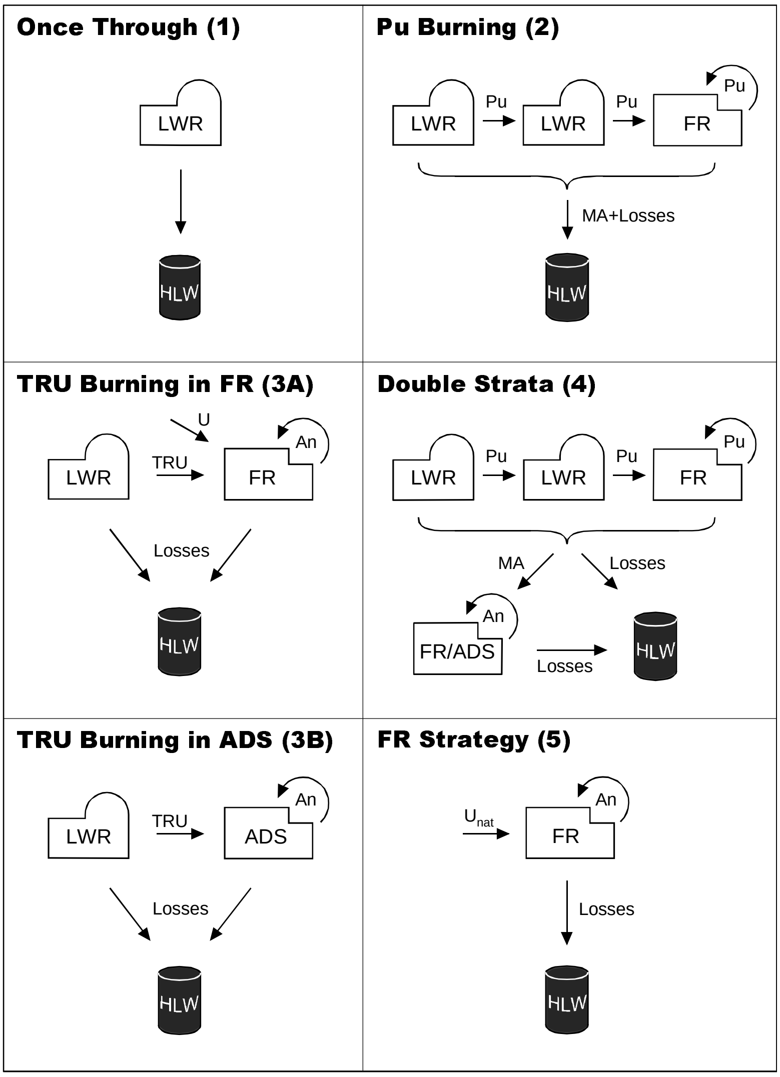
The OECD/NEA expert group on "Comparative Study of ADS and FR's in Advanced Fuel Cycles" [1] confined its scope of inquiry to a subset of ADS configurations – those targeted for nuclear waste incineration with ancillary power production, and specifically those which operate on a fast neutron spectrum with a solid fuel pin lattice. Moreover, the expert group set a requirement of maximum "support ratio" (i.e. maximum energy from the reactors in the complex compared to energy from the ADS in the complex) which leads to inert matrix fuel (i.e. ^{238}U and ^{232}Th – free fuel) for the ADS. The scope of this discussion of safety strategy is similarly confined in scope. Even within the limited scope, a range of possibilities exists. The ADS might be a minor actinide (MA) burner or a TRU burner; the physics and safety characteristics of these cases differ because of differences in their values of β_{eff} (which helps to set the degree of sub-criticality of the ADS) and in their reactivity burn-up swing (which helps to set the control strategy). The choice of coolant (liquid metal or gas) and fuel type (oxide, nitride, metal) also distinguishes members of the ADS class considered by the expert group. The choice of recycle (partitioning) technology (aqueous, dry) directly affects the architecture of the energy complex and indirectly affects the ADS itself. Figure 1 illustrates the several energy producing complexes which were considered by the expert group and identifies the waste management function of the ADS studied in the single strata architecture (3B) and (the double strata architecture (4)).

The fast spectrum, solid fuel, waste incinerating class of ADS considered by the expert group shares with all ADS a distinction from critical reactors in relying on an external neutron source rather than a self generated delayed neutron source for maintaining the neutron population in balance – with attendant changes in dynamic response and in control strategy. However, the class of ADS considered here offers design and safety challenges which are unique vis-à-vis other ADS classes in the areas of burn-up control compensation and reactivity feedback characteristics; these unique challenges are traceable to a small number of salient design features which derive directly from the requirements of the TRU or MA incineration mission – with ancillary power production. The salient design features of the ADS whose safety features were considered by the OECD/NEA expert group include the following:

- Fertile-free transuranic or minor actinide fuel.
- Multiple recycle of fuel to (near) complete fission incineration of transuranics.
- Fast neutron spectrum.
- Choice of coolant (Na, Pb-Bi or He).
- Sub-delayed critical operating state.
- External neutron source created via spallation reactions of high-energy protons on a heavy atom spallation target.

The approach taken by the expert group to identify ADS safety issues and discuss strategies for addressing them was as follows. First, the top level safety functions to be satisfied for any fission chain reacting system (reactor or ADS) were enumerated. Then, the distinguishing features of the class of ADS considered here were traced back to the mission assigned to it in the complex; as a way to indicate which features (and safety issues) would be changed by a change in mission requirements. Then, an impact matrix was constructed (with “safety function” columns and “distinguishing feature” rows) to identify where the ADS distinguishing features have raised safety-relevant challenges which are different from the more familiar situation for a fast reactor. Finally, for each identified challenge, a set of alternative safety strategies for addressing it were discussed with the views that:

Figure 1. **Nuclear fuel cycle schemes**



- Safety should be “designed in” from the outset.
- The vast experience base from fast reactor development should be exploited where possible, e.g.:
  - Defence in depth principles.
  - Single failure criterion.
  - Exploit passive safety principles.

And that in devising ADS strategies, one must:

- Bear in mind that safety implications on recycle and re-fabrication operations accrue to choices made for the ADS *per se* and must be factored in.

The work of the expert group is ongoing with a target for completion by late spring 2001. This paper provides a status report.

2. Safety functions and strategies for fissioning systems

2.1 Basic safety functions for fissioning systems

At a basic level, there are six safety functions to be fulfilled when operating fissioning systems.

1) The nuclear fuel must remain contained within a controlled space because of its radiotoxicity; this is traditionally accomplished by use of multiple containment barriers.
2) Shielding must be kept in place between fissioning and fissioned fuel and humans to avoid suffering radiation damage.
3) A heat-transport path must be in place to carry energy away from the fissioning medium to a heat sink; usually an energy conversion plant.
4) The rate of release of fission energy in the chain reacting medium must be regulated to remain in balance with the rate of energy delivery to the heat sink, so as not to overheat the containment barriers around the fuel and challenge their integrity; a capacity to store heat in the reacting medium and heat transport channel will buffer mismatches of short duration or small amplitude.
5) Since some 5% of the energy liberated from each fission event is initially retained in nuclear bonds of unstable fission products, and since these fission products subsequently decay according to their natural radioactive-decay time constants, a means must be provided for transporting heat from the fission products and transuranics in the fuel for all times subsequent to the fission event. Failure to satisfy the latter two safety functions could lead to overheating of the fuel with the potential to defeat the integrity of the containment and shielding.
6) Operation of the fissioning device in a quasi steady state mode requires a balance of neutron production and destruction rates from one fission chain generation to the next – even as the composition of the chain reacting medium changes due to transmutation and as the absorption, leakage, and neutron production properties of the fissioning medium change with changes in composition and temperatures.

2.2 Safety strategies

Strategies to fulfil the six basic safety functions have been developed and refined over many years for conventional (critical) reactors. The strategy employs defence in depth such that any single failure will not defeat the strategies for meeting safety functions and thereby result in unacceptable release of radiotoxicity; multiple barriers (fuel cladding, primary coolant boundary, and reactor containment building) are used to prevent release of radiation even under accident conditions. Highly reliable (diverse and redundant) systems for controlling and terminating the chain reaction are used to match heat production to removal rate. Highly reliable, redundant/diverse systems for decay heat removal are provided. High quality construction and verification norms minimise manufacturing flaws, and rigorous maintenance, formal procedures, and exhaustive training and certification of operators and maintenance workers are used to minimise the occurrence of human error which could subvert the achievement of the safety functions. Once safety is "designed into" the system, its efficacy is judged by an independent safety regulative authority on a plant-by-plant basis prior to deployment and during its operation.

In recent years, the fast reactor safety design strategy has gone beyond those traditional measures, and the system architecture consisting of the reactor heat source coupled to the balance-of-plant heat engine is configured to achieve the safety functions by exploiting the natural laws of physics to the maximum degree achievable. This *passive safety approach* partially supplants the traditional engineered devices by exploiting passive systems or inherent characteristics that play the role of "functional redundancies" (i.e. they can, in case of failure of the upstream line of defence achieve the same safety related mission); the approach is so implemented to assure safe response[7] – even if the engineered systems which require assured sources of power and highly reliable "active" sensing and switching equipment were to fail, or if multiple, compounding failures and human errors were to occur simultaneously. The passive safety approach can be applied for all the defence in depth levels, i.e. accident prevention, accident management and consequence mitigation. The passive concepts can employ inherent reactivity feedbacks to keep heat production and removal in balance. Designs having minimal reactivity loss upon burn-up and minimal reactivity vested in control rods can preclude reactivity addition accidents. Designs having large margins to damage temperatures and large thermal mass provide reactivity feedbacks with room to operate without reaching damage temperatures or conditions. Designs using buoyancy-driven flows and always-operating heat transport paths to ambient remove decay heat without systematic reliance on switching of valve alignments or active monitoring. These passive safety approaches for fast reactors have been demonstrated [2] in full-scale tests at EBR-II, RAPSODIE, FFTF, BOR-60, etc.

Given that the safety approaches for FRs are well known, the plan for this paper is to first describe the chain of logic which gives rise to the salient differences between FRs and that class of ADS studied by the OECD/NEA expert group. Then a broad survey is made of each salient difference of the ADS design as compared to a FR to identify which of the six basic safety functions might be affected by this particular salient difference. Following that, for each case having an identified difference; potential strategies for fulfilling the function for an ADS are discussed.

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[7] A passive system should be theoretically more reliable than an active one. The reasons are that it does not need any external input or energy to operate and it relies only upon natural physical laws (e.g. gravity, natural convection, conduction, etc.) and/or on inherent characteristics (properties of materials, internally stored energy, etc.) and/or "intelligent" use of the energy that is inherently available in the system (e.g. decay heat, chemical reactions, etc.). Nevertheless passive devices can be subject to specific kinds of failure like, e.g. structural failure, physical degradation, blocking, etc. Generally speaking, the reliability of passive systems depends upon:

- The environment that can interfere with the expected performance.
- The physical phenomena that can deviate from the expectation.
- The single components reliability.

3. Minor actinide and/or transuranic burning ADS design rationale and distinguishing design features

Overall purpose; support ratio, and fertile-free fuel – First, the overall purpose of the class of ADS considered here is to function as one element of an integrated nuclear power enterprise comprised of conventional and advanced power reactors for energy production and ADS for reducing the radiotoxicity of the nuclear waste produced by these power reactors – prior to its entombment in a geologic repository. The radiotoxic materials targeted for incineration may be minor actinides (MA) or may be transuranics (TRU), depending on the configuration of the overall enterprise. The ADS also may incinerate selected fission products (see Figure 1, which illustrates the several power production complexes considered by the expert group). The ATW [3] (US design) is an example of a TRU incinerator such as case 3B; the JAERI double strata ADS [4] is an example of a MA incinerator such as case 4.

The transuranics are fissioned in the ADS to transmute them to fission products with the concomitant release of heat amounting to about 1 gm TRU incinerated per MW_{th} day energy release. *For a fissioning device, the incineration rate of TRU depends on the power rating of the heat removal equipment – be it an ADS or a reactor* and while the ADS plant will likely use the liberated heat for power production to offset the cost of its operation, its primary function is to reduce the transuranic and long-lived fission product inventories emanating from the power reactors deployed in the nuclear energy complex. The "support ratio" of the integrated power producing complex is the ratio of power of the reactors in the enterprise to the power of the ADSs in the enterprise. A large support ratio is targeted for the class of ADS designed for waste incineration with ancillary power production considered here so as to relax the demands on ADS cost and energy conversion ratio – inasmuch as the ADS will then comprise a smaller segment of the overall integrated energy supply complex. The primary purpose of the ADS is to *maximise incineration rate per unit of heat that has to be removed. Fertile-free fuel is the first salient design feature shared by proposed ADS systems of the class considered here* – to avoid *in situ* production and incineration of new transuranics. A 3 000 MW_{th} ADS plant operating for 300 days per year transmutes about 900 kg of TRU into nearly 900 kg of fission products and releases 900 Gigawatt days of thermal energy.

Multiple recycle – The ADS will operate on a closed fuel cycle with a feedstream of transuranics or minor actinides arriving from the power producing reactors and with fission-product-containing (largely actinide-free) waste forms leaving destined for a geologic repository. Internal multiple recycle of the ADS fuel will be required to reconstitute the fuel into fresh cladding because the fluence required for total fission consumption exceeds the neutron damage endurance of any known cladding. Recycle is required also to inject new feedstock into the ADS lattice to sustain the neutron multiplication within its design range as well as to extract the fission products destined for geologic disposal. Although not unique to ADS, a *need for multiple recycle constitutes a second salient feature of the ADS considered here.*

Except for the "once-through cycle" (Case 1 of Figure 1), the recycle step in the overall complex is where the waste stream to the geologic repository is generated. It is comprised of fission products and of TRU or MA trace losses which escape the recycle/refab. processes back to the ADS or FR. These trace losses of TRU or MA to waste are to be minimised if the ADS is to achieve its assigned mission; it is clear that both the trace loss per recycle pass and the number of recycle passes fully control the ADS contribution to the complex's total loss – and that therefore a high average discharge burn-up from the ADS is desirable. Moreover, since the radiotoxicity per gram and also the half life of the various TRU or MA isotopes vary, it is desirable that the transuranic isotopic spectrum achieved upon multiple recycle should be favourable in terms of long-term toxicity (including accounting all post emplacement decay daughters[8]) – the ADS neutron spectrum is controlling in that regard.

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[8] For example for the US (oxidising environment) geologic repository, ^{237}Np (a post emplacement daughter in the $^{241}Pu \rightarrow ^{241}Am$ decay chain) dominates the long term toxicity.

Fast neutron spectrum – Upon multiple recycle to achieve total fission incineration, the TRU or the MA isotopic composition of the LWR or FR spent fuel feedstock evolves to an asymptotic ADS recycle feed composition; this composition depends on the neutron spectrum to which it is subjected. (see Table 1) The ADS considered here is designed to operate on fission chains in the fast neutron range so that all transuranic elements stand a good chance to fission upon a single neutron absorption and thereby to minimize the development of an isotopic spectrum which is skewed toward heavier mass transuranic isotopes. Table 2 shows [5] that a fast neutron spectrum (having high fission probability for all TRU) is entirely essential to achieve total consumption in an MA burning ADS and it is preferable to a thermal spectrum for TRU burning. Table 3 indicates [6] that the asymptopic isotopic spectrum from multi-recycle in a fast spectrum will lead to a more favourable long term radiotoxicity burden that does that arising from thermal spectrum burning. *A fast neutron spectrum is the third salient design feature of the class of ADS systems considered here.*

Table 1. **Equilibrium distribution of transuranic isotopic masses for high fluence exposure to thermal and fast neutron spectra**

Isotope	Thermal neutron spectrum	Fast neutron spectrum
^{237}Np	5.51	0.75
^{238}Pu	4.17	0.89
^{239}Pu	23.03	66.75
^{240}Pu	10.49	24.48
^{241}Pu	9.48	2.98
^{242}Pu	3.89	1.86
^{241}Am	0.54	0.97
^{242m}Am	0.02	0.07
^{243}Am	8.11	0.44
^{242}Cm	0.18	0.40
^{243}Cm	0.02	0.03
^{244}Cm	17.85	0.28
^{245}Cm	1.27	0.07
^{246}Cm	11.71	0.03
^{247}Cm	0.75	2.E-3
^{248}Cm	2.77	6.E-4
^{249}Bk	0.05	1.E-5
^{249}Cf	0.03	4.E-5
^{250}Cf	0.03	7.E-6
^{251}Cf	0.02	9.E-7
^{252}Cf	0.08	4.E-8
Total	100.00	100.0

Note: all values are atom % of transuranic inventory built up as a result of extended exposure to a neutron flux. (Calculated as the steady-state solution of the depletion-chain equations independent of criticality considerations.)

Table 2. **Values of D_j (neutron consumption per fission) for isotopes j or for a fuel type (D_j<0: implies excess neutron self production; $D_j \geq 0$ implies a source of extra neutrons is required)**

Isotope (or fuel type)	**Neutron spectra and flux level φ (n/cm^2.s)**			
	Fast spectrum	Standard PWR		Highly thermalized
	10^{15}	10^{14}	10^{16}	10^{16}
Th (with extraction of ^{238}Pa)	-0.39	-0.24	-0.24	-0.27
Th (without extraction of ^{238}Pa)	-0.38	-0.20	1.22	1.14
^{238}U	-0.62	0.07	0.05	0.1
^{238}Pu	-1.36	0.17	0.042	-0.13
^{239}Pu	-1.46	-0.67	-0.79	-1.07
^{240}Pu	-0.96	0.44	0.085	0.14
^{241}Pu	-1.24	-0.56	-0.91	-0.86
^{242}Pu	-0.44	1.76	1.10	1.12
^{237}Np	-0.59	1.12	0.53	-0.463
^{241}Am	-0.62	1.12	0.076	-0.54
^{243}Am	-0.60	0.82	0.16	0.21
^{244}Cm	-1.39	-0.15	-0.53	-0.48
^{245}Cm	-2.51	-1.48	-1.46	-1.37
D_{TRU} (discharge from a PWR)	-1.17	-0.05	-0.35	-0.54
$D_{TRUPu + Np}$ (discharge from a PWR)	-0.70	1.1	0.3	0.4
D_{TRU} (discharge from a PWR)	-1.1	-0.20	-0.40	-0.53

Choice of coolant – Although not a design feature which distinguishes ADS from fast reactor concepts, the choice of coolant plays a strong role in core design strategy and safety strategy for fast reactor and ADS alike. It is useful for clarifying the discussions to explicitly include coolant choice among the ADS distinguishing features. Since the neutron spectrum is to be fast, the candidate coolants are sodium, heavy liquid metals (e.g. Pb or Pb-Bi) and gas.

Features shared with fast reactors – As indicated in Figure 1, fast reactors are themselves employed for TRU or MA consumption in several of the fuel cycle schemes studied by the expert group and whereas the features discussed above – i.e. fast neutron spectrum, multiple recycle, and alternate coolant choices are shared by those FRs with the ADS, the fast reactors do not employ fertile-free fuel. The neutronic properties of fertile-free fuel *dictated by the a-priori requirement to maximise support ratio* motivate the features of the ADS which most clearly distinguish it from a fast reactor.

Features which are unique to the ADS – Fertile-free fuel is prescribed for the ADS – motivated by the goal to maximise ADS support ratio in the power producing energy complex. The neutronics properties of fertile-free TRU or MA fuel – its η value and its delayed neutron fraction – give rise to the remaining distinguishing ADS features: specifically sub-critical operating state driven by a spallation neutron source.

Table 3. **Radiotoxicity data (CD = Cancer Dose Hazard)**

Isotope	**Toxicity factor CD/Ci**	**Half-life Years**	**Toxicity factor CD/g**
Actinides and their daughters			
^{210}Pb	455.0	22.3	3.48E4
^{223}Ra	15.6	0.03	7.99E5
^{226}Ra	36.3	1.60E3	3.59E1
^{227}Ac	1185.0	21.8	8.58E4
^{229}Th	127.3	7.3E3	2.72E1
^{230}Th	19.1	7.54E4	3.94E-1
^{231}Pa	372.0	3.28E4	1.76E-1
^{234}U	7.59	2.46E5	4.71E-2
^{235}U	7.23	7.04E8	1.56E-5
^{236}U	7.50	2.34E7	4.85E-4
^{238}U	6.97	4.47E9	2.34E-6
^{237}Np	197.2	2.14E6	1.39E-1
^{238}Pu	246.1	87.7	4.22E3
^{239}Pu	267.5	2.41E4	1.66E1
^{240}Pu	267.5	6.56E3	6.08E1
^{242}Pu	267.5	3.75E5	1.65E0
^{241}Am	272.9	433	9.36E2
^{242m}Am	267.5	141	2.80E4
^{243}Am	272.9	7.37E3	5.45E1
^{242}Cm	6.90	0.45	2.29E4
^{243}Cm	196.9	29.1	9.96E3
^{244}Cm	163.0	18.1	1.32E4
^{245}Cm	284.0	8.5E3	4.88E1
^{246}Cm	284.0	4.8E3	8.67E1
Short-lived fission products			
^{90}Sr	16.7	29.1	2.28E3
^{0}Y	0.60	7.3E-3	3.26E5
^{137}Cs	5.77	30.2	4.99E2
Long-lived fission products			
^{99}Tc	0.17	2.13E5	2.28E-3
^{129}I	64.8	1.57E7	1.15E-2
^{93}Zr	0.095	1.5E6	2.44E-4
^{135}Cs	0.84	2.3E6	9.68E-4
^{14}C	0.20	5.73E3	8.92E-1
^{59}Ni	0.08	7.6E4	6.38E-3
^{63}Ni	0.03	100	1.70E0
^{126}Sn	1.70	1.0E5	4.83E-2

Table 4. **Delayed neutron fraction**

Isotope	γ_d/γ_{total}
^{238}U ^{232}Th	0.0151 0.0209
^{235}U	0.00673
^{239}Pu	0.00187
^{241}Pu ^{242}Pu	0.00462 0.00573
^{237}Np ^{241}Am ^{243}Am ^{242}Cm	0.00334 0.00114 0.00198 0.00033

⇒ <u>10% Fertile fission raises β in fertile containing fast reactor fuel</u>

$$\beta(^{238}U) \quad \beta(^{239}Pu)$$

$$0.10 \times 0.0151 + 0.90 \times 0.00187$$

$$= 0.00151 + 0.00168$$

$$= 0.00319$$

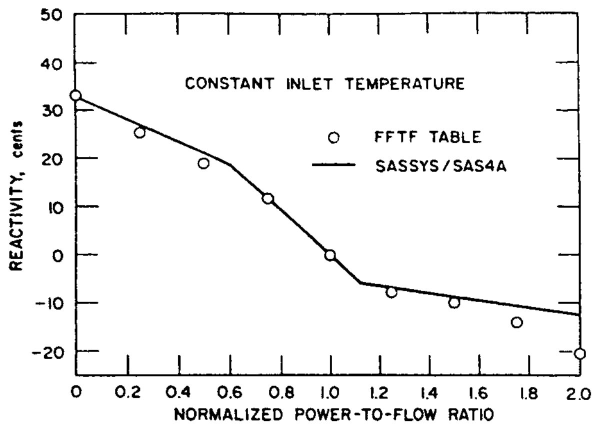
(Nearly doubles β vis-à-vis fertile-free fuel)

Sub-delayed critical operating state – Transuranic fuel containing no fertile (^{238}U and ^{232}Th) atoms exhibits a delayed neutron fraction for fast fission which is in the range of 0.0015 to 0.0020 i.e., about half the value for a conventional fast reactor and about a sixth the value for a conventional LWR. Table 4 displays β for fast fission of various actinide isotopes and shows that even at only 10% contribution to fissions, as is typical for a fast reactor, fertile ^{238}U or ^{232}Th contribute very significantly to delayed neutron fraction – doubling its value from what applies for fertile-free fuel. For fertile-free TRU or MA fuel compositions the delayed neutron fraction is remarkably small and therefore the margin to prompt critical is correspondingly small. This feature, when combined with reactivity feedback considerations discussed next, leads to further salient design features of ADS *specifically as a safety strategy approach.*

The neutron leakage in a fast neutron lattice is sensitive to the assembly geometry because of the long neutron mean free path. Subtle thermo-structural-induced geometry changes which are dependent on power to flow ratio (P/F) – such as fuel bowing, grid plate expansion, etc. – change the neutron leakage fraction in response to power and flow changes. For example Figure 2 illustrates for the FFTF sodium cooled fast reactor the normalised power to flow ratio dependence of the radial expansion plus bowing component of thermostructural reactivity feedback. Several features are notable [10]; first the amplitude is nontrivial with respect to β over the range $0 < P/F < 1$; clamping and duct wall tolerances and stiffness are designed [7] so as to assure negative bowing reactivity feedback at P/F in the vicinity of the operating point, $P/F \simeq 1$; and reactivity increases with decreasing P/F may become indeterminant [7] at low values of P/F owing to the "unlocking" of above core load pad structural contact. Numerous other leakage dependant thermostructural reactivity feedbacks (grid plate expansion, fuel axial expansion, etc.) are also individually nontrivial in amplitude compared to β, as illustrated in Figure 3 for a power change transient in the modular PRISM reactor [8].

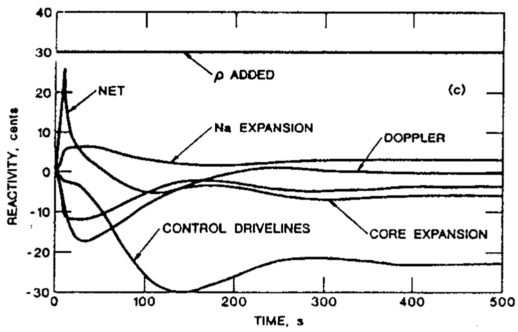
ADS designs using fertile-free fuel have high values of k_∞ and correspondingly high neutron leakage fractions [9]. With a reduced delayed neutron fraction of 0.002 or less and even assuming an unrealistically small neutron leakage fraction of only 5%, a change in leakage fraction of only a few per cent of its value – induced by thermostructural feedbacks – would exceed the .002 Δk/k offset from prompt critical. Not only is it impossible to design for and to control thermostructural response to that degree of precision [10], but variability as well as controllability is the issue here. In an ADS functioning as a waste burner, the fuel composition itself and its η value and β value can be expected to vary from loading to loading as LWR spent fuel and/or FR spent fuel of differing burn-up, differing cooling times and differing origins supply the ADS fuel feedstock. These feedstock variabilities change not only k_∞ and the concomitant leakage fraction and resulting amplitudes of thermostructural feedbacks, but they also change the delayed neutron fraction and offset from prompt criticality itself. Consider the effect on core k_∞ of even small variability in ^{239}Pu/^{241}Pu/^{241}Am ratios in ADS feedstock[9] as indicated by their vastly differing η values illustrated in Figure 4. Or, referring to Table 4, consider the effect on β of the transformation of ^{241}Pu (14.35 year half life) to ^{241}Am over different cooling periods prior to introduction into the ADS – a factor of four change in β contribution.

Figure 2. **Reactivity from radial core expansion as a function of normalised power-to-flow ratio, comparing the FFTF correlation and the SASSYS/SAS4A calculation**



(β = 0.003)

Figure 3. **Unprotected transient overpower for ALMR (β = 0.003)**



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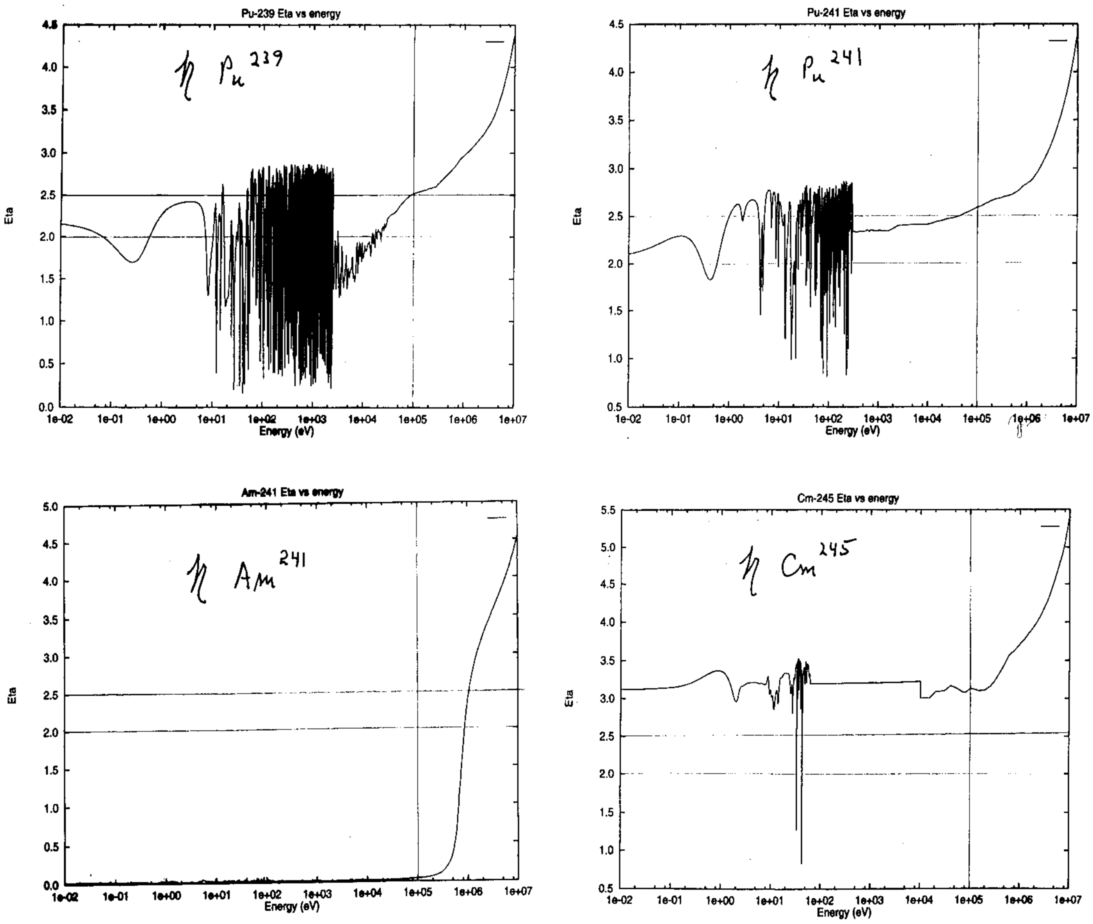
[9] Local power peaking in reload assemblies also are affected by these variabilities.

Figure 4. η **(Neutrons released per neutron absorbed) for several isotopes**



Taken all together, the variability and non controllability of the reactivity state of a fertile-free MA or TRU lattice relative to the reduced offset from delayed critical to prompt critical requires a safety strategy to assure that no potential can exist for power/flow induced reactivity feedback to carry the lattice into the super prompt critical range – even accounting for the variability in β, k_∞, and leakage fraction which result from feedstock of varying composition. The ADS strategy is one approach to this need – an increased offset of operating state from prompt critical is achieved by operating sub delayed critical. So as to avoid any potential for power/flow induced reactivity feedbacks to inadvertently carry the system into the super prompt critical regime, the geometry and composition of the ADS lattice is configured so that the operating margin to prompt critical will always substantially exceed the maximum power/flow reactivity feedback – while accounting for expected variability in the values of η and β owing to differing feedstock compositions. But the resulting offset then exceeds the value of the delayed neutron fraction itself – so it makes the operating point of the ADS lattice sub-delayed critical. An external source is required, therefore, to drive a continuing fission reaction. The fissioning system multiplies the externally supplied neutron source. *A sub-delayed critical operating state driven by an external neutron source is the fourth and defining design feature of all ADS.*

Spallation neutron source – At 1 gm of TRU or MA incinerated per $MW_{thermal}$ day, ADS facility heat ratings must lie in the range of 1 000 MW_{th} or more to support any reasonably – sized energy complex. The size of the neutron source required to drive a sub-delayed-critical ADS depends on both the desired heat rating and on the degree of neutron self multiplication of the lattice, which depends on the degree of sub-criticality (see Equation 1, below). With the required offset from prompt critical no less than 2 or 3% Δk/k (i.e. a source neutron fission chain multiplication no greater than 30 to 50), it is clear that no passive neutron-emitting source is strong enough to meet the requirement for ~1 000 MW_{th} power rating. However, plausible extensions in proton beam current capability which are now achieved in linear accelerators (i.e. beams of multi megawatt levels), could achieve required neutron source strength by driving a heavy metal spallation target. *This leads to the fifth salient design feature of an ADS; namely the external source must derive from a spallation neutron target driven by a high power proton accelerator.*

3.1 Summary of distinguishing features for TRU or MA burning ADS

The distinguishing features of the type of ADS considered by the expert group derive directly from the mission assigned to it in the energy complex: namely – *TRU or MA (and LLFP) incineration for waste management in the integrated energy complex with power generation only secondary to partially offset cost,* – combined with the *a-priori assumptions* on scope of cases considered by the expert group: namely *fast spectrum*, s*olid fuel, and maximised support ratio*.

The resulting distinguishing features are:

Those shared with FR:

- Fast neutron spectrum.
- Solid fuel lattice.
- Multiple recycle.
- Choice of coolant: Na, Pb-Bi, gas.

And those unique to ADS:

- Fertile free fuel.
- Sub-critical operating state.
- Spallation neutron source driven by a high power proton beam.

4. Safety-related challenges arising specifically from ADS design features

The salient design features of ADS give rise, in some cases, to different safety-related challenges and different approaches to fulfilling the six cardinal safety functions for fissioning systems as compared with the more familiar issues and safety strategy which apply for a fast reactor. Table 5, which tabulates salient design feature (matrix rows) versus required safety function (matrix columns), identifies where these differences exist. In Table 5 the effect of salient design features on strategy for meeting safety functions is indicated for both *normal operational safety* and for *off-normal safety* situations. The Table 5 impact matrix is overviewed here and the safety strategy options to accommodate the new issues are briefly discussed.

Table 5. **ADS Distinguishing feature vs. basic safety function impact matrix**

		Neutron balance		**Heat removal**		**Regulation of power/flow**		**Containment**		**Shielding**		**Decay heat removal**	
		Normal	Off-normal	Normal	Off-normal	Normal	Off-normal	Normal	Off-normal	Normal	Off-normal	Normal	Off-normal
Distinguishing features	Fast spectrum	■											
	Choice of coolant			■	■		■			■			■
	Fertile-free fuel	■				■	■						
	Sub-critical state	■				■	■						
	Spallation source	■		■			■	■	■	■	■		■
	Multiple recycle		■							■		■	

■ Legend: new issues arise vis-à-vis a fast reactor.

Proton beam transport tube and spallation neutron source effects – The most readily obvious geometrical difference occurs via the introduction of the proton beam tube. First is its topological effect on the multiple containment barrier defence in depth containment safety strategy. In fast reactors, the fuel is contained first by its cladding (or by multiple layer ceramic barriers in particle fuel), then by the primary cooling circuit boundary and lastly by the containment building. For the ADS based on linacs, the proton beam tube penetrates the last of these and employs a metallic proton beam window as a topological continuation of the primary coolant boundary. The safety issue pertains to the preservation of defence in depth for the containment and shielding functions. In a fast reactor similar topologies result from steam lines which penetrate the containment, and from IHX tubes which comprise a topological extension of the primary coolant boundary. In BWRs, the steam lines penetrate both the containment and the reactor vessel. Fast acting values at the containment boundary of steam pipes and robust heat exchanger tube walls are the safety strategies used for these reactors. Fast acting valve safety strategies employed for reactors will be considered for the ADS. For the ADS, the beam window operates in an especially hostile environment in light of its temperature and the proton and neutron bombardment that it experiences; the hazard deriving from the multi-megawatt proton beam potentially impinging on any of these barrier boundaries or valves is unique in an ADS.

The beam tube introduces new issues as well in the area of shielding safety function – comprising a streaming path from the fissioning lattice to the exterior of the vessel as well as an unshieldable pathway for radiation activation of the bending magnets or accelerating structures of the accelerator. Finally, the several tens of centimetre diameter evacuated beam tube presents a new issue in the area of a potential positive reactivity effect should the beam tube flood and decrease the neutron leakage; the degree of reactivity offset from prompt critical must be sufficient to safely accommodate such potential flooding.

The presence of an strong spallation neutron source has an effect on power density peaking factor [11] and on the change in power peaking as k_∞ of the lattice changes with burn-up and as the ratio of source to fission multiplied neutrons is altered by changes in source strength or reactivity. Also, depending on beam tube entry geometry, the fuel-loading pattern may be non-azimuthally symmetric – again affecting power density profile. Tailored spatial k_∞ zoning can be applied and, a design strategy, which relies on, increased margins so as to accommodate local shifts in power/flow ratio – while undesirable for a dedicated power producer, is quite consistent with the ADS mission where power production is an ancillary function only.

The ADS power output is proportional to spallation source strength and sub-critical reactivity offset via the relationship:

$$P \ \alpha \frac{S}{\frac{1}{k}-1} = \frac{S}{-\rho} \tag{1}$$

$$where \ \rho = \frac{k-1}{k}$$

Asymptotic adjustment of power (or power density) scale to first order with source changes or reactivity changes as:

$$\frac{\delta P}{P_0} = \frac{\delta S}{S_0} - \frac{\delta P}{\rho_0} \tag{2}$$

While a favourable ADS safety feature derives from its asymptotic rather than rising period response to a positive reactivity insertion [12], a safety challenge still remains in assuring that positive source strength or source importance changes cannot take the ADS to damaging overpower conditions. Equation 2 indicates that e.g. at an beginning of cycle offset of $-\rho_o$ equals 3% $\Delta k/k$ and a burn-up reactivity loss of 6% $\Delta k/k$, the source for maintaining end of cycle power level would have to exceed beginning of cycle requirement by 100%, leading to a factor of two overpower potential should the full source strength be introduced prematurely. Options to minimise burn-up reactivity loss include multi-batch fuel loading [9] and optimal mixes of plutonium and minor actinides [13] to flatten the reactivity change with burn-up. However, given fertile-free fuel, it has proven impossible for ADS designers to achieve small burn-up reactivity loss; so that compensation by either external reactivity changes (control rods) or by source strength or importance changes is unavoidable. In every case then, an overpower potential exists.

At the other extreme, if ADS heat removal equipment were to fail (loss of flow or loss of heat sink), then the beam would be required to trip off within seconds to avoid overheating and melting of the fuel [14].

Such considerations of controlling ADS on the basis that the beam current will assume the functions assigned to control rod in fast reactors might lead to a "nuclear safety grade" designation for the accelerator equipment and its maintenance, or at least for its controller – having significant unfavourable cost implications. Alternately, the proton beam might be operated at 100% strength at all times with a safety grade scram circuit, while burn-up reactively loss could be compensated by (safety grade) control rod actuators. Using the same example as above, a control rod bank worth of 6% $\Delta k/k$ would accomplish the same burn-up reactivity compensation as a factor of two larger proton accelerator – with a significant favourable cost advantage likely. Or, mechanical adjustments of neutron source importance via changes in source location or spectral importance may be options. Even adjustable volume fraction mixes of various spallation target materials having differing neutron yield per proton might be considered. In all cases a safety hazard exists in potential for premature actuation of the excess source or reactivity prior to burnout of the lattice; it simply cannot be avoided, short of letting the power rating decrease with burn-up.

Coolant choice effects – The distinguishing characteristic of the coolant choices relate to system pressure, lattice power density, effect on neutron spectrum, and chemical activities – as tabulated in Table 6.

Table 6. **Coolant characteristic features**

	Na	**Pb-Bi**	**He**
System pressure	Low	Low	High
Lattice power density	High	Low	Lower
Neutron spectrum	Hard	Harder	Harder
Chemical activity	High	Low	Null

These distinguishing features permeate the entire design approach for ADS and fast reactor alike and influence the resulting safety strategies. High pressure gas cooling introduces a loss of coolant vulnerability but eliminates chemical compatibility issues. Gas cooling shares with Pb-Bi cooling the need for a low power density, open fuel pin lattice – which leads to potential for significant reactivity additions upon hypothetical pin disruption or compaction but reduces potential for blockage from foreign objects.

Freezing temperatures and coolant/structural/fuel chemical interactions and potential for "local fault propagation" into flow blockages are important safety relevant issues for liquid metal coolant choice, and given that every fertile-free fuel under consideration for ADS use lacks a data base of inservice experience, this issue will require a substantial R&D effort in every case.

The coolant voiding reactivity coefficient is of reduced safety relevance because the ADS provides an added degree of freedom in the sub-critical offset from prompt critical sufficient to cover voiding worths [15].

The high density of Pb alloy coolant introduces several new issues for ADS and fast reactor alike; first is the structural support and the seismic structural response of large reactor vessels when filled with dense lead alloy. Second is the design of refuelling equipment and fuel assembly hold-down devices for the case where the fuel and the structures are less dense than the coolant and tend to float in it. Its high boiling point, on the other hand, provides more than sufficient margin to boiling.

A significant safety-relevant issue for fast reactors and ADS also is the consequence of failing to maintain leak tightness of the primary coolant system. Rank ordering of coolant favours liquids over gas for this issue because only gas operates at above-ambient pressure. However, each coolant displays a vulnerability which is unique to itself. Since gas-cooled systems operate at high pressure, a loss of integrity *anywhere* in the gas heat transport circuit could lead to a loss of coolant accident. Loss of coolant accidents are of extremely low probability for liquid metal cooled systems using a pool layout but each liquid metal displays a safety vulnerability upon leakage of primary coolant. Sodium burns in air, creating an aerosol containing (24-hr γ-emitting) radioactive ^{24}Na. Pb-Bi alloy does not burn but none-the-less releases 138-day (α-emitting) ^{210}Po. Safety approaches have been developed in the fast reactor communities to mitigate and recover from Na and Pb-Bi leakage events and, as compared with a gas leakage loss of coolant vulnerability in a gas cooled fast reactor, the liquid coolant mitigation technologies are at a more mature state of development. However, in-service inspection and repair are a serious vulnerability for opaque liquid metal cooling as compared with gas cooling.

For fast spectrum ADS applications, safety-related issues upon loss of primary boundary integrity should be evaluated first at the particular point of vulnerability innate to ADS: the single thin-wall boundary between the transmuter coolant and the vacuum extension of the proton beam tube leading into the spallation target located at the centre of the core. The window operates in a hostile environment of proton and neutron damage and it alone lies between the centre of the fissioning lattice and the proton accelerating structures external to the containment building. Beam tube melt-through upon a beam misalignment similarly presents a loss of containment boundary vulnerability.

Fertile-free fuel effects – Fertile-free fuel has a high value of η (see Figure 4) and requires a design strategy for safely disposing of excess neutrons. The options are leakage or internal parasitic capture – either discrete absorbers or absorbers homogeneously mixed with the fuel. Thermostructural reactivity feedback variations can be reduced the smaller is the leakage fraction and this is desirable for reasons discussed above. Recycle/re-fabrication batch sizes may benefit from the homogeneous absorber option. On the other hand, radial k_∞ zoning using only a single fuel pin fabrication specification may be achievable using discrete absorber pins.

As already discussed above, the absence of internal conversion of fertile to fissile species with burn-up will place demands for burn-up reactivity compensation on other design approaches – such as source strength or source importance changes, batch refuelling, or absorber control rod changes. For minor actinide burners, in situ isotopic transmutations mitigate but do not eliminate this issue.

Optimised mixes of MA and Pu can be tailored [13] to limit burn-up swing; but in every case source or reactivity compensation strategies are needed.

An off-normal safety related challenge derives from fertile-free fuel – which excludes the traditional Doppler contributor to prompt negative reactivity power feedback in a FR. Small (but not zero) Doppler feedback has been accommodated (and beneficially exploited for a passive safety mechanism) in metal-fuelled fast reactors. However, an HCDA termination mechanism will have to be devised for an ADS having fertile free fuel [16], high melting point oxide-fuelled FRs traditionally rely heavily on prompt Doppler feedback to limit the pre-disassembly energy generation which controls severity of HCDAs. Inertial resistance to disassembly in an HCDA sequence is an additional issue with Pb-Bi cooling.

Pure TRU or MA fuel presents issues in recycle batch sizes and processing geometries because of a small critical mass. Experience exists with metal-fuel/pyro recycle where discrete rather than continuous processing is employed and batch size is limited by relatively larger fast criticality constraints; this issue would require special care in the case of continuous aqueous reprocessing having very small critical masses.

Sub-critical operating state and dynamics effects – A fundamental distinction between ADS and critical reactor safety-relevant control arises because of the dramatic differences in dynamic response of critical versus sub-critical source-driven lattices. In a source-driven system, a change in source strength or in source importance or a change in reactivity will cause the neutron population and power level to promptly[10] adjust to a new asymptotic level in accordance with Equation 2; whereas in a critical reactor a change in reactivity leads (absent reactivity feedbacks) to an asymptotic period (or exponential time change) of neutron population, the promptness of which is controllable by the reactivity insertion magnitude. In a critical reactor, the period of power adjustment is chosen to match the thermal and structural time constants – which are in the range of 0.1 to 100 seconds (see Figure 3).

The dynamics and control challenges can be illustrated under the excellent assumption that the neutron population, n(t) is in prompt quasi-static equilibrium with the source. For a reactor it is the delayed neutron source; for the ADS it is the external spallation source plus the delayed neutron source:

$$\frac{dn}{dt} = 0 = \frac{\rho - \beta}{\wedge} n + \lambda C + S$$
$$n(t) = \frac{\wedge}{\beta - \rho(t)} \left[\lambda C(t) + S(t) \right]; \qquad [units] = \left[\frac{neutrons}{cm^3} * Vol\ of\ Core \right] \tag{3}$$

where:

Λ	=	prompt neutron generation time ~ 10^{-7} [sec]
$1/\lambda$	=	delayed neutron precursor lifetime ~ 10 [sec]
β	=	delayed neutron fraction ~ .002
$\beta-\rho(t)$	=	$\beta - \rho o - \Delta\rho(t)$
$\beta-\rho_o$	=	reactivity offset from prompt critical $\left[\frac{\Delta k}{k}\right]$
$\Delta\rho(t)$	=	feedback + external control reactivity

[10] The adjustment will occur within 30 to 50 prompt neutron generation times for sub-criticality of 2 to 3% Δk/k. Given a generation time of ~10^{-7} sec, *prompt* means several microseconds adjustment times for an ADS.

The prompt neutron population establishes equilibrium immediately (<10^{-6} sec) to any:

- external source change, S(t)
- delayed neutron precursor source change, λ C (t)
- reactivity change, $\rho(t) = -\rho_o + \Delta\rho(t)$

The relative nimbleness of the two sources which drive the neutron population is very different: S(t) is fast and can change by 100% in 10^{-7} sec while the delayed neutron source, λ C (t) is sluggish with a time constant for one Θ – folding factor of 1/λ ~10 sec. Moreover, the delayed source has a memory of previous history of n(t):

$$\frac{d}{dt}C(t) = \frac{\beta\, n(t)}{\wedge} - \lambda C(t)$$
$$C(t) = \int_{-\infty}^{t} e^{-\lambda(t-\tau)} \frac{\beta}{\wedge} n(\tau)d\tau \qquad (4)$$

Finally, whereas for a critical reactor the delayed neutron source is the only source present, for the ADS the delayed source is but a very small fraction of the total source and it depends on sub-criticality level:

From Equations 3 and 4:

$$\frac{S_o}{n_o} = \frac{-\rho_0}{\wedge};\ \frac{\lambda C_o}{n_o} = \frac{\beta}{\wedge} \qquad (5)$$

so, for the ADS:

$$\frac{\textit{delayed source}}{\textit{total source}} = \frac{\lambda C_0}{\lambda C_0 + S_0} = \frac{\beta}{\beta - \rho_0} = \frac{\begin{pmatrix}\textit{delayed critical offset}\\ \textit{from prompt critical}\end{pmatrix}}{\begin{pmatrix}\textit{total offset from}\\ \textit{prompt critical}\end{pmatrix}} \qquad (6)$$

$$\textit{for example, given a } 3\%\Delta k/k \textit{ sub-critical state and } \beta = .0015, \textit{then} = \frac{1}{21}$$

Because it is only a small faction of the total source, and the neutron population adjusts promptly to changes in total source, the delayed source cannot be counted on in the ADS to slow down dynamic response of the neutron population (and concomitant power density) even though such a showdown is highly desirable because the time constants of heat removal, relaxation of thermal stresses, and relaxation of reactivity feedbacks all lie in the range of 0.1 to 100 seconds (see Figure 3). Since delayed neutrons won't buffer the differences between the prompt neutron power adjustment time and the slow thermostructural relaxation times, new control challenges arise for the ADS; specifically *the controller and actuator must themselves perform this moderation function* so that the control actuator (whether on source strength, source importance, or reactivity) must achieve:

- Very slow adjustments.
- Very precise changes.
- Be very reliable.

Moreover, the fuel is where neutron and heat removal time constants clash continually; giving rise to new requirements on the fuel also, specifically *it must be structurally tough to thermal shocks, and must have heat storage capacity to slow down heat release transients.*

Controller options include traditional control rod actuators as well as actuators controlling source strength or source importance (either spatial or spectral dependencies). As in the case of burn-up reactivity swing compensation, the control actuator will likely be required to assume a "nuclear safety grade" level of reliability.

In summary, the dependence on spallation source neutrons rather than on delayed neutrons to maintain the fission chain reaction in balance from one fission chain generation to the next leads to extremely abrupt response to control actions, reduced influence of power/flow dependent reactivity feedbacks, and puts added importance on the fuel and on the control actuator itself to moderate the vastly different time constants of nuclear and heat removal processes.

Beam reliability effects – Current multi megawatt proton beam accelerators have not been designed for second-to-second reliability; they trip off many times a week due to accelerator cavity sparking; they restart after a spectrum of time delays ranging from a fraction of a second to tens of minutes [17]. Since ADS power scales linearly with the source strength (Equation 2) such source trips lead to ADS power trips which in turn induce abrupt fuel and coolant temperature transients. Such temperature transients induce thermal stresses in the core support and heat transport heavy-walled structures; repeated trips give rise to life-shortening low cycle fatigue damage of these structures [18]. Moreover, if the restart delay exceeds several minutes, the balance of plant must undergo a major restart procedure to connect to the grid [4].

Accelerator designers are devising means to reduce the frequency of trips – but do not foresee means to reduce frequency to only a few per year (similar to frequency of unplanned reactor trips). Thus, design options to mitigate their effects on the transmuter core and the heat transport circuits have been studied. Options include multiple accelerators to avoid total loss of power given any single accelerator trip. Other options include power density de-rating to lessen the amplitude of temperatures swings. Thermal storage – in the fuel [18], in the coolant, and in the steam generator [4] – are also considered so as to mitigate the abruptness of downstream temperature swings.

Application of passive safety principles – For liquid metal cooled ADS, the passive decay heat removal strategies used for fast reactors apply without modification.

Passive power self-regulation based on thermostructural reactivity feedbacks which has been exploited for fast reactor passive safety [19] is precluded by the fundamental feature of ADS sub-critical source-driven systems. For an ADS, the operating point is offset from prompt criticality by (β - ρ_o) where -ρ_o is the sub-criticality operating point. This is compared to an offset of only β for a critical reactor. As is evident from observation of the denominator in Equation 3, the effect is to decrease sensitivity of ADS power level to reactivity feedbacks as compared to a reactor. Moreover, as is also evident from the inhomogeneous source term in Equations 3 and 4, the *power can never be driven to zero by reactivity changes as long as the spallation source is nonzero*. These differences give rise to a need in the ADS for different strategies for employing passive concepts to keep heat production and removal in balance. Specifically, some means for source strength or source importance to be adjusted passively in response to power changes is needed. Options include accelerator powered by ADS-generated electricity[11] [20]; or source – transmuter coupling which is dependent on coolant temperature or density. Absorber curtains or moderator curtains in the buffer surrounding the source or target spatial relocations (all activated by coolant temperature or density changes) affect coupling and might offer opportunities to apply passive *source* feedbacks analogous to the passive *reactivity*

[11] The exceedingly long time constant for feedback presents a major challenge with this option.

feedbacks successfully exploited and demonstrated in fast reactors as the means to passively self regulate the heat production rate to match the heat removal rate.

Activation product effects – Given the ADS function to reduce waste losses to the repository from the fission energy complex per unit of useful energy from the complex, care must be taken in ADS design to minimise production of incremental waste. This is a safety-related issue not only for the long term, but for operational safety as well. Issues arise in choice of coolant [21], choice of spallation target material [22] and level of sub-criticality operating state and in beam misalignment and halo effects on activation of accelerator structures [23].

Recycle facility safety – The recycle and re-fabrication processes for TRU and MA fuel introduce safety issues of criticality, pyrophoricity and atmosphere control; these do not differ in character from the recycle safety issues for reactors intended for TRU or MA use. In either case, however, small critical mass of fertile-free fuel and the demands on shielding and atmosphere control when working with high concentrations of minor actinides (displaying characteristics of spontaneous fission, neutron emission, and low temperature volatility) raise new challenges compared to current practice with UOX or MOX fuel.

Accelerator safety – The accelerator brings with it the usual accelerator safety issues (high-voltage safety, control of worker dose owing to components activated by beam divergence, etc.). These issues are not peculiar to ADS applications except for shielding issues at the ADS/accelerator beam tube interface, already discussed.

5. Summary

The work of the expert group in studying the safety issues of a specific class of ADS – that employing fast neutron spectrum, solid fertile-free fuel, and multiple recycle – with a primary mission of TRU or MA incineration has comprised an ancillary element of the OECD/NEA "Comparative Study of Fast Reactors and ADS in Advanced Fuel Cycles". Safety-related challenges which derive from the distinguishing design features of the ADS for this specific mission have been identified. The expert group has discussed safety strategy options available for addressing each safety-relevant issue based on a presumption that safety should be designed in from the start; that relevant fast reactor safety principles and practices should be applied where applicable and that safety of the entire cycle (including recycle, refab, and waste disposal operations) should be kept in mind during each ADS safety-related design decision.

While the work is still ongoing, multiple options for addressing nearly all issues have been developed, drawing on experience from reactor safety approaches. An impact matrix (of ADS distinguishing design feature vs. required safety function) has been developed, and a tracking of distinguishing design feature back to specified ADS mission element has been produced. These materials will be useful to designers and safety analysts in optimising the design of their ADS concepts within their specific set of constraints and mission requirements.

Several issues merit special note. First, the issue of ADS dynamic response to reactivity or source changes and the achievement of buffering between nuclear and thermo/structural time constants without benefit of delayed neutron buffering is the area of greatest difference between fast reactor and ADS safety-related characteristics and an area where no precedents exist in the fast reactor experience base. Second, a prompt negative feedback mechanism for quenching HCDA sequences will have to be developed for the ADS which will rely on phenomenology other than the traditional Doppler coefficient of reactivity of fertile atoms in the fuel – or else the maximum support ratio requirement which dictated fertile-free fuel could be relaxed. Finally, opportunities for application of passive safety principles can be foreseen and should be exploited; straightforward adoptions are available for passive decay heat removal; innovation will be required to achieve passive power self-regulation.

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