Nuclear Development

Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles

A Comparative Study

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

5. FAST REACTOR (FR) AND ACCELERATOR-DRIVEN SYSTEM (ADS) SAFETY

5.1 Safety functions and strategies for fissioning systems

5.1.1 Cardinal safety functions for fissioning systems

At a basic level, there are five safety functions to be fulfilled when deriving energy from actinide fission. First, the nuclear fuel must remain contained within a controlled space because of its radiotoxicity; this is traditionally accomplished by use of multiple containment barriers. Second, shielding must be kept in place between humans and the fissioning and fissioned fuel to avoid suffering radiation damage. Third, a heat-transport path must be in place to carry energy away from the fission chain reacting medium to a heat sink; usually an energy conversion plant. Fourth, 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 the heat-transport channel will buffer mismatches of short duration or small amplitude. Fifth, since some 5% of the 200 MeV from each fission event is initially retained in nuclear bonds of unstable fission products, and since these fission products subsequently decay at their natural rates, a means must be provided for transporting heat from the fission products and transuranics in the fuel for all times after the fission event. Failure to satisfy the latter two safety functions could lead to overheating of the fuel with the potential to compromise the integrity of the containment and shielding. Finally, operation of the fissioning devise in a quasi steady state mode requires a balance of neutron production and destruction rates from one generation to the next in a fission chain even as the composition changes owing to transmutation and as the absorption, leakage, and neutron production properties of the fissioning assembly change with changes in composition and temperature.

5.1.2 Safety strategies

Strategies to fulfil the basic safety functions have been developed and refined over many years for conventional (critical) reactors. The strategy employs defence in depth so that no single failure can 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 in accident conditions. Highly reliable systems for controlling and terminating the chain reaction are used to match heat production to removal. Highly reliable, redundant and diverse systems for removing decay heat are provided. High quality construction minimises manufacturing flaws and rigorous maintenance, formal procedures and exhaustively trained and certified operators are used to minimise 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 regulating authority.

In recent years, the FR design strategy for safety has gone beyond those traditional measures: the system 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 safety approach partially supplants the traditional engineered devices by implementing passive systems or using inherent characteristics that play the role of "functional redundancies": in case the upstream line of defence (LOD) should fail, they can achieve the same purpose. The approach is so implemented as to ensure safe response[37] 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 valuable for all the levels of defence-in-depth, i.e. accident prevention, accident management and consequences mitigation; for instance, the passive concepts can employ inherent reactivity feedbacks to keep heat production and removal in balance. Designs with minimal loss of reactivity upon burn-up and minimal reactivity vested in control rods preclude accidents due to reactivity. Designs having large margins to damaging temperatures and large thermal mass provide the feedback loops with room to operate safely. Designs using buoyancy-driven flows and uninterruptible heat transport paths to the environment remove decay heat without systematic[38] reliance on operating valves or active monitoring. These passive safety approaches for FRs have been demonstrated in full scale tests at EBR-II, RAPSODIE, FFTF, BOR-60, etc. [138].

Given that the safety approaches for FRs are well known, the plan for this chapter is first to describe the chain of logic that gives rise to the salient differences between FRs and that class of ADS studied here. Then the ADS design is broadly compared with a FR so as to identify which of the basic safety functions might be affected by each of these particular salient differences. This is done in Section 6.2.

Following that, in the Sections 6.3 and 6.4 we go through each case having an identified difference; describe how the safety function is provided for a FR; and (if they are different) discuss potential strategies for fulfilling the function for an ADS.

5.1.3 Definition of the subset of ADS considered

This study is considering the roles of fast reactors (FR) and of accelerator-driven systems (ADS) to serve as transmuters in applications of Partitioning and Transmutation (P&T) for nuclear waste

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37. A passive system should theoretically be 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, such as structural failure, physical degradation, blocking, etc. Generally speaking, the reliability of passive systems depends upon:
    - Insensitivity to external interference with the expected performance.
    - Accurate prediction of relevant physical phenomena.
    - The reliability of individual components.

    This is why the need for reliability assessment, even for passive devices, remain a key concern for future reactors.

38. According to IAEA definitions a passive component does not need any external input to operate. The term "passive" identifies a system which is composed entirely of passive components and structures or a system which uses active components in a very limited way to initiate subsequent passive operation. A categorisation has been developed by the IAEA (mainly on the background of thermal hydraulic systems) distinguishing:
    A: physical barriers and static structures.
    B: moving working fluids.
    C: moving mechanical parts.
    D: external signals and stored energy (passive execution and active actuation).

management. A FR serving as a transmuter would be designed as a net burner of some or all transuranic isotopes, i.e. having a breeding ratio less than one. Similarly, for this function the ADS would be designed as a net burner of some or all transuranic isotopes. The general term, ADS, comprehensively includes all manner of non-self-sustaining, fissioning, neutron-multiplying assemblies driven by an external neutron source that is provided by a charged particle accelerator and a neutron-producing target. ADS systems under current worldwide study include both thermal and fast neutron-multiplying media comprising either liquid or solid (lattice) fuel and driven by either cyclotron or linear proton accelerators. The underlying missions targeted for ADS systems span the range from nuclear waste incineration with incidental power production, through power production with integral waste self-incineration, to finally, excess neutron production for the purpose of generating artificial elements by neutron capture reactions in targets.

The Expert Group has confined this study to a subset of ADS configurations: those targeted for nuclear waste incineration with incidental power production, and specifically those which operate on a fast neutron spectrum with an array of solid fuel pins. The scope of this chapter on ADS safety strategy is similarly confined.

Even within this limited scope, a broad range of possibilities is considered. For example, the ADS in scheme 4 is a minor actinide (MA) burners whereas in scheme 3b the ADS is 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 swing in reactivity upon burn-up (which helps to set the control strategy). Moreover, the choice of coolant (liquid metal or gas) also distinguishes members of the ADS class considered here.

This class of fast spectrum, solid fuel, waste-incinerating ADS shares with all others a distinction from critical reactors in relying on an external neutron source rather than self-generated delayed neutrons for maintaining the neutron population in balance, with attendant changes in dynamic response and in control strategy. However, the class considered here differs from others in offering unique design and safety challenges in the areas of compensation for burn-up 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 target TRU or MA incineration mission, with incidental power production.[39] The origin of these salient features is discussed next.

5.2 ADS design features that affect safety

5.2.1 Design principles for an ADS burning minor actinide or transuranics and resulting features

Overall purpose; support ratio, and fertile-free fuel

First, the overall purpose of this class of ADS is to function as one element of an integrated nuclear power enterprise comprising conventional and advanced power reactors for energy production and ADSs for reducing the radiotoxicity of the nuclear waste produced by these power reactors before entombment in a geologic repository. The radiotoxic materials targeted for incineration may be minor actinides or may be transuranics, depending on the configuration of the overall enterprise. The ADS may also incinerate selected fission products.

The transuranics are fissioned in the ADS to transmute them to fission products with shorter radiotoxic half-life. A fission of one TRU atom releases approximately 200 MeV of energy. Expressed

39. Not only ADS, but also FRs for pure burner missions (i.e. no fertile material in the fuel) differ dramatically in behaviour from standard FR’s and require addressing new safety challenges.

in different units, 200 MeV/fission corresponds to about 1 g TRU incinerated per MWth day energy release. For a fissioning device, the incineration rate of TRU depends on the power rating of the heat removal equipment and nothing else, whether in ADS or a reactor. While the ADS will probably use the heat liberated in the transmutation of transuranics 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 enterprise.

The "support ratio" of the integrated power producing enterprise is the ratio of the power of the reactors to that of the ADS in the enterprise. A large support ratio is targeted for the ADS designed for waste incineration with incidental power production because it relaxes the demands on ADS cost and energy conversion efficiency, inasmuch as the ADS represents only a small segment of the overall enterprise. The primary purpose of the ADS is then to maximise incineration rate per unit of heat that has to be removed from the device so as to minimise its cost. This leads to a need to avoid in-situ production of new transuranic elements and thus to avoid use of fertile atoms (U^{238} or Th^{232}) in the ADS fuel composition.

A 3 000 MWth ADS plant operating for 300 days per year transmutes about 900 kg of TRU into nearly 900 kg of fission products, and releases 9×10^5 MWth days of energy together with an excess of neutrons (~2.5 neutrons/fission). If the fuel were to contain fertile atoms, some of the excess neutrons which are not required to sustain the chain reaction would unavoidably be absorbed in the fertile material and would produce new TRU atoms in-situ. To avoid this, fuel for the class of ADS considered here will contain no fertile (U^{238} or Th^{232}) atoms so as to maximise the net rate of TRU incineration per unit of heat which has to dispelled (and per unit cost of equipment to dispel it). Fertile-free fuel is the first salient design feature shared by proposed ADS systems of the class considered here.

Multiple recycling

Given the goal of totally consuming the TRU or MA fuel by fission and a lattice of solid (rather than fluid) fuel, it is evident that multiple recycling of the fuel will be required. The ADS will operate on a closed fuel cycle with a feedstock of TRU or minor actinides arriving from the power producing reactors of the overall enterprise, and the system will discharge waste containing fission products but hardly any actinides in a form destined for a geologic repository. Internal multiple recycling the ADS fuel will be required to reconstitute the fuel with fresh cladding, because the fluence required for total fission consumption exceeds the neutron damage endurance of any known cladding. Recycle is also required 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, this need for multiple recycle constitutes a second salient feature of the ADS considered here.

Except for the "once-through cycle" (scheme 1), the recycle step in the overall complex is where the waste stream to the geologic repository is generated. It is composed of fission products and trace losses TRU or MA which escape the recycle and refabrication processes for return to the ADS or FR. These trace losses waste must 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 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 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 that of all post-emplacement decay daughters).[40] The ADS neutron spectrum determines this.

Fast neutron spectrum

Upon multiple recycling to achieve total fission incineration, the TRU or the MA isotopic composition of the LWR spent fuel feedstock evolves to a different asymptotic composition depending on the neutron spectrum to which it is subjected. The ADS of the class considered here is designed to operate in the fast neutron range so that all transuranic elements stand a good chance of fission upon a single neutron absorption, minimising the production of heavier transuranic isotopes with a less favourable long-term radiotoxicity burden per unit lost to the waste stream. Table 5.1 (see also Table 2.1 and respective discussion in Chapter 2) shows that a fast neutron spectrum is essential for total consumption of MA and is preferable to a thermal spectrum for burning TRU. Moreover, it will become clear later that per unit of energy released, the fractional reduction in TRU content upon irradiation, and its effect on reactivity, are smaller and can be more easily compensated if the in-core fuel inventory is large, as is the case when the spectrum is fast. A fast neutron spectrum is the third salient design feature of the class of ADS systems considered here.

Table 5.1. **Values of D (neutron "consumption" per fission) for ^{238}U and different fuel types (-D: neutron production)**

Top-up fuel	Thermal TRU burner (ADS)		Fast TRU burner (ADS)		MA burner (ADS)		Critical fast reactor	
	η_{ec}	-D	η_{ec}	-D	η_{ec}	-D	η_{ec}	-D
Uranium-238	0.92	-0.24	1.28	0.64	1.28	0.64	1.41	0.85
Plutonium	1.15	0.40	1.80	1.34	1.74	1.28	2.03	1.53
Minor actinides	0.89	-0.37	1.37	0.86	1.33	0.79	1.52	1.10
Transuranics	1.11	0.30	1.75	1.29	1.69	1.23	1.96	1.48

Choice of coolant

Although not a design feature which distinguishes ADS from FR concepts, the choice of coolant, plays a strong role in both core design and safety strategy for FRs and ADS alike. It is useful for clarifying the following discussions, therefore, 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 2.4, fast reactors are themselves employed to consume TRU or MA in several of the fuel cycle schemes studied by the Expert Group. However, whereas the features discussed above (fast neutron spectrum, multiple recycling and alternative 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 the support ratio motivate the features of the ADS which most clearly distinguish it from a fast reactor.

40. For example, in the proposed US geologic repository with an oxidising environment, ^{237}Np (a post emplacement daughter in the ^{241}Pu→^{241}Am decay chain) dominates the long-term toxicity.

Features that are unique to the ADS

Fertile-free fuel is prescribed for the ADS in order to maximise the ADS support ratio in the power producing energy complex. The neutronic 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 a sub-critical operating state driven by a spallation neutron source.

Sub-delayed critical operating state

Transuranic fuel containing no fertile atoms exhibits a delayed neutron fraction for fast fission in the range of 0.0015 to 0.0020 i.e. about half the value for a conventional FR and about a sixth the value for a conventional LWR. Table 5.2 displays ν_d for fast fission of various actinide isotopes and shows that even at only ~10% contribution to fissions, as is typical for a FR, fertile U^{238} or Th^{232} would contribute very significantly to delayed neutron fraction. The delayed neutron fraction is remarkably small for fertile-free fuel compositions, and therefore the margin to prompt criticality is correspondingly small. This feature, when combined with considerations of reactivity feedback discussed next, leads to another salient design feature of ADS specifically on grounds of safety.

Table 5.2. **Delayed neutron fractions**

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

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

$$\begin{array}{ccc} \beta(^{238}U) & & \beta(^{239}Pu) \\ 0.10 \times 0.0151 & + & 0.90 \times 0.00187 \\ = 0.00151 & + & 0.00168 \\ & = 0.00319 & \end{array}$$

(Nearly twice the β of fertile-free fuel)

In a fast spectrum, with a fertile-free fuel and no parasitic neutron absorption, the k_∞ of the lattice will be determined by the transuranic η values:

$$k_\infty = \frac{\left(\nu\Sigma_f\right)_{TRU}}{\left(\Sigma_a\right)_{TRU}\left[1+\frac{\Sigma_{a\ parasitic\ absorber}}{\Sigma_{a\ TRU}}\right]} \quad (1)$$

$$\simeq \eta_{TRU}$$

A reactor fuelled purely with transuranics will exhibit $k_\infty \cong \eta \cong 1.5$ to 1.8 in a fission spectrum. A critical mass of such fuel composition is small, in the range 5 to 20 kg.

ADS designs, even with fertile-free fuel, are not without parasitic absorption. Calculations for Pb-Bi cooled TRU incinerator ADS indicate that structure, fuel diluent (Zr in this case), coolant and fission products will absorb about half as many neutrons as the TRU itself, reducing the k_∞ by a third [26,139].

Given that the neutron reproduction ratio per fission chain generation, k, is specified by k_∞ and the leakage probability, LP:

$$k = k_\infty (1\text{-LP}) \tag{2}$$

a fertile-free fast spectrum lattice will experience a leakage probability in the region of 20%:

$$(1 - \text{LP}) \simeq \frac{0.98}{1.2} \Rightarrow \text{LP} \simeq 1/5$$

The neutron leakage in a fast neutron lattice is sensitive to the assembly geometry because of the long neutron mean free path. Subtle geometry changes induced by thermo-structural effects dependent on power to flow ratio, such as fuel bowing, grid plate expansion, etc., will change the neutron leakage fraction in response to power and flow changes. With 20% of the neutrons leaking, changes in these structurally dependent leakage rates would have to be kept within 1% of their values to avoid exceeding the value of β_{eff}:

$$0.20 \times x = 0.0015$$

$$x = \frac{15}{2\,000} < 3/4\,\%$$

But thermo/structural power feedback cannot be designed for nor can it be controlled to a degree of precision less than 10% [140,141]. Even if parasitic absorbers were purposely added to the fuel to consume the majority of the excess neutrons and reduce the leakage fraction to 5%, it would not change the situation; reactivity changes due to leakage fraction could still not be held reliably to less than a dollar.

Taken by itself, a power-dependent reactivity feedback which exceeds a dollar is not uncommon in FR designs. For example, in an oxide-fuelled fast reactor, the Doppler reactivity vested in the temperature difference between fuel and coolant is in the region of several dollars.

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 the source is spent fuel from LWR or FR, differing in burn-up, cooling times and origins. These feedstock variabilities change not only k_∞, and thermo-structural feedback but also the delayed neutron fraction and even the offset from prompt criticality.

Taken all together, the variability and uncontrollability of the reactivity state in an ADS lattice relative to the reduced offset between delayed criticality and prompt criticality leads to the fourth and dominant design feature of ADS systems, the use of an external source to drive a sub-critical assembly. To avoid any potential for unintended feedback of reactivity, induced by fluctuations in power/flow ratio, to carry the system into the super-prompt-critical regime, the geometry and composition of the ADS assembly are configured so that the operating margin to prompt criticality will always substantially exceed the maximum power/flow reactivity feedback, allowing for the expected variability in the values of η and β_{eff} due 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 with the fissioning system multiplying the externally supplied neutron source. A sub-delayed-critical operating state driven by an external neutron source is the fourth and dominant salient design feature of all ADS.

Spallation neutron source

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. The classical derivation of the asymptotic neutron population resulting from injecting a sequence of source neutrons into a neutron multiplying medium provides for superposing an infinite number[41] of sub-critical fission chains following each source injection:

$$\text{Power a} \begin{Bmatrix} \text{asympotic} \\ \text{neutron} \\ \text{population} \end{Bmatrix} = S\Lambda \begin{Bmatrix} 1 & \\ +k & \text{for those multiplied once} \\ +k^2 & \text{for those multiplied twice} \\ \vdots & \\ +k^n & \\ + & \\ \vdots & \end{Bmatrix} \tag{3}$$

$$= \frac{S\Lambda}{1-k} \quad \text{when } k < 1$$

Here, $S = \frac{\text{neuts}}{\text{sec}}$ and Λ = prompt neutron generation time (s.) $\simeq 10^{-7}$ s. Allowing for the fact that energy is released in the generation of fission-multiplied neutrons but not of the external source neutrons (subtracting the external source term, $S\Lambda$, in the power series above), and with appropriate conversion factors, the total fission rate (Power) and the power density are related to the external source and neutron reproduction factor k as:

$$P \simeq \frac{S}{\frac{1}{k_0} - 1} \equiv \frac{S}{-\rho_0} \text{ where reactivity, } \rho_0 \equiv \frac{k_0 - 1}{k_0} \tag{4}$$

With 1 g of TRU or MA incinerated per MWth day, ADS facility heat ratings must lie in the range of 1 000 MWth or more to support any reasonably sized energy complex. With the required offset from prompt criticality no less than 2 or 3% Δk/k (i.e. source neutrons multiplied in the fission chain by no more than 30 to 50), it is clear that no passive neutron-emitting source is strong enough to meet the requirement for ~1 000 MWth power rating. However, plausible extensions in proton beam current capability targeted for linear accelerators (i.e. beams of multi megawatt levels), could achieve the 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.

5.2.2 Summary of salient features for ADS TRU and MA burners

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 to offset cost; combined with,

41. The power series is extended only for a finite but large number of terms in the light of the discrete lower bound on neutrons equal to one.

- The *a priori* assumptions on scope of cases considered by the Expert Group, namely fast spectrum, solid fuel, and maximised support ratio.

The resulting distinguishing features are:

- Those shared with FR:
  – Fast neutron spectrum.
  – Solid fuel lattice.
  – Multiple recycling.
  – Choice of coolant: Na, Pb-Bi, or gas.

- Those unique to ADS:
  – Fertile-free fuel.
  – Sub-critical operating state.
  – Spallation neutron source driven by a high power proton beam.

5.2.3 Optimising the support ratio

Since the ADS is considered as an element of the overall energy supply enterprise, the support ratio should be optimised. Along with the several schemes considered in this study (single strata, double strata, etc.), another optimisation considers trading off the removal of all fertile isotopes from the fuel, thereby increasing the support ratio of the overall enterprise against adding some fertile isotope content to the fuel and perhaps lowering the cost of an ADS owing to potentially improved safety characteristics deriving from the fertile content's increased β and Doppler coefficient of reactivity. That optimisation is beyond the scope of this study and in any case it would be conducted country-by-country on the basis of their individual policies, existing infrastructure and financing situation. Hence, in this chapter we discuss only the specific case of fertile-free fuel – an extreme but perhaps not ultimate optimisation.

5.2.4 Overview of safety-related issues attendant specifically to ADS design features

The salient design features of ADS give rise, in some cases, to different safety-related issues and different approaches to fulfilling the six cardinal safety functions for fissioning systems as compared with the issues and safety strategy which apply for a FR. Table 5.3, which tabulates salient feature versus required safety function, identifies where these differences exist. In Table 5.3, the effect of these features on strategy for meeting safety functions is indicated for both normal operational and abnormal situations. The rows of Table 5.3 are briefly overviewed here. The entries in Table 5.3 indicate where in the subsequent sections of this chapter the safety strategies to accommodate these new issues are discussed in more detail.

Table 5.3. **Areas where ADS features provide unique differences from FRs***

	Neutron balance		**Heat removal**		**Regulation of power/ Flow & Reactivity feedback**
	Normal	Abnormal	Normal	Abnormal	Normal
Fast spectrum	5.3.1.1 Neutron balance 5.3.1.2 Compensating burn-up loss				
Choice of coolant			5.3.2.2 Fuel & clad compatibility clad breach sludge 5.3.2.2 Na burning Pb-Bi Po issue	5.3.2.2 Freezing potential of liquid metals 5.3.2.2 Depressurisation/ LOCA potential of gases	
Inert matrix (fertile-free) fuel	5.3.1.1 Neutron balance 5.3.1.2 Compensating burn-up loss				
Sub-critical state	5.3.3.1 Asymptotic response of neutron density to source and to reactivity changes		5.3 Operational safety related strategies for FR & ADS systems		5.3.3.2 Dynamics of response to source or to reactivity changes 5.3.3.3 Thermo/structural response to abrupt source changes 5.3.3.4 Trim control options
Spallation neutron source	5.3.1.2 Source importance as a control mechanism		5.3.2.1 Power peaking effect on heat removal		
Multi-recycle		Criticality limited equipment & batch size			

Table 5.3. **Areas where ADS features provide unique differences from FRs* (cont'd)**

	Regulation of power/ Flow & Reactivity feedback	**Containment**		**Shielding**		**Decay heat removal**	
	Abnormal	Normal	Abnormal	Normal	Abnormal	Normal	Abnormal
Fast spectrum							
Choice of coolant	5.3.2.2 Void coeff. of liquid metals 5.4.4 • Pb tamping in HCDA • Coolant channel blockage in HCDA			5.3.2.2 Choice of coolant 5.4.6 Coolant activation products			Loss of pressure in gas systems
Inert (fertile-free) fuel							
Sub-critical state							
Spallation neutron source		5.4.1 Beam tube penetration through containment & vessel	5.4.2 Entry alignment Dropping hazards power density asymmetry hazard	5.4.2 Entry alignment Refuelling activation of magnets 5.4.5 Beam tube activation 5.4.1 Bending magnet activation			5.4.3 LOCA for gas or for side entry beam
Multi-recycle	5.4.4 • HCDA energetics w/no Doppler • Pb tamping in HCDA • Gas coolant blockage in HCDA			Shielding, pyrophoricity, volatility of MAs feedstreams		Heat load of Mas	

* Not only ADS, but also FRs which are targeted for pure burner missions (i.e. no fertile material in the fuel) differ dramatically in behaviour from standard FRs and require solution to new safety challenges.

Spallation neutron source effects

The most readily obvious physical difference is due to introducing the proton beam tube. First is its topological effect on the strategy of multiple containment to provide defence-in-depth. In standard FRs, 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. In the ADS, if driven by linacs, the proton beam tube penetrates the last of these and employs a metallic beam window[42] 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 FR, similar topologies result from steam lines, which penetrate the containment, and from intermediate heat exchanger (IHX) tubes which represent a topological extension of the primary coolant boundary. In BWRs, the steam lines penetrate both the containment and the reactor vessel. Fast acting valves at the containment boundary of steam pipes and robust heat exchanger tube walls are the means of safety strategies used in standard reactors. For the ADS, the window operates in an environment especially hostile in its temperature and the proton and neutron bombardment that it experiences, and the hazard due to the multi-megawatt proton beam potentially impinging on these barrier boundaries is unique to an ADS.

The beam tube also introduces new issues in the area of shielding, by offering a streaming path from the fissioning lattice to the exterior of the vessel. Finally, being several tens of centimetres in diameter, the evacuated beam tube presents a new issue in the form of a potential increase in reactivity should the beam tube flood and decrease the neutron leakage. The degree of reactivity offset from prompt critical must be sufficient to accommodate such potential flooding safely.

The presence of an external neutron source also has an effect on power density peaking factor [142] in the transmuter core 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. Also, depending on the geometry of the beam tube entry, the fuel loading pattern may be azimuthally asymmetric, again affecting the power density profile. 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 wherein power production is only an supplementary function.

Fertile-free fuel effects

A second obvious safety related difference derives from fertile-free fuel, which excludes the traditional Doppler contribution to prompt negative feedback of reactivity in a FR. Small, but not zero, Doppler feedback has been accommodated (and beneficially exploited as a passive safety mechanism in metal-fuelled FRs where a low fuel melting point provides a fast-acting mechanism to terminate HCDA), but FRs with high melting point oxide-fuels rely heavily on prompt Doppler feedback to limit the severity of HCDAs. A mechanisms to terminate HCDA will have to be devised for an ADS with fertile-free fuel.

Pure TRU or MA fuel also presents issues in recycle batch sizes and processing geometries because of a small critical mass. Experience does exist with pyrochemical recycling of metal-fuel in small, discrete batches, limited by criticality constraints. This issue would require much greater care in the case of continuous aqueous reprocessing.

42. In some cases, a fluidic “windowless” target design is considered.

The absence of internal conversion of fertile to fissile species with burn-up will also place demands for reactivity compensation on other design strategies, such as changes to source strength or source effectiveness, batch refuelling, or moving absorber control rods. For minor actinide burners, *in situ* isotopic transmutations mitigate but do not eliminate this issue.

Coolant choice effects

The distinguishing characteristics of the coolant choices relate to system pressure, lattice power density, effect on the neutron spectrum, and chemical activities as tabulated in Table 5.4.

Table 5.4. **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	None

These distinguishing features permeate the entire approach to ADS design and the resulting safety strategies. High pressure gas cooling introduces a loss-of-coolant vulnerability but eliminates issues of chemical compatibility. Gas cooling shares with Pb-Bi cooling the need for a low power density in an open fuel pin lattice (which leads to a potential for reactivity additions should hypothetical pin disruption lead to compaction and reduced leakage). The potential for blockage from foreign objects, sludge, or re-freezing fuel debris remains an issue even in an open lattice. The list goes on and on for ADS and FR alike, and is addressed in detail in the later sections as indicated in Table 5.3.

Sub-critical operating state effects

A fundamental distinction arises between ADS and FR in the differences in dynamic response between critical reactors and sub-critical source-driven neutron-multiplying lattices. In a source-driven system, a change in strength or effectiveness of the source or a change in reactivity will cause the neutron population and power level to adjust to a new asymptotic level; whereas in a critical reactor a change in reactivity leads (in the absence of reactivity feedback) to an asymptotic or exponential evolution in the neutron population. While a favourable ADS safety feature derives from its asymptotic rather than exponential response to a positive reactivity insertion [143], a safety challenge still remains in assuring that increases in strength or effectiveness of the source cannot take the ADS to damaging over-power conditions. Eq. (4) indicates that for instance at a Beginning of Cycle offset of $-\rho_o$ equal to 3% $\Delta k/k$ and a reactivity loss of 6% $\Delta k/k$ on burn-up, the source to maintain the End of Cycle power level would have to exceed the Beginning of Cycle requirement by 100%, leading to a potential over-power by a factor of two should the full source strength be introduced prematurely. Options to minimise burn-up reactivity loss include multi-batch fuel loading [139] and optimal mixes of plutonium and minor actinides [144] to flatten the reactivity change with burn-up. However, given fertile-free fuel, it has proved impossible for ADS designers to achieve small burn-up reactivity loss, so that compensation must be by external changes in reactivity (control rods) or in strength or effectiveness of the source. In every case then, a potential for over-power exists, and a highly assured beam trip capability is essential. If heat removal were to fail (loss of flow or loss of heat sink), then the beam would likewise have to trip off promptly to avoid overheating and melting of the fuel [145,146].

For an ADS, the operating point is offset from prompt criticality by ($\beta + \Delta_o$) where Δ_o is the sub-criticality operating point. This is compared to an offset of only β for a critical reactor. The effect of this is a lower sensitivity to reactivity feedbacks in the ADS than in a FR. This difference gives rise to a need for different strategies in passive safety concepts to keep heat production and removal in balance.

Of equal consequence relevant to safety and controllability is that the time constant of dynamic response of an ADS is the lifetime of prompt neutrons ($\sim 10^{-6}$ s.) rather than of delayed neutrons (effectively ~10 s.) which forms the experience base for a FR.

In summary, the dependence on source neutrons rather than on delayed neutrons to maintain the fission chain reaction leads to more abrupt responses to control changes, and reduced benefit from power/flow dependent reactivity feedbacks, but it provides a new degree of design flexibility in the ability to control the offset from prompt criticality of the operating state.

The issues of dynamic response to reactivity and source changes are the area of greatest difference between FR and ADS in safety-related characteristics and are an area where few precedents exist in the FR experience base.

Accelerator safety

The accelerator brings with it the traditional accelerator safety issues (high-voltage, control of worker dose owing to components activated by beam divergence, etc.). Since these issues are not peculiar to ADS applications, they are left to be handled in accelerator-specific publications.

Recycle facility safety

The recycling and refabrication processes for TRU and MA fuel introduce issues of criticality, pyrophoricity and atmosphere control; these are discussed briefly in Section 5.5 and do not differ in character from those in FRs intended for TRU or MA. In either the ADS or FR case, however, the 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 with current practice.

5.2.5 Guide to location of detailed discussions of safety approach

Table 5.3 indicates the top-level correlation between the salient design features of an ADS and the basic safety functions, which must be provided in any fissioning system. In the table, each safety function pertains to two situations, normal operations and abnormal events, which in general are discussed in different sections.

The order of discussion presented below follows a general pattern covering safety strategy primarily for normal operation in Section 5.3 and then primarily for abnormal conditions in Section 5.4:

5.3.1 Managing the neutron balance and burn-up-induced decrease in source multiplication.

- Fast spectrum and fertile-free fuel effects.
- Effects of source effectiveness.

5.3.2 Removal of heat.

- Effects of coolant choice and source-induced power-peaking effects.

5.3.3 Dynamic control

- Effects of sub-critical operating state dynamics.
- Value of reactivity feedback vs. adjustment of source strength.

5.4 Containment, shielding and removal of decay heat.

- Implications of the source beam transport tube for containment, shielding and refuelling.
- HCDA termination strategy.
- Passive safety response.

5.5 Fuel cycle facility safety.

- Effects of fertile-free fuel.

5.6 Summary.

The entries in Table 5.3 provide a guide for locating the discussion.

5.3 Strategies related to operational safety for FR & ADS systems

5.3.1 Effects of fertile-free fuel and fast neutron spectrum in ADS

5.3.1.1 Neutron balance and choices for disposing excess neutrons

As shown in Eqs. (1) and (2), a multiplying lattice of fertile-free fuel operating on fast neutron chains produces a vast excess of neutrons upon each fission. Only one neutron per fission is required to produce the next fission in the chain reaction. Thus, as many as 50% of the released neutrons are discarded either by leakage or by absorption in non-fuel material. The external source is not needed to produce sufficient neutrons for incineration, but rather because of the approach chosen to accommodate a changing fuel composition and thermo-structural reactivity feedback that may exceed the delayed neutron fraction.

Structure, coolant, fission products and inert diluent in the fuel will parasitically absorb around half of these excess neutrons; the question is how best to dispose of the rest; whether by absorption in the fuel itself by admixing a parasitic neutron absorbing material with the TRU, absorption in other structures added to the lattice but outside the fuel, or leakage?

The following comments concern the trade-off between leakage and parasitic capture in the lattice:

- When the probability of leakage is large, even small changes in it due to thermo-structural effects will cause changes in reactivity feedback. This has two undesirable effects. First it requires an increased offset from prompt-criticality, thereby requiring a larger spallation source strength (larger accelerator) for a given power level. Second, it requires constant adjustments of the source strength or of a reactivity trimmer to compensate and hold power constant as feedback relaxes following a change in power level (discussed in 5.3.3.3).
- A design strategy requiring most of the excess neutrons to leak from a fast spectrum lattice, whether FR or ADS, would create an unnecessary risk of re-criticality upon compaction under hypothetical severe accident conditions, even given that the fuel might float in the coolant (in the case of Pb-Bi case).

These considerations favour parasitic absorption over leakage as the means to dispose of excess neutrons. Should it be in the fuel pin itself, or in separate discrete absorber pins dispersed in the lattice? Several observations include:

- Pure TRU or MA fuel without an absorbing diluent has a small critical mass, requiring small batches in fabrication and recycling processes with a consequent impact on costs.
- Using fixed absorbers, separate from the fuel, would provide an opportunity to "zone" the k_∞ radial distribution without varying the composition of fuel. Such zoning will be highly desirable to overcome power peaking, and shifts in it with burn-up, which are inherent in source-driven lattices.
- On the other hand, fixed absorbers separate from the fuel present a vulnerability should some abnormal event remove the absorbers from the lattice and thereby add reactivity.
- These considerations suggest that absorbing diluent in the fuel itself is the preferred choice. Many considerations will affect the choice of material for the purpose:
  - The absorber composition should be chemically similar to TRU so that it will naturally follow the TRU or MA during chemical separations on recycle (e.g. consider choices already made for CAPRA).
  - The diluent should preferably be a resonance absorber so as to achieve a measure of prompt Doppler feedback.

It may be desirable to poison the core even further with diluent absorbers as a way to increase the critical mass of the core despite a still smaller leakage fraction. As discussed the following section, this will reduce the fractional decrease of fissile content per unit of energy released and will therefore reduce the fractional increment in reactivity or source required to compensate for burn-up. An opportunity for neutronics optimisation occurs here – to balance discharge burn-up and fluence at their respective limits so as to minimise the number of recycle passes required to achieve complete transmutation.

In summary, safety and other design issues all favour the use of absorbing diluents in the fuel rather than leakage as the means to dispose of excess neutrons in a lattice of fertile-free TRU or MA fuel.

5.3.1.2 Compensating burn-up reactivity loss

Countervailing cost saving goals exist in ADS design. The required source strength can be made smaller (less expensive and requiring less electricity to operate) by making the fission multiplying assembly less sub-critical so that it produces more fissions per unit source. To minimise the size and cost of recycling equipment and to minimise TRU losses to the waste steam, it is desirable to maximise burn-up at discharge. These two goals work in opposite directions because each additional fission (to increase discharge burn-up) increases the sub-criticality, which means the source may have to be increased in order to maintain power at a constant level over the refuelling cycle.[43] Thus, if we hold the power constant by adjusting source strength, the source will be oversized for most of the cycle. Alternately, if we hold the source constant and let the power fall with burn-up, the heat removing equipment will be oversized for most of the cycle.

If we reduce discharge burn-up so as to mitigate reactivity loss, the recycle equipment will be larger than it could have been, and the unavoidable trace losses of TRU to the waste stream will be larger than otherwise. Alternatively, if we refuel partial batches frequently (to approximate continuous refuelling) we will reduce plant capacity factor and all plant equipment will be idle for a greater percentage of the year.

In light of these trade-offs, the ADS design must certainly find a way to reduce burn-up reactivity loss per unit energy release, and then as complementary measures:

- Compensate for declining reactivity with frequent partial core refuelling as burn-up occurs.
- Load excess fissile material and then compensate for loss of reactivity by withdrawing external neutron-absorbing control rods.
- Increase the source strength as burn-up occurs.
- Increase the source effectiveness as burn-up occurs.
- Some combination of the above.

The first step – which clearly should be taken – is to increase the critical mass so that each TRU atom fissioned is a smaller fraction of the total fissile mass and will lead therefore to a smaller percentage increase in sub-criticality thus requiring a smaller percentage change in compensating absorber reactivity or source strength.

- This is one additional reason to employ a fast spectrum system where critical mass is larger than in a thermal spectrum system.
- It is reason also to increase neutron wastage by diluent absorption, lowering k_∞ to nearly unity and requiring a larger and less leaky lattice of maximum fissile inventory.

The second approach is to refuel the core in parts and provide for an adjustable parasitic neutron absorber (a control rod) which can be moved so as to hold sub-critical reactivity constant as fissile content is burned out. This is well-established and reliable technology from FR experience.[44]

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43. Alternative burn-up compensation options are discussed next.
44. Semi continuous refuelling, as in a CANDU, has received some consideration, but is not currently being pursued.

The third potential approach is to adjust the proton beam current and resulting source strength. While widely discussed, this approach requires an accelerator substantially oversized for all but the end-of-cycle conditions. Besides cost considerations, a safety vulnerability is introduced should the full beam power be applied at the beginning of a cycle. An alternative approach of operationally running a constant proton beam but adjusting the effectiveness of the spallation neutron source can be considered. The spatial dependence of source effectiveness could possibly be exploited by moving the spallation target from top of core to core centre, making it more effective. Alternatively, the energy spectral dependence of source effectiveness could be exploited by introducing the spallation neutrons into the core at an ever-increasing energy. As shown in Figure 5.1, the spallation neutron emissions spectrum is much harder than the fisison emission spectrum, with a very substantial tail above 6 MeV. Figure 5.2 also shows that η of the TRU isotopes rises dramatically above 6 MeV. Thus, increasing the energy of the source neutrons from 3 MeV to 10 MeV would increase υ (and η) of the TRU or MA fuel by as much as 33 to 50%.

Figure 5.1. **Comparison of spallation and fission neutron source spectrum**

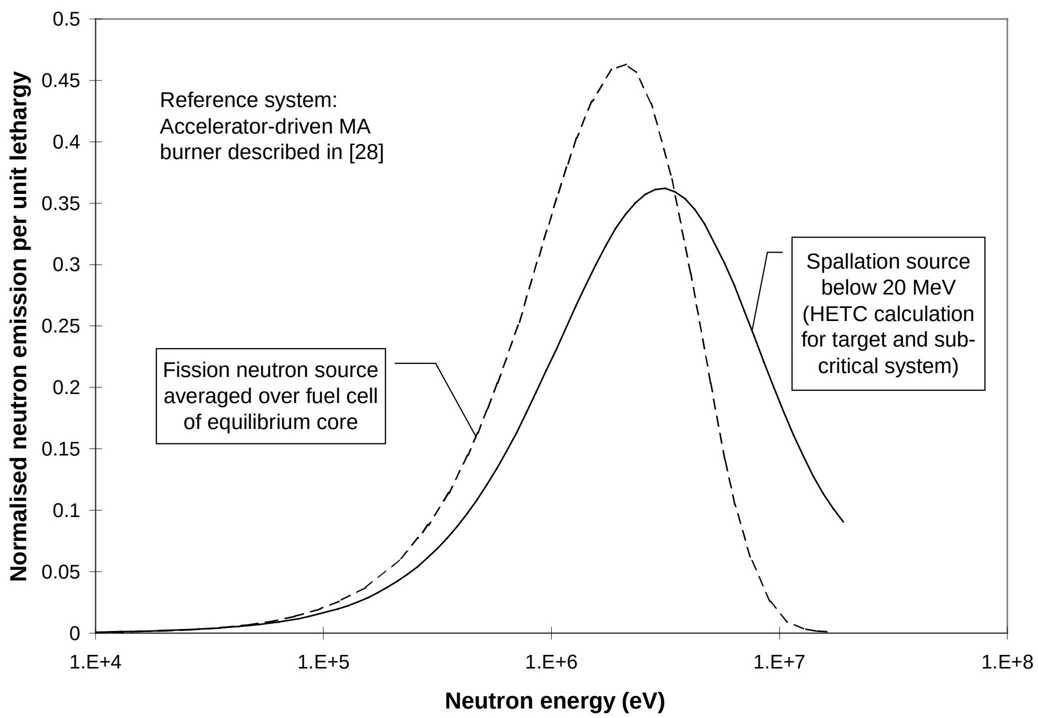
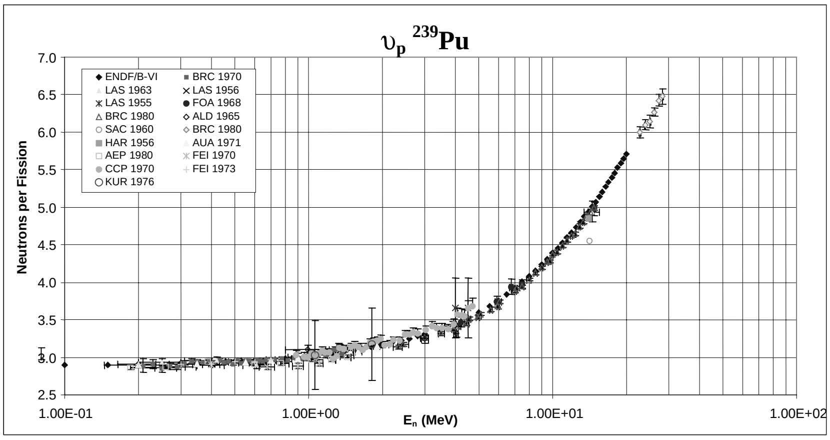
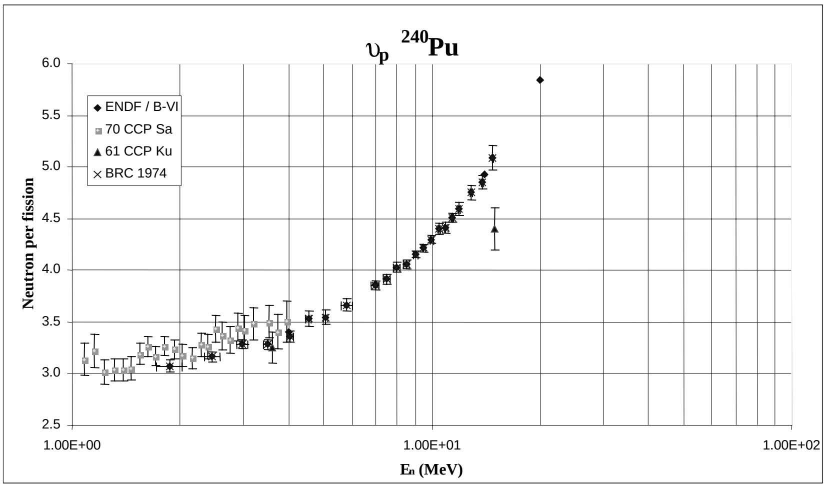


Figure 5.2. **Average prompt neutrons per fission for ^{239}Pu and ^{240}Pu**





Assume for example the first collision of a 10 MeV spallation neutron with TRU and it causes fission. Whereas k for a fission spectrum neutron is 0.98, the k for a ~10 MeV neutron is 50% larger because υ has increased by 50%. All subsequent multiplications in each prompt chain will be sustained by fission neutrons where υ and η return to their fission-spectrum average values, but that first fission with a 10 MeV neutron has already amplified the source by the ratio [υ(10MeV)/υ(2MeV)]. Repeating the derivation which led to Eq. (3) gives:

$$\text{Power} \sim \begin{pmatrix} \text{asymptotic} \\ \text{neutron} \\ \text{population} \end{pmatrix} = S\Lambda \left(\begin{array}{l} 1 \\ +k' \\ +k'k \\ +k'k^2 \\ + \ . \\ \quad . \\ \quad . \end{array} \right.$$

$$= \left(S + k'S\left[1 + k + k^2 + ...\right]\right)\Lambda$$

$$= S\Lambda \frac{1 + (k'\text{-}k)}{1 - k}$$

So with k'/k = 1.5 and k = 0.98 we get a 49% increase in source strength. This can compensate for a 49% increase in -ρ, the sub-criticality of the lattice, due to burn-up. Such changes in first flight spallation neutron energy could potentially be achieved by mechanical or pneumatic adjustments of the optical thickness of the buffer around the spallation target – quite sufficient to compensate significant burn-up loss.

Some comments can be made regarding the relative safety advantages of the several options:

- First, increasing the working inventory by reducing k_∞ with an absorbing diluent in the fuel would appear to impair no safety function.

- All the other complementary options for burn-up compensation create a vulnerability to transient over-power because compensating for the reactivity loss upon fuel burn-up, requires either added reactivity or more (or more effective) source neutrons; there is no other choice. Since the option to do this must be designed in, then the risk of doing it prematurely by inadvertence cannot be avoided: each option has a potential to initiate an over-power transient.

- Adjustments to the depth of control rod insertion, location of the spallation target or optical thickness of the spallation neutron buffer are all mechanical in nature; are subject to inherent speed limitations; and (for control rods) are within the experience base of FRs, all attractive features from a safety viewpoint.

- Design efforts to optimise the control strategy for burn-up will have to await some quantification of the relative capital and operational costs of the source, the recycle equipment and the heat removal equipment. However, several observations about cost are obvious without detailed optimisation studies; they pertain to the relative costs of fissile material, neutrons, and protons. The ADS mission is to incinerate fissile TRU or MA which is viewed as a waste; in this mission, fissile material has no commercial value and is cheap. As discussed above, the neutrons exist in excess and must be discarded to parasitic capture; in this mission, they too are cheap. On the other hand the protons are costly, produced in expensive equipment at high operating cost. Finally, as is easily seen by differentiating Eq. 4, to the first order, power scales linearly with changes to source strength or to sub-criticality but with very different factors. Multi-megawatt changes in the proton beam are required to achieve the same power increment that only a few tenths of a percent change in sub-critical reactivity can produce. These observations suggest that a cost effective approach for holding power constant during the ADS fuel burn cycle is to load cheap excess fissile material and discard a variable number of cheap excess neutrons in an adjustable parasitic absorber (control rod) so as to avoid sizing the accelerator for the neutron multiplication level otherwise needed at the end of cycle.

5.3.2 Heat removal in ADS; effects of coolant choice

An important objective is to maintain adequate cooling of all fuel pins throughout their lifetime while avoiding cost penalties involved in over-designed pumps, over-cooled pins and the consequently low coolant outlet temperature with reduced efficiency in energy conversion. This is more challenging for an ADS than for FRs because of inherently greater power peaking in the ADS. Both the source and the beam entry geometries are contributors; source effects are discussed here and those of beam entry geometry in 5.4.2.

5.3.2.1 Power density peaking and its changes with burn-up

In a source-driven sub-critical multiplying lattice, the classical convex fundamental mode neutron flux distribution of a critical reactor is not retained; instead, a concave flux shape peaks at the source and decays with distance from the source prevails. Power-peaking factors are controlled by radially "zoning" the k_∞ distribution of reactivity, whether by fuel shuffling or by grading the radial distribution of fuel volume fraction or of absorber distribution.[45]

A strategy of uniform flow through either FR or ADS cores would require sizing the pumps for the pins of highest power, with consequent pump over-sizing and with substantial over-cooling of most fuel pins. The traditional way to address this issue in FRs of high power density is to use ducted assemblies (i.e. preventing cross flow) with flow metered to individual assemblies by means of orifice plates. This works well when the radial power density profile changes little with burn-up. Such invariance of radial power profile may not be achievable to the same degree in an ADS, depending on the approach taken to compensate for declining reactivity. For example, adjusting source amplitude or the spatial distribution of its effectiveness will necessarily exacerbate the shifts in neutron flux profile by changing the ratio of source to fission multiplied neutrons; it will exacerbate the effects of changes in the radial k_∞ distribution as the fuel preferentially burns out in regions of higher power density.

Assurance of adequate cooling under normal and abnormal conditions is a significant safety issue for ADS and FR alike, and the higher power peaking and its change with fuel burn-up in an ADS will demand careful attention during design optimisation. A general strategy cannot be formulated before the approach to controlling the decline in reactivity is decided. However, an avenue for consideration is to design the ADS with low power density in a loose lattice of ductless assemblies and to assist pumped flow by natural circulation, which tends inherently to distribute itself radially so as to maintain a temperature rise in the coolant that is relatively uniform across the core. This option is available to liquid (but not to gas coolants) and it carries a cost penalty owing to increased vessel size for a given power rating when the power density is decreased.

5.3.2.2 Choice of coolant

Several different coolants are under current consideration for fast neutron ADS designs. Sodium-cooled designs comprise the least extensive departure from the traditional fast reactor experience base. Lead-bismuth eutectic alloy designs are considered, owing especially to the excellent proton-induced neutron spallation properties of lead and the possibility of incorporating a common database of materials properties and design experience for both liquid metal spallation target and reactor coolant. Gas cooling (He or CO_2) of a fast spectrum ADS is also under consideration. Taking a sodium-cooled fast reactor as the reference, the safety-relevant differences to be addressed by coolant choice are discussed below.

One of these is activation of the coolant and of the impurities which are either initially contained in it or dissolved or suspended into it through corrosion and erosion of structural materials. This issue, which is common to FR and ADS, is significant both throughout operational lifetime and later, during D&D and ultimate disposal of the coolant. Neither He nor CO_2 is activated by neutron irradiation. Sodium is activated, producing a 15-hour β-emitter (^{24}Na), but owing to excellent chemical compatibility with structural material, it picks up essentially no activated impurities. Lead-bismuth is activated producing a 138-day α-emitter (^{210}Po) and it tends to pick up scale and dissolved material from chemical interactions with structural materials.

45. Enrichment zoning is precluded by the choice of fertile free fuel.

A second significant safety issue concerns chemical compatibility between coolant and structural material, ease and practicality of controlling structural corrosion, mass transport and sludge formation. The rank order of most to least favourable chemical compatibility at temperatures contemplated for ADS operations (450 to 550°C) is gas, sodium, and lead alloy. Especially in the case of lead alloy, extreme diligence is required to avoid building up of a sludge of corrosion products which could block coolant flow and lead to damage by overheating fuel pins. In the case of lead alloys, an oxide film is maintained on the cladding surface to prelude chemical attack by the coolant. Experience outside Russia is limited on two issues, the increase in impedance to heat transfer due to the oxide film, and the film's robustness during rapid power density changes attendant on beam trips, as will be discussed later in Section 6.3.3. In all cases, in-service inspection of structures with core support or heat transport function will be required; both liquid metal coolants present challenges here.

Liquid metal coolants freeze above ambient temperature and may require trace heating to maintain liquidity in the event of a long shut-down. The issue is of special relevance for lead which freezes at about 325°C, so the flow and temperature of feed water to the heat transfer equipment must be designed and controlled with this high temperature in mind. The high boiling point of lead and lead-bismuth, on the other hand provides more than sufficient margin to boiling.

The coolant voiding coefficient of reactivity owing to the energy dependence of the η of TRU fuel is a significant safety issue in liquid-metal cooled FR systems. Reducing the density of a liquid metal coolant, or creating voids in it, causes two opposing reactivity changes: increased neutron leakage (reducing reactivity) and reduced neutron moderation with a resulting increase in the energy-averaged value of η (increasing reactivity). The rank order of most to least favourable net feedback effect occurs with gas, lead alloy, and sodium; gas has little effect on either leakage or moderation, and lead alloy has less than sodium. Steam entry in a gas-cooled system driving a Rankine cycle through a steam generator is similar in effect to positive void, it adds reactivity. Change of phase is not an issue for gas or Pb-Bi but is for Na. In every case however, an ADS is purposefully designed to reduce the safety significance of reactivity effects as compared with a FR by increasing the offset to prompt criticality and operating below delayed criticality. The coolant void effect will do no more than influence the degree of sub-criticality in an ADS [147].

The high density of lead-bismuth introduces two issues on which little experience exists. 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 they tend to float in it.

The larger thermal mass of liquid metals compared to gas provides a mitigating feature in loss-of-cooling accidents, providing longer periods of grace for removing decay heat.

A significant safety issue is the consequence of leaks in the primary coolant system. Rank ordering of coolant for ADS and FR 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 circuit could lead to a loss-of-coolant accident (while thermal neutron spectrum, graphite moderated gas systems with TRISO fuel particles have a huge thermal storage capacity and a very high temperature threshold for damage and can ride this event out, it remains to be shown that the same could be accomplished in a gas cooled ADS design). Loss-of-coolant accidents have extremely low probability in liquid-metal cooled systems in a pool layout (e.g. 10^{-4} to 10^{-6} for the EFR primary vessel leakage). Each liquid metal, however, displays a safety vulnerability upon loss of integrity in the primary boundary. Sodium burns in air, creating an aerosol containing (24 hr β-emitting) radioactive ^{24}Na. Lead-bismuth 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 leakage of Na and Pb-Bi and are more mature than in a gas cooled fast reactor. However, in-service inspection and repair are much more difficult with cooling by opaque liquid metal rather than by gas.

For fast spectrum ADS applications safety-related issues upon loss of primary boundary integrity should be evaluated first at the particular point of vulnerability inherent to ADS: the single thin wall between the transmuter coolant and the evacuated extension of the proton beam tube leading into the spallation target at the centre of the core. That 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 outside the containment building. Melting through the beam tube presents a similar vulnerability to losing containment.

5.3.3 Sub-delayed critical operating state; dynamics

5.3.3.1 Asymptotic response of power to changes in source and sub-critical reactivity changes

The neutron multiplication of an external source in a sub-critical lattice relates asymptotic neutron population to steady-state source strength as shown in Eq. (2).

With an appropriate conversion factor, the asymptotic neutron population is proportional to the total fission rate (Power) or the power density as shown in Eq. (4) and repeated here:

$$P \simeq \frac{\Lambda S}{\frac{1}{k_0} - 1} \equiv \frac{\Lambda S}{-\rho_0} \quad \text{where } \rho \equiv \frac{k-1}{k}$$

The asymptotic fractional change of power or of power density to fractional changes in source strength, δS, or in reactivity, δρ, is given, to first order, by differentiation:[46]

$$\frac{\delta P}{P_0} = \frac{\delta S}{S_0} - \frac{\delta \rho}{\rho_0} \tag{5}$$

and, for example:

- 10% source change causes 10% asymptotic power change.
- 10% reactivity change causes 10% asymptotic power change.

Changes in power are directly proportional to those in source or sub-critical reactivity at sufficiently small values, but the baseline values of source and of sub-critical reactivity are very different in magnitude: the source is very large, requiring proton beams in the range of tens of megawatts, whereas the sub-critical reactivity is only a few percent in the neutron reproduction factor, k. Because hundreds of megawatts of fission power are required to incinerate, but accelerator can deliver only tens of megawatts of proton beam, source multiplication of 50 or more are needed and require a sub-criticality, ρ_o, no more than a few percent.[47]

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46. For large changes, ΔS, or Δρ, the non linear terms may be important: $\frac{\Delta P}{P_0} = \frac{\Delta S}{S_0} - \frac{\Delta \rho}{\rho_0 \left(1 + \frac{\Delta_0}{\rho_0}\right)}$

47. Additionally, the rate of generating radiotoxic spallation products, an unavoidable consequence of ADS operations, is minimised by operating near criticality so that spallation products do not outweigh TRU incineration in the net balance of radiotoxicity.

This has profound practical relevance to controllability because when ρ_o is near zero and the source is strongly multiplied, any small changes in contributions by reactivity feedback to the value of k translate into big changes in sub-criticality, ρ, and to big changes in source multiplication. For example, each source neutron is multiplied 50 times if k = 0.98.

$$\rho_0 \approx -0.02$$

In this case, a change Δk of only 0.002 represents a substantial 10% change in ρ_o (and in power when the source remains constant). Although the change in k seems minute, it is the range of thermo-structural feedback.

Thus, in an ADS, even slight changes to thermal or structural reactivity feedback would require multi-megawatt changes in proton beam strength (or in source effectiveness) to compensate for them and hold power level constant. But such thermo-structural reactivity feedbacks will unavoidably occur and will relax over several minutes following every power change, suggesting the consideration of a compensating control rod in the ADS to avoid the need for continual large adjustments of the multi-megawatt proton accelerator.

Reactivity changes due to fuel burn-up will be very much larger than thermo-structural feedback, causing increases in sub-criticality in the region of several hundred percent. However they occur on a longer time scale. Design options accommodating them were discussed in Section 6.3.1.2 but again are profoundly affected by the implications of Eq. (5).

Whatever the strategy chosen for adjusting power level in the face of reactivity changes, the degree of sub-criticality, ρ_o, takes on a safety significance in the ADS because it is the basis for assuring that no plausible reactivity variation can take the chain reaction into the super-prompt-critical range. Thus ADS systems will require a safety-standard means of monitoring the level of sub-criticality to ensure that it never falls below the specified minimal value.

5.3.3.2 Dynamics of power response to changes in source and to changes in reactivity

In a critical FR system, a reactivity change leads to an asymptotic[48] change in power over a period controlled by a time constant, 1/λ, of about ten seconds as determined by the delayed neutron half lives $1/\lambda_i$.

$$1/\lambda = \Lambda_0 + \sum_i \frac{\beta_i}{\beta} \frac{1}{\lambda_i} \simeq 10 \text{ s.}$$

The initial prompt jump step change in power (which takes place on the 10^{-6} second scale of the prompt neutron generation time, Λ), is very small at about 0.003, and is followed by the slower period response which takes off from the post-prompt-jump power level, the rate of which depends on the magnitude of the inserted reactivity. The rate 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 6.1).

Sub-critical operating state and dynamics effects

A fundamental distinction between ADS and critical reactor in safety control arises from the dramatic differences in dynamic response between critical and sub-critical source-driven lattices. In a source-driven system, a change in strength or in effectiveness of the source, or a change in reactivity,

48. Feedback effects were discussed in the previous section.

will cause the neutron population and power level to adjust promptly[49] to a new asymptotic level in accordance with Eq. (4). By running the neutron multiplying lattice below delayed criticality and making-up the deficiency in neutrons by supplying them from an external source, an increased margin between the operating state and prompt criticality can be achieved, and this strategy has the beneficial effect of allowing for greater variations in reactivity without entering the range of a prompt-critical abnormal accident where power would increase exponentially with a time constant of microseconds. Moreover, in the sub-prompt critical range of normal operations, it leads to bounded rather than exponential power density responses to reactivity changes. These are desirable effects for the reasons discussed previously. However, the price that is paid is that the microsecond time constant of the prompt neutron dynamic response now prevails even in the normal operating range.

The dynamics and control challenges can be illustrated under the realistic 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:

$$\frac{dn}{dt} = 0 = \frac{\rho - \beta}{\Lambda} n + \lambda C + S \tag{6}$$

$$n(t) = \frac{\Lambda}{\beta - \rho(t)} \left[\lambda C(t) + S(t)\right]; \quad [\text{units}] = \left[\frac{\text{neutrons}}{\text{cm}^3} \times \text{vol. of core}\right]$$

where:

Λ	=	prompt neutron generation time ~ 10^{-7} s.
$1/\lambda$	=	delayed neutron precursor lifetime ~ 10 s.
β	=	delayed neutron fraction ~0.002.
β-$\rho(t)$	=	$\beta - \rho_0 - \Delta\rho(t)$.
β-ρ_0	=	reactivity offset from prompt critical $\left[\frac{\Delta k}{k}\right]$.
$\Delta\rho(t)$	=	feedback + external control reactivity.

The prompt neutron population establishes equilibrium immediately (~10^{-6} s.) after any change in:

- External source change — $S(t)$
- Delayed neutron precursor source change — $\lambda\, C(t)$
- Reactivity change — $\rho(t) = -\rho_0 + \Delta\rho(t)$

The responsive rates of the two sources which drive the neutron population are very different: S(t) is fast and can change by 100% in 10^{-7} sec. while the delayed neutron source, $\lambda\, C(t)$ is sluggish with a time constant of $1/\lambda$ ~10 sec.

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49. The adjustment will occur within several prompt neutron generation times for a sub-criticality of 2 to 3% $\Delta k/k$. Given a generation time of ~10^{-7} s., prompt means adjustment times of no more than a few microseconds for an ADS.

Moreover, the delayed source has a memory of previous history of n(t):

$$\frac{d}{dt}C(t) = 0 = \frac{\beta n(t)}{\Lambda} - \lambda C(t) \tag{7}$$

$$C(t) = \int_{-\infty}^{t} e^{-\lambda(t-\tau)} \frac{\beta}{\Lambda} n(\tau) d\tau$$

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 the level of sub-criticality.

From Eqs. (6) and (7):

$$\frac{S_0}{n_0} = \frac{-\rho_0}{\Lambda}; \frac{\lambda C_0}{n_0} = \frac{\beta}{\Lambda} \tag{8}$$

So, for the ADS:

$$\frac{\text{delayed source}}{\text{total source}} = \frac{\lambda C_0}{\lambda C_0 + S_0} = \frac{\beta}{\beta - \rho_0} = \frac{\left(\begin{array}{l}\text{delayed critical offset} \\ \text{from prompt critical}\end{array}\right)}{\left(\begin{array}{l}\text{total offset from} \\ \text{prompt critical}\end{array}\right)}$$

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

Because it is only a small fraction of the total source, to changes in which the neutron population adjusts promptly, the delayed source cannot be counted on in the ADS to slow down the dynamic response of the neutron population (and concomitant power density) even though such a reaction is highly desirable because the time constants of heat removal, relaxation of thermal stresses, and relaxation of reactivity feedback all lie in the range of 0.1 to 100 seconds (See Figure 5.1). Since delayed neutrons cannot buffer the differences between the prompt neutron power adjustment time and the slow thermo-structural relaxation times, new control challenges arise for the ADS; specifically, the controller and actuator must themselves perform this function so that the control actuator (whether acting on source strength, source effectiveness, or reactivity) must achieve:

- Very gradual adjustments.
- Very precise changes.
- High reliability.

Moreover, the fuel is where neutronic and heat removal time constants clash continually; giving rise to new requirements on the fuel, as well; specifically it must be structurally resistant 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 effectiveness (either spatial or spectral dependencies). As in compensating for reactivity swing with burn-up, the control actuator will probably be required to have 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 an extremely abrupt response to control actions, reduced influence of reactivity feedback from changes in power or flow-rate, and adds to the importance of the fuel and of the control actuator itself in reconciling the vastly different time constants of nuclear and heat removal processes.

5.3.3.3 Thermo-structural time constants and ADS tolerance to abrupt power density changes

The time constant for the response of power to changes in source or reactivity is evidently very much shorter than that of heat transfer from fuel to coolant (~0.1 to 1.0 s.) so that all incremental heat from a change of source or reactivity is initially deposited in the fuel and remains there for up to a second. As an example, for pin linear heat rates typical of FRs, the temperature difference between coolant and centre line in oxide-fuel is ~1 500°C; accordingly, a 10% source increase leads to a 10% step change in power density and so to a 150°C increase in ΔT across the fuel pin radius, occurring over the several hundred millisecond time constant of thermal diffusivity in the fuel. For metal or nitride, the fuel temperature rise is ~200°C from coolant to fuel centre line so that a 10% source change gives rise to a 20°C increase in ΔT across the fuel pin radius in several hundred milliseconds. To prevent the resulting thermal shocks from reducing the fuel to rubble, the potential ADS design approach is to employ fuel of high thermal conductivity and heat capacity but especially with a high degree of structural toughness.

The time constant of power change is also very much shorter than the transit time for coolant through the lattice and than the time constant for heat transfer from the coolant to the heat sink across heat exchanger tubes. Structural members in the transmuter are of heavy gauge metal for which thermal stress resulting from rapid changes in surface temperature is serious degradation; thermal shocks to structural members having safety related functions in core support or heat removal are clearly to be avoided.

Proton beam trips occur frequently in current linear accelerators [127], and they provide an ADS-specific safety issue in that power density has a time constant much shorter than that of structural thermal response. Upon a proton beam trip, the coolant temperature rise will promptly collapse to zero and all structures downstream from the core outlet will be bathed by coolant which is much cooler than it was just a few seconds previously. Since the time constant for structural temperature equilibration is longer than for temperature change in the coolant, thermal stresses will exist, and if the beam trip events occur frequently, low-cycle fatigue failure of the structures becomes a safety and an operating issue [148,149]. (Because it is a poorer heat transfer medium than liquid metals, gas coolant leads to reduced thermal shocks on downstream structures, but does not eliminate the phenomenon as a safety issue).

Any of numerous design approaches could be taken. First, it is clear that intentional power changes would have to be controlled so as to be gradual. Second, the fuel has to be capable of adiabatic heat storage to buffer any sharp changes, (i.e. to have very large margins to damage temperatures, structural toughness, and high heat capacity). Finally, since temperature changes upon power change are proportional to the nominal temperature rise across the core; de-rating power density to reduce core temperature rise can be considered, at the expense of increase in size and cost of all capital equipment; alternatively, flow could be rapid forced circulation to yield a smaller temperature rise across the core. Either way, abrupt changes in power would yield smaller changes in the outlet temperature of coolant.

5.3.3.4 Options for trim control of power to compensate for thermo-structural reactivity feedback

Thermo-structural mechanisms of reactivity feedback have amplitudes which are individually significant in relation to ADS operating sub-critical set-points in the range of $\rho_0 \cong -0.02$. the following mechanisms adjust to power changes with time constants which vary from a few seconds to several hundred seconds:

- Fuel axial expansion (~5 s.)
- Fuel assembly radial bowing (~5 s.)
- Grid plate radial dilation (~200 s.)
- Core support structure axial expansion (~400 s.)
- Control rod driveline expansion (~60 s.)

Experience in FRs indicates (See Figure 6.3) that these thermo/structural feedback mechanisms each have values in the range of 20 to 50 β (on β of 0.003), i.e. in the range of 0.0006 to 0.0015 Δk/k. Therefore, following any power change in an ADS, the net level of sub-criticality, ($\rho_0 + \Sigma$ feedbacks) will fluctuate by up to 50% of its value with net positive and negative effects relaxing over several minutes. How should these variations in net sub-criticality be trimmed to hold power constant?

To avoid constantly adjusting the multi megawatt proton beam strength to trim feedback, it would be preferable to hold the proton beam current constant and use a mechanical actuator to trim the reactivity or the source effectiveness to hold power constant as the feedback relaxes; such mechanical adjustments are simple to implement and the technology is within the extensive FR experience base for reliable controllers and actuators. Moreover, from a controllability point of view, since moving absorber actuators (control rods) is naturally slow whereas proton beam changes are naturally fast, it would be preferable to trim control mechanically rather than through beam strength, because, as discussed previously, it is important to increase the time constant of the change in power density to match that of heat removal.

Finally, controlling the power level of an ADS through the accelerator beam current might lead to a "nuclear safety grade" designation for the accelerator equipment and its maintenance, with significantly unfavourable cost implications. Alternately the proton beam could be operated at 100% strength at all times with a safety grade scram circuit, while effects of declining or fluctuating reactivity could be compensated by mechanical actuators of safety grade. Assuming a beginning of cycle $-\delta_o$=3% and a burn-up swing of 6%, a control rod bank worth of 6% Δk/k would accomplish the same compensation for burn-up reactivity as a proton accelerator larger by factor of two, probably at a significantly lower cost. Mechanical adjustments of neutron source effectiveness through changes in source location or spectrum may be other options. Even adjustable mixes of various spallation target materials having differing neutron yields per proton might be considered.

In any case, even when controlling with reactivity, adjustments in power density will follow within microseconds and therefore the controller should move the actuators quite gradually, while the fuel should have high thermal storage capability and be mechanically tough.

5.3.4 Spallation neutron source and beam tube effects

The spallation target and associated proton beam tube introduce vulnerabilities to added reactivity and increased source strength unique to an ADS. The most obvious is the potential for positive reactivity insertion upon flooding the beam tube and shutting off the streaming leakage path for neutrons out of the core. The second is the potential to increase inadvertently the strength or the effectiveness of the source neutrons in a way that increases power density. Penetration of containment is a third issue and will be discussed later in Section 5.4.

5.3.4.1 Beam tube flooding

Should the beam tube wall or window loose integrity, then in the cases of Na or Pb-Bi cooling, the coolant would immediately flood the evacuated beam tube to a level at least the height of the coolant free surface. Although the spallation source would move to the upper regions of the flooded column and its neutronic coupling to the transmuter core (i.e. its effectiveness) would drop to nearly zero, an increase in reactivity would result from extra neutron reflection due to filling the tube with coolant which acts as a reflector more than an absorber. It will be essential to design the ADS so that this event would not take the core into prompt criticality. Scoping calculations for a 840 MWth Pb-Bi cooled system with a 40-cm diameter beam tube indicate that reactivity additions in the range of 0.5% $\Delta k/k$ (i.e. several dollars) are possible.

The beam tube flooding scenario will be one among many of the considerations for setting the sub-criticality level on the transmuter fissile loading.

5.3.4.2 Source importance changes; buffer voiding event

The "effectiveness" of the neutrons which are injected into the sub-critical transmuter lattice depends not only on properties of the transmuter lattice core itself but also on the spatial position and the energy spectrum of the source neutrons. Current ADS design concepts place the spallation target near the centre (axially and radially) of the transmuter lattice where its is most effective. When central placement of the target is the design approach, abnormal events which move the source location off centre (e.g. the beam tube flooding event described above) will reduce the effectiveness of source neutrons, and without changes in reactivity the neutron population and associated ADS power level will tend to decrease.

In addressing the energy dependence of $S^*(R,E)$ for source neutrons, it is noted that after the first flight leading to a fission event, multiplication in the subsequent prompt fission chain will be determined by the familiar formula for sub-critical source multiplication shown in Eq. (3), which depends on the properties of the transmuter core geometry and composition ß and particularly on the η value of the transuranic fuel averaged over the fission neutron emission energy spectrum as slowed down by the lattice materials. This fission-multiplied neutron energy spectrum never exceeds the top end of the fission emission spectrum at a few MeV. The fission power is directly proportional to this fission-multiplied neutron source strength as shown in Eq. (4).

However, the spectrum of spallation neutrons has a tail in its distribution which goes well beyond 6 MeV as shown in Figure 5.2. Therefore, spallation target designs incorporate a row of "buffer" assemblies around the target, filled with coolant and other scattering materials to moderate the energy distribution of the neutrons down to the MeV range and to spread their directions of emission so as to produce a more nearly isotropic source. Should this moderator material be somehow removed, the most energetic spallation neutrons would pass through the buffer on their first flight with little or no scattering moderation and undergo their first fission interaction at high neutron energy (e.g. > 6 MeV), with a higher value of η than intended and releasing substantially more fission neutrons. All subsequent events in the fission chain would continue as before. Thus a vulnerability exists in that an abnormal loss of moderation in the buffer would significantly raise the power to flow ratio at a fixed value of sub-criticality.

Since an abnormal buffer voiding event will constitute a vulnerability in any case, this mechanism can perhaps be put to good use and included among the options considered in Section 6.3.1.2 for deliberate control of the transmuter power level in the face of declining reactivity with burn-up.

5.4 Containment, shielding, and decay heat removal

The traditional FR design approach for assuring the containment of radioactivity is based on defence in depth with three containment boundaries: the fuel cladding, the primary coolant system boundary, and the containment structure. Each barrier has provisions for cooling so as to maintain its integrity in both normal and abnormal conditions. The outermost barrier, the containment structure itself, must be designed to ensure containment when the middle barrier is vulnerable during refuelling operations, and it must provide a highly reliable channel for transmitting decay heat to an exterior ultimate heat sink without loss of containment even under severe accident conditions. The strength requirements of the containment derive from considering hypothetical core disruption events and the amount of internal heat, pressure, and missiles that they could conceivably generate. While many containment issues are similar for FR and ADS, several are peculiar to features of the ADS.

5.4.1 Proton beam tube penetration of containment barriers

The presence of a spallation target at the centre of the transmuter core and the arrangements made to direct a high energy proton beam on to it are features totally absent from a fast reactor. Several safety issues related to the containment function, but also pertaining to refuelling, shielding and coolability, are discussed here.

An obvious issue raised by the beam tube of an ADS is that of maintaining multiple containment barriers. For linac-driven ADS, the proton beam tube penetrates the containment-building barrier. (Cyclotron-driven ADS could conceivably place the cyclotron inside the containment structure and avoid penetrating the outermost of the three containment barriers). In both cases, the proton beam tube itself (and the proton window if one is employed) comprise a re-entrant segment of the primary coolant boundary barrier.

The beam tube penetration of the containment boundary is similar in character to the secondary coolant loop penetration of a standard sodium cooled fast reactor or the steam line penetration of a thermal reactor, where safety-grade closure valves can be provided. The multi-megawatt proton beam itself, however, comprises an ADS-specific hazard to the integrity of the tube and the fast acting valve alike, because beam misalignment would promptly melt through the tube wall and if not immediately tripped the beam would melt the fast acting valve.[50]

The beam tube as a re-entrant segment of the primary coolant boundary is topologically similar to an intermediate heat exchanger tube in a FR. In the latter case, the tube contains secondary coolant at ambient pressure whereas in the former it is under vacuum.[51] Again the beam misalignment hazard to proton beam tube integrity and the particularly hostile environment experienced by the beam window are unique to ADS design. Ruptures of either window or tube wall will open up a connection into vacuum so that flows of atmosphere will initially be inward into the accelerator cavities; moreover, loss of vacuum will itself trip the beam as a response to sparking in the HV accelerator cavity. Longer-term containment must be addressed.

50. Upon loss of vacuum, sparking in the acceleration cavity would normally lead to accelerator trip.
51. In the BREST reactor concept an integral steam generator replaces the intermediate heat exchanger, and the tube walls separate high-pressure steam from ambient pressure coolant.

For pressurised gas-cooled ADS, loss of integrity in the beam tube or window represents one of the ubiquitous potential pathways to loss of coolant.

An ADS-specific challenge to the primary coolant boundary barrier may derive from the position of the bending magnet. If, on the one hand, a top-entry beam tube is employed, then the multi-ton bending magnet is placed directly above the transmuter vessel, where it represents a falling hazard in the event of structural flaws or damaging seismic accelerations. If, on the other hand, the beam penetrates the transmuter vessel from the side so as to eliminate this hazard, and penetrates at an elevation below the surface of the liquid metal coolant, then the beam tube provides a vulnerability for coolant draining on failure of nozzle weld or window. With gas cooling, vulnerability to loss of coolant is independent of entry arrangement.

5.4.2 Refuelling and shielding

For the most part, the maintenance of sub-criticality, of containment, and of decay heat removal during refuelling operations present issues common to ADS and FR. The presence of the proton beam tube, however, presents several challenges which are unique to the ADS.

The most obvious is the issue of shielding. Because an unobstructed flight path is essential to deliver the proton beam on target, the opportunity for shielding inside the beam tube is foreclosed. The beam tube comprises a radiation streaming path of significant cross sectional area for gammas and neutrons from the centre of the transmuter core to the exterior of the primary coolant vessel, or even beyond the containment building and into the proton acceleration structures. If the beam enters from the top, the beam tube gives rise also to a straight neutron streaming path from the core centre to the region of the bending magnets, causing their activation by neutron bombardment. If the beam enters from the side, the streaming path extends further into the accelerator segments themselves with the potential for activating them. Bending magnets could provide a labyrinth path, but would be subject to activation of the magnet itself so that shielding and appropriate maintenance procedures become necessary. Both activation of structures outside the vessel and direct radiation streaming present challenges to keep worker dose exposures low during operations and maintenance.

If the beam enters from the top, then bending magnets and their shielding are located directly above the core, and difficulties of access may arise in refuelling, notably through interference with the polar crane and constraints on height. Nonetheless, if top entry beam geometry could accommodate refuelling, it would be beneficial in that the fuel-loading pattern would be azimuthally symmetric, as is not possible with other beam entry orientations.

If the beam enters from the side, interference with refuelling will be avoided, but the fuel-loading pattern will necessarily be azimuthally asymmetrical to accommodate the beam tube. "Teapot" configurations have been considered for conceptual ADS layouts; the beam enters the transmuter vessel at an angle from above, down the spout, and thereby avoids the loss-of-coolant vulnerability, interference with refuelling, and the vulnerability to impact on the magnet. Like the side entry configuration, the teapot approach introduces an asymmetry in core layout and refuelling, giving rise to radial and azimuthal distortions of power density.

The safety relevance of distortions to power density arising from the side and the teapot beam entry configurations is not known without analysis, but will pertain to ensuring cooling, and to accuracy in predicting fissile burn-up. These could affect certain approaches to guaranteeing the specified degree of sub-criticality and in any case will increase uncertainties in the margins from criticality in recycling facilities assumed in sizing process equipment and to control recycle operations.

5.4.3 Decay heat removal

A heat transport pathway sized at 0.1 to 1.0% of rated power must be maintained to the ultimate ambient heat sink from the fuel pins, and must be guaranteed to function under conditions following a severe accident. Enough thermal storage capacity must be provided to absorb the temporary initial excess of decay heat over the capacity of the heat removal channel.

Traditionally in FR plants, the heat transport path to the balance of plant (BOP) heat engine equipment carries a requirement for safety-grade removal of decay heat. Recent fast reactor designs have relied instead on dedicated redundant heat transport circuits from the reactor vessel pool to the air outside the containment structure and often configure them to operate continuously and "passively" on the basis of buoyancy-driven flows. The "pool" category of liquid metal cooled FRs utilises double walled vessels to assure that primary coolant is confined to the pool even if the primary vessel leaks, and the coolant inventory is maintained by this second "guard vessel" to cover the core and the heat exchange surfaces dedicated to removing decay heat (DRACS). With thermal ratings of 1 500 MWth the outer of the two vessels (the guard vessel) is sometimes declared the (close-coupled) containment structure and its outer surface is itself cooled by a natural draught of ambient air (RVACS) as the final link in the decay heat removal channel; (some licensing authority regulations do not accept this close coupled containment).

For liquid metal cooled ADS with top or teapot entry beam tube, a similar approach should apply with no additional issues. For gas cooled ADS or liquid-cooled ADS with a side entry beam tube, the issue of loss-of-coolant accidents would have to be addressed as for LWRs and HTGRs.

Whatever the design for decay heat removal (RVACS, DRACS, or BOP), safety-related testability will be required for ADS as for FR.

5.4.4 Containment loading criteria; HCDA termination

The size (internal volume) and design pressure rating of containment structures for LWRs and FRs have historically been determined by the loadings they must sustain in their role as the final barrier to reactivity release, even in the event of a severe accident which leaves the fuel cladding and primary coolant boundary in tatters. For water-cooled thermal reactors, the determining event is the loss of coolant accident and large hydrogen deflagration (from Zircaloy-water reaction at high temperature); for fast reactors it is the Hypothetical Core Disruptive Accident (HCDA).

Fast neutron lattices of all kinds are not in their most reactive configurations; changes which decrease surface to volume ratio will reduce neutron leakage and increase reactivity, conceivably to reach super-prompt criticality. This unavoidable vulnerability has led to decades of work on severe accident evaluations to determine bounds on energy release resulting from hypothetical core disruption, so as to provide the information for sizing and design of the containment building to contain that release and release rate. Early small prototype sized metal fuelled FRs relied on fuel dispersal to quench the postulated prompt critical burst while later, the larger commercial-sized oxide fuelled FR relied on prompt-acting negative feedback from Doppler absorption in fertile material contained in the fuel to reduce energy release from the burst. The recent modular-sized ALMR relied on melting of the metal fuel and its immediate dispersal by fission gases to preclude a prompt critical burst. In all cases the goal was to quench the chain reaction quickly and thereby limit the energy released, to put lesser demands on the containment structure.

The absence of a fertile Doppler feedback combined with potentially low neutron leakage in an ADS core built of a tough fuel capable of high energy storage will quite obviously necessitate a changed strategy for terminating a severe accident. If, in response to an abnormal initiator, a large ADS composed of fertile-free fuel were to reach prompt criticality, it would then present an exceptionally severe challenge to containment because it lacks both of the historically employed mechanisms to quench a prompt burst in a fast reactor, i.e. it has neither the Doppler feedback in large cores of robust oxide fuel nor the prompt dispersal achievable in small cores of low-melting fuels [150,151].

Both the lead-cooled and gas-cooled versions of FR and ADS have high volume fractions of coolant in the array with greater vulnerabilities than in sodium-cooled FRs. With the geometry for gas cooling, the disrupted fuel pins would block the neutron streaming paths provided by the coolant channels, and thereby add reactivity.[52] With lead cooling, the high density of the coolant itself would offer inertial resistance to spatial disassembly of the lattice thereby requiring a larger deposition of energy for ultimate disassembly and quenching.

It will be important for the ADS safety strategy to devise means of precluding prompt bursts in HCDA using intrinsic properties of the lattice, as was possible for the modular ALMR. An extra degree of freedom is available in the ADS design to cope with HCDA initiators; it is the initial degree of sub-criticality. If it can be made large enough to overcome the reactivity addition of any plausible compaction or coolant voiding, then the potential for super-prompt criticality can perhaps be foreclosed by design. The need to do so provides one of the strongest incentives for designs which consume the excess neutrons generated in a pure transuranic fuel by using internal neutron absorbers integral with the fissile within the fuel pin, rather than by relying on neutron leakage.

Upon fuel pin disruption – even in the absence of prompt bursts – the issue of re-criticality in the fuel debris must be addressed. The situation might turn out to favour the lead-cooled option where the fuel would float and possibly disperse radially as dross on the lead surface. For the gas and sodium option, the traditional FR re-criticality issues will apply.

5.4.5 ATWS initiators; passive versus engineered safety approach

In design and safety considerations for a FR, transients with scram constitute part of the design basis while Anticipated Transients Without Scram (ATWS) are often considered as Beyond Design Basis and used for sizing the containment structure and its pressure rating. Rod run-out (transient over-power) without scram (TOPWS), loss of heat sink without scram (LOHSWS), and loss of pumping action (flow) without scram (LOFWS) are considered whereas loss of coolant is not considered credible for double-vessel pool designs with liquid metal cooling.[53]

For FRs, the term “scram” refers to inserting the bank of safety rods, always with a single rod assumed to be stuck. Depending on specific licensing requirements, simultaneous tripping of primary and secondary pumps may also be assumed. For ADS the term “scram” has not yet been defined, but must certainly mean that at least the proton beam is turned off.

In some FR designs, completely passive accommodation without damage of LOFWS and LOHSWS events has been designed in and even demonstrated in pilot-scale plants such as RAPSODIE and EBR-II [138]. This FR passive safety approach has relied on thermo-structural

52. Particle-fuel gas-cooled fast reactors require careful scrutiny to identify their potential strengths and vulnerability.
53. The leakage through the double vessel has been considered for Superphenix to represent the “Ultimate (BDB) for which public evacuation procedures must be defined. US licensing procedures for CRBR used the HCDA resulting from a transient over-power driven by loss of flow (positive sodium void worth) as the basis for public evacuation procedures.

reactivity feedback to self-regulate heat production to match the available heat removal rate [150,151]. And in the case of TOPWS, a favourable passive safety response can be demonstrated for FRs designed to have near-zero reactivity loss upon burn-up, so that very little excess reactivity is vested in the control rods.

The favourable performance of ADS in reactivity insertion (TOPWS) events has been well documented for reactivity additions which do not take the system super prompt critical and where a beam trip occurs in time to avoid fuel damage [145,146]. Loss-of-heat-removal events in an ADS lead quickly to overheating if the beam remains on as has also been well documented [145,146]. Even with the beam off, it is useful to suppress multiplication of delayed fission neutrons by reducing reactivity when heat removal has failed.

In keeping with the trend in FRs to place increased emphasis on passive means to reinforce active engineered safety systems, several passive safety features affecting cooling rates and source strength are currently being considered for ADS:

- Natural convection at full or significant power levels (to accommodate LOFWS) [146].
- Passive beam interrupts or relocation to a position of lower effectiveness upon overheating of coolant (to accommodate LOHSWS) [146].
- Electricity to drive the accelerator derived not from the grid, but instead fed back from the ADS itself (to accommodate LOHSWS, LOFWS) [151].

Passive power self-regulation based on thermo-structural reactivity feedback, as has been exploited for fast reactors, is precluded by the fundamental characteristic of 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-critical operating point. The offset is only β for a critical reactor. As is evident from the denominator in Eq. (6), the effect is that the power level in an ADS is less sensitive than in a reactor to reactivity feedback. Moreover, as is also evident from the inhomogeneous source term in Eqs. (6) and (7), the power can never be driven to zero by reactivity changes as long as the spallation source is non-zero. The ADS must therefore adopt different strategies for employing passive concepts to keep heat production and removal in balance. Specifically, it needs some means for passively adjusting the strength or effectiveness of the source in response to power changes. Options include powering the accelerator with ADS-generated electricity[54] [152], or source-transmuter coupling dependent on coolant temperature or density. Absorber or moderator curtains in the buffer surrounding the source, or spatial relocation of the target (all activated by temperature or density changes in the coolant) affect coupling and might offer opportunities to apply passive source feedback analogous to the passive reactivity feedback successfully exploited and demonstrated in fast reactors as the passive means to self-regulate the rate of heat production to match removal.

Among research efforts on safety in ADS, applications of passive safety approaches to accommodating ATWS should be stressed, because the efforts for the past decade on FRs have shown significant potential for benefits.

5.4.6 Activation products

In both FRs and ADSs, the activation of materials of construction affects safety, both by exposure to workers during operations, maintenance and decommissioning, and later as a long-term toxicity hazard attendant on waste disposition from the decommissioned plant. Since the function of the class

54. The exceedingly long time constant for feedback presents a major challenge with this option.

of ADS discussed here is to reduce the long-term radiotoxic legacy of nuclear energy, it is especially important that they should not add to it.

The issues of coolant activation and its effect on operational safety issues are similar for ADS and FR and were discussed in Section 5.3.2.2. Activation effects on long term waste management were studied by Oussanov *et al*. [153], who found considerable differences in the character of long-term residual activity arising from sodium, lead, and lead-bismuth coolants. For Na, 50 to 80 years of storage should be sufficient to allow unrestricted further use, for lead perhaps 1 000 years, and re-use is not feasible for Pb-Bi.

Spallation products and activated proton accelerator structures and beam tubes in an ADS are features not shared by a FR. The production rate of radiotoxic species depends directly of course on source strength, providing an incentive for small levels of sub-criticality. The study of long-lived toxicity generated in spallation reactions is at an early stage [154,155]. The mass spectrum of spallation products spans the range from tritium up to the mass number of the target material, and the relative yields depend on the energy of the incident proton beam. Notably, long-lived alpha-emitting rare earth spallation products (e.g. Gd, Sm, and Dy isotopes) could be avoided through use of a target of mass number less than 145 amu – e.g. tin. Preliminary model studies on yields of alpha-emitting rare earths in heavier targets suggest [156] their significance relative to polonium (in Pb-Bi targets) and generally vis-à-vis toxicity reductions obtained by transmuting technetium and iodine.

Beam loss is one of the crucial design factors in the high-current accelerators required for ADS; it also activates accelerator structures, affecting both operations and ultimate disposition of equipment. Detailed calculations were made [157] for the 100 MeV to 1 GeV section of a normal-conducting linac assuming a loss of 0.48 nano A/m (i.e. 1.2×10^{-8} proton/meter) in a 40 mA machine based on the TRISPAL design. Ordinary concrete shielding of between 1 to 4 metres would be required to limit surface dose rate to 1 mrem/h. Misalignment of the beam (40 mA) into the structures for 50 μ s. was also studied and found to produce activation which has largely decayed away after about 15 min. Like the spallation product issue, structural activation in high-current proton beams is at an early stage of investigation.

5.4.7 Propagation of local faults

Issues of local faults (such as breached fuel clad or plugging of coolant channels) which could be propagated and exacerbated into full core events are common to FR and ADS. They have been extensively studied for sodium cooling with oxide and metal alloy fuels where it is shown that chemical interactions between coolant and fuel should preferably avoid forming low-density products. Also, chemistry control of Pb-Bi alloy coolant to avoid both cladding attack and sludge formation has been thoroughly studied in Russian military experience, but scant experience exists outside Russia. It is clear that extensive, multi-year in-pile irradiation testing campaigns will be required for any new combination of fuel, cladding and coolant, as in every one of the inert matrix (non-fertile) fuels considered for TRU/MA ADS burners.

5.5 Safety in fuel cycle facilities

Complete consumption of the transuranic feedstock requires multiple recycling because the neutron fluence required to fission all the transuranic atoms exceeds the neutron damage endurance of the cladding material. Three of the five cardinal safety functions (containment, shielding, and removing decay heat) are identical whether the fuel is in core, out of core in transfer casks, or out of core in a recycle facility; thus the discussions of such issues already given for the transmuter core carry over to the fuel cycle facility as well. However, in the recycling facilities the cladding is purposely removed. Instead of matching heat production and removal, the cardinal safety requirement out of the core becomes simply "avoid criticality".

The safety issues related to containment, shielding, and decay heat removal during fuel transfer and recycle operations are essentially identical for the ADS and FR fuel cycles, but the use of fertile-free fuel in the ADS or FR cycle will affect the functional requirement for avoiding criticality because the fast-spectrum critical mass of pure TRU is small. Pure transuranic fuel, with an η of ~1.8 and a fast-spectrum critical mass of 5 to 15 kg, will have to be handled in small batches. Particular care will have to be taken in accounting for effects of reflection and inventory coupling when designing process equipment and deciding on layout. Similarly, moderating materials will have to be excluded or carefully controlled within the casks and the recycle facility.

Criticality constraints within recycle facilities add still further weight to the preference for use of parasitic absorber material, intimately blended with the fertile-free transuranic fuel itself and chemically similar to a rare earth or actinide so as to follow the transuranics through every stage of recycling and refabrication.

Whether in ADS or FR designed for incineration, shielded remote operations are required because the transuranic elements include strong neutron emitters (e.g. ^{244}Cm), spontaneous fissioning isotopes (e.g. ^{240}Pu), pyrophoric chemical characteristics, and low-temperature volatility (e.g. ^{241}Am). These materials must be handled in remotely operated and remotely maintained shielded facilities under inert atmospheres. Their small critical mass demands that process control and material inventory tracking meet high standards of accuracy and that operations be conducted under strict discipline. Atmosphere control of the hot cells (maintaining inert atmospheres to address pyrophoricity) and discharging aerial effluent only through filtered channels places special requirements on seismic design of structures and equipment. It also makes conflicting demands to maintain effluent filtering during abnormal events (such as a breach of cell containment) while stopping flows in order to smother fires following the access of air to pyrophoric materials. Such issues are peculiar to the presence of TRU or MA fuel types and are common to fuel cycle facilities for FR and ADS alike.

5.6 Conclusions

This chapter analysed the safety-related challenges of a specific class of ADSs employing a fast neutron spectrum and solid, fertile-free fuel with the primary mission of transmuting transuranics or minor actinides.[55] Multiple options for addressing nearly all relevant issues have been developed in the framework of an impact matrix of safety functions required for each distinctive design feature of an ADS, and each distinctive design feature has been tracked back to a specified mission element.

From this analysis, the following conclusions can be drawn:

- The ADS's dynamic response to changes in reactivity or neutron source strength is the area of greatest difference in safety characteristics between fast reactors and ADSs and an area where no precedents exist in the fast reactor experience base.

- The primary cause for this is (a) the external neutron source which can provoke rapid and, depending on the sub-criticality level, large neutron-kinetic responses, unmitigated by the delayed neutrons, and (b) the fertile-free fuel which features very weak reactivity feedbacks, especially from the Doppler effect.

55. A summary of this chapter has been reported in [158].

- This puts high demands on the control actuators, the fuel behaviour, and the heat removal processes. In particular, the strong dissimilarity of the neutron-kinetic and thermo-structural time constants requires the fuel to be capable of sufficient adiabatic heat storage.
- The weak Doppler effect exhibited by fertile-free fuel affects the energetics of hypothetical core disruptive accidents. If such accidents have to be taken into account in the safety analysis of an ADS, a prompt quenching mechanism relying on a phenomenology other than the traditional Doppler effect will have to be developed.
- The management of the surplus neutrons in sub-critical cores with fertile-free fuel by means of neutron leakage and/or absorption involves delicate trade-offs which affect core design. This applies particularly to TRU burners which feature a high burn-up reactivity loss.
- Regarding passive safety principles, it appears that means for passive decay heat removal are already available, but innovation is needed to achieve passive self-regulation of power.