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Inherent shutdown capabilities in accelerator-driven systems

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Abstract

The applicability for inherent shutdown mechanisms in accelerator-driven systems (ADS) has been investigated. We study the role of reactivity feedbacks. The benefits, in terms of dynamics performance, for enhancing the Doppler effect are examined. Given the performance characteristics of source-driven systems, it is necessary to manage the neutron source in order to achieve inherent shutdown. The shutdown system must be capable of halting the external source before excessive temperatures are obtained. We evaluate methods, based on the analysis of unprotected accidents, to accomplish such means. Pre-concepted designs for self-actuated shutdown of the external source suggested. We investigate time responses and evaluate methods to improve the performance of the safety system. It is shown that maximum beam output must be limited by fundamental means in order to protect against accident initiators that appear to be achievable in source driven systems. Utilizing an appropriate burnup control strategy plays a key role in that effort. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

In the design process of a nuclear reactor, important consideration is given to the utilization of passive safety systems and inherent safety features. There is a consensus among reactor designers, supporting the value of passive safety designs. Passive safety systems rely on natural physical phenomena, such as thermal expansion, fundamental nuclear properties, gravity, and heat-transfer by natural convection, to perform essential safety functions. The laws of physics dictate such properties and their effectiveness is not influenced by human action. In the ideal case, passive safety

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design does not require the action of any mechanical or electrical device, making safety functions less dependent on active components. The incentives for employing such designs are improved reliability and simplified operation, both resulting in better safety performance. Inherent features are valuable means for minimizing public concern and gaining public perception on new reactor concepts.

Most work on passive safety in the past has been related to the study of the innovative use of natural convection, decay heat removal, and inherent negative reactivity feedbacks. Such schemes have been successfully implemented in many reactor designs, including water-cooled reactors, gas-cooled reactors, and liquid metal-cooled reactors.

In this paper, we explore the use of passive safety mechanisms to accelerator-driven systems (ADS). While an intrinsic heat-transport path and sufficient natural convection are necessary to achieve passive safety in any reactor system, those requirements are of a general character and are treated elsewhere e.g. (Karlsson and Wider, 2000). Our attention is focused on inherent shutdown capabilities. We evaluate the applicability for such schemes and we suggest some concepts for that purpose.

2. Reference design and modelling

In the assessment, we employ a reference design of an ADS to obtain operating performance data. Accident analysis is performed with the aid of the SAS4A safety code (Cahalan et al., 1994).

The reference design is a model of an ADS that has evolved at the Royal Institute of Technology, Sweden (Wallenius et al., 2001a,b). The core has a nominal power of 800 MW_{th}. It is cooled by liquid lead-bismuth eutectic (LBE) and the fuel is based on a nitride matrix. Fuel pins are configured in an open pin lattice with core average volume fractions of 8/12/80% (fuel/structure/coolant). The fuel consists of (core average): 58% plutonium, 12% minor actinides, 14% boron carbide, 10% uranium-238, and 6% zirconium nitride. Uranium-238 is used in the inner zones to compensate for burnup and poisoning effects (Tucek et al., 2001). Boron carbide is utilized to increase fission-to-absorption probabilities in even neutron number americium isotopes. Radial zoning is applied with an optimized distribution of minor actinides, plutonium, burnable absorbers, and diluents to mitigate power peaking factors and reduce long-term reactivity swing. Taking advantage of a multi-batch fuel loading strategy (Yang and Khalil, 2000), where some fuel sub-assemblies are added to the perimeter of the core on an intermediate time schedule (150 days), the required beam insertion capacity can be reduced. In the present design, it is necessary to ramp the beam by a factor of 1.8 to maintain constant power through an irradiation period of 510 days. Basic design parameters are listed in Table 1.

The primary circuit is illustrated in Fig. 1. The core, heat exchangers, and primary pumps are immersed in a single pool containing LBE. Coolant temperatures, in steady state, range from 573 K at inlet to 702 K at the outlet. In the present design, the inlet flow velocity is set to 2.5 m/s. Deterioration of the protective oxide film

Table 1
Reference ADS design parameters

Core power, MWth	800
Coolant	LBE
Core inlet temperature, K	573
Core outlet temperature, K	702
Flow velocity, m/s	2.50
Volume hot pool, m ³	435
Volume cold pool, m ³	197
Volume inlet plenum, m ³	20
Fuel composition (core average)	Nitrides: 12%MA/73%Pu/15%U238
Inner radius, mm	1.00
Outer radius, mm	2.40
Cladding	HT-9
Inner radius, mm	2.49
Outer radius, mm	2.94
P/D	1.83 and 2.33
k_{eff} eigenvalue, BOL, steady-state	0.954
β_{eff} , %	0.160
Doppler constant, $T_f dk/dT_f$	$-3.87 \cdot 10^{-4}$
Coolant density reactivity feedback, dk/dT_c	$-2.28 \cdot 10^{-6}$

layer on structural material imposes an upper limit on the flow velocity. The actual limit depends on the temperature and is not well known, however, it is estimated to be in the range of 2–3 m/s (Novikova et al., 1999). The reactor vessel is filled with LBE to a prescribed level, with the remainder of the vessel being occupied by an inert cover gas. The steam generators are elevated well above the core to promote natural convection.

A primary system model is set-up in SAS4A, including a detailed multi-channel model of the core, heat exchangers, pumps, compressible pool volumes, etc. Point kinetics is used for calculating transient power. The neutronic response between core regions is strongly coupled and space-time effects may be neglected for our purposes.

3. Applicability of reactivity feedbacks in ADS

Intelligent use of inherent reactivity feedbacks (e.g. Doppler effect, coolant density effect, structural expansion, etc.) has provided excellent safety characteristics to advanced, critical, reactor. In the design process of a new reactor, it is simply good engineering practice to utilize the inherent nuclear properties of the reactor to ensure optimal safety performance. In particular, operating experience and experiments on liquid metal reactors have demonstrated that better use of the inherent nuclear properties may provide a high level of safety even in severe accidents where the shutdown system fails completely (Lucoff et al., 1992). Nowadays, because of design efforts and increased understanding, the safety characteristics of critical, liquid metal

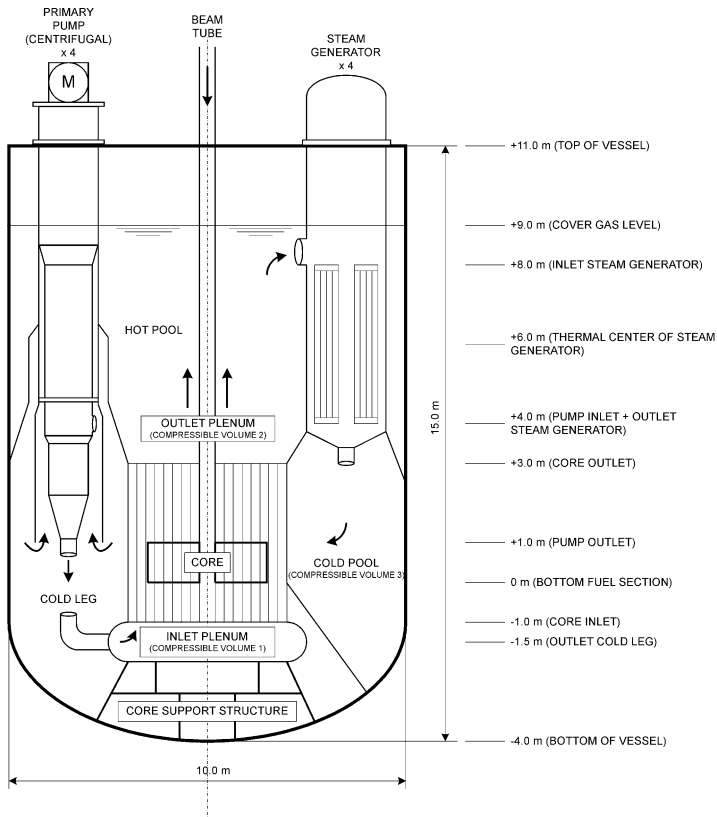


Fig. 1. Primary circuit of reference ADS design.

reactors, are considered as a principal advantage. In that context, it may seem natural to use a similar strategy for ADS's. However, an ADS does not respond to reactivity feedbacks like a critical reactor. While the critical reactor is sensitive to reactivity feedbacks, the ADS is not. The ADS is largely offset from criticality. The net effect is a substantially reduced sensitivity to reactivity changes. This feature diminishes the practical use of reactivity feedbacks as a means for natural safety mechanisms in accelerator-driven systems.

To study these features we exposed the reference design to an unprotected transient overpower (UTOP) event. The initiator for the accident is a sudden increase in source intensity. The intensity of the external neutron source is promptly increased by a factor of 1.8, corresponding to the insertion of maximum beam power at begin-of-life. It represents a strong transient, integral power increases by a factor of 1.8 within a few hundred prompt periods. In Fig. 2, the impact of subcriticality on the combined reactivity effect from Doppler feedback ($Tdk/dT = -3.87 \times 10^{-4}$) and coolant density feedback ($dk/dT = -2.28 \times 10^{-6}$) is illustrated. The unconstrained response, when no feedbacks are accounted for, is also shown to facilitate comparison.

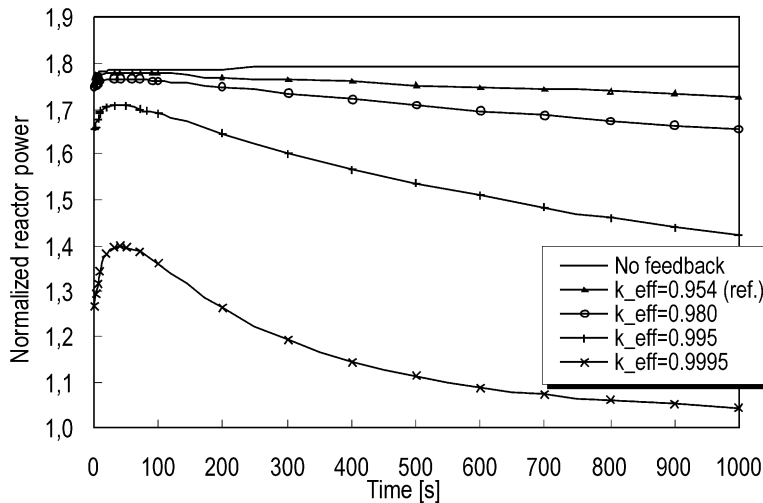


Fig. 2. Impact of reactivity feedbacks in a source-driven system. Accident initiator by sudden increase in source intensity ($S = 1.8 \cdot S_0$). Subcriticality is a parameter.

The response is calculated for a varying degree of subcriticality, $k_{\text{eff}} = 0.954$ (reference design), $k_{\text{eff}} = 0.98$, $k_{\text{eff}} = 0.995$, and $k_{\text{eff}} = 0.9995$. Structural reactivity feedback phenomena (e.g. radial and axial core expansion) are not incorporated into the model. Nevertheless Fig. 2 is instructive in the sense that it demonstrates the general characteristics of a source-driven system subject to reactivity feedbacks.

The reference ADS ($k_{\text{eff}} = 0.954$) experiences minor influence from Doppler and coolant density feedback whereas the close-to-critical system ($k_{\text{eff}} = 0.9995$) exhibits strong feedback effects. Approaching criticality, at the expense of reducing the margin to prompt criticality, results in a stronger reactivity feedback coupling. Thus the significance of reactivity feedback depends on the specific design and in particular the choice of the subcritical level. Taking advantage of reactivity feedbacks calls for a careful balance between the desired feedback performance and the subcritical margin. It is clear, however, that reactivity feedbacks will not be as effective a means in source-driven systems as they are in critical systems. Much stronger reactivity effects, from what is experienced in critical reactors, are necessary to impact on the source driven system. Therefore, it is not practical to implement reactivity feedbacks, by physics or engineering design, as the sole means to bring an ADS to safe shutdown condition. Inherent shutdown must be reinforced by other means.

3.1. Doppler effect

There has been considerable interest in the use of so-called “dedicated” fuels as to achieve maximum transmutation rate in accelerator-driven systems. The dedicated fuels contain large amounts of minor actinides (Np, Am, and Cm) and plutonium, but lack the classical fertile isotopes (i.e. ^{238}U and ^{232}Th). Subsequent deterioration

of safety parameters, when using such fuels, is well known (Maschek et al., 2000). While Doppler broadening of capture resonances is the most important inherent shutdown mechanism in a liquid–metal reactor, the effect is vanishing in accelerator-driven systems using dedicated fuels. The reduction of the fertile inventory and the spectrum hardness are the main reasons for this impairment (Maschek et al., 1999, 2000). It has been argued that a typical ADS core, based on dedicated fuels, contains several critical masses, which in principle provides the potential for criticality if the fuel is rearranged in a more dense configuration. In the absence of the Doppler effect, such accidents may occur without any restraining prompt negative reactivity feedback. Provisions for increasing the Doppler effect in dedicated cores have been proposed (Tommasi and Massara, 1999). In Table 2, values of the Doppler constant are listed for various heavy-metal cooled reactors. The Doppler constant for a sodium-cooled reactor is also included.

The Doppler constant for the dedicated cores (cases 1 and 2) are an order of magnitude lower than those of the mixed U–Pu fuels (cases 4 and 5) with their large Doppler constant. Tommasi and Massara (1999) enhanced the Doppler effect in a fertile-free core by adding some amount of hydrogenated moderator. The Doppler effect obtained in the sodium design (case 6), by Hill et al. (1999), surpasses the Doppler values in the lead-based designs by a factor of two. The argument is that the softer spectrum of the sodium design allows more neutrons to appear in the resonance region. Practically all the Doppler effect occurs below about 25 keV, where cross section variations with temperature are large (Hummel and Okrent, 1978).

We have investigated the merits; in terms of safety performance of the core, of increasing the Doppler effect in an ADS. By explicitly taking into account the Doppler feedback, we studied the response following a sudden “source jump” (same as previous transient). The source transient was chosen because it results in high fuel temperatures, which is the driver for reactivity input by the Doppler effect. Different values for the Doppler constant were modelled, $Tdk/dT = -3.87 \times 10^{-4}$ and $Tdk/dT = -2.71 \times 10^{-3}$, representing a core containing dedicated fuels and a core containing large amounts of fertile material, respectively. The results are presented in Fig. 3.

The dynamics response, including Doppler reactivity feedback in the reference ADS ($k_{\text{eff}} = 0.954$) with dedicated fuel is tiny. Even if the Doppler constant is increased by a

Table 2
List of Doppler constants in various LMR designs

Case	Tdk/dT	Fuel composition	Coolant	Comment	Reference
1	$-3.87 \cdot 10^{-4}$	(U _{0.1} Pu _{0.7} MA _{0.2})	PbBi	Mostly MA and Pu	Present design
2	$-1.50 \cdot 10^{-4}$	(Pu _{0.5} MA _{0.5})	Pb	Very hard spectrum	Tommasi and Massara (1999)
3	$-2.03 \cdot 10^{-4}$	(Pu _{0.5} MA _{0.5})	Pb	Added moderator	Tommasi and Massara (1999)
4	$-1.63 \cdot 10^{-3}$	(U _{0.8} Pu _{0.2})	PbBi	Compact design	Hill et al. (1999)
5	$-2.71 \cdot 10^{-3}$	(U _{0.9} Pu _{0.1})	PbBi	Derated design	Hill et al. (1999)
6	$-4.89 \cdot 10^{-3}$	(U _{0.9} Pu _{0.1})	Na	Derated design	Hill et al. (1999)

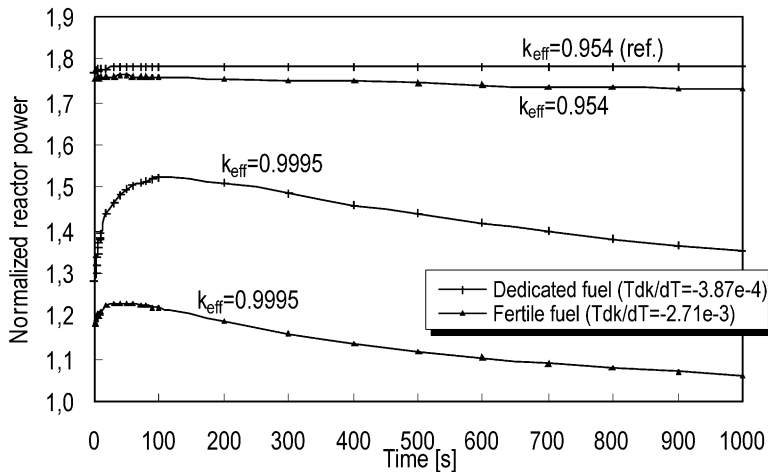


Fig. 3. Issue of enhancing the Doppler effect in ADS's. Lower Doppler value representing a dedicated core, higher Doppler value representing a core containing a large fraction of ^{238}U . Two different subcritical levels are considered. Accident initiator by sudden increase in source intensity ($S = 1.8 \cdot S_0$).

factor of seven, by introducing massive amounts of fertile material, the gain in feedback effect is small. There seems to be little benefit for increasing the Doppler effect in an effort to obtain a more benign response to accidents that remain in the subcritical state. In general, the importance of the Doppler effect in an ADS is strongly related to the level of subcriticality. In a close-to-critical system an equivalent increase of the Doppler effect would result in a significant improvement (see Fig. 3) ($k_{\text{eff}} = 0.9995$). The role of Doppler feedback in hypothetical accidents exceeding the critical margin must be further evaluated.

4. Time response

The thermal response of core constituents and the time to reach failure in various accidents influences the requirements on the shutdown device. Knowledge of the grace period, as defined by IAEA (1991), is essential in the evaluation of such devices. The plant must survive long enough for a passive safety action to be initiated in time to prevent core damage.

The numerical value of the grace period is necessarily specific to the particular design and is of less interest, but the time responses of accidents. Our intention is to study the response in order to assess the requirements on the safety system and to evaluate possible safety actions to enhance the performance. We may express response times defined by time constants rather than by absolute values, which has a broader range of applicability.

We subjected the reference design to three representative sequences of unprotected (i.e. no shutdown or plant protection system action) accidents, namely:

- (a) *Unprotected transient overpower (UTOP)* by a prompt insertion of maximum beam current. It is assumed that the steam generators remove heat at a rate of nominal power (constant temperature drop in steam generators).
- (b) *Unprotected loss-of-flow (ULOF)* by a loss of primary pump power. Feed-water flow is assumed to remain at its initial value and coolant inlet temperature is constant (constant outlet temperature in steam generator).
- (c) *Unprotected loss-of-heat-sink (ULOHS)* by a sudden inability of the steam generators to remove heat (zero temperature drop in steam generators).

Constant steam generator boundary conditions are assumed. The actual boundary condition depends on the particular accident (see above). Safety margins that are applicable to the reference design are indicated in the figures. These are based on postulated transient failure temperatures (listed in Table 3).

The dissociation temperature of minor actinide nitride fuel (NpN, AmN, CmN) is not well known (Suzuki and Arai, 1998). However, it is known that stable AmN has been fabricated at 1573 K (Takano et al., 1999). Mechanical failure limits, used to evaluate cladding failure, are those for 20% cold-worked 316 stainless steel due to lack of reliable data on HT-9. Mechanical strength properties are based on transient burst tests conducted on unirradiated and internally pressurized cladding specimens (Hunter et al., 1975).

In Figs. 4 and 5, peak fuel temperatures and peak cladding temperatures, respectively, are displayed as a function of time.

In the source transient (UTOP), the power “jumps” by a factor of 1.8, see Fig. 2. Since no time is required for heat flow, the fuel suffers a rapid, almost adiabatic thermal excursion, Fig. 4. Coolant and structure are heated at a rate determined by the characteristic time constant of the fuel element. The fuel itself, has the shortest time response and is most sensitive to source transients. After a few seconds, the fuel pins have adjusted to the new power level and temperatures temporarily settle in a quasi-equilibrium (not visible in the figure). For an extended period, mainly determined by the primary loop circulation time and the coolant heat capacity, the coolant inlet temperature remains at its initial value. The steam generators are assumed to remove heat at a rate of nominal power, resulting in a mismatch in the heat production and heat removal. The net effect is increasing inlet temperature, which causes the reactor core, coolant, and other components to overheat, inevitably leading to core damage unless the reactor is shut down.

Table 3
List of failure temperatures for the reference design

Failure mechanism	Failure temperature	Comment
Dissociation of AmN	1573 K	Conservative assumption (Takano et al., 1999)
Cladding burst temperature	1333 K	20% CW SS316, 5.56 °C/s, hoop stress 100 MPa (Hunter et al., 1975)
Cladding/coolant corrosion	946 K	Extended operation (Novikova et al., 1999)

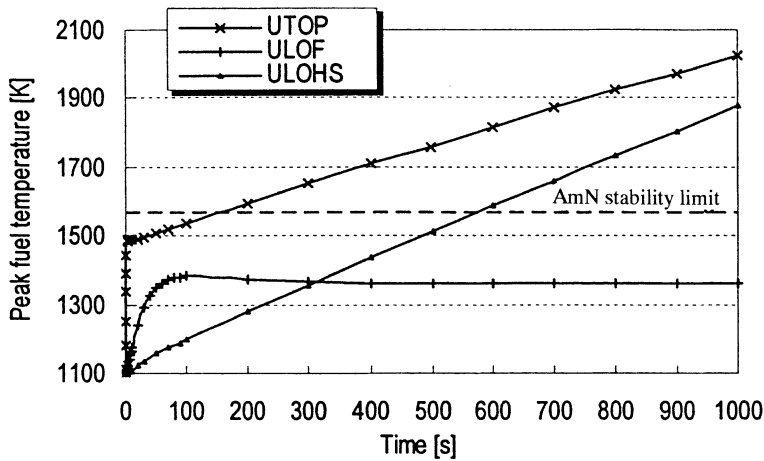


Fig. 4. Peak fuel temperatures in unprotected TOP, LOF, and LOHS.

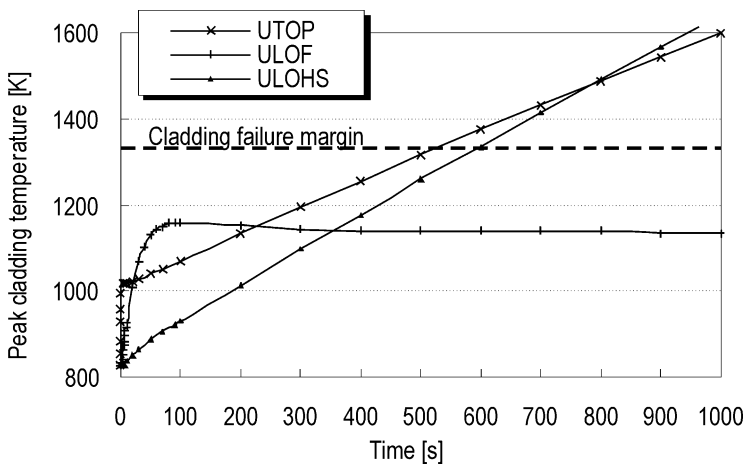


Fig. 5. Peak cladding temperature in unprotected TOP, LOF, and LOHS.

In the loss-of-flow (ULOFS) accident, core heat-up occurs at a rate determined by the flow coast-down. Inertial forces help to push the coolant through the primary system for an extended period. Peak temperatures occur as the pump impeller comes to a complete rest. Core temperatures and buoyancy forces eventually balance. In the asymptotic state, flow is sustained by natural convection alone. Reactivity feedbacks have negligible effect on the transient. For this particular system, an unprotected loss-of-flow accident should result in little or no damage. The integrity of the fuel and the cladding is not compromised. The protective oxide film layer on the cladding may suffer some damage that potentially could harm the cladding in the long run.

The loss-of-heat-sink (ULOHS) accident tends to be a more slowly evolving accident than the source transient and the loss-of-flow accident. The accident manifests as rising inlet temperature, which accompanies loss of primary heat sink. Response time is determined by the primary loop circulation time and coolant heat capacity. The prolonged grace period in a ULOHS accident facilitates successful performance of the safety system. Core damage is inevitable unless safety measures are taken to shut down the reactor.

In the unprotected LOHS accident shown in Fig. 4, we assumed that the primary pumps continued to operate. We also studied the response to a combination of loss-of-heat-sink and malfunctioning primary pumps. The temperature increased much more rapidly as the initial response, in that case, is mainly determined by the flow coast-down. It turned out that the grace period in a combined ULOHS and ULOF accident for this specific system was reduced by 50% compared to an isolated ULOHS. It should be taken into account, however, that it is likely that a loss-of-heat-sink accident will be in the form of impairment rather than a sudden and complete loss of heat rejection capability.

In Fig. 6, the thermal response of the coolant in the hot pool is displayed. The coolant temperature is an important safety system parameter since it is related to the heat production in the core. It can be used to sense power excursions and reduction in coolant flow rate. The coolant temperature may be used as an actuator in a passive safety device.

The thermal response of the coolant in the hot pool following a change in power or flow is delayed by the heat capacity of the coolant and transport lags. Therefore, it must be ascertained whether the time response of the coolant is sufficient to serve as an accident indicator and protect against the fastest transients conceivable in an ADS. Rapid coolant response is advantageous since it promotes prompt action of the safety system. In general, UTOP caused by insertion of maximum beam power, is likely to exert the fastest transient. The absence of any moveable control rods, that may rather quickly add or remove large amounts of reactivity, diminishes the

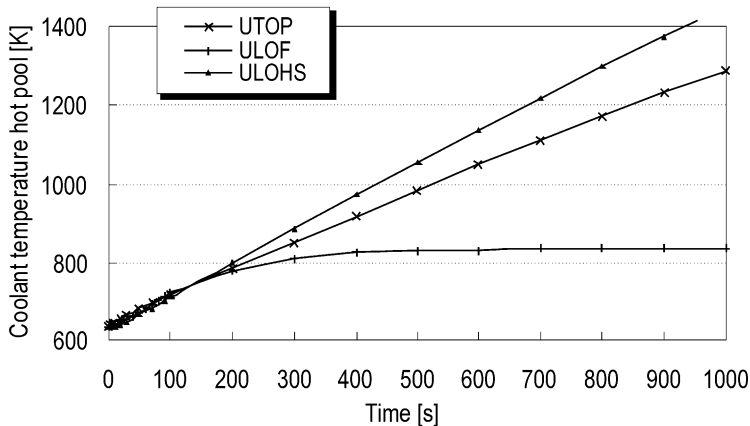


Fig. 6. Coolant temperature in the hot pool.

potential for fast transients caused by reactivity insertion. Significant reactivity is potentially available in core compaction or voiding phenomenon, but such sequences stretch over a longer period. It is noticeable in Fig. 6, that the initial response (<200 s) is more or less the same for all transients. However, source transients introduce the shortest grace period (with respect to fuel damage), while the temperature rise in the coolant is modest. In that sense, source transients impose the highest demands on a passive device that relies on the thermal response of the coolant.

5. An approach to inherent shutdown

Compared to reactivity changes, variations in source strength or source importance have a strong influence on the ADS. The power is linearly proportional to the source, 10% reduction in source strength yields 10% reduction of power, and so on. Shutdown of the external source effectively halts the fission process in the entire core.

Our approach is to design a passive system for the primary purpose to shut down the source in an emergency. The passive device would be comprised in an overall plant control system strategy similar to (Table 4): (a) use an active, regulating system that adjusts the source during normal operation. The regulating system function is to meet the power demand rather than to shut the reactor down if an accident occurs. (b) Use an active plant protection system (PPS) as a first level of protection to shut off the beam in an accident. The PPS would signal on excess temperature levels, low coolant flows, high neutron flux levels, etc. (c) Use the passive, self-actuated, shutdown system providing the second line of protection whenever the PPS function is not properly carried out. The passive system must be inherently independent of the normal beam control system.

It should be recognized that system redundancy makes the assumption of PPS failure highly unlikely. In fact, actual activation of the passive shutdown system must be regarded as hypothetical. Indeed, it affects the requirements on the device.

The shutdown system must be capable of halting the external source before excessive temperatures are obtained. This may be accomplished by reducing the time required for the shutdown system to act and by limiting the thermal response by design considerations. As mentioned previously, the fastest credible transient in an ADS is a source insertion transient. Worst conditions occur when the maximum

Table 4
Plant control system strategy

Control system	Classification	Action
Regulating system	Active	Source regulation. Online usage during normal operation
Plant protection system (PPS)	Active	Beam/source shutdown. Actuated in an off-normal event
Passive shutdown system	Passive	Source shutdown. Actuated when PPS malfunctions

beam power is inserted in a step fashion at the begin-of-life. Source transients result in a rapid, but bounded power excursion. Consequently, it is unsafe to rely on a safety system to assure protection in the early phase of a source transient. Instead, protection must be accomplished through safety-by-design principles, e.g. minimizing the beam output capability by utilizing an appropriate burnup control strategy. While the speed of the beam controller may be limited by fundamental means, the capacity of the accelerator (beam power) is dictated by reactivity losses governed by fuel burnup. Various options exist, for example, shorter irradiation-cycle time and multi-batch fuel loading strategy (Yang and Khalil, 2000), lower power density and higher transuranic inventory (Hill and Khalil, 2000), optimal distribution of plutonium and minor actinides (Gonzalez et al., 2000), use of burnable absorbers (Wallenius et al., 2001a, b). Safety-by-design relaxes the requirements on the shut-down system.

In UTOP and ULOHS accidents, the grace period may be prolonged by the primary loop circulation time and the coolant heat capacity. Typical accidents where the coolant inventory has an appreciable effect on the thermal response involve situations when there is a net change in internal energy (primary system). Loss-of-flow accidents do not necessarily involve any accumulation of internal energy in the primary system, as the heat-removal rate may be unaffected. For loss-of-flow transients, the initial response is determined by the flow coast-down. It may be influenced by changing the moment of inertia of the pump and by increasing natural convection.

Taking these circumstances in consideration, our approach is to prolong grace periods, increase safety margins, and utilize safety-by-design principles, all easing the demands on the safety system. Prolonged grace periods do not only improve our chances for successful safety performance but reduces the probability for false actuation and interference of the passive system during normal operation. The second objective, in order to achieve high reliability, is to design simple, redundant and diverse shutdown systems, and to use components of proven high reliability. Greater complexity generally means reduced reliability.

6. Inherent shutdown mechanisms

In this section, we suggest some concepts for inherent beam shutdown. The intention is to demonstrate the basic working principle. Appropriate references are included for strategies suggested by separate authors.

6.1. Flooding of the beam tube

Shutdown of the external source can be accomplished by flooding the beamtube with coolant. The main purpose for filling the beamtube is to shift the axial position of beam impact, which in principle reduces the importance of source neutrons. Actuation may be based on thermal expansion of coolant or use of bursting disk devices. Several authors have proposed designs that utilize such principles.

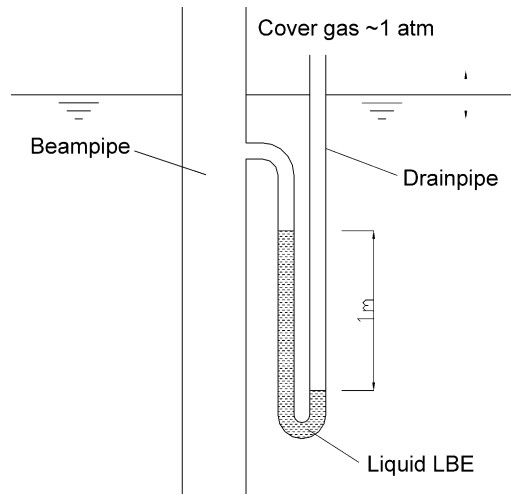


Fig. 7. Basic scheme for filling the beamtube with coolant through a U tube. Concept relies on a working moving fluid (class B device).

Rubbia et al. (1995) proposed a technique for the “energy amplifier” in which coolant rising above a prescribed level activates an overflow path and floods the cavity in the beam tube.

To fill the beamtube, we suggest installing a drainpipe in the shape of a U tube, shown in Fig. 7.

One side of the U tube is open to the cover gas region while the other side is connected to the beamtube. A portion of the coolant is retained in the U bend, forming a liquid seal that separates the beamtube from the cover gas region. A liquid column is supported by the pressure difference. A pressure difference of 1 atm is equivalent to a column height of LBE of 1 m (11 m for sodium). The inlet is located at a certain height above the surface. As the coolant expands, it would rise to the inlet, flood the drainpipe, and subsequently spill into the beamtube. The intake to the drainpipe must be elevated high enough to reduce the risk for false actuation. Difficulties may exist if the surface is seriously disturbed by turbulence and vapor bubbles.

In our reference design, the coolant level rises at a rate of 10 cm/100 K. In Fig. 8, the coolant surface elevation is calculated for unprotected TOP, LOF, and LOHS accidents. Zero level is the surface elevation at steady-state. The points at which the fuel and the cladding exceed their safety margins are also indicated. For the source transient (UTOP), the surface rises approximately 10 cm before fuel failure, corresponding to the smallest level change yet leading to core damage. In a loss-of-flow accident there is a gradual loss of pressure head why the coolant level actually drops during pump coast-down. The rate at which the coolant rises can be affected by the geometry of the vessel.

The basic design only relies on the integrity of the components and a moving working fluid. It does not require signals, external power, moving mechanical parts.

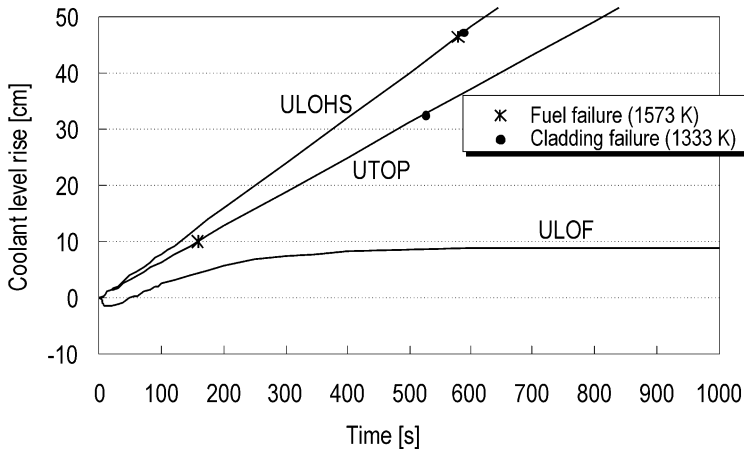


Fig. 8. Rise of coolant level in hot pool in unprotected accidents.

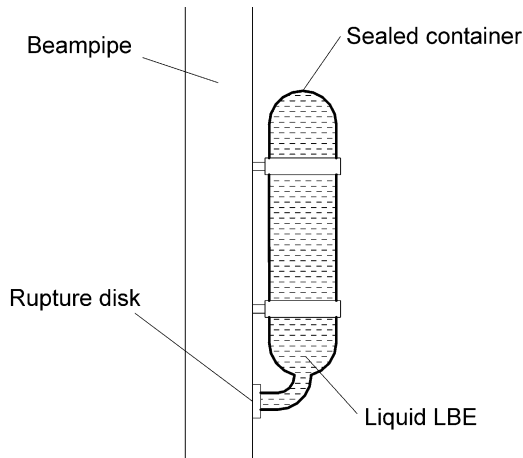


Fig. 9. Scheme for filling the beamtube using a pressurized container. Concept relies on a bursting disk device (class C device).

In that case, it is classified as a passive device in category B, in compliance with IAEA's categorization of passive systems (IAEA, 1991).

A straightforward method was proposed by Wider et al. (1999), in which a melt-rupture disk is installed in the side-wall of the beam tube. The membrane is in contact with the coolant. Source shutdown is actuated as the disk fails and the vacuum tube is flooded with coolant.

Another option is to have a liquid, e.g. LBE, completely fill a sealed container of fixed volume, see Fig. 9. The container is placed in thermal contact with the coolant and it is sealed off to the beamtube by a rupture disk. When excessive pressures occur then the rupture disk fractures releasing the liquid to the beamtube.

In general, bursting disk devices tend to be less accurate. The burst pressure or temperature is unpredictable. The problem is accentuated due to ageing and when used in a hostile environment. A drawback is that the disk is destroyed in the action, thus eliminating the possibility of testing the device prior to its installation or when it is in service. In order to attain a short time response, the disk must be operated close to its bursting point, which increases the possibility for false actuation. Passive safety based on bursting disk devices is classified in category C, in accordance with IAEA regulation.

Beam chambers typically require high vacuums and chemically clean surfaces to prevent proton interaction with trapped gas. Filling the beamtube with coolant may cause serious contamination of the accelerator tunnel. One option is to install a second beam window at the top of the tube to separate the beamtube from the accelerator tunnel. If the passive system provokes a shutdown, it may require replacing the beamtube, however, it is likely the plant needs correction anyhow, to assure its integrity and to reinstate the original safety function. In that perspective, filling of the beam tube could possibly serve as a last resort. False actuation, however, must be eliminated.

6.2. *Alternative methods*

In most pre-conceptual ADS designs, the beam is subject to some bending action before entering the vessel. Bending of a charged particle beam is normally carried out by magnets. In principle, a bending magnet could serve as an on/off switch for the external source. If the magnet is de-energized, the beam would safely end-up in a beamstop, otherwise the beam is diverted to the target.

For such a device switching is necessary, e.g. an electrical circuit must open/close, which limits the safety level achievable by this principle. Preferably, the passive switch is of a fail-safe type, i.e. unless connection is established the magnet is off. Possible agencies for actuating such a switch include:

- A ferromagnetic Curie-point-operated device. Above the Curie temperature, the magnetization of a permanent magnet vanishes. Such a device could either be used for switching or in a lock-release function acting on safety rods. Similar devices showed considerable promise for application in self-actuated shutdown systems in liquid-metal fast breeder reactors (Sowa et al., 1976). The Curie temperature of carbon steel is 1043 K.
- Elongation of a metal rod that is submerged in the coolant or bending of a bi-metallic component could be used as a temperature-sensitive switch.
- Rising coolant levels could elevate a float device that is connected to an electrical circuit. Alternatively, the medium itself could act as a conductor and establish connection.
- Pressure build-up in the cover gas region (or some other compartment), due to thermal expansion of the medium could actuate a switch that operates at a predetermined pressure. A weighted lever or a spring could set the limiting pressure. Alternatively, thermal expansion of a fixed mass of a fluid (LBE) in a confined space could perform a similar task.

- A generator that is connected to the coolant flow may supply power to the bending magnet. The generator may be driven by mechanical forces or as a reversed electromagnetic pump. However, the drawbacks include, obstruction of flow in a free-convection mode, need for significant pumping power, and lack of temperature feedback.
- Liquid metal coolants feature temperature-dependent resistivity. Increasing the temperature will increase the resistivity. Resistivity rising above a limiting value could trigger an electrical or magnetic switch.

7. Conclusions

The applicability for passive safety to accelerator-driven systems was studied. The current study focused on means for inherent shutdown. The usefulness for reactivity feedbacks was evaluated and some schemes for inherent source shutdown were suggested.

It seems that inherent shutdown based solely on reactivity feedbacks is fruitless in accelerator-driven systems. Inherent shutdown must be reinforced by other means. It was shown that increasing the Doppler effect, by introducing massive amounts of fertile material, have limited effect on transients that remain in the subcritical state. Doppler feedback may be important for accidents exceeding criticality. The significance of reactivity feedbacks, in general, depends on the specific design and in particular on the choice of the subcritical level. Taking advantage of reactivity feedbacks calls for a careful balance between the desired feedback performance and the subcritical margin.

Safety analysis indicated that transient overpower accidents, caused by insertion of the maximum beam power, is likely to exert the fastest transients conceivable in an ADS. In that perspective, source transients have profound impact on the requirements for a shutdown device. Safety-by-design principles must be utilized to assure protection to source transients.

Some concepts to accomplish passive source shutdown were presented. Two methods that seek to block the beam by filling the beamtube with coolant were proposed. Actuation is caused by thermal expansion of coolant. Other options include shutdown of beam bending magnets or insertion of shutdown rods by passive means.

Shutdown of the beam by passive means can provide an important additional safety feature for accelerator-driven systems. Such systems may contribute significantly to the reliability of the overall plant protection system. At this point, however, considering the premature nature and the lack of experimental validation, further work is necessary in order to determine the practicability of the present design concepts.

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