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Applicability of Passive Safety to Accelerator-driven Systems

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Abstract - *We examine the use of reactivity feedbacks as a means for passive safety in accelerator-driven systems (ADS). In particular, we evaluate the potential for inherent shutdown by Doppler reactivity feedback in a subcritical core dedicated for transmutation of waste. Given the dynamic characteristics of a source-driven system, it is necessary to manage the external neutron source in order to achieve passive shutdown capability. Conceptual designs of self-actuated shutdown devices are suggested. Operating characteristics is obtained by studying the performance of a reference ADS subject to a set of typical accident initiators. It is shown that maximum beam output must be limited in order to protect against accident initiators that appear to be achievable in ADS. Utilizing an appropriate burnup control strategy plays a key role in that effort.*

I. INTRODUCTION

In the design process of advanced reactors, major 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. In case of an emergency, the plant would 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 study 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 general character and are treated elsewhere, e.g. [1]. Our attention is focused on inherent shutdown capabilities. We evaluate the applicability of self-actuated shutdown devices and we suggest some actual design concepts for that purpose.

II. REFERENCE DESIGN & MODELLING

Accident analysis is performed with the aid of the SAS4A safety code [2]. The thermal, hydraulic, neutronic, and mechanical models employed in the SAS4A computer code were formulated, implemented, and validated in the U.S. liquid metal reactor development program. These models have been extensively validated with experimental test data from the EBR-II, FFTF, and TREAT reactors [3][4][5]. More recently, the coolant thermophysical property database used in SAS4A has been extended to include the properties of lead and lead-bismuth eutectic, based on evaluations of available U.S. and Russian experimental

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data [6][7]. Validation of the SAS4A coolant hydraulics models with heavy liquid metal coolants will require the availability of prototypic reactor test data. It is judged that the combination of experimentally based coolant thermophysical property data with the already validated, first-principles coolant thermal-hydraulics models in SAS4A provides a satisfactory basis for conceptual design basis analysis.

In the assessment, we employ a reference design of an ADS to obtain essential data and to verify predictions. The reference design is a model of an ADS that has evolved at the Royal Institute of Technology, Sweden [8][9]. The core has a nominal power of 800 MWth. It is cooled by liquid lead-bismuth eutectic (LBE). The pins are configured in an open pin lattice (P/D=1.83 in inner zones and P/D=2.33 in outer zones). The fuel consists of (core average): 70% plutonium, 15% minor actinides (americium, curium, and neptunium), and 15% uranium. A detailed description of this design is available in the present proceedings [10].

A primary system model is set-up 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.

III. APPLICABILITY OF INHERENT REACTIVITY FEEDBACKS

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 [11]. Nowadays, because of design efforts and increased understanding, the safety characteristics of critical, liquid metal reactors, are considered as a principal advantage. In that context, it may seem natural to use a similar strategy for ADS's. However, a source-driven system 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. On one hand, this feature is advantageous since it mitigates the consequences of reactivity insertion accidents; on the other hand, it diminishes the practical use of negative reactivity feedbacks as a means for natural safety mechanisms in accelerator-driven systems. The present paper addresses the latter feature.

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 capacity 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 1, the effect of subcriticality on the combined reactivity effect from Doppler feedback (Tdk/dT=-3.87×10-4) and coolant density feedback (dk/dT=-2.28×10-6) is illustrated. The unconstrained response, when no feedbacks are accounted for, is also shown to facilitate comparison. The response is calculated for a varying degree of subcriticality, k_{eff}=0.954 (reference design), k_{eff}=0.98, k_{eff}=0.995, and k_{eff}=0.9995. Structural reactivity feedback phenomena (e.g. radial and axial core expansion) are not taken into account. Employing more sophisticated feedback models is of little interest for our purpose. Fig 1 clearly demonstrates the resistance of a source-driven system subject to reactivity feedbacks (prompt and delayed feedbacks).

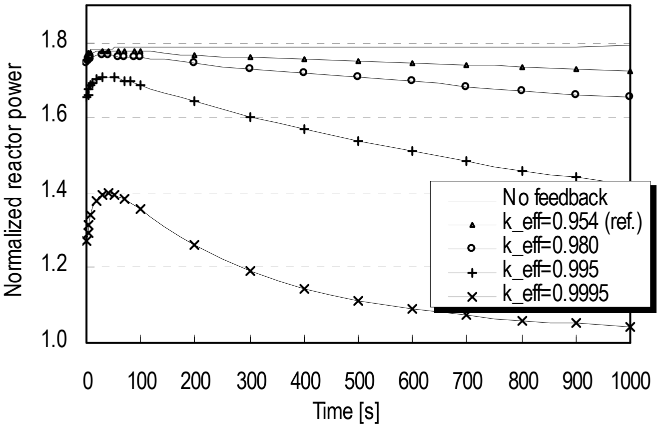

Fig 1. Influence of reactivity feedbacks in a source-driven system. Accident initiator by sudden increase in source intensity ($S=1.8*S_0$). Subcriticality is a parameter.

The reference ADS (k_{eff}=0.954) experiences minor influence from reactivity feedbacks whereas the close-to-critical system (k_{eff}=0.9995) exhibits strong feedback effects. Approaching criticality, on the expense of reducing the margin to prompt criticality, results in stronger feedback coupling. The significance of feedback mechanisms in a source-driven system depends on the reactivity worth of these feedbacks, i.e. reactivity coefficients, but more important on the choice of the subcritical level. Thus, taking advantage of reactivity feedbacks calls for a careful balance between the desired feedback performance and the subcritical margin. It is seen, Fig 1, that it is not until we approach a multiplication constant close to k_{eff}>0.999 (~1$ below critical) that reactivity feedbacks have a significant influence and possibly could serve as a means for inherent shutdown. The level of subcriticality being suggested for most conceptual ADS's is at least an order of magnitude larger (typically ~10$ subcritical or k_{eff}<0.98-0.99). It is clear 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 traditional reactors, are necessary to have an effect 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 conditions. Inherent shutdown must be reinforced by other means.

III.A. Doppler Effect

There has been considerable interest on 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 [12]. While Doppler broadening of capture resonances is the most important inherent shutdown mechanism in a liquid-metal reactor, the effect is vanishing small in accelerator-driven systems using dedicated fuels. The reduction of the fertile inventory and the spectrum hardness are the main reasons for this impairment [13]. It has been argued that a typical ADS, based on dedicated fuels, contain 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 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 [14]. In TABLE I, values of the Doppler constant are listed for various heavy-metal cooled reactors. The Doppler constant for a sodium-cooled reactor is also shown.

TABLE I

List of Doppler constants in various LMR designs

Case	Tdk/dT	Fuel	Coolant	Comment	Ref.
1	$-3.87\cdot10^{-4}$	$(U_{0.1}Pu_{0.7}MA_{0.2})$	PbBi	Mostly Pu and MA	Present design [10]
2	$-1.50\cdot10^{-4}$	$(Pu_{0.5}MA_{0.5})$	Pb	Very hard spectrum	Tommasi, et al. [14]
3	$-2.03\cdot10^{-3}$	$(Pu_{0.5}MA_{0.5})$	Pb	Added moderator	Tommasi, et al. [14]
4	$-1.63\cdot10^{-3}$	$(U_{0.8}Pu_{0.2})$	PbBi	Compact design	Hill, et al. [15]
5	$-2.71\cdot10^{-3}$	$(U_{0.9}Pu_{0.1})$	PbBi	Derated design	Hill, et al. [15]
6	$-4.89\cdot10^{-3}$	$(U_{0.9}Pu_{0.1})$	Na	Derated design	Hill, et al. [15]

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 [14] 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. [15], 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 [16].

We have investigated the merits; in terms of safety performance, for enhancing 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 Doppler effect. Different values for the Doppler constant were modeled, Tdk/dT=-3.87×10-4 and Tdk/dT=-2.71×10-3, representing a core containing dedicated fuels and a core containing large amounts of fertile fuel, respectively. The results are presented in Fig 2.

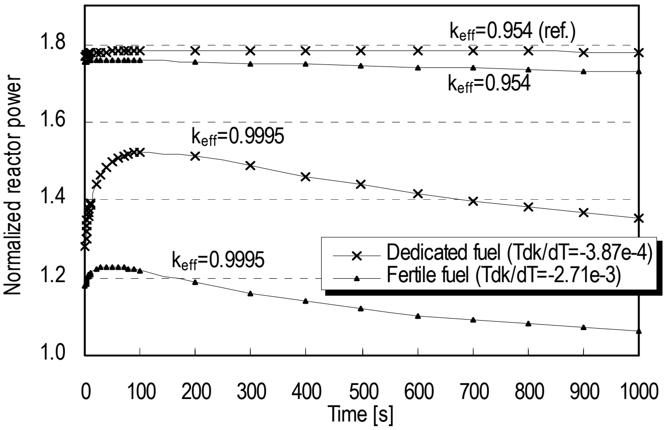

Fig 2. Dynamics effects of Doppler feedback in source-driven systems. Two different subcritical levels are considered. Accident initiator by sudden increase in source intensity ($S=1.8*S_0$).

The Doppler effect has negligible influence on the dynamics of a subcritical assembly with a multiplication constant of k_{eff}=0.954 and a core loaded with dedicated fuel. Even when the Doppler constant is increased by a factor of seven, by introducing massive amounts of fertile material, the actual gain in safety performance 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 Doppler feedback in an ADS is strongly related to the level of subcriticality. There is no doubt that the Doppler effect is of great value if the system is close-to-critical, see Fig 2 (k_{eff}=0.9995). It is the chief limiting safety mechanism in supercritical excursions. In that perspective, the Doppler effect must not be excluded as an important safety means in source-driven systems. The role of Doppler feedback in hypothetical accidents exceeding the critical margin must be further investigated.

IV. TIME RESPONSE

The thermal response in core structures and the time to reach failure under various accidents influences the requirements on the shutdown device. Knowledge of the grace period is essential in the evaluation of such devices. The plant must survive long enough that a passive safety action can 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 transient response in order to assess the requirements on the shutdown system and to evaluate possible actions to enhance the safety performance. We may express response times defined by time constants rather than by absolute values, which has broader range of applicability.

We subjected our 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 power. 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). In Fig 3 peak fuel temperatures are displayed as a function of time. Cladding temperatures were calculated, but turned out to be less serious and is not included in this paper.

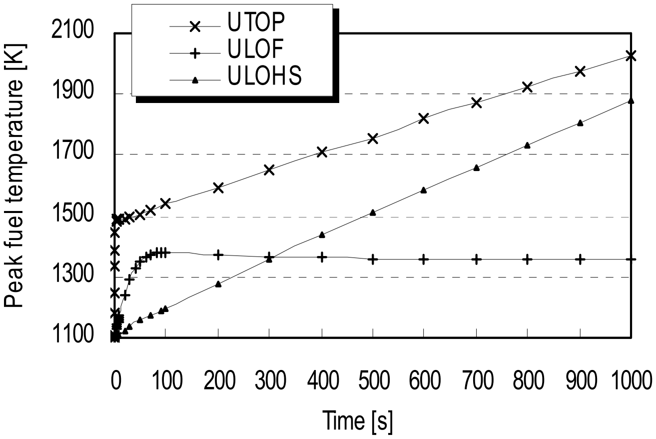

Fig 3. Peak fuel temperatures in Unprotected TOP, LOF, and LOHS.

In the source transient (UTOP), the power "jumps" by a factor of 1.8, see previous Fig 1. Since no time is required for heat flow, the fuel suffers a rapid, almost adiabatic thermal excursion, Fig 3. 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-stationary level (not visible in the figure). For an extended period (~30 seconds in present design), 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 as the accident proceeds. 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.

In the loss-of-flow (ULOF) accident, core heat-up occurs at a rate determined by the flow coast-down. Inertial forces help to push 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 Fig 4, 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. Most likely, an inherent shutdown device will be actuated by the coolant temperature some way or the other.

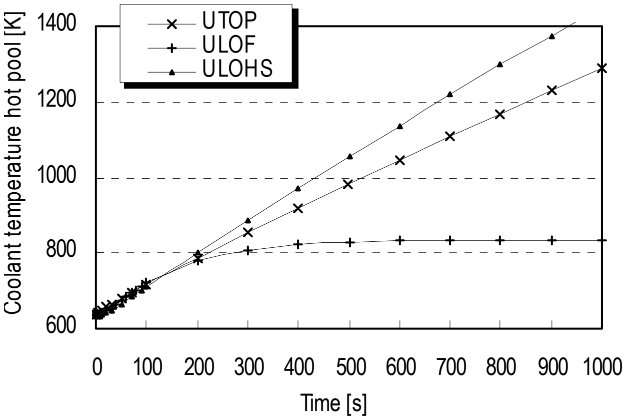

Fig 4. Average coolant temperature in the hot pool.

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 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 4, that the initial response (<200 seconds) is identical for all transients. However, source transients introduce the shortest grace period (with respect to fuel damage), see Fig 3, 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.

V. 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. It should be recognized that system redundancy makes the assumption of failure of the active plant protection system highly unlikely. In fact, actual activation of the passive shutdown system must be regarded as hypothetical. Indeed, it affects the design 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 speed of the temperature rise by design considerations. As mentioned previously, the fastest credible transient in an ADS is a source insertion transient. Worst conditions occur when maximum beam power is inserted in a step fashion at 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 (maximum 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 [17], lower power density and higher transuranic inventory [18], optimal distribution of plutonium and minor actinides [19], use of burnable absorbers [8]. Safety-by-design relaxes the requirements on the shutdown system.

In UTOP and ULOHS accidents, the grace period may be prolonged by the primary loop circulation time and the coolant heat capacity. We studied the benefits of increasing the coolant inventory. Results are summarized in TABLE II. In effect, 10% more coolant resulted in ~10% longer grace period, and so on. 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 in the steam-generators 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.

TABLE II

Lengthening of the grace period corresponding to a certain increase in coolant inventory. The slash separates fuel failure from cladding failure.

Coolant inventory	Grace period TOP	Grace period LOHS
+10%	+12% / +11%	+12% / +12%
+50%	+56% / +57%	+57% / +58%

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.

VI. INHERENT SHUTDOWN MECHANISMS

In this section, we suggest some concepts for inherent beam shutdown. The intention is to demonstrate the basic working principle.

VI.A. Flooding of the beam tube

Shutdown of the external source may 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 [9]. Actuation may be based on thermal expansion of coolant [20] or use of bursting disk devices [21]. Several authors have proposed designs that utilize such principles.

To fill the beamtube, we suggest installing a drainpipe in the shape of a U tube. 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. The drainpipe is in thermal contact with the coolant. 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. The conceptual design only relies on the integrity of the components and a moving working fluid. It does not require signals, external power, or moving mechanical parts. In that case, it is classified as a passive device in category B, in compliance with IAEA's categorization of passive systems [22].

In our reference design, the coolant level rises at a rate of 10 cm/100 K. For the source transient (UTOP), the surface rises approximately 10 cm before fuel failure, corresponding to the smallest change in coolant level (in comparison with ULOF and ULOHS) yet leading to fuel damage. The rate at which the coolant rises can be affected by the geometry of the vessel.

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.

VI.B. 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 (IAEA Class D device). 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) 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 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 [23]. The Curie temperature of carbon steel is 1043 K.

b) 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.

c) Liquid metal coolants feature temperature-dependent resistivity. Increasing the temperature lead to higher resistivity. Resistivity rising above a limiting value could trigger an electrical or magnetic switch.

VII. 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 indicate 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. A method that seeks 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, e.g. ferromagnetic Curie-point-operated device.

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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