ASPECTS OF SEVERE ACCIDENTS IN TRANSMUTATION SYSTEMS

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Abstract

The different types of transmutation systems under investigation include accelerator driven (ADS) and critical systems. To switch off an accelerator in case of an accident initiation is quite important for all accidents. For a fast ADS the grace times available for doing so depend strongly on the total heat capacity and the natural circulation capability of the primary coolant. Cooling with heavy metal Pb-Bi has considerable advantages in this regard compared to gas cooling. Moreover it allows passive ex-vessel cooling with natural air or water circulation. In the remote likelihood of fuel melting, oxide fuel appears to mix with the Pb-Bi coolant. Fast critical systems that are cooled by Pb-Bi will automatically shut off if the flow or heat sink is lost. Reactivity accidents can be limited by a low total control rod worth. High temperature reactors can achieve only incomplete burning of actinides. If an accelerator is added to increase burn-up, a fast spectrum region is needed, which has a low heat capacity.

Nomenclature

ADS:	Accelerator driven system.
ATW:	Accelerator driven transmutation of waste.
GT-MHR:	Gas turbine modular high temperature reactor.
LOF:	Loss-of-flow accident.
LOHS:	Loss-of-heat-sink accident.
LBE:	Lead bismuth eutectic (MP 123ºC).
Pb:	Lead (MP 327ºC).
RVACS:	Reactor vessel auxiliary cooling system.
TRISO:	Coated particle with three layers pyrocarbon, siliconcarbide and again pyrocarbon.
TRUs:	Transuranium elements: neptunium, plutonium, americium, curium.

1. Introduction – Some ADS designs

Important for the acceptability of nuclear power is a strong reduction in the long-lived higher actinides and soluble fission products in the nuclear waste is. And thus, it is imperative for keeping the nuclear option open for the future. Of course, the transmutation reactors should also meet modern safety criteria such as the one of Generation IV [1] which require future reactors to be demonstrably safe and deterministically free of catastrophic behaviour. Furthermore, transmuters should not only lead to the reduction of the waste but also to a new generation of reactors for an economical and clean energy generation.

The first proposal to use an accelerator driven sub-critical system for burning nuclear waste was made in 1986 by Bonnaure, Mandrillon, Rief and Takahashi [2]. The first realisation of this concept and the first preliminary design for a sub-critical waste burner was presented by Prof. Rubbia *et al.* [3,4]. It is a fast sub-critical system (k = 0.97) with a thermal power of 1 500 MW. The proposed accelerator is a cyclotron with proton current of 15 mA. This pool-type ADS features natural circulation Pb cooling in a 30 m tall vessel. It has an overflow device for passively blocking the beam and emergency decay heat removal by passive ex-vessel air cooling (RVACS).

The next ADS design, which is already quite advanced, is the Ansaldo demonstration facility of 80 MWt [5]. The sub-criticality is also about 0.97 and it has a cyclotron that delivers a 3 mA proton current. It features LBE cooling using an “enhanced natural circulation” by the addition of argon bubbles above the core and gas removal from the upper plenum. This allows the reduction of the primary pool height to 8 m and provides good control of the primary flow. Moreover, the coolant flow path is rather simple, passing from the core up through the riser section, then through the heat exchangers that are in the downcomer and further down to the core inlet. This allows arrangement such a good natural circulation that the full power can be removed even if the injection of gas bubbles fails. The secondary coolant is a diathermic fluid with low vapour pressure. For emergency decay heat removal a new type of RVACS is proposed, schematically shown in Figure 5.

Another LBE-cooled ADS with three proton beams has been presented by FZK [6]. This relies on mechanical pumps. This means that the coolant, after having passed through the heat exchangers, has to get back up to the inlet of the pumps, a fact which degrades the natural circulation capability. The full power can rather certainly not be removed without the pumps running, but the decay heat and the emergency decay heat can be easily removed due to the good natural circulation capability of the LBE coolant.

Framatome has presented a gas-cooled fast ADS demonstrator [7]. It has a thermal power around 100 MWt. The sub-criticality is 0.95 and the proton beam has a current of 10 mA. The design is a direct cycle gas-cooled fast spectrum reactor with the vessel and the gas turbine as in the GT-MHR reactor. However, this ADS uses fast reactor fuel pins and the helium flow in the core is upwards. In case of loss of the forced circulation of helium, the decay heat can be removed by helium natural circulation using the heat exchangers of the shutdown cooling system. In the case of loss-of-pressure, blowers (an active system) and the intermediate helium/water heat exchangers of the shutdown cooling system remove the decay heat. The same approach is used during handling operations of the shutdown ADS.

Another ADS that is proposed by General Atomics [8,9] is the 600 MWt Integrated Thermal – Fast Transmuter. It works as a gas cooled HTR with TRISO fuel that contains LWR waste and erbium poison in order to get an extended burn-up. After three years of critical operation, a horizontal proton beam is used to drive the inner transmutation region that occupies about 15% of the active region and is surrounded by a graphite reflector. It operates in the fast energy neutron spectrum and contains tungsten rods that house TRISO particles already transmuted before in the thermal region. Since the TRUs will only be burnt by a little more than 80%, a three-year further burn-up follows in fast gas-cooled ADS (as in the Framatome approach above) in which the 50-mm tall compacts containing the already burnt up TRISO particles will be inserted. This approach is somewhat complex. But it requires only the reprocessing of the LWR waste. However, TRISO particles of 500-μm diameter for HTR have only been licensed for 80 000 MWd/t burn-up. The validation of the accident behaviour for longer burn-up and plutonium/neutron absorber containing 200 μm TRISO particles is still necessary [10].

Several critical LBE or Pb cooled critical designs have recently been proposed that can at least burn a considerable amount of the plutonium isotopes. The amount of minor actinides in such a core should not be too high because this would reduce the delayed neutron fraction, which has safety implications. If larger amounts of minor actinides should be burned, an ADS is more appropriate. In this conference a paper describes the burn-up of nuclear waste by fast critical systems. The most prominent recent announcement was by Minatom, Russian Federation, to build the 300 MWe Brest-300 reactor [11] within 10 years. It is claimed that it will burn waste, be “naturally safe” and proliferation proof. There are also LBE- cooled designs proposed by IPPE Obninsk, Russian Federation – the SVBR-75 reactor [12] and the Tokyo Institute of Technology proposes a compact Pb-Bi cooled reactors with long-lived (12 years) fuel. A very economical 300 MWt LBE-cooled design is proposed by ANL, US that features natural circulation cooling [13,14]. The University of Berkeley proposes a small proliferation-proof reactor for which the entire core can be removed [15]. The South Koreans are proposing the PEACER reactor that can burn considerable amounts of waste and is claimed to be very safe [16].

A potentially important way of reducing the excess plutonium with existing water-cooled reactors is the use of plutonium fuel with a thorium matrix. Galperin and Raizes [17] have shown that a large PWR can burn more than 1 000 kg of plutonium per year. The ^{233}U that is bred in the process can be separated from the thorium and could replace some of the ^{235}U enrichment necessary for LWR fuel. Proliferation problems can be avoided by denaturing the ^{233}U with ^{238}U.

2. Problems if the accelerator is not switched off following an accident initiation in an ADS

It can rather certainly be assumed that regulators will want to know what happens if the accelerator is not switched off when one of the generic accident initiators occurs. These include the loss-of-flow (LOF) accident (also called loss-of-forced circulation accident for gas-cooled systems); loss-of-heat sink (LOHS) accident – e.g. due to loss of feedwater; a depressurisation in a gas-cooled system; reactivity insertion accidents; a new type of accident for the ADS is the beam power increase accident and for LBE-cooled systems inlet blockages due to crud formation have to be considered

Regarding switching off the beam, one accident type does not have to be considered – the station blackout accident. This is because the accelerator will be automatically switched off when the electricity supply is interrupted.

Quite a few scoping analyses on the behaviour of LBE-cooled ADS in accidents without beam shut off have been performed earlier [18,19,20]. They generally show that negative reactivity effects such as the Doppler effect, axial fuel expansion or even molten fuel sweepout cannot bring the power much below nominal as long as the beam is on. On the other hand, positive feedbacks due to the introduction of reactivity, even at a fast rate do not lead to a power burst but to an overpower condition of a few tenths of percent above nominal. The latter will lead to some fuel pin failures after several tens of seconds. The resultant sweepout will bring the power back to near nominal. The same type of behaviour occurs when the beam power is increased (a 50% increase and a doubling of the beam strength was investigated). At any rate, the reactor coolant will be contaminated (and could possibly be cleaned afterwards) but there will be no major problem.

Analyses with the STAR-CD code [21] of an LBE-cooled ADS undergoing a major coolant disturbance such as a LOF or LOHS gave the following results: In the Ansaldo design with its excellent natural circulation capability, the gas injection can be shut off (LOF) and the heat generated by the full power can still be removed. However, the outlet temperature is about 80 K hotter and this should not be maintained for long periods. ADS with mechanical pumps and a worse natural circulation capability may have considerably greater outlet temperature increases. But this will depend on the specific design and on the thermal power of the ADS.

For the LOHS accident with the beam on and the argon injection working, there is a grace time of about 40 min in the 80 MWt Ansaldo ADS before the 900ºC limit for vessel creep is reached. This is due to the large heat capacity of the heavy metal coolant. The long decrease of the temperature is due to the ex-vessel cooling with a PRISM type RVACS. For a combined LOHS and LOF (but not a station blackout, which would shut off the accelerator), there is only a 30 min grace time. This is because a map of hot LBE collects near the top of the vessel and is only intermittently removed by the natural circulation. If the beam is still not switched off after this grace time it can be assumed that the beam pipe will rupture before the vessel fails. This would flood the beam pipe with LBE so that the spallation source could be removed from the core. Later in the section on beam shut off, it will be shown that a deliberate weak spot in the beam pipe (a so-called melt-rupture disk) increases the grace time significantly.

Figure 1. **LOHS in 80 MWt ADS – beam on for 40 min**

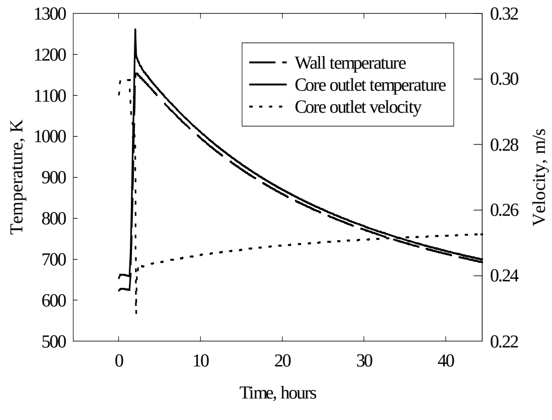
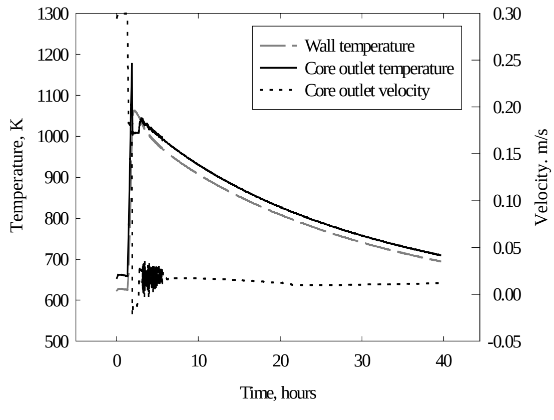


Figure 2. **LOHS + LOF with beam on for 30 min**



If an inlet blockage occurred in an LDE-cooled ADS it could lead to some fuel melting. However, an accident in an early LBE-cooled Russian submarine showed that molten fuel (at least oxide fuel) disperses in the heavy metal coolant in a coolable manner. To detect such a blockage in order to avoid a longer term blockage propagation may require instrumentation at each subassembly outlet although coolant activity measurements might be sufficient.

For a gas-cooled ADS hand calculations have shown that the core will melt in a few minutes if the beam is not switched off in a LOHS accident [22]. The grace times in depressurisation accidents may be even shorter; the one in a loss of circulation accident is probably somewhat longer. The melting of a sub-critical fast core can lead to a re-criticality. In reactivity or beam power increase accidents it is not clear whether an efficient molten fuel sweepout from the core is likely. Otherwise there will be fuel blockage formations that may propagate.

For an HTR-ADS, the inner fast zone will also have a low heat capacity. Thus it will also have short grace times for LOHS, loss-of-circulation or depressurisation accidents without beam shut off.

3. Beam shut off possibilities

In principle it is simpler and faster to switch off an accelerator than to insert shutdown rods in a critical system. The manual switching off of the accelerator based on increased temperatures (which will occur in all the important ADS accident scenarios) will remain an important option. There should also be an automatic interruption based on high temperature readings. If these methods fail, a melt-rupture disk in the wall of the beam pipe that would fail and flood this vacuum tube with heavy liquid metal would be useful as a last resort [23]. The STAR-CD calculations of an LOHS and a combined LOHS and LOF in the Ansaldo design show the effect of the melt-rupture disk failing after different heat ups of the coolant. It can be seen that for the combined LOHS and LOF the triggering (i.e. the melting of the solder material around this disk) should occur sooner. This is a difficult natural circulation problem with a 3 MW heat source in the upper part of the primary pool together with the decreasing core decay heat and the ex-vessel air cooling. The latter can only remove the entire heat when the vessel temperature is around the creep limit. But this is only reached after nearly 2 days in the LOHS accident. In the unlikely case of LOF + LOHS accident without beam shut off a map of hot coolant will collect in the upper part of the vessel due to the loss of forced circulation. After about 7 hours the wall temperature will surpass the creep limit. When a core with a higher thermal power and a stronger spallation source is used in the same vessel, the grace time gets shorter [23]. In a gas-cooled ADS this passively activated beam blocking is not possible. We are presently investigating further approaches for passively switching off the accelerator in heavy metal cooled systems. These are based on the thermal and electrical conductivity of liquid metals.

Figure 3. **Beam blocking 10 min (200 K) after LOHS initiation**

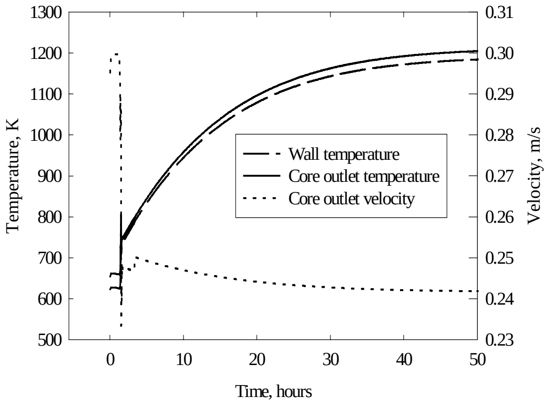
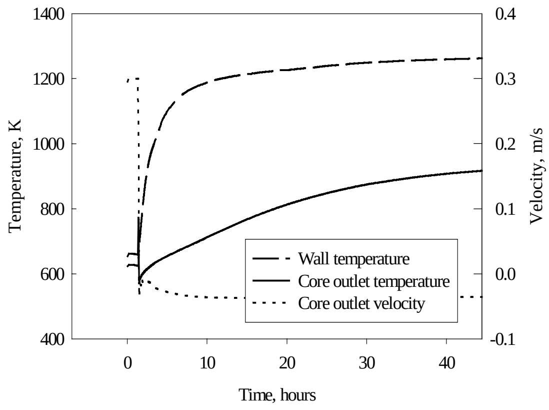


Figure 4. **Beam blocking 3 min (60 K) after LOHS + LOF**



4. Emergency decay heat removal

Emergency decay heat removal is necessary after beam shut off in the case of a station blackout accident or a LOHS e.g. due to the lack of feedwater. Liquid metals with their good heat conductivity allow ex-vessel cooling by natural air (RVACS) or water circulation or in – vessel cooling by direct reactor auxiliary cooling systems (DRACS). Ansaldo [5] is proposing a new approach for an RVACS (see Figure 5). This new design forms an additional barrier and would prevent fission product releases even in the remote eventuality of a guard vessel failure. Moreover, it could still cool a disintegrated core. Since this design consists of many U-shaped pipes, even the failure of a few of them would not be a problem. Calculations with the STAR-CD code have shown that the decay heat can be easily removed for the 80 MWt design

Figure 5. **Schematic of new Ansaldo RVACS**

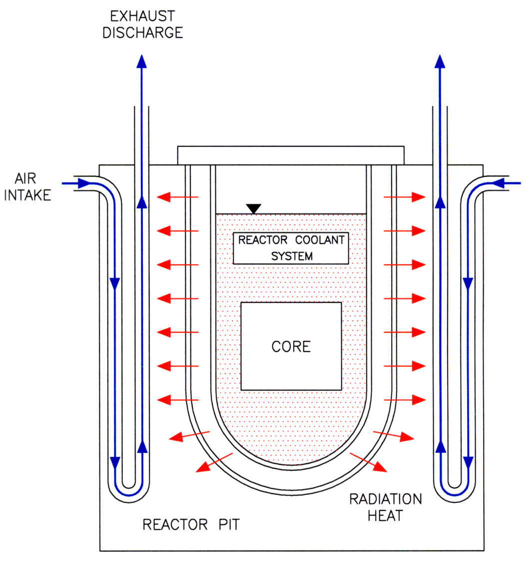
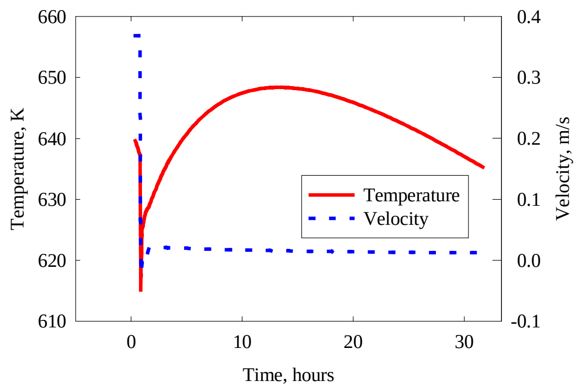


Figure 6. **Coolant temperatures and velocities at the top of the core during a station blackout. The initial temperature decrease is due to the large momentum of the LBE flow**



Another innovative approach is part of the BREST-300 design [11]. A thick concrete wall that contains pipes through which water is circulated surrounds the main vessel.

The emergency decay heat removal in gas-cooled systems can also be done passively for systems not much larger than 600 MWt. However, in a depressurisation accident, diesel-driven blowers are needed to remove the decay heat.

All heavy metal cooled critical reactors can also use the above mentioned passive means for removing the emergency decay heat.

5. Conclusions

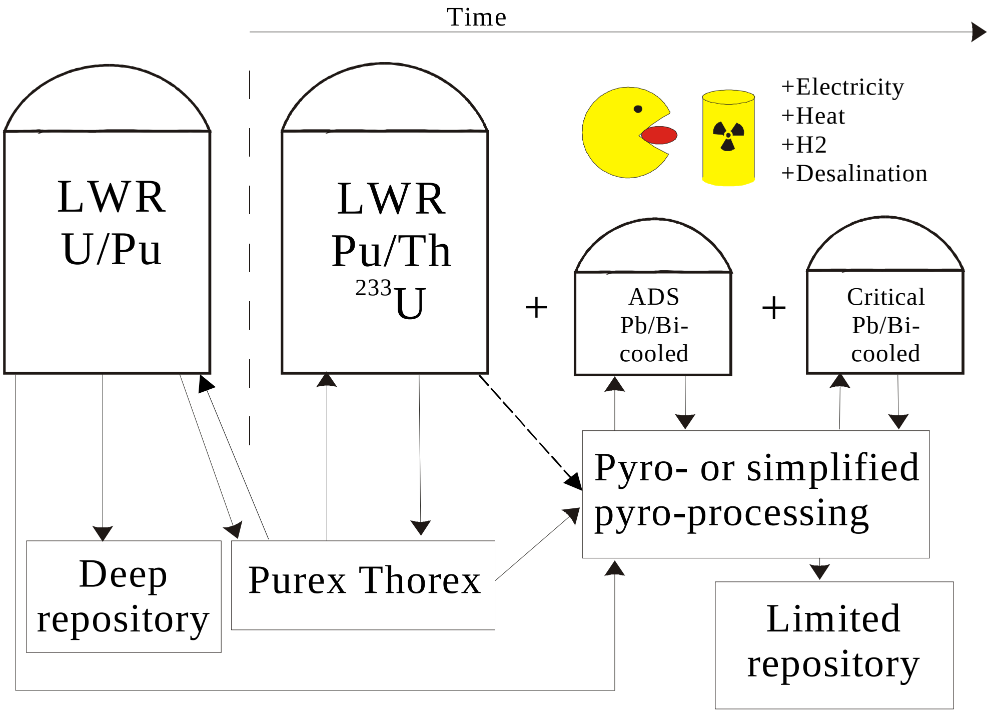
It has been shown that heavy-metal cooling of accelerator-driven system has considerable advantages regarding the behaviour of an ADS in severe accident conditions and in particular when the proton beam is not switched off during an accident initiation. Heavy metal cooling also allows passive approaches for the beam blocking or switching off the accelerator. An equally important aspect is the possibility of passive emergency decay heat removal systems that can also be used for critical reactors with heavy metal cooling. In contrast to sodium heavy metals do not burn and react mildly with water.

However, it should also be mentioned that the functionality of heavy metal cooling in normal operation is not yet well established in Western countries. Russian Federation has a considerable advantage in this regard because of its earlier experience with lead/bismuth cooling in submarine reactors. But considerable research on the corrosion behaviour and thermal hydraulics is now also underway in Western countries.

On the other hand gas-cooling is well understood and if one wanted to build an ADS in the near future, the functionality of a gas-cooled system would be more assured.

Once Pb-Bi or Pb-cooling is well established, critical reactors with heavy metal cooling that are also very safe, could be built for clean energy generation. These systems would benefit strongly from the research on heavy metal cooling for accelerator driven systems. A possible future scenario using both critical and accelerator-driven systems is shown below. In the nearer future one could start using thorium based fuels in LWRs to reduce excess plutonium and to avoid the generation of higher actinides.

Figure 7. **A possible scenario for nuclear power development**



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