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SAFEGUARDS APPROACH FOR ACCELERATOR DRIVEN SYSTEMS

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ABSTRACT

An Accelerator Driven System (ADS) utilizes a particle beam to bombard a target that generates spallation neutrons, which are subsequently used to transmute fertile material into fissile material, or to burn minor actinides in spent fuel. However, a Safeguards Approach has not been developed for potential ADS facilities. In this study, fissile material production rates were estimated using a new and simplified model, illustrating that ADS facilities could produce significant quantities of fissile material of concern to the IAEA. The Belgian MYRRHA ADS concept and its publications were used as a starting point for a Safeguards Approach, although a generic approach was ultimately used. We considered in detail the full ADS system to include material balance areas for spent fuel receiving, reprocessing, storage & cooling, fuel fabrication, subcritical reactor area, and waste storage & handling. Furthermore, aqueous-based separation methods like PUREX cannot tolerate the intense heat of the ADS fuels, so pyroprocessing will likely be required. We find that the recycled fuels likely intended for ADS will be thermally and radioactively hot to such a degree that it is likely reprocessing and fuel fabrication will have to be co-located with the ADS reactor facility to avoid impractical hot fuel transportation issues. We also conclude that significant diagnostic development is needed, and provide safeguards recommendations.

INTRODUCTION

An Accelerator Driven System (ADS) uses a particle accelerator generating high-energy (generally 600 MeV – 1 GeV) protons or deuterons that could potentially be used to produce fissile material utilizing either natural uranium or thorium fuel cycles. However, ADS safeguards have not been developed, resulting in a potentially significant proliferation concern.

A generic diagram of an ADS facility is shown in Figure 1 as modified from the original of Rubbia *et al* [1]. Note that Rubbia *et al* were considering ADS for both burning transuranics (TRU) as well as producing energy, and devised the name “Energy Amplifier”. The overall ADS facility consists of:

- An Accelerator Complex
- A Reactor, or “Energy Amplifier” where the accelerator projectiles strike the ADS target surrounded by fertile blanket material
- Balance-of-Plant (BoP) including heat exchangers and electric turbine
- A Fresh Fuel Storage Area
- Hot Cells and Spent Fuel Storage Area

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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Beyond these aspects, of course the full fuel cycle (whether uranium-based or thorium-based) will require a fresh uranium or thorium supply, fuel fabrication, reprocessing (if a closed fuel cycle) and final disposition of spent (potentially reprocessed) fuel.

Material Balance Areas (MBAs) were considered for the MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) ADS system under development at the Belgium Nuclear Research Center (SCK-CEN) [2], [3], [4], as highlighted in Figure 1, and consist of the Fresh Fuel Storage Area (MBA-1), the Reactor/Energy Amplifier (MBA-2), and the on-site Hot Cells/Spent Fuel Storage Area (MBA-3). We used MYRRHA's safeguards approach as an initial basis, and expanded upon their work to develop a broader approach applicable beyond the specifics of MYRRHA.

In addition to MYRRHA, many other experimental systems and facilities have been demonstrated internationally, with varying accelerator particle types and power levels, coolants, target materials, and fuels [5]. In 2015 the IAEA reported on 11 national ADS programs, and several international consortiums [6]. Argonne National Laboratory (ANL) has many activities including cooperative programs with the Kharkov Institute of Physics & Technology in Ukraine and the Joint Institute for Power and Nuclear Research in Belarus. Japan has several activities including OMEGA (Option Making Extra Gain from Actinides), under which the conceptual design has been completed for several systems, and research and development work for reprocessing [7]. China has significant work in this area, including Venus No. 1, a subcritical ADS developed by China Institute of Atomic Energy. A joint effort between the European Union, U.S., Japan and China was planned to develop an ADS prototype on an industrial scale.

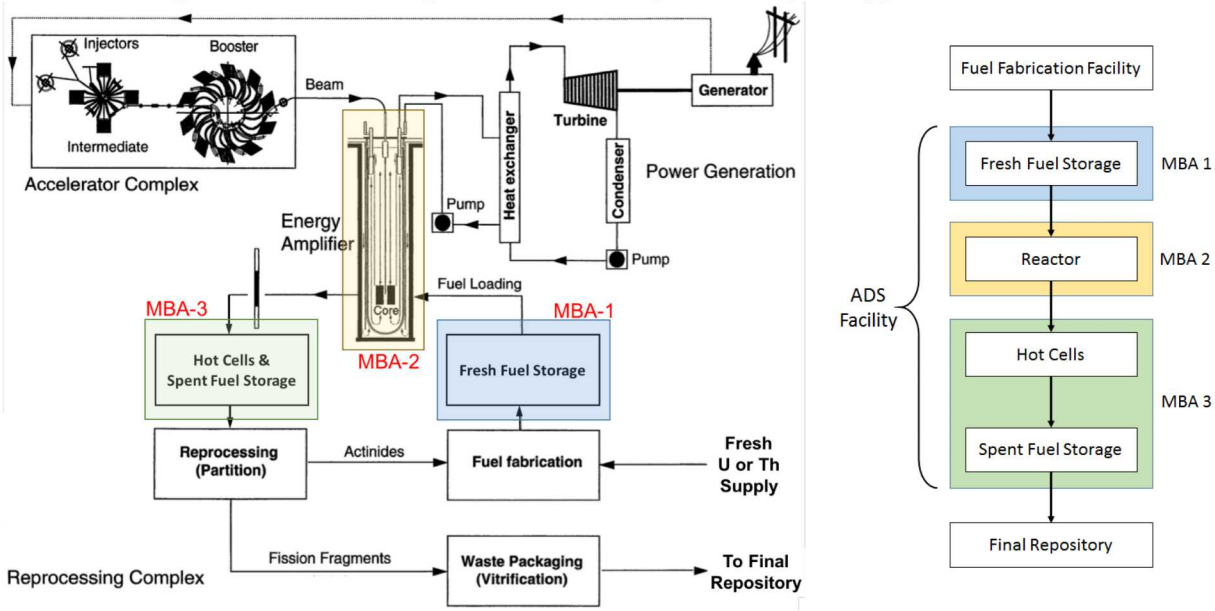


Figure 1. (a) Schematic representation of the basic concept of the ADS system, modified from the original figure of Rubbia *et al* [1]; and (b) Illustration of the Material Balance Areas (MBAs) envisioned for the MYRRHA ADS facility [3].

Based on this survey of existing and planned ADS facility development, we pursued a generalized Safeguards Approach, as well as considered special implications of ADS that may impact inspections and access. In particular, we assess that spent fuel to be processed by ADS

would very likely require pyroprocessing (electrorefining), and that such reprocessing would need to be co-located at the reactor site since transportation of such hot nuclear materials would be logistically difficult. Furthermore, safeguards diagnostics need to be enhanced or devised to deal with some unique aspects of ADS over other fuel cycle systems with which the IAEA normally deals.

FISSILE MATERIAL PRODUCTION RATES

It is useful to determine how much fissile material an ADS facility can produce in a timeframe relevant to IAEA inspections. In general, production rates for specific geometries are calculated using neutronics codes such as the Monte Carlo N-Particle (MCNP) code [8]. However, we wanted a simpler method to estimate fissile material production rates, where geometries and materials can be easily adjusted, to get a rough order of magnitude for fissile material production of any particular ADS design.

For this simple model, we used the annular cylinder geometry shown in Figure 2a. As can be seen, a proton beam of arbitrary energy impacts a cylindrical spallation target with diameter *d* and length *L*, which could be made of lead or depleted uranium (we did not consider enriched uranium, but natural uranium should result in the same results as depleted uranium). An annular blanket of fertile material (uranium or thorium), also of length *L*, surrounds the spallation target, and has a radius *r* extending from the surface of the spallation target to a maximum radius of r_{max}. When the proton beam scatters within the lead or uranium spallation target, spallation neutrons are generated. Findlay [9] provided a generalized 'back of the envelope' model for spallation neutron spectra, which appears to provide reasonable results (within a factor of 2) for a variety of target materials (Pb, U, W, Ta), noting that all spallation neutron spectra have a similar profile regardless of target or impacting proton energy (order of 1 GeV). We reproduce Findlay's model spectrum in Figure 2b, shown as the solid black curve. However, we also looked at published experimental and simulated data for both lead and uranium spallation targets [10] [11] [12] [13], and found different trends for their low-energy tails. We therefore created best-fit curves for these two targets, as shown as the colored lines in Figure 2b.

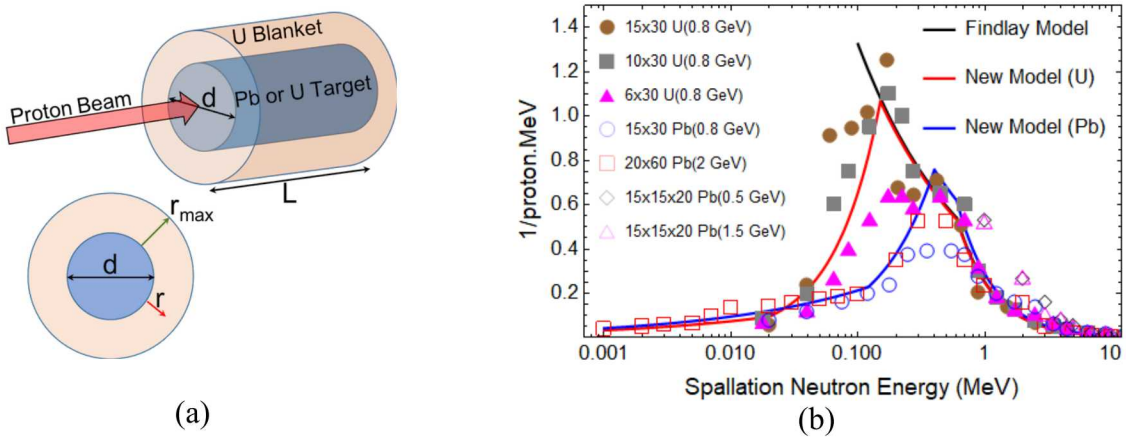
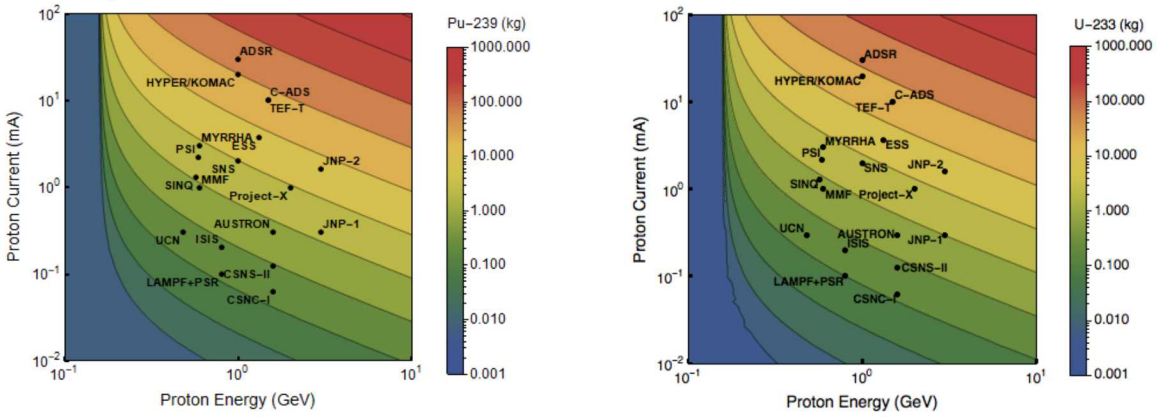


Figure 2. (a) geometry of ADS spallation target and fertile blanket; and (b) spallation neutron spectrum based on experimental and simulated data [10] [11] [12] [13] and the original estimate of Findlay [9].

We took the radiative neutron capture cross sections for ^{238}U and ^{232}Th from the ENDF library [14] (ENDF/B-VII.1) as a function of neutron energy, and integrated with respect to the various experimental and simulated spallation neutron data as shown in Figure 2. We used linear interpolation between spectra data points as well as for the downloaded ENDF cross sections, and also used ENDF cross sections for overall loss of neutron flux as the neutrons propagate through the fertile blanket. The results of these calculations are shown in Figure 3 for a lead spallation target and either a uranium or thorium fertile blanket, along with some representative ADS reactor systems. As can be observed from Figure 3, the larger ADS systems produce significant quantities of fissile materials, and thus should be of concern to the IAEA.



(a) (b)

Figure 3. Fissile material production rates for ADS having proton beam energies from 100 MeV to 10 GeV impacting a lead target for (a) a uranium blanket; and (b) a thorium blanket.

MATERIAL HANDLING ISSUES FOR VARIOUS ADS APPLICATIONS

We studied radiotoxicity and decay heat loads for a variety of potential ADS applications. Below we summarize our results using ADS as a spent fuel burner of TRU and minor actinides-only (MA-only), and as an "energy amplifier" and fissile material producer.

ADS as a Spent Fuel Burner

We took data from the comprehensive U.S. Nuclear Energy Agency (NEA) ADS report [15], and renormalized their heat loads, radioactivities, and reprocessing mass flows into the more safeguards-relevant form given in Table 1. Whereas the NEA document listed their data normalized by mass of heavy metal (kgHM) for radioactivity and heat loads, we normalized by the total heavy metal in one fuel load per reactor type. The reason we renormalized the data was that if left in the NEA form, the radioactivity for the ADS burners (TRU and MA-only) are an order of magnitude higher than LWR spent fuels (UOX and MOX) and several times higher than Fast Reactor (FR) burners, yet the total mass involved in the ADS reactor is an order of magnitude less than these other reactor types. We believe it is more relevant for safeguards to consider the heat loads and radioactivity of one fuel load per reactor, since the entire reactor fuel load will need to be monitored by safeguards technology and inspectors. Also, ADS involves large burnups, and therefore the likely fuel residence time in the ADS reactor is ~5 years, so much of the worker activity will be conducted on ADS fuel on such time scales, and thus an inspector would want to know the radioactivity of the entire fuel load, rather than per kgHM.

As shown in Table 1, per core fuel load, the ADS reactors have similar radiotoxicity (actinide & fission product decays, plus neutron emissions) as LWR and FR reactor cores. Again, the amount of heavy metal mass in the ADS reactors is an order of magnitude less than LWRs or FRs, so the ADS radiotoxicity is certainly more concentrated than the others, but as far as monitoring the entire core, they are all about the same. Decay heat of an ADS spent fuel core, however, is still nearly triple the amount of LWRs or FRs, even after renormalizing for the smaller fuel masses of ADS cores. Even if one waits years longer than specified in Table 1 for ADS spent fuel cooling (2 years), the ADS heat loads remain elevated much higher than LWR or FR spent fuel. Such ADS heat loads make using PUREX or its extensions (e.g. UREX) unusable for ADS spent fuel, which leads to the conclusion that dry reprocessing (i.e. pyroprocessing) will have to be utilized for ADS spent fuel reprocessing.

Table 1. Activity (actinides & fission products), decay heat and neutron source strength per reactor full fuel load; Reprocessing and fuel fabrication mass flow rates per reactor type [15].

Parameter	LWR-UOX	LWR-MOX	Pu Burner (FR)	TRU Burner (ADS)	MA Burner (ADS)	FR Strategy
Cooling time (years)	4	7	7	2	2	2
An&FP Activity/fuel load (x10^{18} Bq)	4.1	5.6	4.0	1.8	2.3	2.8
Neutrons/fuel load (x10^{12} n/sec)	0.109	1.22	1.01	1.69	5.71	0.173
Decay Heat/fuel load (kW)	389	707	559	501	1,433	329
Reprocessing Mass Flow Rate (gHM/hr)	2,300 PUREX	340 PUREX	130 PUREX	5,000 UREX 21 pyro	23 pyro	1,270 PUREX
Fuel Fabrication Mass Flow Rate (gHM/hr)	2,400	360	160	28 (Ac-Zr clad)	28 (AcN-ZrN clad)	1,340

ADS as a Fissile Material Producer

A relevant set of numerical simulations using Monte Carlo neutronics and spallation codes were conducted [16] using a nominal ADS reactor scenario consisting of a lead target impacted by 1 GeV protons, surrounded by a blanket of fuel and molten lead following the design of Rubbia [17]. Breeding of either ^{233}U through the thorium fuel cycle, or ^{239}Pu breeding with the uranium fuel cycle were considered. For the thorium cycle, they considered both a design with ^{233}U as the fissile starter material as well as plutonium as a starter fissile material as taken from PWR spent fuel (33 GW_td/t burnup).

In a realistic ADS design, fission products should be incinerated or removed from the fuel, and the consumed fertile elements replaced. The simulations indicated that recycling the fuel once every 5 years is appropriate. Also, some structural materials may need a periodic replacement, and 5 years was a realistic estimate to deal with such other issues. The burn-up during one 5-yr cycle in the simulated ADS systems considered is equal to 61 thermal Gigawatt-day per ton (GW_td/t).

Two different fuel regeneration/reprocessing schemes were used in the simulations:

1. Type-A fuel regeneration (full recycling) consists of removing all the fission products from the fuel and replacing the used mass of fertile matrix every 5 years. All the heavier elements are left in the fuel, in this way severely reducing the mid- and long-term activity of the waste, since the actinides remain as part of the reactor inventory.
    a. This optimistic scenario requires chemical separation techniques not yet available, but perhaps feasible in the near future [18]. They assumed that 0.1% of the plutonium and uranium, and 1% of the minor actinides go into the wastes under this type of reprocessing.
2. Type-B regeneration (partial recycling) consists of leaving in the fuel only the main fissile element, uranium or plutonium, while fission products and all other actinides flow into the wastes. The new fuel is topped with fresh ^{232}Th or ^{nat}U.
    a. This simple scenario corresponds to the techniques presently used at existing reprocessing plants. It was assumed that 0.1% of the reprocessed materials go into the waste.

Two ADS breeder scenarios were considered and the radiotoxicity estimates are shown in Figure 4. The ^{232}Th/^{233}U scenario assumes the fuel is started with 9.5% $^{233}UO_2$ imbedded in a thorium fertile matrix, whereas the ^{nat}U/Pu ADS scenario uses natural uranium as fertile matrix material, started with 12% PuO_2, where the plutonium is taken from PWR spent fuel (33 Gw_td/ton burnup) and the plutonium starter isotopics are 59.6% ^{239}Pu, 23.0% ^{240}Pu, 12.3% ^{241}Pu and 5.1% ^{242}Pu. The ^{232}Th/^{233}U scenario assumes ^{233}U is available as a starter fuel, which is not currently the case, but could be plausible if an overall nuclear strategy includes creating ^{233}U from ^{232}Th using some other starter fissile material (e.g. ^{239}Pu or highly enriched ^{235}U).

As can be observed in Figure 4, the thorium fuel cycle results in at least an order of magnitude less radiotoxicity than the uranium fuel cycle, regardless of whether pursuing the Type-A or Type-B fuel regeneration/reprocessing schemes. However, even for the thorium fuel cycle, the radiotoxicity lingers just as long as that due to the uranium fuel cycle minor actinides, and do not reach natural radiotoxicity levels (i.e. uranium ore at ~10^4 Sv/GW_ty) for at least 100,000 years. In Type-B regeneration for the ^{232}Th/^{233}U fuel cycle, if plutonium were included in the fuel reprocessing with a 99.9% efficiency (technically feasible at the moment), protactinium would be the most toxic component in the wastes in Figure 4, and then the total radiotoxicity shortly after the discharge would decrease two orders of magnitude, but regardless still becoming about ten times higher than the results for the type-A scenario and still lingering for over 100,000 years.

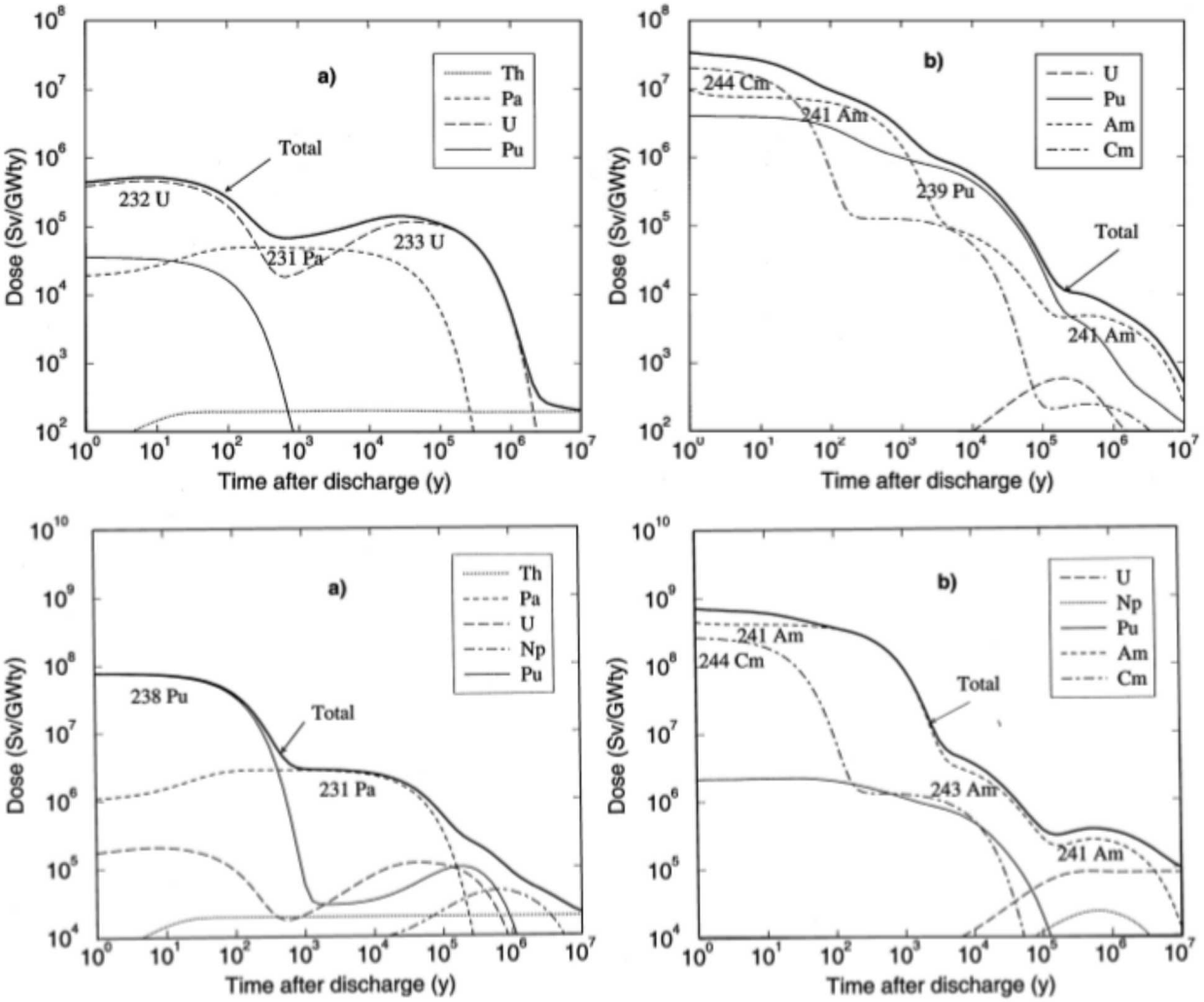
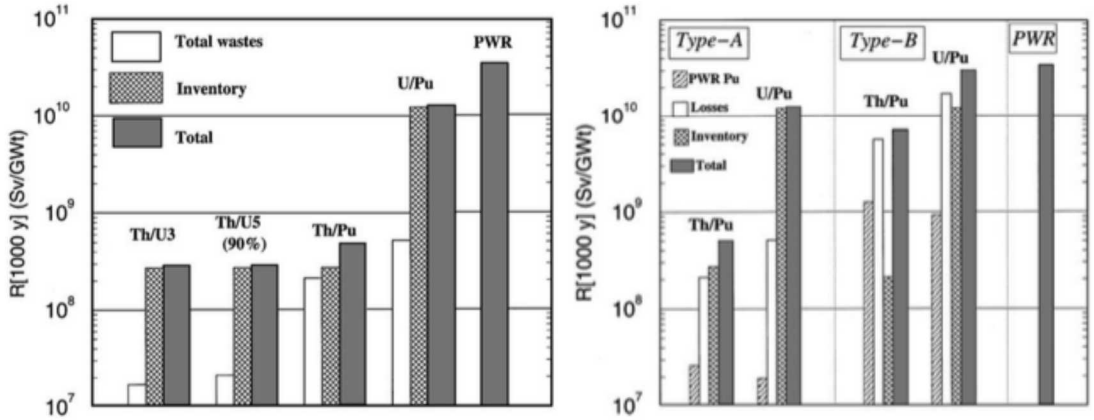


Figure 4. Radiotoxicity due to the actinides in the wastes of the $^{232}Th/^{233}U$(a) and $^{nat}U/Pu$(b) fuels at the end of the 5th cycle (25 years of burnup). The top row is for type-A fuel regeneration (full recycling); and the bottom row is for type-B regeneration (partial recycling). The radiotoxicity has been normalized to the thermal energy produced during one fuel cycle. Labels indicate the nuclides which contribute the most at a given time. [16]

A good summary of these results is shown in Figure 5. Note that here the label Th/Pu refers to an ADS breeder system that uses plutonium taken from spent PWR fuel as the starter fissile material. Note further that "waste" or "losses" in Figure 5 refers to the tails from reprocessing, whereas "inventory" refers to radiotoxicity left within the spent fuel. Figure 5(a) considers only the Type-A fuel regeneration scheme (full recycling), whereas Figure 5(b) considers both Type-A and Type-B, but only considers plutonium from PWR spent fuel as the starter fissile material (which was deemed to be the most likely breeder scenario while ^{233}U remains largely unavailable).

From Figure 5 it is observed that radiotoxicities involved in any of the ADS scenarios are less than the current PWR waste radiotoxicity, although not by much for some of the ADS cases considered. We stress that this is the case for the breeder strategy of ADS, although for Type-A

regeneration all the actinides remain in the fuel to be partially burned while breeding the desired fissile material. We see from Figure 5 that as regards to radiotoxicity, whether using plutonium from spent PWR fuel or ^{233}U from thorium, makes little difference if Type-A fuel regeneration is pursued (Th/U5-90% means ^{235}U enriched to 90% as the starter fissile material). Also, it appears that the U/Pu fuel cycle in an ADS system does not offer a significant radiotoxicity reduction when compared with a traditional PWR, whether using full recycling (Type-A) or partial recycling (Type-B). The reasons to utilize the U/Pu fuel in a ADS system would therefore be to burn the ^{239}Pu from PWRs while starting the ADS breeding/energy production cycle, although this is not a large benefit since most of the Pu lingers in the fuel as shown in Figure 5; or the inherent safety of ADS coupled with a sub-critical reactor offers benefits over a PWR that justifies the ADS approach. For the Th-based fuel cycle started with PWR plutonium (Th/Pu labels in Figure 5), after 200 years of energy generation the reduction of the total radiotoxicity is reduced 5X with respect to the use of PWR reactors without minor actinide reprocessing, and 70X if minor actinides are reprocessed.



(a) (b)

Figure 5. Radiotoxicities, 1000 years after discharge, due to the actinides generated by 200 years of energy generation by hybrid reactors assuming Type-A regeneration for a variety of fertile/fissile starter fuel combinations; and (b) for both Type-A and Type-B regeneration schemes which use Pu from PWR spent fuel to start the cycle. The four bars indicate, from left to right, wastes from the Pu reprocess, hybrid reactor wastes, hybrid reactor final inventory, and total values. For comparison, the radiotoxicity of PWR spent fuel is included. All values are normalized to the installed thermal capacity. [16]

ENHANCED SAFEGUARDS APPROACH FOR ADS

As has become apparent from above analysis, reprocessing of spent fuel in ADS systems, including re-fabrication after burning in either ADS or fast reactors, will be the main difficulty in applying safeguards to an overall ADS facility. The limited ADS scenario used for Figure 1 only considered MBAs for Fresh Fuel Storage (MBA-1), assumed arrived from an off-site separate facility, the ADS subcritical reactor (MBA-2), and the Spent fuel Storage (MBA-3). However, that limited scope was prior to our current realization that the ADS as a burner of spent fuel, which may be recycled, is so hot that shipping to a separate off-site reprocessing facility would be impractical. Similarly, fuel fabrication should also be co-located with the overall ADS burner facility. For a breeder ADS facility, assuming a once-through fuel cycle, one could still have off-site reprocessing and fuel fabrication facilities. However, as will be detailed below, if the

thorium fuel cycle is the preferred fuel cycle for ADS as a breeder, then this fuel will also become "hot" due to the intense gamma radiation from generated ^{208}Tl. Therefore, it may still be practical to co-locate reprocessing facilities for an ADS breeder scenario, depending on the circumstances.

A physical layout of the MBAs, including for the fuel fabrication and reactor areas, is shown in Figure 6. As shown, spent fuel arrives at MBA-1, which could be spent fuel from a LWR or fast reactor, or fuel that has been burned in the ADS reactor (i.e. recycling). If recycling, the MAs will require significant shielding, so MBA-1 must be constructed to handle the level of heat and radioactivity anticipated. If no recycling from ADS spent fuel will be done, then construction based on LWR or FR spent fuels (including MOX fuel) can be followed. All the pyroprocessing steps are shown within MBA-2, which includes spent fuel chopping and dissolving, and the rest of the separation steps, culminating in fuel element fabrication. This work would be done in a very high radioactivity and high heat load environment, so significant infrastructure will be required in MBA-2, such as hot cells and remote handling equipment. Diagnostics, including those useful for the IAEA, will have to be hardened to survive the MBA-2 environment. Even though fuel elements are to be produced at the last stage of MBA-2, these elements will still be hot and need to cool for 1-2 years prior to making a fuel assembly. This cooling storage area will be MBA-3 since it will likely be separated physically from the pyroprocessing area and the fuel fabrication area. After cooling in MBA-3, the fuel elements can then be sent to MBA-4 for fabrication of fuel assemblies ready to be placed in the ADS subcritical reactor (MBA-5). After transmutation in the ADS subcritical reactor, the ADS-burned fuel can then be recycled (sent back to MBA-1) or sent to waste handling pending final disposition (MBA-6). As stated earlier, the accelerator facility is not safeguarded, so no MBA for it.

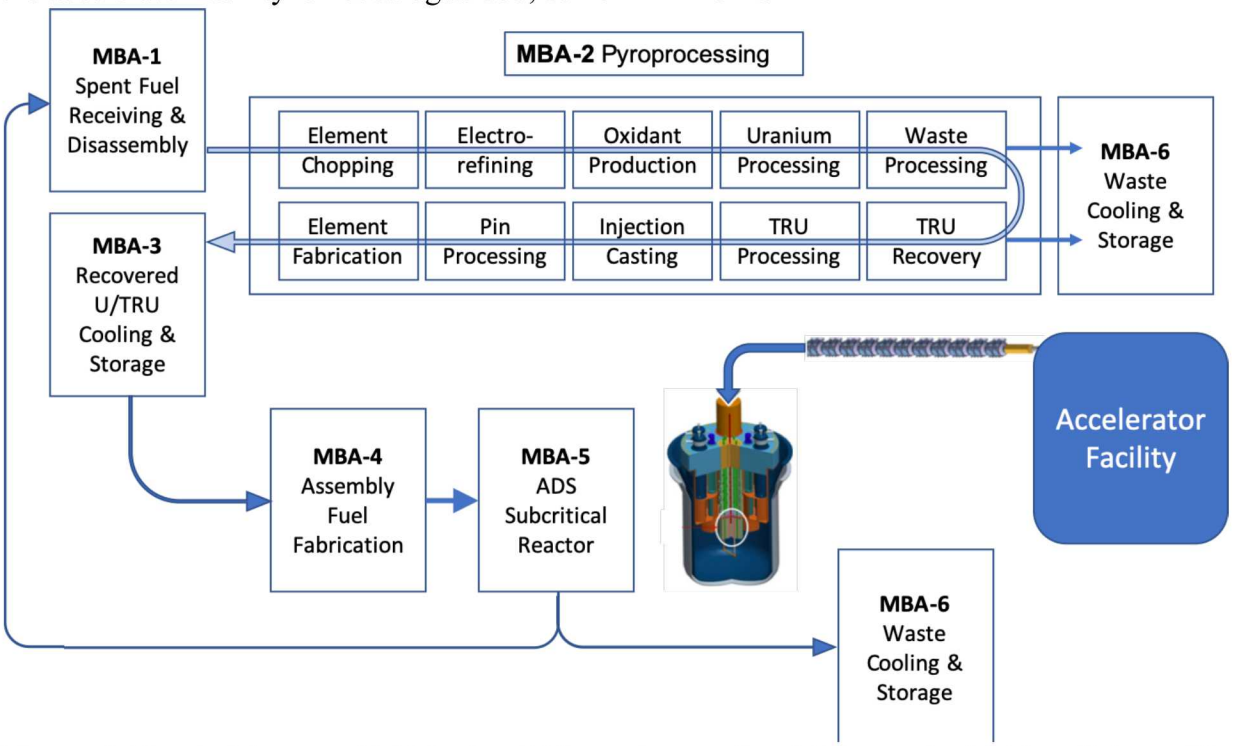


Figure 6. Physical layout of MBAs for ADS as a burner. In addition to the MBAs of Figure 22, added are MBA-4 for fuel fabrication and MBA-5 for the subcritical reactor. Note that burned

fuel from the reactor can either return to be recycled at MBA-1, or sent for interim storage pending final disposition in MBA-6.

Note that it is assumed all these MBAs are co-located on-site. However, there may be significant separation between MBAs (meters to km), but the point is that there is no large-scale transportation needed between separate off-site locations. Again, for an ADS breeder, reprocessing and fuel fabrication may still be practical to ship off-site, and in Figure 6 one could substitute "THOREX" for "Pyroprocessing" for the MBA-2 label, for example.

Not shown in Figure 6 are the key measurement points (KMPs) to maintain continuity of knowledge (CoK) between MBAs. Such KMPs are necessary, but those measurements will be very difficult due to the "hot" nature of the materials as well as the inexperience involved in these ADS processes. Many of the diagnostics that will be needed simply do not exist because there has not been a need.

Diagnostic Needs

The IAEA and safeguards community do have examples of reprocessing safeguards approaches and diagnostic recommendations, in particular those reprocessing activities in Japan, that can be applicable to ADS diagnostic needs. The Tokai Reprocessing Plant (TRP) started reprocessing operations in 1977, but is currently in the process of decommissioning the facility. TRP reprocessed about 1,000 tons of spent fuel. As illustrated in Figure 7, the aqueous reprocessing steps of the TRP flow chart is similar to the pyroprocess shown in Figure 6. From 1978-1981 the U.S. participated with Japan, France, and the IAEA on the Tokai Advanced Safeguards Technology Experiment (TASTEX) to assist IAEA with the development and implementation of safeguards techniques to meet the challenges of continuous inspection [19]. This experience was useful to all parties, and resulted in safeguards diagnostics improvements, as well as laying the groundwork for safeguarding the Rokkasho Reprocessing Plant (RPP).

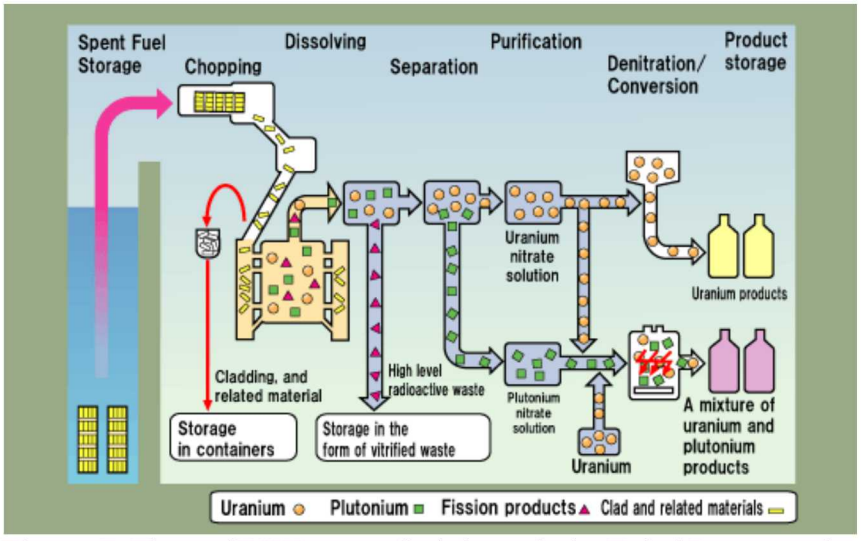


Figure 7. Flow of LWR spent fuel through the Tokai Reprocessing Plant [20].

From this Japanese experience, multiple lessons were learned [19], [21]. The ability to collect information from vessels in the main process line proved to be invaluable. It was determined that

operations need to be able to accommodate high frequency random sampling or in-process analyses for IAEA inventory verification to meet timeliness requirements. The installation of in-vessel measurement and monitoring systems is critical in addressing IAEA timeliness requirements. The operator needs to establish and then declare the expected waste stream components with capabilities to sample and analyze for them. This includes Np, Am, Cm, and any other signature components that would indicate that the plant is being operated as declared. [19]

It was also found that diversion at points early in the process area, after the spent fuel is dissolved in hot nitric acid but before the fission products are removed in Figure 7, would be difficult because of the intense radioactivity and low plutonium concentration of the solution. At this stage in the process, for instance, there might be only 2 g plutonium per liter of solution, requiring thousands of liters to be bled off to divert 1 significant quantity (SQ) of plutonium [22]. The total number of shielding penetrations in a large reprocessing plant is in excess of 1,000, including buried pipes to adjacent process buildings and to waste storage tanks. Design verification is essential to ensure that pipes suitable for plutonium transfer are identified and controlled [22]. The current approach is to move toward increasing the amount of data in the process available to the IAEA, enabling localization down to small process cells, through process monitoring and near-real-time accountancy (NRTA), but without the burden of additional MBAs. [22]

From the experience gained implementing safeguards at Tokai Reprocessing Plant and Rokkasho Reprocessing Plant, in addition to the issues explored in this effort, multiple measures should be pursued to enhance the safeguardability of ADS facilities, with particular emphasis on diagnostics for the reprocessing and fuel re-fabrication areas since these are the issues uncovered to be the most difficult, as detailed below [19], [21], [22], [23]:

- Improve the accuracy associated with each of the various measurement techniques used in applying material accountancy, in particular better accuracy for K-edge densitometry for plutonium concentration measurements
- Development of diagnostics for ^{233}U and ^{233}Pa measurements in the case of a thorium fuel cycle, especially since such diagnostics do not currently exist for the safeguards purpose
- An extensive array of ^{244}Cm-based non-destructive assay systems to monitor all major high, medium and low-level waste streams.
- Use of near-real-time accountancy (NRTA) techniques, in which material inventories within various stages of processing, as well as flows in and out of these stages, are monitored daily or weekly.
- Real-time data on inter-vessel transfers. This monitoring will help assure that the plant is being operated according to the operator's declarations and also provides input data for NRTA.
- Use of electromanometers for significantly more accurate volume measurements (displacing the contemporary water manometers for the required differential pressure measurement)
- Use of resin bead technology for sample preparation to allow transport of independent samples for analysis at remote IAEA laboratories

- An automated Solution Monitoring System (SMS) to monitor the volume and nuclear material solution transfers from the large number of vessels, verifying nuclear material inventory, inventory change, or other transfers
- A neutron detector network in the reprocessing MBA to provide real-time inventory of Pu-bearing materials and process glove box "hold-up" for additional continuity of knowledge (CoK) assurance
- An automated and authenticated system throughout the plant for collecting samples for Destructive Assay (DA) and Non-Destructive Assay (NDA)
- An on-site radiochemical laboratory, jointly operated by inspector-analysts from the IAEA and the Member State regulator, which analyzes samples for plutonium and uranium content by DA and NDA
- An extensive computerized inspector data collection and analysis system (I3S) that collects data from over many measurements, monitoring systems, and surveillance camera systems

As highlighted above, pyroprocessing will likely be needed for ADS, especially for a burner, and there are some published approaches for dealing with pyroprocessing safeguards. We provide these potential approaches here, since they are more general than the diagnostic specifics and facility recommendation given above. The design of such pyroprocessing facilities and the characteristics of major process components are not well defined at this stage, so the safeguards approach is only conceptual. The most vulnerable element in the pyroprocessing process, from the standpoint of diversion, is the TRU electro-refiner [21].

Since pyroprocessing is not a homogeneous process like PUREX (i.e. the concentrations are not uniform throughout the electrorefiner volume), samples at a given location may not represent the actual amounts of fissile material in the process. Additionally, flushing out the electrorefiner to do material balance is not practical since the electrolyte maintains a current, which would be disrupted, and much of the U or Pu could be on the cathode plate or elsewhere that would make accurate quantification difficult [24]. Assay of the nuclear materials in metal or salt solutions by DA or NDA will be very challenging, partly because there is not the same level of experience analyzing these materials as with the solutions from a PUREX-type reprocessing plant. Also, IAEA safeguards instruments will be in the harsh environment of electrorefining, such as operating at high temperatures (450-550 °C), and the molten salt and metal solutions are very corrosive.

Los Alamos National Laboratory (LANL) proposed four prospective safeguards approaches for pyroprocessing, which are provided below and should be considered in the overall Enhanced Safeguards Approach detailed above, [21], [24], [25]:

- *Neutron balance method by Cm accounting* – With the assumption that Pu and Cm have similar separation behaviors, Pu can be accounted for through the accounting of Cm, assuming the Pu/Cm ratio is constant or can be calibrated as a function of pyroprocessing parameters (e.g. temperature). In this method, the total neutron count is monitored across different sections of the pyroprocessing system, and any anomalous total neutron measurements are an alarm to investigate possible Pu diversion. This method assumes that the Cm is never separated from the

Pu, and that the U/TRU material is homogeneous. One drawback of this option is that the approximately 30 kg hold-up of plutonium in the process would not be directly verifiable.

- *Assay of Pu in spent fuel via Pu/Cm ratio and DA* – This method is the same as the neutron balance method, but with the extra step of conducting a DA analysis on a sampling of spent fuel pieces from the head-end step to quantify the actual Pu/Cm ratio. Detailed total neutron axial profile measurements of each pin entering the process stream must be done, and DA on a select number of rod pieces to determine the Pu/Cm ratio on a pin by pin basis. Total neutron measurements can then be used on the electro-refiner and waste streams. NDA or DA of U/TRU product would be used to confirm the Pu/Cm ratio and provide Pu assay for transfer to the next MBA. This ratio would also be used with electro-refiner neutron data to obtain the Pu inventory in the electro-refiner. This method assumes the Pu/Cm ratio is constant thereafter, and quantities must have an overall low uncertainty to meet detectability concerns for 1 SQ of Pu.

- *Electrorefiner assay* – This method attempts to take as many measurements as possible of the electrorefiner electrolyte, cathode products, metal waste, and recovered salt to account for all Pu, requiring a complex set of assays on the Pu content of all U cathodes removed from the electro-refiner, all metal waste streams, the electro- refiner salt prior to daily removal (must be homogeneous), recharge salt returning to the electro-refiner, and the recovered salts from the metal waste and U product processing units. A weight of the electro-refiner salt removed daily is also needed. The contents of the electro-refiner are assumed to be well mixed and homogeneous. This method requires a significant amount of samples and effort.

- *Homogenized input* – This method simply tries to ensure the Pu/Cm ratio is accurate prior to entering the electrorefiner stage and involves adding a homogenization step (e.g., oxidation/reduction and melting) after the element chopping step to produce a homogeneous molten salt solution for DA sample taking, to obtain Pu composition and Pu/Cm ratio for Pu accountability and downstream analysis steps. This approach may require changing the pyroprocess to accommodate such pre-electrorefining homogenization.

CONCLUSIONS

ADS as a burner of TRU or as a breeder of fissile materials has merit from a technological and safety perspective, potentially greatly aiding in closing nuclear fuel cycles. However, safeguards do not exist for ADS, and will encounter all the complications of a reprocessing facility in addition to the challenges posed by such a new and unfamiliar reactor type.

We have provided here a Safeguards Approach for ADS facilities, which should allow for a comprehensive assessment of next steps to safeguard ADS reactors built as burners or breeders. Much can be borrowed from other safeguards studies and experience, such as reprocessing safeguards, fast reactor safeguards, and GEN IV reactor safeguards like molten salt reactors, but ADS also poses unique safeguards challenges as noted throughout this report. In particular, the very hot material conditions of an ADS facility, especially for a burner, but also the lack of appropriate diagnostics. A more comprehensive monitoring regime will be needed to safeguard an ADS facility compared to previous IAEA experiences, and significant work needs to be done to improve the accuracy of existing diagnostics, like K-edge dosimetry, and development of diagnostics that can withstand the harsh ADS environment.

We suggest R&D efforts be focused on diagnostic development. Better diagnostics will enable the Safeguards Approach, and without such diagnostic development the IAEA will be ill-prepared for safeguarding ADS facilities.

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