Energy Amplifier Systems as Sustainable Nuclear Reactors: An Overview

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*Review*

# Energy Amplifier Systems as Sustainable Nuclear Reactors: An Overview

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**Abstract:** One of the present major issues for industrialised societies is the environmental impact of energy production. Nuclear power is identified as a possible sustainable opportunity to provide a technological answer to this problem. This review aims to overview the physical bases of accelerator-driven systems, focusing on spallation and transmutation phenomena. A discussion on the possible use of these nuclear devices is developed in the context of sustainable energy production, showing a possible new approach to nuclear energy, based on the developments of accelerator physics and technology during the last century.

**Keywords:** energy engineering; nuclear engineering; nuclear physics; ADS—accelerator-driven system; sustainability



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## 1. Introduction

Energy represents one of the fundamental pillars of socio-economic growth. World-wide demand for energy is continuously growing, and it is expected to double by 2050. On the other hand, there is an environmental need to reduce $CO_2$ emissions, with a related decrease in the use of non-renewable resources.

Since 1954, nuclear power has been used for energy generation and it can be considered a sustainable non-renewable source due to its carbon-free characteristics. Traditional nuclear power systems for energy generation use fission nuclear reactors, driven by neutrons emitted as a consequence of the very fast fission interactions ($[10^{-5}$–$10^{-3}]$ s [1]) of fissioning nuclei. However, nuclear fission powers present some difficulty concerning nuclear waste. Some solutions to the waste problem are represented by the development of nuclear reactors based on the incineration of long-lived transuranic elements and transmutation of fission products.

Nuclear fusion reactions represent an improvement in the use of nuclear reactions in power engineering because they are safer and generate short-lived nuclear waste. On the other hand, they require high temperatures to work [2], which need improving technologies. Moreover, fusion reactors use tritium as fuel, but tritium, ${}^3_1$H, is a rare and radioactive isotope of hydrogen, ${}^1_1$H, with a half-life of around 12 years [3].

In nature, tritium is extremely rare on the Earth. In the atmosphere, it is generated by the interaction between air molecules/atoms and cosmic rays. Consequently, it must be produced artificially, after and also during the fusion reaction through contact with lithium, which is a more abundant material in the Earth's crust, even if it belongs to the group of critical raw materials. The actual availability of tritium amounts to approximately 20 kg [4], and to improve this amount the *breeding* concept has been introduced in the new nuclear fusion reactors, creating a contact between the blanket modules with lithium and the hot plasma. In this way, a reaction can occur where the incoming neutron is absorbed by the lithium atom, which recombines into an atom of tritium and an atom of helium. Thus, the tritium can then be removed from the blanket and recycled into the plasma as fuel. At present, the first industrial nuclear fusion reactors will operate around 2050. In the meantime, a solution for environmental depletion must be introduced.

In the context of innovation in nuclear power generation, accelerator-driven systems (ADSs) could be also considered. The first idea of ADSs dates back to the early 1950s, when Ernest Orlando Lawrence at Livermore National Laboratory and Wilfrid Bennett Lewis at Chalk River Laboratory developed Glenn Theodore Seaborg's results, starting two independent accelerator-based breeding projects: Lawrence producing $^{239}$Pu and Lewis breeding $^{233}$U in view of the thorium-based, heavy-water moderated CANDU line. Unfortunately, economic reasons induced the abandonment of these early projects [5]. In the late 1970s, physicists at Brookhaven National Laboratory developed a great number of designs for accelerator breeders, but they pointed out that the proton beam currents ($\sim$300 mA) required for direct transmutation by the spallation process were much larger than an accelerator could achieve. However, the transmutation rate of a 300 mA proton accelerator was highlighted to correspond to a small part of the annual waste generated by a 1 GW$_e$ light water reactor. So, in the late 1980s, Charles D. Bowman at Los Alamos National Laboratory and Hiroshi Takahashi at Brookhaven National Laboratory introduced the accelerator-driven system concept to use the high-energy proton beam from an accelerator to produce spallation neutrons to drive a subcritical blanket [5]. Then, in 1993, Carlo Rubbia proposed the Energy Amplifier (EA) concept [6], as an ADS, that improved a power-generating system based on an incinerating–transmuting device for nuclear waste. Here, we wish to highlight that an ADS also generates light-charged particles, in particular tritium, that could be used as fuel for nuclear fusion reactors.

In this paper, we wish to summarise the physical bases of accelerator-driven systems, present these nuclear devices as sustainable power plants, both in relation to energy generation and concerning the production of fuels for fusion plants. To do so, in Section 2 we will discuss nuclear transmutation and spallation phenomena to summarise the numerical tools for ADS engineering design, in Section 3 the results will be presented with particular regard to the advantages and disadvantages of ADSs, and in the last section a discussion on these devices will be carried out.

## 2. Physical Bases of ADS

Accelerator-driven systems are external source-driven subcritical nuclear reactors characterised by a high neutron redundancy and subcritical safety [7].

An ADS is driven by a proton accelerator to inflow GeV proton beams into heavy metal targets in order to produce spallation neutrons.

The following subsections develop the theoretical approach to the physical processes for designing accelerator-driven systems, summarised as methodology in Figure 1 and in mathematical summary in Figure 2. In the following, the physical bases (transmutation and spallation phenomena) are summarised, and the numerical model INCL4 is presented in order to show a good tool for the designing of the ADS.

### *2.1. Nuclear Transmutation*

Nuclear transmutation represents the fundamental nuclear process of the ADS.

In 1901, Ernest Rutherford discovered that radioactive thorium converts itself into radium

$$^{230}_{80}\mathrm{Th} \rightarrow^{226}_{88} \mathrm{Ra} + \alpha$$

Rutherford and Frederick Soddy showed natural transmutation as a part of radioactive decay of the $\alpha$ nuclear decay [8]. It was Rutherford (in 1919) together with his collaborator Patrick Blackett (in 1925) who showed the transmutation of $^{14}$N to $^{17}$O by using an $\alpha$-particles beam:

$$^{14}_{7}\mathrm{N} + \alpha \rightarrow^{17}_{8} \mathrm{O} + \mathrm{p}$$

In the period 1921–1924, Blackett experimentally identified the residual nuclei of transmutation processes. In 1932, John Cockcroft and Ernest Walton used artificially accelerated 800 keV protons against $^{7}$Li to split the nucleus into two $\alpha$ particles

$$^{7}_{3}\mathrm{Li} + \mathrm{p} \rightarrow 2\alpha + 17.2\ \mathrm{MeV}$$

Then, in 1933, always using $\alpha$-particles, Irène Curie and Frédéric Joliot obtained the transmutation of boron and aluminium into radioactive nitrogen and oxygen. The difficulty of extending transmutation to heavier nuclei [9] was overcome by the invention of the cyclotron by Ernest Orlando Lawrence. By coupling accelerator beams with the spallation process, a great number of neutrons can be obtained, with a related possible innovative approach to nuclear reactors.

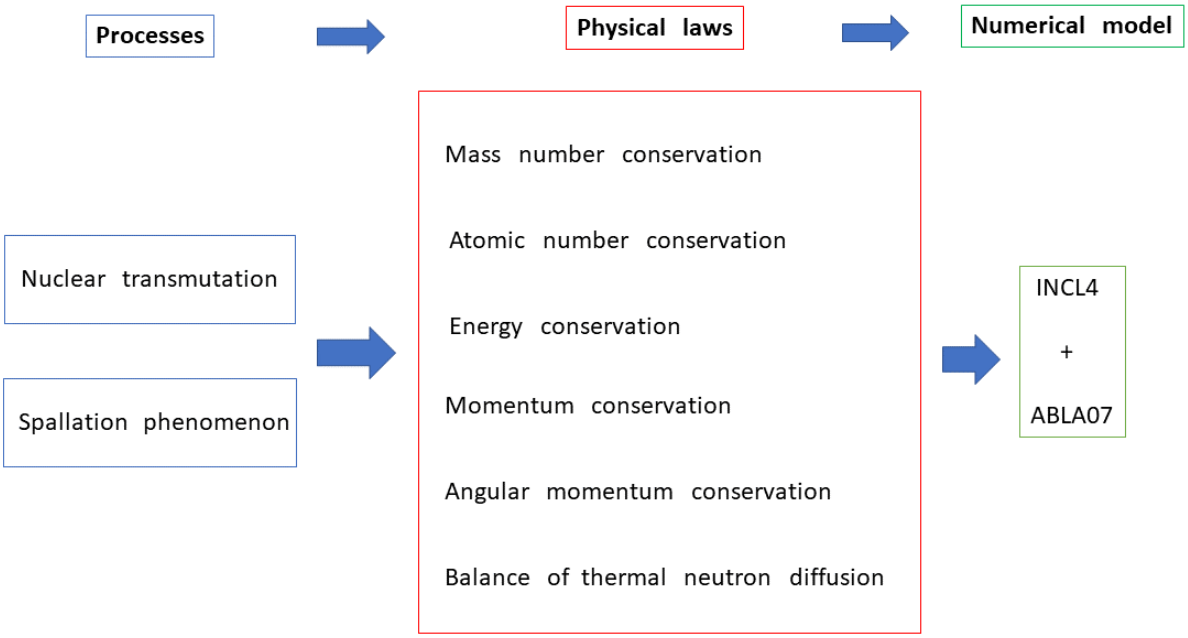


**Figure 1.** Flow chart of the approach methodology.

The term "spallation" depicts the interaction of high-energy light nuclei with a target nucleus, proceeding in a sequence of nuclear processes:

- High-energy projectile (∼GeV) collides with the target, leading to intranuclear cascade;
- This cascade causes the ejection of nucleons from the target nuclei;
- The target nuclei remain in an excited state;
- Consequently, they are subjected to multi-fragmentation fission or evaporation;
- Spallation neutron yield is a function of accelerator power;
- The number of emitted neutrons is related to the target nuclei and the energy of projectiles, saturating around 2 GeV;
- The energy distribution of spallation neutrons is similar to the one of fission neutrons.

| **Principle/Quantity** | | **Equation/Symbol** |
|---|---|---|
| Conservation of the mass number | | $A_P + A_T = A_{ej} + A_\pi + A_{rem}$ |
| projectile | | $P$ |
| target | | $T$ |
| ejectiles | | $ej$ |
| pion | | $\pi$ |
| remaining part of the target | | $rem$ |
| Conservation of the atomic number $Z$ | | $Z_P + Z_T = Z_{ej} + Z_\pi + Z_{rem}$ |
| Conservation of the energy $E$ | | $E_{lab} = E_{kin,ej} + E_{t,\pi} + E_{rec} + E^* + E_{sep}$ |
| laboratory | | $lab$ |
| kinetic | | $kin$ |
| total | | $t$ |
| recovery | | $rec$ |
| excitation | | $*$ |
| separation | | $sep$ |
| Conservation of the momentum | | $\mathbf{p}_{lab} = \mathbf{p}_{ej} + \mathbf{p}_\pi + \mathbf{p}_{rem}$ |
| Conservation of the angular momentum | | $\vec{\ell}_{lab} = \vec{\ell}_{ej} + \vec{\ell}_\pi + \vec{\ell}_{rem} + \vec{\ell}^*$ |
| Balance of thermal neutron diffusion at equilibrium | | $D\,\nabla^2\phi - \Sigma_a\,\phi + S = 0$ |
| Diffusion coefficient | | $D$ |
| Macroscopic adsorption cross-section | | $S$ |
| Neutron source | | $\Sigma_a$ |
| Energy cascade component | $\Downarrow$ | $C$ <br> $S = C$ <br> $B_M^2 = \Sigma_a / D$ |
| | $\nabla^2\phi - B_M^2\,\phi + \dfrac{C}{D} = 0$ | |
| Solution | $\phi(\mathbf{r}) = L_c^2\,\sum_{\ell,m,n} \dfrac{c_{\ell,m,n}}{1 + B_{\ell,m,n}^2\,L_c^2} \cdot \dfrac{\phi_{\ell,m,n}(\mathbf{r})}{1 - k_{\ell,m,n}}$ | |
| | | $k_{\ell,m,n} = \frac{k_\infty}{1+L_c^2\,B_{\ell,m,n}^2}$ <br> $c_{\ell,m,n} = \dfrac{1}{D}\,\int_V \psi_{\ell,m,n}(\mathbf{r})\,C(\mathbf{r})\,dV$ <br> $C(\mathbf{r}) = D\,\sum_i c_i\,\psi_i(\mathbf{r})$ |
| Gain | | $G = \dfrac{k}{1-k} \cdot \dfrac{n_s}{n_f}\,\dfrac{E_f}{E_p}$ |

**Figure 2.** Flow graph of the theoretical approach.

The neutron spatial distribution in an accelerator-driven system core can be obtained considering the balance of thermal neutron diffusion at equilibrium [10]:

$$D\,\nabla^2\phi - \Sigma_a\,\phi + S = 0 \tag{1}$$

where $\phi$ is the neutron flux, $\nabla^2$ is the Laplacian operator, $D$ is the diffusion coefficient, $S$ is the neutron source and $\Sigma_a$ is the macroscopic adsorption cross-section. Now, the neutron source can be split in the fission component, $k_\infty\,\Sigma_a\,\phi$, with $k_\infty$ the number of neutrons produced at each adsorption in the target, and in the high energy cascade component, $C$, Equation (1) becomes:

$$\nabla^2 \phi - B_M^2\, \phi + \frac{C}{D} = 0 \tag{2}$$

where $(1 - k_\infty)/L_c^2$ and $L_c = (D/\Sigma_a)^{0.5}$ are named "material buckling" and "neutron diffusion length", respectively.

The solution of Equation (2) can be written as:

$$\phi(\mathbf{r}) = L_c^2 \sum_{\ell,m,n} \frac{c_{\ell,m,n}}{1 + B_{\ell,m,n}^2\, L_c^2} \cdot \frac{\phi_{\ell,m,n}(\mathbf{r})}{1 - k_{\ell,m,n}} \tag{3}$$

where

$$B_{\ell,m,n}^2 = \pi^2 \left( \frac{\ell^2}{a^2} + \frac{m^2}{b^2} + \frac{n^2}{c^2} \right) \tag{4}$$

with $a$, $b$ and $c$ dimensions of a reference parallelepiped geometry with the origin at one edge, such that $\psi(\mathbf{r}) = 0$ for the planes $x = 0$, $x = a$, $y = 0$, $y = b$, $z = 0$ and $z = c$, and

$$\psi_{\ell,m,n}(\mathbf{r}) = \left( \frac{8}{a\,b\,c} \right)^{0.5} \sin\left( \ell\, \frac{\pi\, x}{a} \right) \sin\left( m\, \frac{\pi\, y}{b} \right) \sin\left( n\, \frac{\pi\, z}{c} \right) \tag{5}$$

the eigenvectors of the characteristic wave equation:

$$\nabla^2 \psi - B^2\, \psi = 0 \tag{6}$$

and

$$\begin{aligned} k_{\ell,m,n} &= \frac{k_\infty}{1 + L_c^2\, B_{\ell,m,n}^2} \\ c_{\ell,m,n} &= \frac{1}{D} \int_V \psi_{\ell,m,n}(\mathbf{r})\, C(\mathbf{r})\, dV \\ C(\mathbf{r}) &= D\, \sum_i c_i\, \psi_i(\mathbf{r}) \end{aligned} \tag{7}$$

In an accelerator-driven system, subcritical fission neutrons generated by spallation are multiplied by fissions through a factor $M$, such that the total number of generated neutrons after multiplication results in:

$$N = N_0\, M \tag{8}$$

where $N_0$ is the number of primary incoming neutrons.

From a nuclear technological viewpoint, the use of [$10^2$–$10^3$] keV deuteron beams for (D,T)-reaction allows us to obtain ∼14-MeV mono-energetic neutrons with a related neutron emission of [20–30] neutrons per proton in the range of [0.8–1.0] GeV, with a required beam current of ∼1 mA for a neutron source strength of $\sim 1.6 \times 10^{17}$ n s$^{-1}$. Recently, the possible use of proton accelerators has been shown, obtaining an improvement by an order of magnitude in the beam current.

The measure of releasing neutrons related to absorptions is obtained by the gain quantity, defined as [1,11]:

$$G = \frac{k}{1 - k}\, G_0 \tag{9}$$

where $k$ is the neutron multiplicity of the reactor core in which the spallation target is located as an isotropic point neutron source and $G_0$ is defined as:

$$G_0 = \frac{n_s}{n_f}\, \frac{E_f}{E_p} \tag{10}$$

where $E_p$ is the energy of a proton, $E_f$ is the energy released in the fission reaction, and $n_s$ and $n_f$ denote the neutron yields per proton in spallation and per fission, respectively.

### 2.2. ADS Engineering Design

The engineering design of ADSs is based just on the physical bases of the spallation process, with particular interest in some physical quantities, i.e.,

- Intensity and spatial distribution of the spallation neutron flux outside the target;
- Radiation damage and gas production in target, window and structural materials;
- Radiotoxicity, activity and corrosion problems inside the target;
- Cross sections for the important materials for all possible reaction channels.

These quantities cannot be completely known by experimental measurements, so nuclear reaction models and numerical simulations have been developed, based on nuclear data libraries, theoretical models and Monte Carlo methods.

Moreover, the system dynamics is affected both by the system characteristics and by the spallation neutrons' energy. Due to neutron fluxes' time–space heterogeneity, the usual neutron kinetics models and methods cannot be easily adapted to study ADS dynamics.

Starting from experimental results, the present ADS dynamic analyses have been developed by numerical simulation based on a great number of codes, such as [12] HERMES, HETC, NMTC, NUCLEUS, SHIELD, GEANT4, GEM, JAM, LAQGSM, MARS, TIERCE, BRIEFF, TUL, Exciton pre-equilibrium decay model and Fermi break-up model, KENO-Va, ALICE, LANCELOT, LILITA, PACE, LCU and FLUKA.

In this context, some considerations of the physical basis of the spallation process must be introduced.

### 2.3. Spallation Phenomenon: Numerical Codes

In 1930, the experimental study of particle cascades in cosmic ray interactions highlighted the evidence of the spallation phenomenon. Spallation is a nuclear process in which a light, but highly energetic, projectile interacts with a heavy nucleus, causing the emission of neutrons and other hadrons [13].

In 1937, V. Weisskopf [14] introduced the hypothesis of the neutron emission from exited nuclei, while, in 1947, R. Serber proposed a theoretical model for the evaluation of the energy lost in the collision of particles ($\geq$200 MeV energy) with nuclei [15]. At the end of the 1950s, Metropolis and Dostrovsky [16–19], improving these previous results, introduced the Monte Carlo method in the analysis of spallation with a model based on two different steps:

1. Energy deposition, a non-equilibrated process that causes intra-nuclear cascade reactions in a time of the order of $10^{-22}$ s, generating excitation of the nucleus in thermodynamic equilibrium ($\sim$MeV nucleon$^{-1}$);
2. Related evaporation, concerning the de-excitation of nuclei in a time range $[10^{-18}$–$10^{-16}]$ s.

These two processes generate isotropic multi-fragmentation and fission: related fission reactions have a negligible probability to be caused by the spallation neutrons [13].

The interest in these neutrons concerns their possible use in ADSs concerning the transmutation of long-life radioactive nuclear waste. Indeed, these neutrons can be multiplied in a subcritical core, causing simultaneous fissions of minor actinides into short-lived or stable nuclei. The ADS system can be realised by coupling a subcritical reactor to a particle accelerator [6].

The physical description of this process can be developed by the simulation time-like model INCL4 [12] coupled to the evaporation–fission model ABLA07 [20], obtaining a good description of the available spallation data for an incident energy range [0.2–3.0] GeV.

Now, we wish to highlight the theoretical foundations of the INCL4 model, based on nuclear transport theories [21–23]. The standard Liège intranuclear cascade (INC) model assumes that the collision mechanism proceeds from a succession of binary collisions and decays well separated in space and time, which define the time evolution of the process. The approach considers the following steps [24]:

- Initial positions of target nucleons are taken at random in the spherical nuclear target volume with a sharp surface;
- Initial momenta are generated stochastically in a Fermi sphere;
- Relativistic kinematics is used;
- Inelastic collisions, pion production and absorption are supposed to proceed from the following reactions:

$$NN \rightleftarrows N\Delta$$

$$\Delta \rightleftarrows \pi N$$

- Isospin degrees of freedom are introduced for all types of particles and isospin symmetry is respected;
- The Pauli principle is enforced using statistical blocking factors.

Moreover, a diffuse nuclear surface is considered up to a maximum distance $R_{max} = R_0 + 8a$, where $R_0 = (2.745 \times 10^{-4} \cdot A_T + 1.063) \cdot A^{1/3} \times 10^{-15}$ m and $a = (0.510 + 1.63 \times 10^{-14} \cdot A_T) \times 10^{-15}$ m, with $A_T$ the target mass number, obtaining the following relation corresponding to a Saxon–Woods density distribution (spatial density $\rho(\mathbf{r})$) [24]:

$$\rho(r) = \begin{cases} \dfrac{\rho_0\, e^{-(r-R_0)/a}}{1 + e^{-(r-R_0)/a}} & r < R_{max} \\ 0 & r > R_{max} \end{cases} \tag{11}$$

where $\rho_0$ allows the distribution to be normalised to $A_T$. From this result, the joint probability distribution, $f(\mathbf{r}, \mathbf{p})$, can be obtained as follows [24]:

$$\int d^3p\, f(\mathbf{r}, \mathbf{p}) = \rho(\mathbf{r}) \tag{12}$$

and

$$\int d^3r\, f(\mathbf{r}, \mathbf{p}) = A_T \left(\frac{4}{3}\pi p_F^3\right)^{-1} \theta(p_F - p) \tag{13}$$

where the second member of the relation is the sharp Fermi sphere momentum distribution with $p_F$ Fermi momentum [25] and $\theta$ Heaviside function [26]. In this approach, Pauli blocking has been introduced to consider only collisions with final states in which the nucleon momenta are all above the Fermi momentum, but it is not applied to $\Delta$ resonance due to its small probability density. So, the phase-space occupation probabilities, $f_i$, of a nucleon $i$, with position $\mathbf{r}_i$ and momentum $\mathbf{p}_i$, which interact with a nucleon $j$, are evaluated as follows [24]:

$$f_i = \frac{1}{2}(2\pi\hbar)^3 \left(\frac{4\pi}{3} r_{PB}\right)^{-3} \left(\frac{4\pi}{3} p_{PB}\right)^{-3} \sum_{k \neq i} \theta\Big(r_{PB} - |\mathbf{r}_k - \mathbf{r}_i|\Big) \cdot \theta\Big(p_{PB} - |\mathbf{p}_k - \mathbf{p}_i|\Big) \tag{14}$$

where $r_{PB} = 3.18$ fm and $p_{PB} = 200$ MeV c$^{-1}$, the sum is performed for all the particles, $k$, with the same isospin component, and $1/2$ is introduced in order to consider that spin components are not included in the evaluation. The collision between the $i$-th and $j$-th particle is allowed or forbidden by comparing a random number with the product $(1 - f_i) \cdot (1 - f_j)$.

In the model is introduced the conservation law in the laboratory system for:

- The mass number $A$:

$$A_P + A_T = A_{ej} + A_\pi + A_{rem} \tag{15}$$

where the suffixes $P$, $T$, $ej$, $\pi$ and $rem$ mean projectile, target, ejectiles, pion and remnant (remaining part of the target up to the end of the cascade, and the residue at the end of the evaporation process), respectively;

- The atomic number $Z$:
$$Z_P + Z_T = Z_{ej} + Z_\pi + Z_{rem} \tag{16}$$
- The energy $E$:
$$E_{lab} = E_{kin,ej} + E_{t,\pi} + E_{rec} + E^* + E_{sep} \tag{17}$$
where $lab$, $kin$, $t$, $rec$, $*$ and $sep$ mean laboratory, kinetic, total, recovery, excitation and separation, respectively;
- The momentum $\mathbf{p}$:
$$\mathbf{p}_{lab} = \mathbf{p}_{ej} + \mathbf{p}_\pi + \mathbf{p}_{rem} \tag{18}$$
- The angular momentum $\vec{\ell}$:
$$\vec{\ell}_{lab} = \vec{\ell}_{ej} + \vec{\ell}_\pi + \vec{\ell}_{rem} + \vec{\ell}^* \tag{19}$$

The INC model considers no interaction between particles (baryons) outside the potential well and with the remnant. So, the previous energy balance equation is evaluated as follows [24]:

$$E_{lab} = \sum_{j=1}^{A_{ej}} \bar{E}_j + E_{t,\pi} + \sum_{i \in A_{rem}} \bar{E}_i - \sum_{i \in A_T} T_i^0 - \left(A_T - A_{rem}\right) T_F + \left(A_T - A_{rem}\right) \cdot \left(V_0 - E_F\right) \tag{20}$$

where $E_F$ is the Fermi kinetic energy.

The INC model is calculated by a numerical code, called INCL4 [12], in which the stopping time is evaluated as:

$$t_{stop} = 70 \left(\frac{A_T}{208}\right)^{0.16} \tag{21}$$

In INCL4, there results a free parameter, $V_0$, which is usually chosen to be 45 MeV in standard interactions [12,24].

INCL4 is coupled with the ABLA07 code, which is a dynamical code that describes the de-excitation of the thermalised system by simultaneous cracking of hot nuclei into several fragments caused by thermal instabilities, particle emission and fission. The evaporation process is developed based on the Weisskopf–Ewing theory [27], and the fission decay width is evaluated from dynamical effects [28]. The ABLA07 code is deeply described and analysed in ref. [20].

## 3. Overview Features on ADS

This review proposes an overview of a possible alternative approach to nuclear energy production, developing a summary of a historical and phenomenological basis of the physical processes for the accelerator-driven system's design. In Table 1, some European ADSs are presented in relation to the context of this overview.

**Table 1.** Parameters of three European facilities from ref. [29] and adapted by the authors.

| Parameters | MYRRHA | XT-ADS | EFIT |
|---|---|---|---|
| Result | Concept demonstration | Prototype Transmuter | Maximum transmutation efficiency |
| Accelerator type | LINAC | LINAC | LINAC |
| Proton energy [MeV] | 350 | 600 | 800 |
| Current intensity [mA] | 5 | 2.5 | 20 |
| Target | Pb-Bi | Pb-Bi | Pb |
| Core power [$MW_{th}$] | 50 | 57 | 100 |

MYRRHA = Multi-purpose hYbridResearch Reactor for High-tech Applications; XT-ADS = eXperimental facility for demonstration of the technical feasibility of Transmutation in ADS; EFIT = European Facility for Industrial Transmutation.

The use of ADSs offers a great number of advantages, e.g.,

- Greater flexibility concerning fuel composition: it is possible to use non-fissile fuels such as thorium, without including uranium or plutonium, usually used in nuclear fission reactors;
- Potentially enhanced safety: when the accelerator is switched off, the system shuts off; indeed, in an ADS, the power control is achieved through the control only of the beam current, so when the beam is absent the ADS cannot independently support the nuclear reaction [30];
- Waste management support: obtaining transmutation of selected isotopes in radioactive waste to reduce their burden on geological storage;
- Energy production;
- Process heat generation: the ADS as a facility for transmutation of waste also generates process heat of the order of kW $cm^{-3}$ [11] (10–75 MW beam power is required [31]), which could be utilised to produce another form of energy (e.g., biofuels) or could be used to generate electrical power [31];
- Nuclear materials production for other nuclear plants.

On the contrary, they present some critical issues, too; indeed, the beam window and targets are stressed, irradiated and corroded, increasing the difficulty of the final installation. Additionally, the accelerator use reduces the plant's electrical efficiency. Consequently, accelerator-driven systems' potential requires further technological advancements, which can be achieved through a technology pathway that will include:

- The transmutation demonstration, in which ADSs and transmutation technologies are demonstrated in research facilities with a subcritical core and proton accelerator of MW-scale (i.e., accelerators that allow us to obtain proton beams of the order of some MW power);
- Industrial-scale transmutation of radioactive waste. Indeed, the transmutation goal is to obtain nuclear waste from long-life time to radiologically harmless in only a few hundred years. But, some barriers are present in the usual transmutation processes in industry, i.e.,
  - This nuclear process is not feasible for all of the waste produced in usual nuclear plants;
  - It can reduce waste quantities, but it cannot eliminate the need for ultimate nuclear waste disposal;
- A power generation facility at an industrial scale that makes use of energy storage technology;
- Industrial-scale power generation as an essential component of the electric grid and uses either thorium-based or transuranic fuel.

Consequently, the advantages of accelerator-driven systems must be balanced with the critical issues concerning their technology. However, they represent an innovative and short-term approach to the environmental problems for sustainable energy generation.

In this review, we have summarised the physical bases useful for designing the ADS, with particular regards to the INCL4 model. In Table 2, the results reported in ref. [24], and adapted to this paper, on the numerical simulation obtained using INCL4 are compared with the experimental data obtained on neutron multiplicities in proton-induced reactions on Pb nuclei, showing an interesting agreement of simulation with respect to the experimental results.

**Table 2.** Comparison between INCL4 model results and experimental data on neutron multiplicities in proton-induced reactions on Pb nuclei. Data collected from ref. [24] and adapted to this review by the authors.

| Neutron Energy [MeV] | Experimental Results | INCL4 Model Results |
|---|---|---|
| Pb target nucleus, 0.8 GeV p kinetic energy in lab reference frame | | |
| 0–2 | | 3.3 |
| 2–20 | 6.5 ± 1.0 | 6.8 |
| 20 | 1.9 ± 0.2 | 2.5 |
| Total | 12.5 | 14.0 |
| Pb target nucleus, 1.2 GeV p kinetic energy in lab reference frame | | |
| 0–2 | | 3.4 |
| 2–20 | 8.3 ± 1.0 | |
| 20 | 2.7 ± 0.3 | 3.1 |
| Total | 14.7 | 17.4 |

## 4. Discussion

In the last few years, the interest in nuclear energy generation has continuously grown as a possible answer for the request for energy and the reduction of $CO_{2eq}$ emissions. However, the public acceptance of nuclear systems for large-scale energy generation depends on the possible answers to address some requirements:

- Economy;
- Safety;
- Adequacy of natural resources;
- Waste reduction.

This last requirement is crucial in light of the long lifetime of radioactive waste from the nuclear fuel cycle. On the other hand, nuclear fusion reactors are still in a preliminary stage and will be used for industrial applications after 2050. In the meantime, a mix of energy generation represents an effective approach to $CO_2$ emission reduction.

Accelerator-driven systems could represent one of the possible energy generation systems, based on technologies for the partitioning and transmutation of actinides and long-lived fission products, with the opportunity of reducing the radiotoxicity and the volume of the high-level waste in comparison with the conventional nuclear fuel cycles (with radioactive hazard to life—if released into the environment—from irradiated nuclear fuel as plutonium, neptunium, americium, curium, iodine and technetium). Indeed, partitioning and transmutation represent a possible approach to reduce the present volume and cost of storage of nuclear waste from conventional nuclear fission plants and their associated residual heat.

The fuels used in accelerator-driven systems are mostly thorium, which in nature does not present fissile isotopes, and transuranic elements, which are produced by neutron capture in $^{238}$U. The use of thorium requires transmutation of $^{232}$Th into a fissile isotope of uranium

$$
\begin{array}{l}
{}^{238}_{92}\mathrm{U} + \mathrm{n} \rightarrow {}^{239}_{92}\,\mathrm{U} \rightarrow {}^{239}_{93}\,\mathrm{Np} + \beta^- \\
\qquad\qquad\qquad\qquad\qquad\searrow \\
\qquad\qquad\qquad\qquad\qquad\quad {}^{239}_{94}\mathrm{Pu} + \beta^- \\
{}^{232}_{90}\mathrm{Th} + \mathrm{n} \rightarrow {}^{233}_{90}\,\mathrm{Th} \rightarrow {}^{233}_{90}\,\mathrm{Pa} + \beta^- \\
\qquad\qquad\qquad\qquad\qquad\searrow \\
\qquad\qquad\qquad\qquad\qquad\quad {}^{233}_{92}\mathrm{U} + \beta^-
\end{array}
$$

There are two different technological implements for these cases:

- The spallation target can be blanketed by a thorium fuel mass, where the emitted neutrons can be absorbed to produce the transmutation of thorium into uranium.

Then, the target, enriched in uranium, is removed for chemical processing in order to use it in the reactor. This system is energy dependent on an external electrical grid;
- The spallation target can be laced in a subcritical neutron-multiplying reactor containing both fissile material and thorium. This solution allows us to obtain energy amplification in the accelerator-driven system, obtaining a device that is energy independent from an external grid.

From a technological viewpoint, there are two types of proton accelerators that can be involved in accelerator-driven systems: the proton cyclotron and the proton linear accelerator. They do not require new scientific principles to evolve but need only consolidation of technologies for this energy generation use; indeed, today, accelerator technology is very consolidated [11], and the two types of particle accelerators used for accelerator-driven systems can be summarized as follows:

- Cyclotron, which is an inherently continuous wave beam current accelerator, ideally suitable for accelerator-driven systems. The idea of the cyclotron was first formulated in 1927 by Max Steenbeck and realised in 1928–1929 by Leo Szilárd, who first introduced the resonance condition, now named cyclotron frequency. In 1929, Ernest Lawrence, assisted by Milton Stanley Livingston, independently developed the design of a cyclotron, using large electromagnets: this cyclotron, with a diameter of 11 cm and a proton energy of 80 keV, started its activity in January 1931. In acceleration-driven systems, the cyclotron occupies a size of the same order as a nuclear reactor complex. This requirement represents a limitation due to the maximum beam current needed. Designs of separated sector cyclotrons were proposed to achieve a 10 MW beam power, being an upper limit for this kind of particle accelerator, which can reach 1 GeV;
- Linear particle accelerator (LINAC), which was designed for pulsed beam current operation. The concept of LINAC was first introduced in 1924 by Gustav Ising, who used a series of accelerating gaps. In 1927, following Ising's results, Rolf Wideroe built a 224 cm long accelerator, using a 25 kV vacuum tube oscillator, with the effect of having accelerated sodium and potassium ions to 50 keV. Today, proton energy of 1 GeV or more can be easily obtained, producing a 100 mA beam current. However, for conserving the electrical efficiency related to input electrical power, superconducting radio-frequency cavities at liquid helium temperature are required in most parts of the accelerator, with difficulty related to this technological complexity.

However, up to now, no accelerator-driven system has been built for industrial use, even if the European Union, United States, Japan, etc., have supported long-term policies for their development [30,32–38], carrying out specific nuclear waste research. In the future, the dead-time for oil and coal will be near and the development of natural gas and hydro-power will be relatively stable [39–46], whereas the growth of nuclear power and renewable energy will be relatively fast. In the energy context, accelerator-driven systems could represent another renewable low-carbon clean energy source, useful for a great number of applications.

## 5. Conclusions

The increase in the use of clean energy is a topic of fundamental importance for sustainability, and it plays a central role in providing answers to environmental and energy-related issues. In this context, nuclear energy represents one of the possible technical solutions to address the requirements of more sustainable energy production. However, concerning nuclear fission plants, the difficulties regarding safety and nuclear waste must be considered, while, for nuclear fusion reactors, studies are obtaining significant results, but their industrial use not occur for two or three decades.

In the context of power production from nuclear systems, another nuclear technology is represented by accelerator-driven systems (ADSs), which are external source-driven subcritical nuclear reactors characterised by a high neutron redundancy and subcritical safety and are driven by a proton accelerator to inflow proton beams into heavy metal targets to produce spallation neutrons. These systems can be used for energy generation, transmutation and neutron sources, but also as tritium sources, with tritium being the principal fuel for nuclear fusion reactors.

In this review, we have summarised the physical bases of these systems, with particular regard to spallation phenomena and transmutation. We have also discussed the possible use of these nuclear devices, which show a possible new approach to nuclear energy, based on the developments achieved by accelerator physics during the last 100 years.

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