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Some parameters and conditions defining the efficiency of burners in the destruction of long-lived nuclear wastes

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Abstract. A number of new wordings and statements regarding the targeted problem of destruction of long-lived wastes (transmutation) is considered. Some new criteria concerning the efficiency of a particular burner type are proposed. It is shown that the destruction efficiency of a specific burner is greatly influenced by the prospective time period of the whole destruction process.

Keywords. Long-lived wastes; burner; transmutation efficiency; transmutation period.

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1. Introduction

One widely discussed method to resolve the problem of long-lived wastes (LLW) is their destruction (transmutation) by means of transmuting into fission products via irradiation in special burners, namely, in the blankets of ADS. Various views, often quite opposite, regarding the most efficient type of burners are being proposed and debated [1–3]. In particular, if such burners should be systems of fast or thermal spectrum, arguments of either burner type proponents do not satisfy their opponents whatsoever, and till now no common point of view concerning this issue is elaborated.

In the author's opinion, such a situation is the logical consequence of the fact that there is no fully formulated problem of destruction. Most interestingly, proponents of quite opposite approaches turn out to be, by essence, absolutely right in their own sense.

Some formulations and notions are proposed which could underlie in general statements of such problem. Also, some new parameters of burner efficiency are proposed to destroy the LLW. In the author's opinion, accounting for these proposals could help eliminate the ambiguity of solution in assessing the final route to be chosen for destroying LLW.

2. Main notions and definitions

Initial LLW – mass of long-lived transuraniums (TRU) of a certain isotopic composition formed as a result of nuclear energy activity and involved in the process of destruction.

LLW destruction – transmuting into fission products through irradiation in multiplying fission systems, commonly referred to as burners.

Final LLW – mass of all TRU (i.e., both initial LLW and TRU formed during initial LLW irradiations) remaining after the completion of destruction process.

Destruction depth – ratio of destroyed LLW mass to initial LLW mass (percentage of initial LLW destroyed).

Ecologic gain – ratio of the ecologic threat level of initial LLW to that of final LLW. Ecologic threat level of LLW may be characterized, for example, by their radio-toxicity.

Destruction strategy choice – choice of the burner type and selection of optimum fuel cycle for the chosen type of burner.

Process inlet – mass of initial LLW meant to be destroyed.

Process goal – reaching the destruction depth that will provide ecologic gain value not lower than some of the given ones.

Process parameters – duration of the process and the required external fission isotopes for consumption.

Process efficiency – goal accomplishing with reasonable values of process parameters. The notion 'reasonable parameter value' is, in general, rather indefinite and its meaning may vary with the conditions of a specific destroying problem.

Burner basic fuel cycle – equilibrium cycle with all destruction period time-constant, composition of the feed-fuel consisting of initial LLW alone by adding external fissile isotopes, if necessary.

Burner optimized fuel cycle – non-equilibrium cycle whose composition of the feed fuel is time-dependent and aimed at increasing the burner destruction efficiency. Initial LLW to be destroyed contain some fissile isotopes (mainly Pu) and some non-fissile isotopes (mainly minor actinides (MA)) in a certain proportion. One of the possible means to optimize transmutation process is timely varying the proportion of fissile and non-fissile isotopes in the feed fuel so that by the end of the process both from the initial LLW are destroyed.

3. LLW Self-destruction potential

In a specific burner's conditions initial LLW possess a self-destruction potential, i.e. potential defining the extent of their ability to be destroyed all by themselves, without the involvement of the external fission isotopes.

The potential is determined by neutron balance equation for a burner in the basic fuel cycle

$$v_{\mathrm{f}}\eta_{\mathrm{a}} = k_{\mathrm{eff}}(1 + \delta^{\mathrm{p}} + \delta^{\mathrm{l}}),$$

where v_{f} is the number of TRU fission neutrons per one fission in TRU, η_{a} is the fraction of fissions of TRU absorptions, δ^{p} is the number of neutron in parasitic absorptions per TRU absorption, δ^{l} is the number of leakage neutrons per number of TRU absorptions and k_{eff} is the eigenvalue of the system.

Numerically, the potential is expressed by the relation,

$$P = v_{\mathrm{f}}\eta_{\mathrm{a}}$$

i.e. physically the fraction of neutrons potentially available to compensate for leakage and parasitic absorptions.

Physical and construction characteristics of the burner core define some minimally possible values of the system's combined leakage and parasitic absorption – $(\delta^{\mathrm{p}} + \delta^{\mathrm{l}})_{\mathrm{min}}$, and qualitatively the potential is characterized as

- *insufficient* – $P < (\delta^{\mathrm{p}} + \delta^{\mathrm{l}})_{\mathrm{min}}$;
- *sufficient* – $P \geq (\delta^{\mathrm{p}} + \delta^{\mathrm{l}})_{\mathrm{min}}$.

In the latter case the potentials are defined as

- *necessary* – $P \approx (\delta^{\mathrm{p}} + \delta^{\mathrm{l}})_{\mathrm{min}}$;
- *surplus* – $P > (\delta^{\mathrm{p}} + \delta^{\mathrm{l}})_{\mathrm{min}}$.

4. Mean destruction time of LLW

Self-destruction potential is defined mainly by the η_{a}-value, i.e. the number of successive neutron absorptions in the chain of TRU transformations initiated by the initial LLW, from LLW loading in the burner's cycle to the act of the final isotope in the chain fission including the TRU fission.

The time in which η_{a} successive absorptions take place, is the mean destruction time of LLW, i.e., the length of the time from the moment the initial LLW has been loaded in the system cycle to the moment of initial LLW destruction (the final TRU in its transformation chain is fissioned), and it is to be determined from the following balance relation:

$$\tau = \frac{G_{\mathrm{c}}}{q},$$

where G_{c} (in tons) is the TRU inventory in the burner's total fuel cycle and q (in tons/year) is the initial LLW feeding rate.

With the given external fuel cycle parameters: q_{p} (t/yr) is the TRU reprocessing rate; x_{loss} is the fraction of the processing losses (fraction of TRU lost during fuel reprocessing).

Mean destruction time of LLW establishes the relation between destruction depth d and the duration of destruction process t.

Initial TRU mass loaded in the cycle by time $t = G_{\rm c} + \frac{G_{\rm c}}{\tau} \times t$.

TRU mass in the cycle at time $t = G_{\rm c}$.

Mass of TRU losses committed by time $t = q_{\rm p} x_{\rm loss} \times t = \frac{G_{\rm c} x_{\rm loss}}{\tau_{\rm p}} \times t$

where $\tau_{\rm p}$ is the time between two successive reprocessing of TRU.

Destruction depth at the time t is,

$$d(t) = \frac{G_{\rm c} + G_{\rm c}/\tau \times t - G_{\rm c} - G_{\rm c} x_{\rm loss}/\tau_{\rm p} \times t}{G_{\rm c} + G_{\rm c}/\tau \times t} = 1 - \frac{1 + \frac{x_{\rm loss}}{\tau_{\rm p}} \times t}{1 + \frac{1}{\tau} \times t}.$$

In the author's opinion the parameters P and τ are the main characteristics of the burner efficiency in destroying LLW.

Less is the mean destruction time of LLW more is the destruction depth achieved for a given destruction process period, or less is the time required for achieving the given destruction depth.

For the destruction process length, $t \ll \tau_{\rm p}/x_{\rm loss}$, i.e., under the condition $q_{\rm p} x_{\rm loss} \times t \ll G_{\rm c}$ (committed loss mass much less than TRU inventory in the cycle),

$$d(t) = \frac{1}{1 + (\tau/t)}. \tag{1}$$

For the length of destruction process, $t \gg \tau$ (mass of destroyed TRU much more than TRU inventory in the cycle)

$$d(t) = 1 - \frac{\tau}{\tau_{\rm p}} \times x_{\rm loss}.$$

More is the self-destruction potential less is the consumption of the required external fissile isotopes and more is the freedom in optimizing the burner fuel cycle.

For all burner types, the general tendency is that the increase of consumption of external isotopes leads to a decrease in mean destruction time of LLW. Optimizing burner fuel cycle is, in essence, the selection of an optimal relationship between these two quantities and such an optimal relationship can be taken for the whole destruction period time, or can be different for different stages of destruction process.

- Should the potential be sufficient for the destruction to be carried out in the burner basic cycle with the initial LLW feeding and without any external fissile isotopes involving? Should the mean destruction time be unacceptably high so that cycle optimization could be practiced by adding the external isotopes and may be useful as content in the varying feed fuel time?
- Should the potential be surplus for the destruction to be carried out in the burner equilibrium fuel cycle with the initial LLW feeding and without any external fissile isotopes involving? At that the surplus 'spare' neutrons increase the leakage and parasitic absorption which implies decreasing TRU inventory and respectively the mean destruction time. The latter is the main advantage of surplus potential over the sufficient one. In addition, the former provides one more way for the fuel cycle optimization. The fraction of fissile elements in the initial LLW composition can be reduced in the feed fuel to

the level of sufficient potential on the earlier stages of the destruction process and can be increased to the level even higher than that in the initial LLW composition on the final stages. That is to say that if the 'spare' neutrons were removed from the earlier stages of the process it can be used in the final ones. This allows the inventory at the end of the process decreasing, thus, increasing the destruction depth. Clearly, cycle optimization could also be practiced, if necessary, using the external fissile isotopes.

- Should the potential be insufficient and the initial LLW composition must be enriched at least up to sufficient potential level by adding the external fissile isotopes? Then cycle optimization could be carried out in a way analogous to the case of TRU sufficient potential.

5. Destruction depth and process period

As noted, the notion 'reasonable value' for the parameters is rather indefinite in general. Nevertheless, some qualitative estimates of the domain of the reasonability for several relevant parameters can be made with a certain degree of validity.

Destruction depth. It appears that increasing the destruction depth higher than the level at which the TRU inventories are less than the mass of committed TRU losses would not be reasonable, since this does not lead to the further increase of ecologic gain. On the basis of current knowledge regarding the possible extent of processing loss values it seems that taking the destruction depth goal value as $d \sim 0.95$ would be quite reasonable.

'Reasonableness' of the destruction period is defined, primarily, by the lifetime of the initial LLW source.

The source of initial LLW is a certain type of reactor installation.

Accounting for such system inertia, it seems appropriate to assume that a certain LLW source will continue to exist during ∼100–150 years. Affirmation that this source will be existing much longer would seem to be excessively categorical.

It is reasonable to assume that after the LLW source stops, that is, after decommissioning all reactors producing this type of LLW, the LLW destruction should be completed not more than 1–2 lifetimes of installations used for destruction, i.e. during ∼50–100 years.

Thus, if the destruction of LLW produced by the source starts after the source stops working, then the reasonable destruction period value appears to be ∼50–100 years. If destruction is to start during the source's existence, then the reasonable destruction period seems to be ∼100–50 years.

6. Blanket spectrum and process period

Spectrum type determines the possible domain of the destruction potential values and the mean destruction time. The harder the spectrum, higher is the destruction potential value and higher is the mean destruction time. In particular, installations with fast spectrum possess, when compared with thermal spectrum installations, much greater destruction potential values. However, at the same time, the mean destruction time in fast spectrum systems are about 10 times higher.

From relation (1), one may see that destruction depth $d \sim 0.95$ is accomplished in time $t \sim 20\tau$. For reasonable destruction process periods, it means that the installations have to have mean destruction times not more than $\tau \sim 7$ years.

In the thermal spectrum systems with the high flux level it is possible, in principle, to reach such mean destruction time values for MA from PWR destruction. True, it is accompanied by a significantly lowered destruction potential, which requires relatively high external fissile isotopes consumption.

In the fast spectrum installations, the mean destruction time values are, as a rule, more than 10 times higher than those required, and achieving in them the reasonable destruction depth for a reasonable destruction process period is hardly possible in principle. It is not obvious that optimization of their fuel cycles, even with external fissile isotopes involving, could help achieve this goal. In any case, the fast system proponents have to demonstrate the possibility of accomplishing the goal, and, if it is possible, what will be the price, that is, the quantities of external fissile isotopes, inevitably being involved.

7. Conclusion

In the author's opinion the cause of ambiguity in evaluating the spectrum type efficiency lies in the fact that there is an absence of proper formulation of full destruction.

The traditional form of posing the question 'In which spectrum the destruction of LLW is most efficient? is not correct. It is necessary to elaborate, what scale of period of destruction process is in question – whether it is one–two hundreds of years, or whether a great many hundreds of years?

Without pretending to be categorical, resting only on the quality considerations and accounting for the necessary elaboration, the author gives his own answer to this question.

- For the period $t \sim 100$–150 years, the thermal spectrum with high flux level is not only the most effective one, but, apparently, that is the only possibility. The consumption of great external isotopes is the necessary price because systems with higher destruction potential are in principle, unable to achieve a reasonable destruction depth for such a range of periods.
- For the periods $t > 500$–600 years the most effective, *a priori*, is the fast spectrum. The required destruction depth may be achieved with the minimal, if any, consumption of external fissile isotopes.
- For the intermediate range of periods, there is no *a priori* answer. The fast spectrum systems may achieve the required depth by using the fuel cycles which involve external fissile isotopes. In the thermal systems, consumption of the external fissile isotopes may be significantly reduced compared to that for the period $t \sim 100$–150 years. Type of the spectrum based on analyzing the external fissile isotopes to be consumed in systems of different spectrum types has to be chosen.

Author notes that his conclusion is based only on the quality considerations and he assumes that the detailed analysis of destruction using the characteristics of the specific system of different spectrums might somewhat vary the time limits of the above time diapasons of destruction process. At this, the author is sure that no principal changes will be followed and hopes that the work's main finding, i.e. the presence of direct dependency between the spectrum type efficiency and the duration of the whole destruction process of LLW will be considered in the future discussions regarding the optimal type of the system for choosing the destruction of LLW.

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