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# APTITUDE A BRULER LE PLUTONIUM ET LES ACTINIDES MINEURS. INTERET D'UN SYSTEME PILOTE PAR ACCELERATEUR PAR RAPPORT A UN REACTEUR CRITIQUE

## *ABILITY TO BURN PLUTONIUM AND MINOR ACTINIDES. INTEREST OF ACCELERATOR DRIVEN SYSTEM COMPARED TO CRITICAL REACTOR*

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EDF
Electricité
de France

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## SYNTHÈSE :

Dans le cadre de la loi française de décembre 1991, EDF est actuellement en train d'évaluer l'intérêt d'un système piloté par accélérateur (ADS) pour la transmutation du plutonium et des actinides mineurs produits par son parc de réacteurs nucléaires.

Les études présentées ici évaluent l'efficacité des ADS et des réacteurs critiques dans l'incinération du Pu et des MA, et l'intérêt éventuel des ADS pour cet usage.

## EXECUTIVE SUMMARY :

In the frame of the French Act of December (1991 ~~law~~), EDF is presently assessing the interest of Acceleration Driven System (ADS) for the Transmutation of the Plutonium and Minor Actinides (MA) produced by its park of nuclear reactors.

The studies presented here assess the efficiency of ADS and critical reactors to incinerate Pu and MA (Minor Actinides) and the potential interest of ADS for that purpose.

## ABILITY TO BURN PLUTONIUM AND MINOR ACTINIDES

# INTEREST OF ACCELERATOR DRIVEN SYSTEM (ADS) COMPARED TO CRITICAL REACTOR

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## I. ABSTRACT

In the frame of the French December 1991 law, EDF is presently assessing the interest of ADS for the Transmutation of the Plutonium and Minor Actinides (MA) produced by its park of nuclear reactors.

The studies presented here assess the efficiency of ADS and critical reactors to incinerate Pu and MA and the potential interest of ADS for that purpose.

## II. INTRODUCTION

The aim of a P&T strategy is to reduce the radioactivity of long live nuclear wastes. The transmutation is obtained by neutron irradiation in critical or subcritical reactor.

Two reactions take place :

- captures which produce another heavy nuclei with a different radioactive period but with an average activity on the long term, close to the initial heavy nuclei.
- fissions which produce fission products with an activity after three centuries much lower than the one of the initial nuclei

So, only fissions can reduce significantly the activity of the long live nuclear wastes.

## III. LIMIT OF THE PU AND M.A. BURNING CAPACITY

Because the fission energy of all heavy nuclei (U, Pu and M.A.) is close to 200 MeV, the total mass of fissionned heavy nuclei depends on the thermal energy generation of the plant. So it is nearly 45 kg/TWh (thermal) and remains constant whatever system is considered.

But the fissionned nuclei are not the same according to the fuel types and reactors.

So we have compared the fissionned masses for two types of fuel burned in present critical reactors : PWR and FBR. The fuels differ by the support : fertile uranium or inert material matrix.

Table 1 summarizes the main results of the comparison.

The previous average of 45 kg/TWh is thus confirmed. When present, U238 generates by capture new Pu 239 which counterbalances the Pu+M.A. fissionned mass. The use of an inert matrix could avoid this phenomena and would allow to burn twice more Pu+M.A.

Unfortunately the safety margins of a critical reactor loaded only with Pu and M.A. fuels would be strongly reduced.

Such a critical reactor with only inert matrix fuel, would be very difficult to design and to operate.

Table 1 : (Consumption : negative values, production : positive values)

| Reactor type fuel type | PWR enriched uranium | PWR MOX | FBR MOX | PWR target |
|---|---|---|---|---|
| Support | | Depleted Uranium | Depleted Uranium | Inert Matrix |
| Burn up | 50 GWd/t | 50 GWd/t | 135 GWd/t | 25 GWd/t |
| Mass variation in kg/TWh (thermal) | | | | |
| U235 | -31.4 | -0;8 | -0.4 | 0.0 |
| U238 | -29.5 | -25.8 | -38.6 | 0.0 |
| **U Total** | **-55.8** | **-26.4** | **-38.9** | **0.0** |
| Pu Total | 10.5 | -23.3 | -7.6 | -42.1 |
| M.A. Total | 1.0 | 5.0 | 1.5 | 0.6 |
| **Total Pu+M.A.** | **11.5** | **-18.3** | **-6.1** | **-41.5** |
| **TOTAL** | **-44.3** | **-44.8** | **-45.0** | **-41.5** |

## IV. INTEREST OF THE ADS TO INCREASE THE EFFICIENCY OF PU+M.A. INCINERATION

### A. Burning rate

A subcritical ADS with a keff ~ 0,9 could operate with sufficient safety margins and therefore allow to use inert matrix fuel without uranium. So it could reach the maximum burning rate of 45 kg/TWh (thermal).

### B. Electrical power balance of an ADS

The total thermal power of an ADS is the sum of the power of the spallation reactions in the target and of the fission reactions in the subcritical reactor. The calculation shows that the spallation power is very close to the proton beam power.

The ratio between the proton beam power and the total thermal power of the ADS, noted f, is given by Mariane UEMATSU (ref. 1) :

$$\boxed{f = A_f * (\frac{1}{keff} - 1)} \quad \text{Equation 1}$$

where : keff is the multiplication factor of the subcritical reactor and $A_f$ a function of the characteristics of the system (proton beam energy, material of the target, type of fuel) calculated for each project. A current value is close to 1,5.

With keff=0.9 and $A_f$=1.5, f is thus equal to 0.17.

In these conditions the fission power represents 83 % of the total thermal power of the ADS, which is also the ratio between the fissionned mass in an ADS and a critical reactor with the same total thermal power.

The ratio between the proton beam power and the supply of electrical power for the accelerator is far from one. So the electrical supply needs for the accelerator lead to two important penalties for the economy of the system. For the same electrical power available on the grid :

*a) the total power of the ADS increases*
In comparison with a critical system the total electrical power of an ADS could be 50 % higher with a strong subcriticality (keff ~ 0,9).

*b) the fissile material utilization decreases*
In the same conditions, consumption of fissile material is 20 % more important.

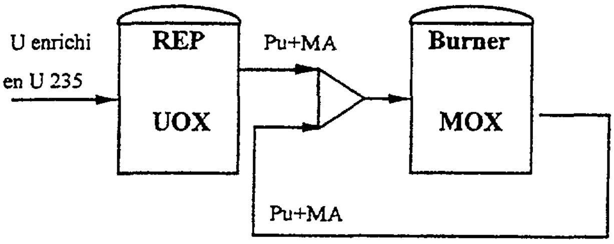
## V. THE THREE PHASES OF A PU AND M.A. LIMITATION SCENARIO

To evaluate the efficiency of the strategy of Pu and M.A. burning, we first analyse the dynamics of all the Pu and M.A. burning scenarios.

### A. Description of fuel cycle scenarios

To simplify the presentation, we have simulated a scenario with a multirecycling of all the plutonium and all the M.A. coming from the reprocessing of used fuels, in burner plants. The electrical power remains constant for the park of reactors and the corresponding electrical production is 400 TWh/year.

Figure 1 Description of the simulated fuel cycle



### B. The three phases for a scenario of plutonium production limitation

During the simulation of this scenario, we meet three phases :

- Scenario starts with **a transient** with an increase of the plutonium masses present in reactors and fuel cycle facilities and an increase of the installed burner power (noted Xburn)

- **An equilibrium** is reached after some recyclings when the production of the Pu and M.A. balances their consumption. During this equilibrium there is a stabilization of :
  - the existing plutonium and M.A. masses (noted CycleInv) figure 1
  - the installed burner power (noted Xburn)

If we note :

| | |
|---|---|
| - Mprod | the Pu + M.A. mass produced by TWh |
| - Mburn TWh | the Pu + M.A. mass burned by |
| - Mloaded for | the Pu+M.A. in reactor inventory the production of a TWh/year |
| - Tin | the residence time in reactor |
| - Tout | the residence time out of reactor |

CycleInv is thus limited to a minimum value. This inventory can be reduced and totally burned only by a strategy of nuclear power phasing out

The equilibrium Xburn and CycleInv values are given by the following equations

$$\boxed{Xburn = \frac{Mprod}{Mprod + Mburn}} \quad \text{Equation 2}$$

And

$$\boxed{\begin{array}{l} CycleInv = Mprod * Tout * (1 - Xburn) \\ +(Mloaded * (1 + \frac{Tout}{Tin})) * Xburn \end{array}} \quad \text{Equation 3}$$

- **The phasing out of the nuclear production**

Theoretically it is possible to burn all the existing plutonium at equilibrium with the following scheme :

- first all the plutonium producers (current REP with enriched uranium fuel) are stopped,
- secondly the plutonium burners are stopped progressively as the available plutonium decreases

The decrease of the Pu+M.A. masses and electrical power are closely exponential .with the following evolution equation :

$$\boxed{CycleInv(t) = CycleInv(0) * e^{-\frac{t}{Td}}} \quad \text{Equation 4}$$

with

$$\boxed{Td = \frac{Mloaded}{Mburn} * (\frac{Tin + Tout}{Tin})} \quad \text{Equation 5}$$

The delay to reduce CycleInv by a factor 100 (noted Del100) is equal to Td*Ln(100)=4,6*Td

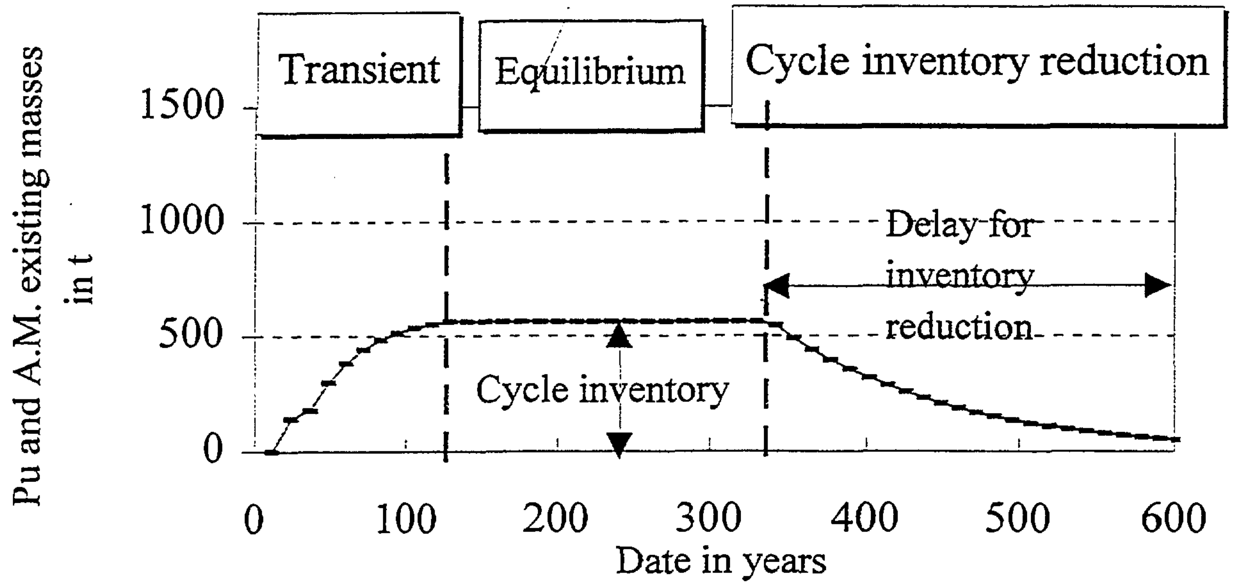
We present:

- on table 1 some figures for Mburn, Xburn, CycleInv and Td for scenario including standard PWR, Fast Neutron Reactors (noted FNR) of different types : EFR without blankets and CAPRA. In these scenarios the annual production is constant to 400 TWhe and Tout is equal to 7 years.
- on figure 2, the evolution of the Pu+M.A. masses for the scenario including FNR of EFR type without blankets

Table 1 Some values of the parameters

| Reactor | PWR MOX Pu content 2% | PWR MOX Pu content 6% | FNR : CAPRA | FNR EFR without blankets |
|---|---|---|---|---|
| Support | Enriched U | Enriched U | Depleted U | Depleted U |
| Mburn Kg/TWhe | 0 | 30 | 60 | 15 |
| Xburn | 100% | 50% | 35 % | 65 % |
| CycleInvt | 250 | 400 | 540 | 650 |
| Td years | infinity | 60 | 40 | 100 |
| Del100 years | infinity | 280 | 200 | 500 |

Figure 2 Example of Pu and M.A. multirecycling scenario with an EFR reactor type without fertile blankets



## VI. ADVANTAGES OF AN INERT SUPPORT MOLTEN SALT CONTINUOUSLY REPROCESSED

- Tout : a molten salt continuously processed fuel reduce
- Mburn: an inert support fuel would increase the burning factor to 150 kg/TWhe available on the network
- Xburn :with Mprod = 35kg/TWhe, Xburn is equal to 20 %. But with the accelerator consumption for keff=0,9, the total electric power of the hybrid systems would be equal to 30 % of the available electric power.

- Tout to some days.
- Mloaded : fuel present in pipe and steam generator would increase Mloaded. We suppose an increase of 50%. So for a production of 1 available TWhe by year Mloaded=1000 kg (average value of Mloaded for critical reactors) * 1,5 (accelerator consumption) * 1,5 (inventory of the pipes, steam generators, etc)= 2250 kg/TWhe-year

- CycleInv : with theses hypothesis for the scenarios of V, CycleInv = 250 t
- Td : in theses condition Td= 15 years.
- And Del100 would be reduced to 70 years

## VII. REACTOR DESIGN ADVANTAGES AND DISADVANTAGES OF AN INERT SUPPORT AND MOLTEN SALT CONTINUOUSLY REPROCESSED FUEL

We summarize on tables 2 to 4 some advantages and disadvantages for the design of an hybrid system , of an inert support and molten salt continuously reprocessed fuel.

Table 2 **Common (critical and hybrid systems) advantages** of an inert support and molten salt continuously reprocessed fuel

| Difficulties | Common advantages |
|---|---|
| Reactivity control | control by fuel composition |
| PU+ M.A. content | Reduced by the low Fissions Products (F.P.)content |
| Chemical reaction with water and air | Chemical inerty of the salt |
| Cooling accident | Low F.P. content<br>Possibility to empty the core very fastly |
| Vessel control | Possibility to empty the reactor |
| Fuel transport and fabrication | Integrated fuel cycled on the reactor site |
| Fuel reprocessing | Low F.P. content<br>Facility for thorium cycle |
| Proliferation | Reduced risk |

Table 3 **Advantages** of an inert support and molten salt continuously reprocessed fuel, **for an hybrid system**

| Hybrid system difficulties | Advantages |
|---|---|
| Beam power variations | Constant reactivity |
| Window behaviour | very low vessel pressure |
| Target behaviour | Target already molten |
| Neutron source location | Possibility to widen the beam radialy |
| Power, temperature and irradiation peaks | Flattening of theses factors by melting |

Table 4 Disadvantages of an inert support and molten salt continuously reprocessed fuel

| Difficulties | Possible solutions |
|---|---|
| High temperature salt corrosion | • Adapted materials<br>• Cold vessel |
| Salt activity | Tele maintenance |
| Fissile material inventory | Reduce the length of the pipes |
| High melting temperature | For the burner in which the neutron economy is not a priority, we can replace Li by Na in the salt and win 100°C on melting temperature |
| Positive void coefficient | Low reactivity |

## VIII. CONCLUSION

The radioactivity (or radiotoxicity) reduction by fission of the Pu and M.A. in an ADS depends on the subcriticality level of the system :

- with a high value of keff (close to 1) the use of a fertile fuel support of thorium is preferable to uranium. E.P. and a critical reactor of similar design have then the same efficiency for burning Pu and M.A.

- with a low keff (~ 0,9) the use of an inert matrix would be possible in the ADS. The Pu+M.A. burning efficiency increases by a factor higher than two in comparison with a critical system loaded with uranium based fuel. But the electrical energy needed by the accelerator implies an increase of the total power of the ADS, which can reach 50 %, and a decrease of the fissile material use efficiency which can reach 20 %

Association of inert support, molten salt in line reprocessed fuel and hybrid system give a very performant Pu+M.A. burner.
But the interest of such a burner appears principaly in the last phase of the use of nuclear energy : the reduction of the cycle inventory during a phasing out of the nuclear reactors.

At least, we must remember that a lot of theorical and technical problems remain to be solved for the design of such a system.

## IX. REFERENCES

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