REACTOR PHYSICS ANALYSIS OF HYBRID SYSTEMS

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Introduction

This paper presents two different approaches to analyse ADS concepts in order to optimise them. One is based on the analysis of external proposals with CEA codes (SPARTE, ERANOS) and using the same data (JEF 2). The second one is a broad study aiming at analysing the physics of different technologies (gas cooled, metal cooled, molten salt,...).

The analysis of hybrid reactors is based on the SPARTE system i.e. the High Energy code modules developed at CEA/DAM coupled to the ERANOS deterministic set of tools and adjusted data and the TRIPOLI Monte-Carlo transport code. The data essentially rely on JEF2.2 in the adjusted library ERALIB. These methods are qualified upon the MUSE experimental program in MASURCA, the mock-up facility at CEA - Cadarache.

External proposals analysis

The aim of the analysis of various concept is to compare the transmutation potential based on same data and method.

The analysis focused on 4 main projects. A solid fuel system like the Energy Amplifier and 3 proposals of fluid fuel systems. Each study presents the CEA vision of the proposal and should not substitute to the actual project. In all configurations the spallation target is liquid lead.

Energy amplifier

The aim of that study was to take inspiration from a project proposed by CERN (The Energy Amplifier of C. Rubbia et al.) in order to test the neutronics computation scheme we use for Accelerator Driven Systems. This computation scheme was tailored to the Energy Amplifier without any ambition to debate on its performances. We described a few distinctive features of ADS's among which φ^* : external neutron source importance in a subcritical core. The neutronics show a behaviour that is almost common for fast reactors as far as damages, flux and power rating are concerned. However, it seems that the uncertainties coming from DATA bases can affect the reactivity swing due to irradiation and the nominal values of most reactivity coefficients. This first phase should lead to a collaboration with CERN in the field of R&D related to ADS's.

Main system feature

Goal=Energy production in the $^{232}Th/^{233}U$ cycle.
Thermal Power: 1.5 $GW_{Th.}$.
Proton beam : E_p = 1 GeV, I_p = 12.5 mA.
K_{eff} = 0.98
Cycle length : 5 years without refuelling. (Burn-up: 115 GWJ/t).
Target, Coolant (natural convection) and Reflector : Lead (Total Mass : 10^4 T).
Annular Core with 2 fuel zones + 1 Breeding blanket.
Fuel : $^{233}UO_2 + ^{232}ThO_2$.

Specifics

In the $^{232}Th/^{233}U$ cycle, the production of minor actinides is ~ 100 times less than in the conventional $^{238}U/^{239}Pu$ cycle. This, obviously, needs to be moderated by the long-term fuel radiotoxicity. In that type of nuclide fuel cycle, 2 elements drive the fuel behaviour as far as it contributes to the neutron balance over the operation cycle. There is, first, a fast effect due to the build-up in ^{233}Pa and, second, the accumulation of fission products versus breeding of ^{232}Th. The appearance of capturing ^{233}Pa is flux dependant, it is worth ~ 2000 pcm and appears ~ 1 month after Beginning Of Life.

Then, the reactivity loss is essentially due to the build-up in Fission Products. The uncertainties affecting the data concerning these nuclides should be deeper investigated, considering the effect a reactivity swing can have on the beam current at that level of subcriticality.

Operational parameters

	Energy Amplifier		*Superphénix*
	t=0	t = 1800 FPD = 5yrs = EOC	t=0
Mean flux (Internal region)	3.8×10^{15} n/s.cm²	3.9×10^{15} n/s.cm²	4×10^{15} n/s.cm²
Radial Peaking factor	1.8	2.2	1.2
Max Linear Heat rating	570 W/cm	670 W/cm	480 W/cm
Speed dpa_{max} Inner core	0.10 NRT/day	0.14 NRT/day	0.15
dpa_{NRT} , inner core	0	216	80
Keff	0.97978	0.94390	1
Source intensity	2.02×10^{18} n/s	6.75×10^{18} n/s	
φ *	1.17	1.03	
Beam current	13.2 mA	43.2 mA	

Accelerator Driven Transmutation technique (C. Bowman)

The molten salt accelerator-driven waste burner proposed by C. Bowman is dedicated to the destruction of transuranic elements. This system is a thermal sub-critical reactor (k_{eff}=0.96). It's composed of fluoride salt flowing through a lattice of graphite channels. It's a big reactor with 5% salt in volume in the graphite. The scenario in which the system is implied (closing of the nuclear cycle) leads to equilibrium notion. After explaining the principal characteristics of the molten salt reactors, we present a description of the Tier 1 system and its chronological evolutions. A neutronic study is made on the cell and on the core to show the principal characteristics of the system (spectra, reactivity, cross sections...). The cell calculations allow to show three important parameters. The graphite temperature has a big impact on the hardness of the spectrum. The proportion of FP's in the feed is also very important because their capture cross section plays a role in the system spectrum and reactivity. A set of parametric studies was conducted to find the best proportion of fission products to reach a target objective in reactivity. The cell diameter also has an effect because of spatial self shielding which impacts over the cell reactivity. The impact of that study over the strategy foreseen for these applications is not negligible. One finds an optimisation at the cell and core level can yield a new vision on the system.

Main system features

Accelerator	
Beam Energy	1 GeV
Beam Current	49.3 mA
Target	Liquid Pb (Cold window upstream)
Core	
Volume	35.8 cm^3
Flux	1.84×10^{15} n/cm^2s
V_{salt}/ $V_{graphite}$	5%
Channel diameter	7 cm
V_{salt} In & Outside	1.925 m^3
Power density (Salt)	390 W/cm^3
Power density (Channel)	19.5 W/cm^3
Salt speed	2 m/s
Salt Temperature	700°C-600°C
Number of salt channels	122
Carrier salt	NaF-ZrF_4
Salt density	3.5 g/cm^3
Salt feed flow	2.2 l/day
Graphite density	2.25 g/cm^3
Construction Materials	Hastelloy N modified
Performances	
k_{eff}	0.96
P_{th}	750 MWth
Carnot Thermal efficiency	42 %
Yearly Actinide burn-up	300 kg/year
Irradiation time	5 years

Accelerator Transmutation of Waste (ATW)

General description of ATW

Objective: Burn TRansUranics (TRU's) corresponding to a PWR spent fuel after 10 years of cooling time. This aim gives the actinides composition at equilibrium. The spectrum is superthermal. The reactor has a liquid fuel in which the carrier salt is a molten fluoride flowing through a lattice of graphite (80 m^3). The salt fraction is 13% amounting to ~ 100 kg of TRU. The spectrum is therefore Superthermal.

Characteristics of ATW

Target: Molten lead.
P = 500 MWth.
I = 11 mA; E_p = 800 MeV; K_{eff} = 0.96; Average.
Flux: 2.45×10^{14} n/s.cm² (Max/Mean flux: 7)

Strategy to equilibrium and performances

After one year of operation, the fraction of heavy nuclei in the refueling stream has to be superior to the fission rate in order to keep K_{eff} at an acceptable level. Otherwise, K_{eff} would rapidly (6 months) fall down to ~ 0.65. The feed rate will have to remain superior to the fission rate for 5.5 years and then decrease down to the level of equilibrium for the 8 following years. The equilibrium is reached after ~ 20 years for all nuclei except ^{246}Cm.

Toxicity: One 500 MWth ATW module can transmute the TRU production of 2/3 PWR (i.e ~ 180 kg).

Sensitivity of reactivity to the feed rate at equilibrium.

- 0.5 $\times$ assigned figure for 24 hrs : Δk = -32 pcm.
- 1.5 $\times$ assigned figure for 24 hrs : Δk = +46 pcm.

We can see that an accident on the feed stream will not have a very severe effect over the core. It also indicates both a necessity for the control of reactivity in that type of system on several time scales as well as a good knowledge of the composition.

Accidental situations (Salt Volume Fraction Constant). In that study, 4 configurations are characterised. The size of the graphite channel is modified, graphite and salt collapse one on the other and mix together & the spallation region is voided.

- Graphite lattice channels +30% : Δk = +1400 pcm.
- Graphite lattice channels -30% : Δk = -1700 pcm.
- Mix graphite and salt : Δk = -7500 pcm.
- Molten lead of the spallation target voided : Δk = -410 pcm.

The design of that type of system is obviously sensitive to the elementary cell dimensions. It should determine what is the most reactive situation in order to avoid positive reactivity transients.

JAERI

JMS : Burn* Minor Actinides. Fast *Spectrum

Objective: Burn Minor Actinides corresponding to a PWR spent fuel after 3 years of cooling time. The core is made of molten chloride. The Salt volume is 2.5 m^3 amounting to ~ 5 Tons of MA's. The spectrum is Fast as no significant moderation occurs onto the carrier salt.

Characteristics of JMS

Target : Molten Salt.
P = 800 Mwth.
I = 24 mA; Ep = 1500 MeV; K_{eff} = 0.95;
Average Flux : 2.06×10^{15} n/s.cm² Max/Mean flux : 15)

Sensitivity of reactivity to the feed rate at equilibrium.

- $0.5 \times$ assigned figure for 24 hrs : $\Delta k = -1.5$ pcm.
- $1.5 \times$ assigned figure for 24 hrs : $\Delta k = +1.6$ pcm.

Study on the effect of a shift in the spectrum of the spallation source. (φ^* is an indicator showing the relative efficiency -importance- of external neutrons as compared to fission neutrons)

- Softer spectrum : φ^* - 9 %.
- Harder spectrum : φ^* + 8 %.

The difference is not negligible. Again, the source configuration should correspond to the maximum efficiency so that any type of transient would not lead to an power excursion.

Strategy to Equilibrium and Performances.

The equilibrium is reached after ~ 15 years of operation.

The initial composition shows an important fraction of MA's. This will lead to a build up in fissile Pu, after ~ 3 years of operation. Then 2 strategies can lead to equilibrium if we intend to keep reactivity constant:

1. The feed rate remains constant : An absorber (^{10}B) has to be dissolved into the salt in order to anchor k_{eff} at 0.95 (Equilibrium).
2. The feed rate is changed : The feed rate is set to 0 for 6 years so that the inventory decays to keep $k_{eff} = 0.95$

Toxicity: One 800 MWth JMS module can transmute the MA's production of 10 PWR (i.e ~ 290 kg).

Conceptual designs of demonstration reactors.

Type of studies conducted

Based on the previous analyses, different concepts were proposed and analysed for a hard spectrum demonstration core.

The motivations for a demonstration hybrid reactor stand fairly simply as the following objectives :

1. Deployment of a facility using non traditional fuels, e.g. Inert matrix, High actinide content and enrichment.
2. Technological coupling of the main components i.e. Accelerator, Target and Sub-critical blanket, including continuous integrated control of the system.
3. Optimisation of an eventual burner in terms of neutron balance excess.

4. Materials behaviour under severe conditions (High and Hard Flux, strong gradients, High temperature and corrosion exposure, maximum damage production, innovative coolants).

A set of complementary applications, with parallel objectives, can further justify the project, i.e. neutron beams for biology or material physics applications and irradiation facility for space applications and future nuclear prospects.

In that perspective, we considered a set of ″Fuel/Coolant/Elementary design″ systems that could match the target objectives of a *Demonstration* device. The concept was applied to MOX, Nitride and Carbide type of fuels, combined with Sodium, Lead (or Lead Bismuth Eutectic), or Gas coolant in a Hexagonal base, a rectangular lattice or a pebble bed elementary cell. The power in each configuration was set to 100 MWth and the reactivity $k_{eff} = 0.92 \div 0.98$ with a computed overall efficiency of external source neutrons $\varphi^* = 1.2 \div 1.4$. No full thermal optimisation was conducted yet each individual system can still yield some indications as to how appropriate it would be to meet the objectives mentioned above. They all have very similar features i.e. high reactivity loss over the cycle, because of a high initial enrichment as well as of a small size, itself because of a high (necessary) neutron leakage rate. Peaking factors are connected to the reactivity and a specific study is addressing the question of what level of subcriticality is sound to an Accelerator Driven System for Transmutation (cf. same conference, paper on *Comparison study of critical vs ADS reactors from the point-kinetics standpoint*).

Apart from those common features, a deeper investigation will be necessary to optimise each type of system.

Basic conclusions.

A generic system with 34% Fuel, 49% Coolant, 17% Structural material, a fissile enrichment ~ 29% in an annular core of less than 400 l will give k_{eff} ~ 0.96. Provided the external source neutron efficiency is more than 1.2, the beam power required to produce 100 Mwth will be ~ 1.3 mA @1GeV. The flux level will be 2×10^{15} n/s.cm² (Peaking factor ~ 2) with more than 65% of the neutrons above 0.1 MeV. The core maximum power density will be ~ 440 W/cc and structural materials will have a damage rate ~ 0.1 dpa_{NRT_Steel}/day. At that level of enrichment, the reactivity swing will follow an average loss of the order of - 20 pcm/day. Of course, most of these features will degrade over the core cycle, just as the reactivity loss. For instance, with a 3 months long cycle, the peaking factor will deteriorate by about 10%.

There is a positive interest to limit the core thickness if the peaking factor has to be low. It would also be sound to put demonstration/irradiation sub-assemblies close to the target in order to maximise the flux efficiency.

This generic image has been pushed ahead and a gas-cooled demonstration reactor was optimised on a first order basis. The hypothesis were taken from existing projects like GBR-4 and a hole was inserted in the centre in order to put the spallation module.

A set of reflexions concerning these cores is still going on and includes the overall core safety as well as generic aspects of control and surveillance issues and long term behaviour.

Nuclear data and Computation tools

The data for actinides, fission products and structural materials are evaluated in the JEF2-2 library. This library is in turn adjusted, within the error bars, groupwise, to match the results of integral experiments. The corresponding adjusted data set is ERALIB. In the Intermediate Energy range the data are computed from double differential cross sections during the Monte-Carlo transport.

SPARTE stands for SPAllation Ralentissement (slowing-down) Transport & Évolution (decay). It is made of three blocks. *T*he spallation source is computed with a CEA **-** Bruyères le Châtel version of HETC. *C*ore calculations propagate the source in either ERANOS (European Reactor ANalysis Optimised System, validated for fast reactor calculations) or TRIPOLI (CEA – Monte Carlo). *D*epletion and fuel management are integrated either in ERANOS or connected to DARWIN (CEA Depletion stand alone tool).

In HETC, the Intra-Nuclear Cascade module can be tuned either on the standard Bertini or on a Cugnon type of model. Then an evaporation module, including the Fermi break-up takes charge of the excited nucleus. The transport is conducted from the energy of the incident particle down to the upper level of reactor physics evaluated libraries (i.e. 20 MeV). This threshold is called the cut-off energy. Whenever a particle is emitted lower than this limit, its main features (type, position, momentum) are "frozen" and stored in a dedicated file. For neutrons, this file is processed and then used into the lower energy transport code as a spallation source. It covers exactly the same geometry and compositions. It is obvious that the hypothesis of direct Nucleon-Nucleon interaction on which Intra-Nuclear Cascade models are based is crude in the range $20 < E < 200$ MeV. That is why a broad international effort has been initiated in order to raise the cut-off energy up to 150÷200 MeV. This ultimate set of evaluations, concerning a high priority list of key isotopes (potential spallation targets & Construction materials), will allow to fulfil reactor physics calculations up to 150÷200 MeV either with a deterministic or with a Monte-Carlo code.

In the Lower energy range, a comprehensive computation scheme has been developed in ERANOS to fully characterise systems in a semi-automatic mode. It includes cell, core (with spallation source), and depletion calculations. Further investigations will focus on the space kinetics features of ADS'. The MUSE experimental programme at MASURCA will build the necessary basis to qualify this tool.

Conclusion

We have focused our attention towards a 2 phase approach to the physics of hybrid reactors. The study and optimisation of external proposals in a first time and the pioneer characterisation of innovative multi domain concepts. The analysis of external systems, from a reactor physics standpoint, is helpful to focus more efficiently our effort towards an application that meets our needs. For that, we use a specific integrated tool, SPARTE, based on the ultimate ERALIB nuclear data library.