WAYS to NUCLEAR POWER RENAISSANCE and VITAL RISK FREE FAST REACTORS

Prof I. Slessarev, Dr. P. Alekseev
Russian Research Centre
“Kurchatov Institute”, Moscow,
Russian Federation

PAPER DESTINATION

- It is wider that fast reactor innovative designs and their safety
- It defines actual « painful points » of current NP as well as means of their elimination

  (« directions of driving forces ») and
- outstanding capabilities of innovative FAST REACTORs + FUEL CYCLEs meeting the corresponding goals

STATUS:

The reasons of the current NP stagnation are determined by the existence of **substantial threats and risks** – i.e. factors capable of either making the considered technology unacceptable, or/and significantly limit its applicability scope.

Now there are no objective reasons for NP renaissance, since the basic factors responsible for cautious attitude to nuclear energy are still present, despite all "innovative designs" proposed in the international framework of GEN-IV and INPRO.

Criteria for selecting the direction of long-term development, as well as the principles for choosing the technological solutions for the future, are still vague.

Several general issues ("painful points") seem to cause the most significant doubts in the society impeding the nuclear energy renaissance:

1. non-eliminated threat of disastrous accidents (with high and hazardous for the society uncertainties of their probabilities);
2. weapons-grade material proliferation risks;

3. indefinite risks related to long-term long-lived toxic waste storage;
4. threats of major investment loss in conditions of limited capitals, economic crises and deep inflation processes;

5. "progressive deadlock" effect in NP development scenario caused by the looming nuclear fuel resource constraints.

COMMENTS

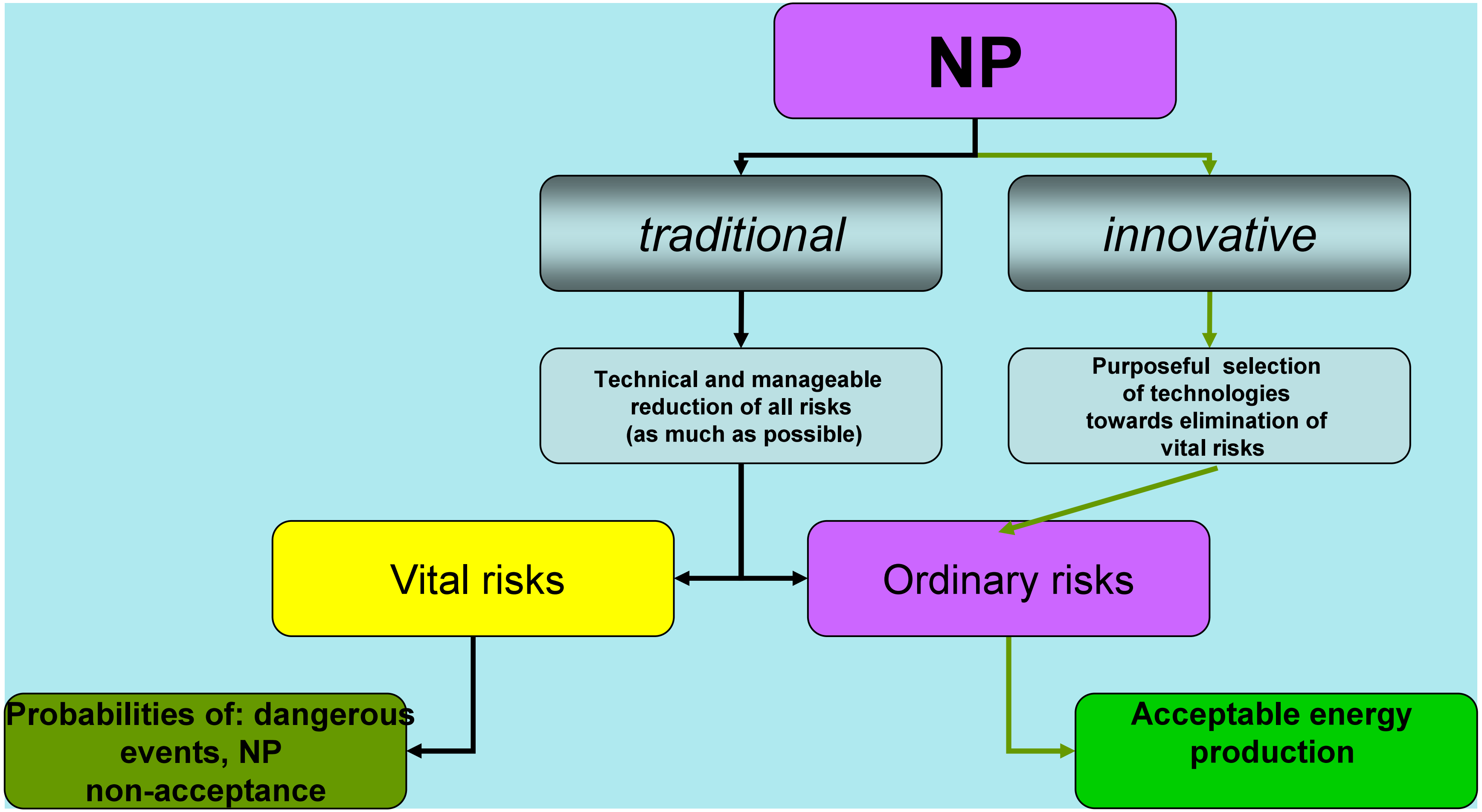
- All these issues, along with the respective risks/threats they involve, are substantial according to the definition explained above and they are decisive **("vital")** ones respecting the fate of this technology.
- Development of an innovative nuclear technology capable of evoking the true nuclear energy production renaissance would necessarily require nuclear reactors and fuel cycles deliberately provided with counter-risk qualities (with known ways of implementation) relative to **all vital risks**. The available thermal nuclear reactors, as well as ordinary fast sodium-cooled reactors using oxide fuel (such as ancient BN and SuperPhenix), **do not definitely possess these qualities.**

On new-quality Nuclear Power

The new Nuclear Power quality concept leading to its accelerated revival should consist of exclusion of substantial threats and guaranteed elimination of vital risks attributable to the contemporary NP at once.

It doesn’t mean that there are no more problems in the nuclear technology, however these problems could be reduced to the category of “ordinary” issues imposing no principal constraints on the sustainable and long-term application of NP in the future.

Traditional and innovative strategies and consequences of their applications



PRINCIPAL DIFFERENCE BETWEEN ORDINARY AND NOVEL APPROACHES

- **IT IS NOW (ordinary):**

  NR are under construction with non-zeroed vital risks measured by their probabilities. This concerns also those NR, which have no chance to eliminate these risks in the future. Certainly, necessity of risk reduction is declared, however with a hudge uncertainty. Dangerous events could happend

- **IT SHOULD BE (novel)**

  In accordance with the new goal, only those NR are under construction which have no vital risks and, hence, there is never dangerous events in the future.

NP renaissance is realistic
if
all painful points
would be eliminated

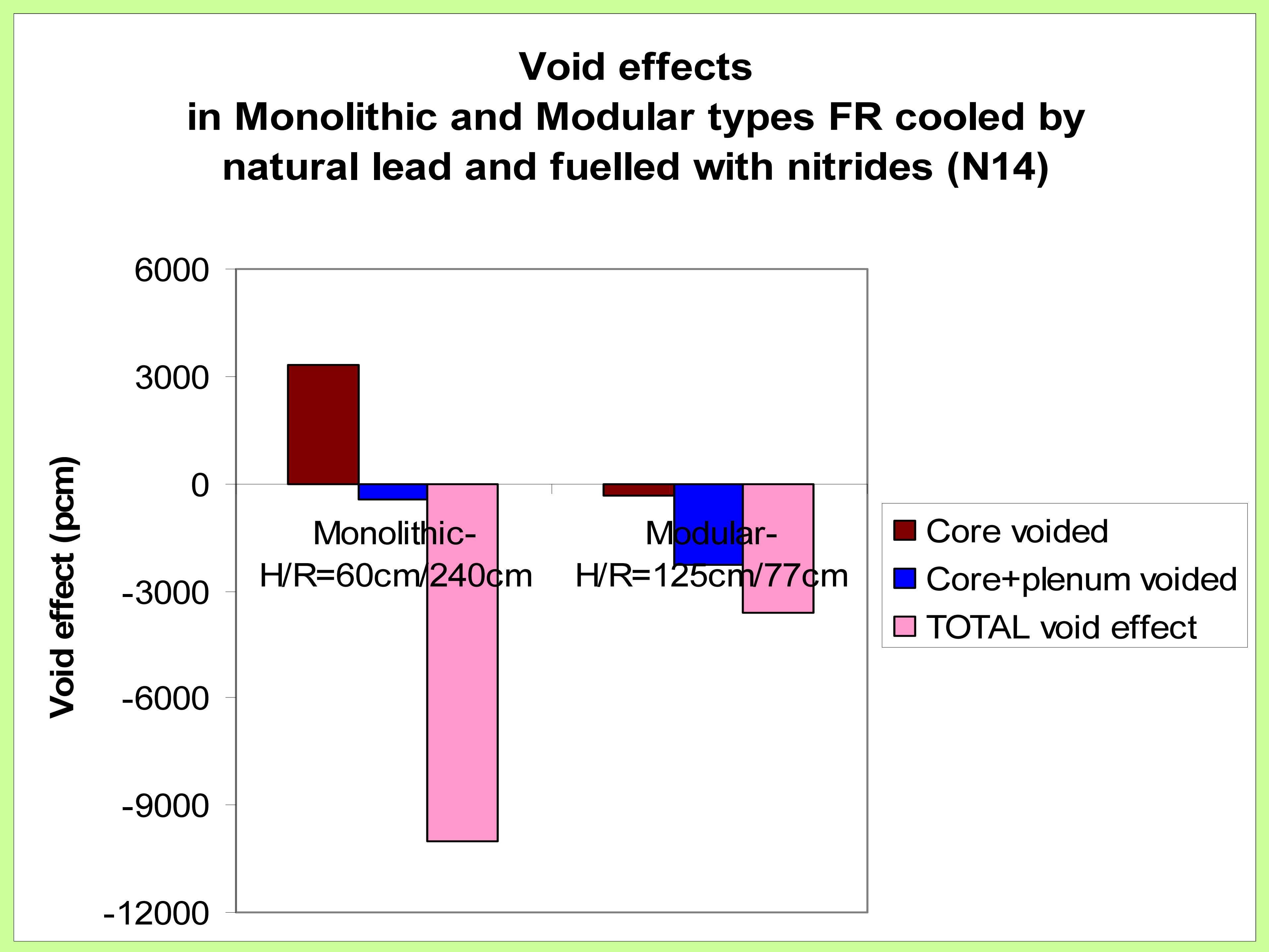
Ways of guaranteed elimination of the vital risks

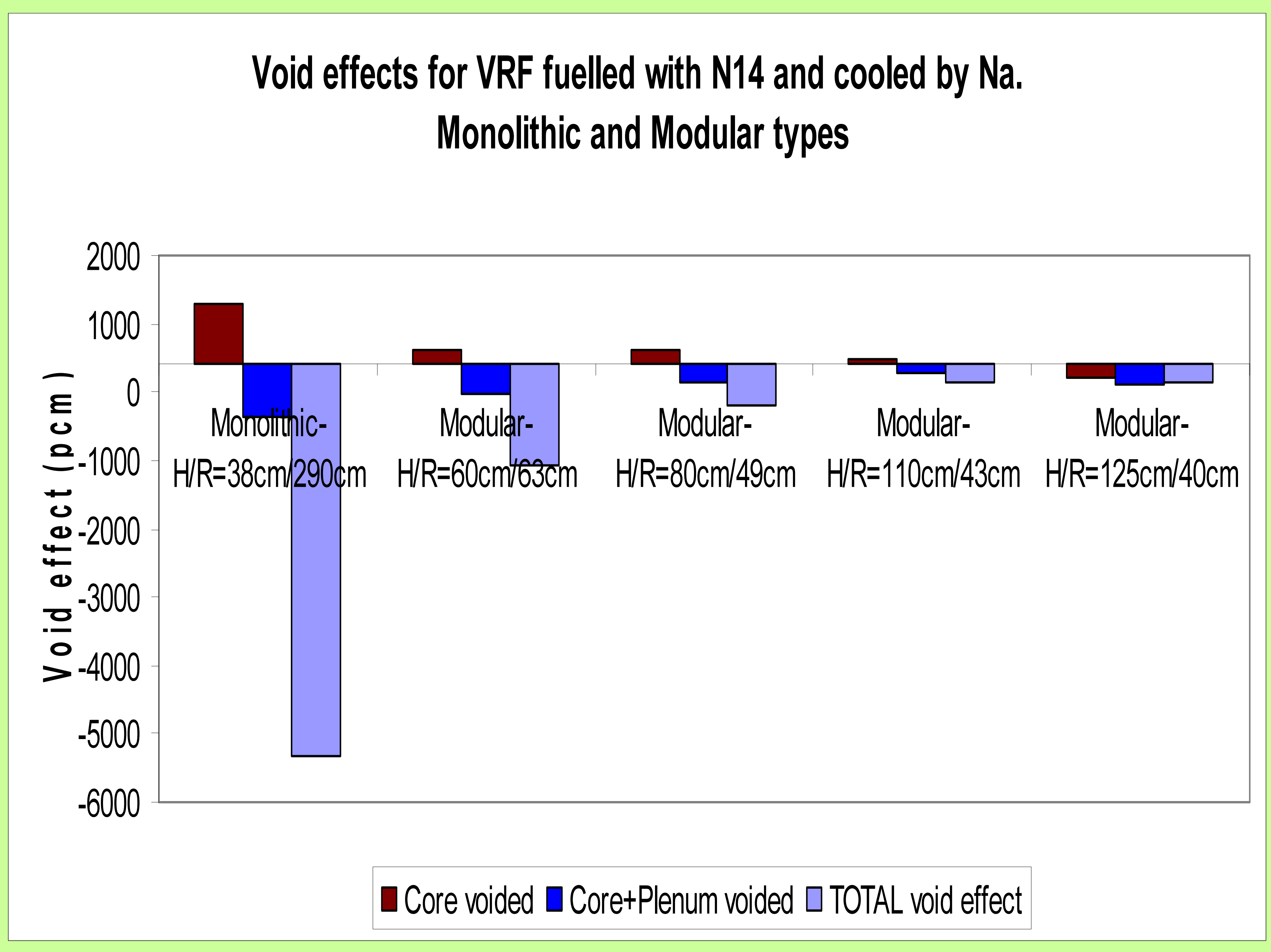
1. **It would be possible to assure guaranteed elimination of severe accident threats by providing the reactor with the quality of "self-protection" against destruction (particularly of the core) which is based upon, for instance:**

   - *core destruction "resistibility" due to both intrinsic reactor properties and sufficient margins to damage even in the case of all anticipated dangerous events including human factors (when uncontrollable dynamical processes with intensive energy releases) are initiated;*
   - *limitation of the accumulated non-nuclear energy by the level unable to cause core disintegration in case an accident-initiating event occurs;*
   - *strongly limited reactivity total margins ($<\beta$eff), etc.*

It is known that negative and small void reactivity effects in are preferable for better safety features

For instance, this could be achieved in FR by:
reduced core volume; use of dense fuel; higher volume fraction of fuel; or/and by "modular" compositions


Void effects
in Monolithic and Modular types FR cooled by
natural lead and fuelled with nitrides (N14)
6000
3000
0
-3000
-6000
-9000
-12000
Void effect (pcm)
Monolithic-
H/R=60cm/240cm
Modular-
H/R=125cm/77cm
Core voided
Core+plenum voided
TOTAL void effect


Void effects for VRF fuelled with N14 and cooled by Na.
Monolithic and Modular types
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
Void effect (pcm)
Monolithic-H/R=38cm/290cm
Modular-H/R=60cm/63cm
Modular-H/R=80cm/49cm
Modular-H/R=110cm/43cm
Modular-H/R=125cm/40cm
Core voided
Core+Plenum voided
TOTAL void effect

2. Preventing the threat of weapons-grade materials' theft (just that very case can be considered as an important one), would be achievable when using only the reactors and fuel cycle technologies self-protected against any unauthorized removal of nuclear fuel,

e.g., by means of:

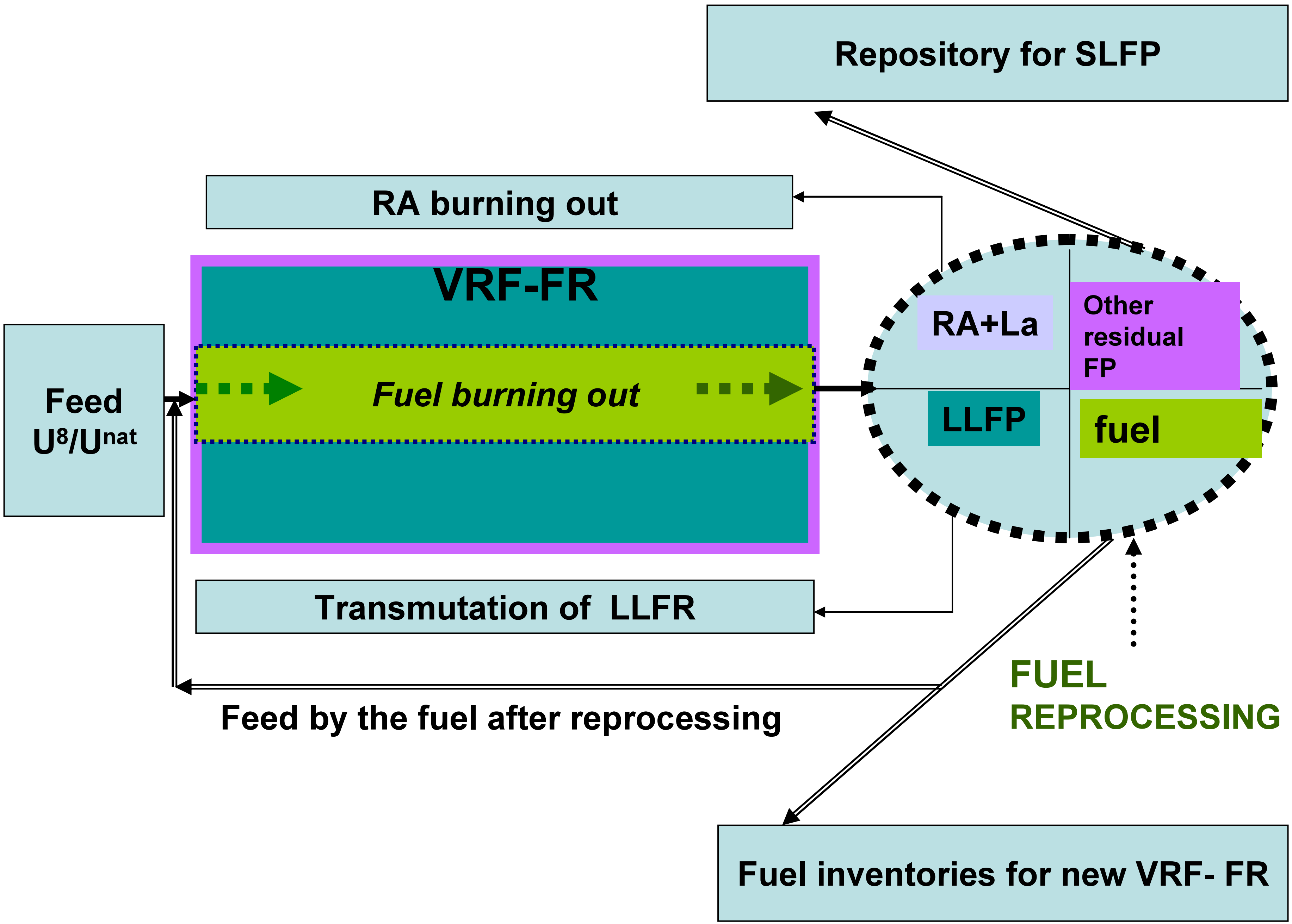
total abandonment of feed enrichment, as well of the enrichment technology in nuclear industry as a whole;

abandonment of re-enrichment (during spent fuel reprocessing) with fissile isotopes…

3. Vital risks of Transuranium wastes + Long Lived Fission Products storage

The task of preserving the radioactive balance at nuclear power development seems to be solvable by using the vital risk free fuel cycle, which should include:

- *reactors fed with non-enriched uranium;*
- *spent fuel separation from Short Lived (SLFP) and Long Lived (LLFP) fission products;*
- *abandonment of residual actinides' separation from lanthanides and creation the special "workspace" in reactors arranged for burning them (assuming a slow "exponentially type" growth of the reactor park);*
- *partial transmutation of highly toxic long-lived fission products in reactors.*


Repository for SLFP
RA burning out
VRF-FR
Feed
U8/Unat
Fuel burning out
RA+La
Other residual FP
LLFP
fuel
Transmutation of LLFR
Feed by the fuel after reprocessing
FUEL REPROCESSING
Fuel inventories for new VRF- FR

COMMENTS

- a certain part of fuel would be used to create new reactor fuel inventories. At the same time,

- only the exponential growth would assure a constant RA fraction in the total amount of heavy nuclei and the limiting “workspace” needed for RA burnout by the neutron flux. These nuclide masses could surround reactor cores and be irradiated by the leaking neutrons. In this case the increased neutron yield from modular cores could also find its useful application.

- These nuclide masses could surround reactor cores and be irradiated by the leaking neutrons.

The longer Nuclear Power exists, the higher would be this burnout effect.

Accumulation/repository of RESIDUAL ACTINIDES

Ratios (R)of the RA+La volumes to core volumes if an « exponentional shape » park's development is envisaged:

Park doubling time (years)	R % %
70	30
140	70

COMMENTS

- RA real burnout would require a slow exponential growth of the reactor park, which, in turn, would need the positive breeding gain. The exact “levels” of both factors are not so important for the solution of the waste issue, and can vary widely.
- Even a relatively slow growth of the reactor park

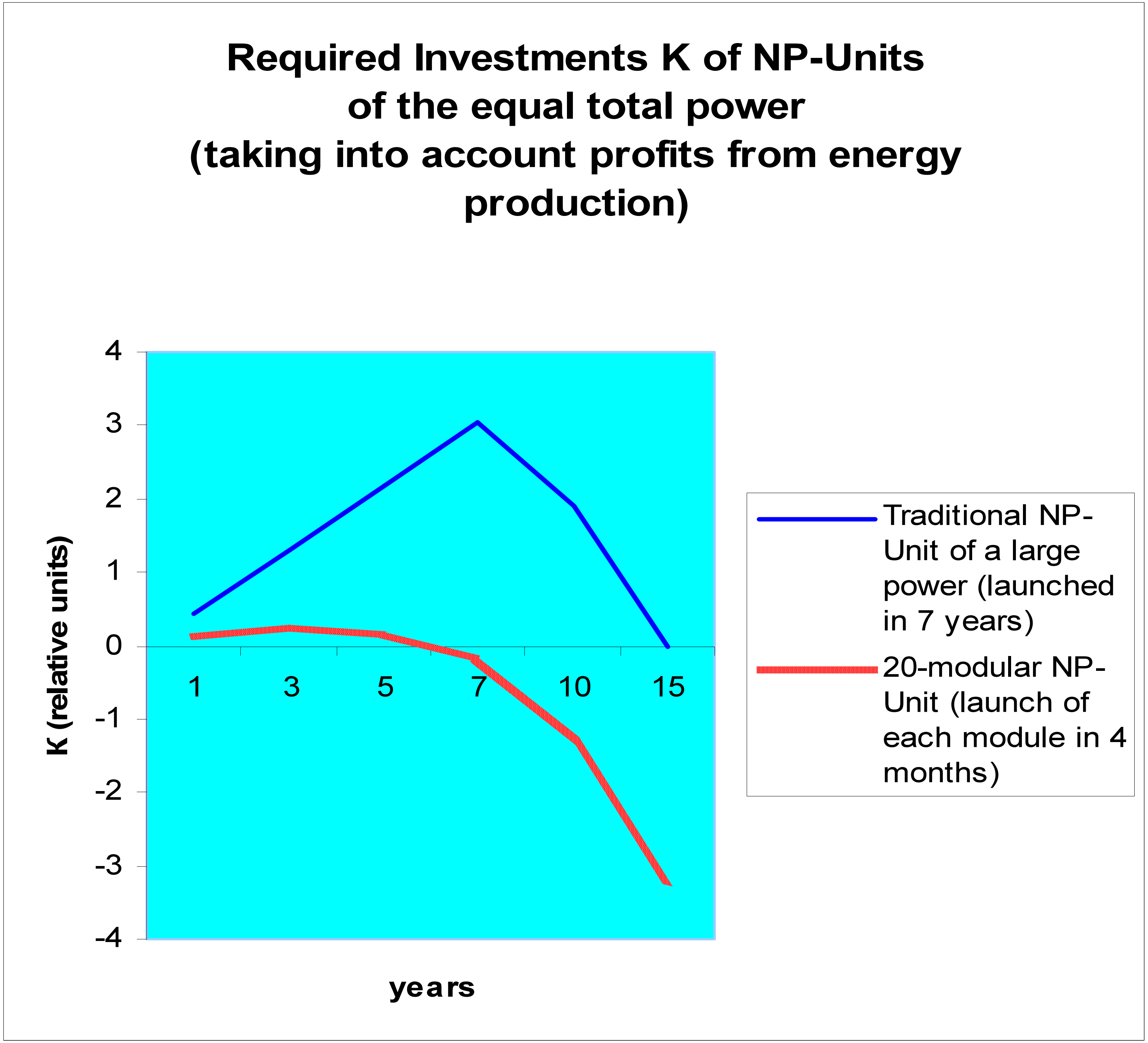
  (0.5–3% per year) with a respectively slightly positive breeding gain would be enough for many cases.

  Such a growth is close to the expected primary energy demand increase according to the UN: by 2030, the increase by 60–70% from the 2000 level is expected.

4. Vital risks of investment loss are important

- **Recently they have considerably increased and still continue growing – mainly because of safety enhancement measures. Crediting conditions also became considerably worse, especially in view of long NPP construction time for nuclear industry.**
- **All these factors aggravate the economics and discourage investments even at the level of governmental orders.**

The importance of investment risks would level down in case of their essential reduction (twice or more). This drastic reduction of investment risks coupled with considerable economy improvement would be possible through a significant reduction of NPP construction periods by using factory-made precision autonomous modules, simpler reactor safety means, and cheaper fuel inventories.


Required Investments K of NP-Units
of the equal total power
(taking into account profits from energy
production)
K (relative units)
4
3
2
1
0
-1
-2
-3
-4
1
3
5
7
10
15
years
Traditional NP-Unit of a large power (launched in 7 years)
20-modular NP-Unit (launch of each module in 4 months)

5. Vital risk of rapid exhaustion of fuel resources

It would be eliminated by addressing to fast reactors, that is becoming the dominant idea of nuclear power in the nearest future.

Fuel self-supply and the growth of NPP park would be possible only in case of positive breeding gain.

Theoretically, such a nuclear power could start almost “from zero level” when first initial inventory of a Vital Risk Free Reactor would be available.

On vital risk free nuclear reactor and fuel cycle concepts

Elimination all the vital risks is complicated task and considered to be **realistic not for all the reactor types** known. Analyses show that fast reactors are the best suited for this purpose, and this task would be solvable even in the currently available technology framework, on the basis of the novel ideas of fast reactors accenting on:

- ***radical improvement of the neutron balance;***
- ***use of modular reactor configurations;***
- ***elongation of the fuel residence time respecting the equilibrium mode;***
- ***fuel cycle proper rearrangement.***

What are the supplementary “neutron needs” of VRF-FRs in comparison with ordinary fast reactors?

How could the firm neutron balance requirements be met, bearing in mind that not all reactor types are ready for this challenge? Two ways are known for fission reactors:

- by finding the most “economic” neutron compositions among from the “arsenal” of prospective reactor fuels and materials;
- by supplying reactors with an external neutron sources. This case supposes the use of a NPP with subcritical core modules and external neutron sources (such as European electro-nuclear hybrid designs (ADS) or thermonuclear fusion hybrids of small unit power).

NEUTRON SUPPLEMENTARY NEEDS and

NEUTRON CONSUMPTION required for LLFP incineration are shown in the two followed Tables

Guaranteed exclusion of severe accidents, when a considerable correction of void reactivity effects is required for this goal achievement	**0.2 neutrons/fission** **in sodium-cooled reactors – in order to reduce the void effect by factor of 2**
Elimination of residual transuraniums from wastes	**0.15 neutrons/fission** **assuming the nuclear reactor park annual growth rate of 2%**
Elimination of toxic fission products from wastes	**<0.15 neutrons/fission** **for transmuting the hazardous Tc, I, Cs (this value could be reduced by skilful use of the neutron leakage)**
Abandonment of the enriched fuel feed (at the equilibrium mode)	**Automatic “penalty” in the reactor neutron balance because of lower equilibrium concentrations of fissile nuclei in cores**
TOTAL (depending on the VRF-FRs completeness)	**≥ 0.3–0.5 neutrons per fission**

Fission products	D, Neutron/fis ***CONSUMPTION***	Radiotoxicity reduction due to natural decay in 1000 years after discharge (Sv/GWe·y)
99Tc	**0.055**	5500
129I + 99Tc	**0.064**	8160
129I + 99Tc + 135Cs	**0.081**	9060
All Tc, I and Cs isotopes	**0.15**	9060
All Tc, I, Cs and Zr isotopes	**0.68**	9930
All Tc, I, Cs, Zr and Pd isotopes	**0.98**	9935

Recommended VRF-FR « configurations »

The following NPPs could be proposed:

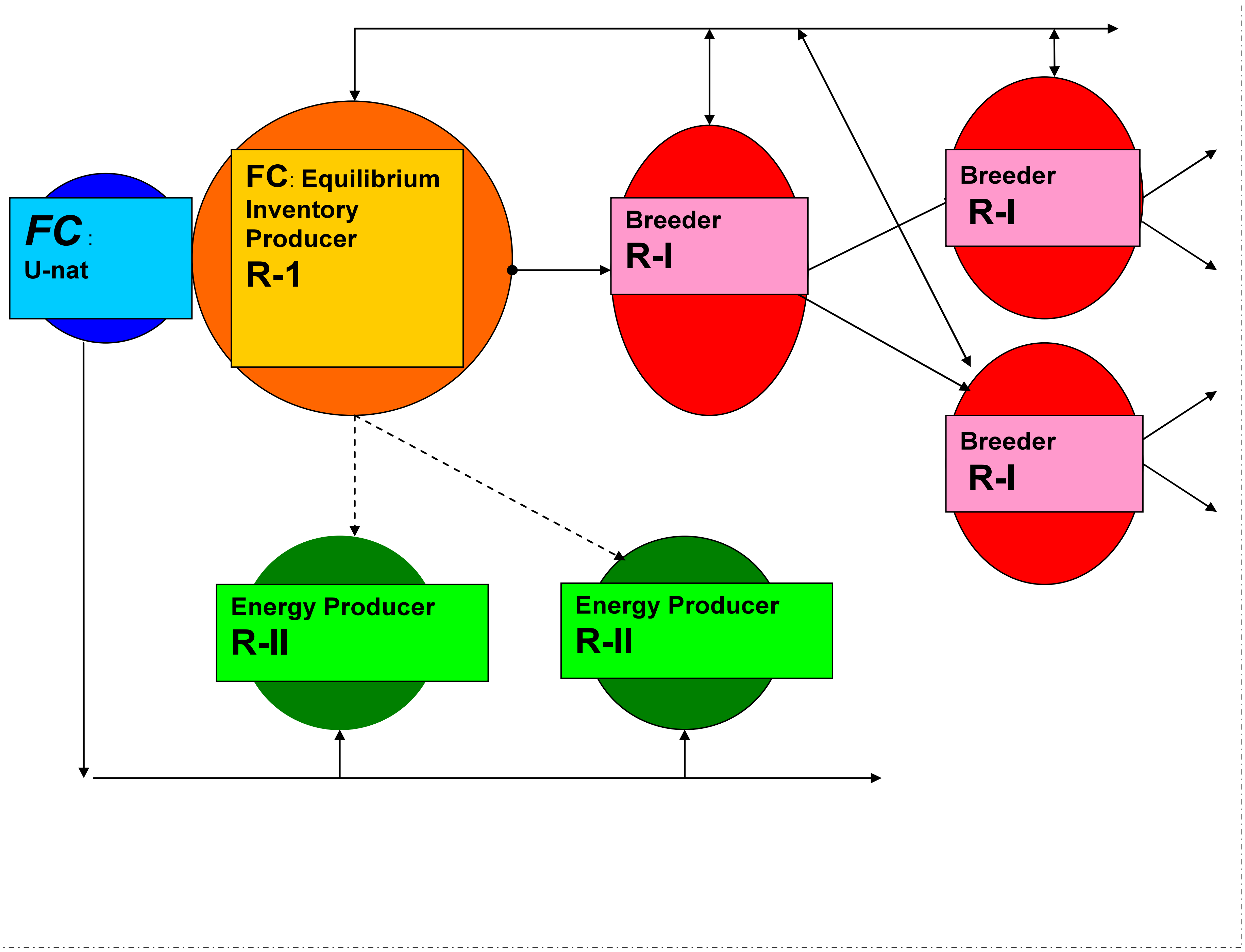
- NPPs consisting of small modular VRF-FRs with hard neutron spectrum (cooled by either heavy metals or sodium), all self-protected against severe accidents;
- NPPs with non-enriched feed, with dense fuel and/or with densely packed cores, zero in-core breeding and elongated fuel residence time,
- combined with the vital risk free fuel cycle and burning of the residual transuraniums/the most toxic long-lived fission products in reactor blankets,
- NPPs with molten salt fast spectrum VRF-FRs of WISE-type.
- Among known projects, the heavy metal cooled FR, PRISM and IFR are the possible candidate to be VRF-FRs after the specially oriented for vital risk suppression redesigning.
- In the case of solid fuel reactors, improvement of the fuel balance could require the use of compact cores containing an elevated fraction of dense solid carbide/nitride (e.g. those enriched with N15) /metallic fuels, a coolant with reduced neutron capture (e.g. Pb208), and – in fast molten-salt reactors – fuel components with reduced neutron capture (e.g. Cl 37).

Marketing FEATURES

Nuclear power based on **VRF-FR**, would allow possessing possibilities both

- **reactor inventory generation** (including fuel reprocessing) and
- **“simple” power generation** (without fuel reprocessing) to be divided between different groups of countries,

that would provide nuclear power with complementary security features relative to weapons-grade material proliferation, and contribute to its international marketing flexibility



FC:
U-nat
FC: Equilibrium
Inventory
Producer
R-1
Breeder
R-I
Breeder
R-I
Breeder
R-I
Energy Producer
R-II
Energy Producer
R-II

CONCLUSION

- NP renaissance becames realisic if **all** (FIVE) vital risks would be eliminated
- This elimination is possible on the base of fast reactors and fuel cycle of innovative design/structure –

  modular, self-withstanding against unprotected dangerous events, fed by natural U, dense core with essentially enhanced neutron balance and capability incinerating residual actinides and LLFP

FOR RADICAL ENHANCEMENT
of NP ACCEPTABILITY
SUCH POTENTIAL
SHOULD BE CLEARLY DECLARED

Vital Risk Free Fast Reactor designs could be realized rapidly (technologies are available!) by application of some already known decisions like it was used in the non-traditional projects:

BREST, IFR, PRISM, WISE,CANDLE, Pb-Bi modular.....

Continuation of NP developments using « traditional » FR concepts seems to be vague

Could the VRF-FR be helpful for GIV activity as a « joining » idea?