Russian Research Center “Kurchatov Institute”, Moscow, Russia

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CRITICAL ANALYSIS OF THE REGIONAL POWER STRUCTURE WITH "BATTERY-TYPE" SMALL CAPACITY REACTORS AND SERVICE CENTERS

(six month report)

IAEA CRP on “Development of Small Reactors Without On-Site Refuelling”

Principal investigator E.A. Ivanov

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Introduction

The common view on small power systems as on the individual installations that are in many features are similar as so-called “big” power unit but has smaller size and capacity does not see the completely different role of small power systems in energy security and in diversification of the global energy production and distribution systems.

Small power systems should be simplified in comparison with the other energy sources and they can be produced by big industrial series, fuelled and equipped on-factory, transported and removed from site without complex and dangerous operations on refueling and packaging of spent and fresh fuel.

Their deployment has not requires in high-skilled staff and therefore does not require development specific engineering schools in the regions, which are interested to construct the nuclear installations.

An opportunity to make the units in industrial way (in great series) should reduce cost in accordance to “learning curve”.

Thus the expected advantages of the system of the small power installation there are in the following items:

- the industrial way of power installation production that makes it cheapest;
- the simplification of operational exploitation of nuclear power installation that exclude the needs in high-skilled personnel and transfers nuclear technology from high-tech to the technology with the middle-kind level of complexity;
- the absence of strong needs in developed electric grids;
- the increasing of the safety level of each individual unit (by the factor of small-scale);
- the principal proper of small installation to be removable from the site of deployment.

It should be noted that expected specific expenses per installed kW in the small power nuclear power plant (SPNPP) can be more in several times than expenses for system of bigger power, but emerging properties of the systems of SPNPPs make their contest advantages for deployment in far regions in the small settlements.

Realization of emerging properties of the small nuclear reactor systems and delivering of their contest opportunities require organizing of SPNPPs in the great system coupled with service centers and holistic approach. Holistic approach has been implemented also in the analysis of the SPNPPs’ system where we should consider them from cave to grave.

Emerging system evidently has a complex behavior and hardly can be described on the base of so-called “the first principles”, therefore we use one kind of the method of analogies.

In this method proposed and sufficiently implemented by Dr. Dobrocheev (RRC Kurchatov Institute [http://www.prognoz.dhtp.kiae.ru]) the base of analysis building is the statistics of development of the energy production system in the one or another region with the accounting of the several basic features of the region. The results of such consideration have been used in the substantiation of the complete expected scale of the system and total consumption of nuclear materials.

Presented below investigation is the half-year report for IAEA CRP I25001 "Small reactors without on-site refueling".

Description of the system of the SPNPPs and relevant service enterprises

In this work we consider the system of small power reactors and emerging properties of these systems. First of all we should take into account that any system defines as compound of elements, their relations (links) and rules of composition. In our case, where mission of the system is evident, i.e. to be producer of energy with required quality and availability by acceptable price, the elements of the system are nuclear power plants and service (fabrication, repairing, fuel reprocessing and mining etc) enterprises, all elements are linked by material, fuel and structure elements transfers. But rules of composition have been done by IAEA and ICRS recommendations on safety, nonproliferation and radiation risks.

Our vision of the organization chart is based on the common organization scheme for any business on the energy production market including specific requirements on the radiation shield, wastes management and nonproliferation.

For example we recognize as inappropriate to directly bury the fuel with plutonium because in that case it will be not easy how to guarantee for long time that all plutonium initially has been put in depositary.

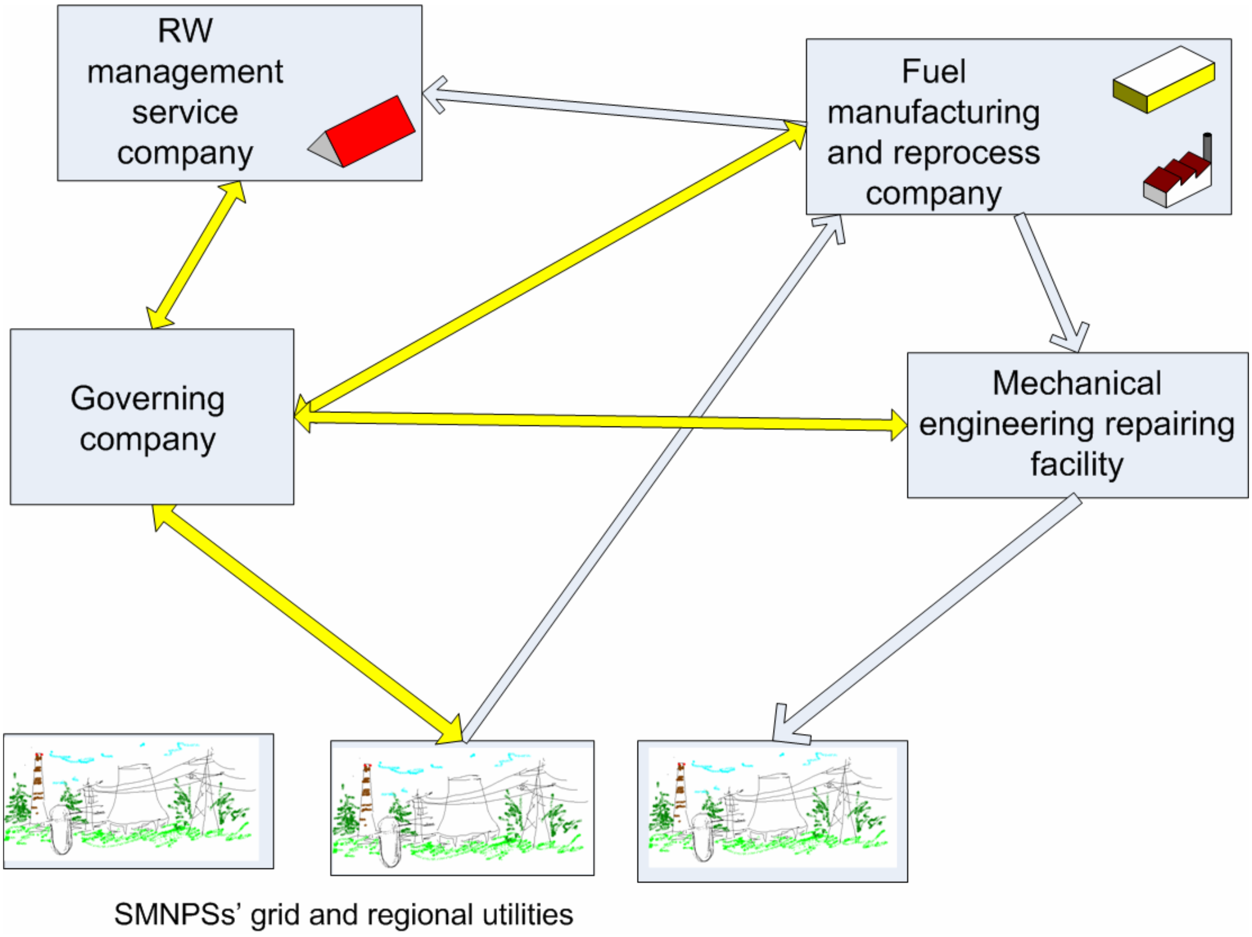

Figure 1 Principle scheme of the organization chart of the small power installations system

On the figure all yellow arrows are the directions of responsibility but another one are the directions of material resources transferring or services.

Looking on the figure we can see that the connection on the material and service flows are not the same with the links on governing.

Talking by another, words we can indicate the graph of the governing structure (control of the business and risk management) and graph (gray lines) of the engineering processes. They are not coincided!

Expected scale of the system of the small power NPP grow

What can be the potential mission of the small power system? Regarding to the Russia they can be applied for the Far North exploration and for crude oil extraction in the Siberian regions and also in the Arctic region. The potential here is evaluated as huge because the Russian North is about 2/3 of territories; 8 % of the population; 25 % of filling of treasury, including 60 % of currency; mid-annual delivery - 2,8 million т mineral oil and 3,8 million т coal. It is unique strategic stocks of mineral resources are concentrated to the territories of the Far North (including about 70 % of oil and 90 % of gas).

At a small share of a zone of the North in gross output of the country its relative density on branches of a mining industry more than 15 %, and by separate kinds - 50 % and more. Meanwhile the circle of mastered resources is limited only to the most valuable. In this case the system of small power NPP can be used for the followed applications

- Production of the potable water in the coastal areas with deficiency of fresh water;
- Production of the district and process heat for small settlements;
- They can be implemented for agriculture production processing and keeping;
- Production of electricity for small and medium sized towns, villages etc;
- Production of hydrogen by using of natural gas and coal for subsequent use it in chemical industry, far heat transfer and for motor fuel (including artificial gasoline);
- Successful solution of the problem of the organizing of the power systems includes the formulation of the adequate vision of the organization chart of the system (see figure).

For the analysis of the system of the NPPs we can use the method which is based on classical system analysis.

A systematic analysis is a common practice in scientific researches in any areas and especially if group's work are required.

The systematic analysis almost is the base of methodology of something studying (in this case of nuclear engineering development) and in this case methodology is not traditional scientific product or, in other words, new knowledge. Methodology is product, which are made only once for this or another studied object. Methodology is, rather, technique of mind organization.

The next product of systematic analysis is establishing (or definition) of abstract image of researched system.

And this image should reflect both images of elements (or subsystems) of analyzed system, definition of connection and interaction between elements and, mostly important for dynamic modeling, rules of elements composition.

Next step which made by most researches is fitting of abstract model to studied system by selection of coefficients and degrees or capacities of each connections. But almost nobody guesses to stop on previous stage and does not immediately analyze real system but stays even just abstract level and seeks where are analogies among various systems, which are similar on their abstract stage and has different nature. Finding of analogous systems allows to avoid extra efforts for researches of parameters or regimes which already studied in another (similar by systematic organization scheme but of different nature).

Before trying to find analogy it's necessary to define elements of system, their connections and they allowable connection – i.e. rules of composition. This definition should be made formally and should have such attributes as completeness and trustworthy.

Also in this presentation there is attempt to define the base of use an analogy between nuclear power systems development and sustainable development of biological systems. But here I limit these analogies only on formal description level.

Indeed, while number of countries who develop nuclear power is not large there is a theoretical opportunity to guarantee of meeting of requirements on non proliferation only by physical protection and inspections. But grow of complete install capacity of global nuclear energy system will give new complexity and variety of objects and their combination that further control would became ineffective.

The next difference between existed and future innovative systems is needs for last to change the radioactive wastes and spent fuel management's strategies. At this time almost everywhere it is applied only precipitation of fuel complete reprocessing and final RW disposition. Thinking about and developing big scale nuclear power we will have to solve the problem (all problems) of RW management and their final burial. We also should be put new "play rules" and new rules international relation about nuclear wastes and spent fuel taking into account a great scale of future energy.

Nuclear energy is implemented on the already established market and must be harmonized with the existing energy technology processes. As a sub-system of the general energy system, nuclear power industry uses natural raw resources (uranium), natural heat discharge resource and an artificial resource – compensatory capability of a large energy system. Here also belongs the technological resource – possibilities and costs related to manufacturing the equipment, which ensures the required efficiency of energy conversion.

Thus, the actual nuclear energy resources consist of the following objects:

- nuclear raw materials: heavy nuclei – uranium and thorium;
- means supporting the chain fission reaction: nuclei with high “neutron potential” – U-235, Pu-239, 241, U-233;
- mineral raw materials needed for creating nuclear reactors and energy converters;
- assimilation capabilities of environment type (in the given context, we understand “development” as the growth of potential possibilities of providing adequate reaction to changing external conditions):
    - ability of resisting radiation burdens and impact of new elements (!) – plutonium, curium, americium and other high actinides;
    - ability to remove discharged heat;
    - ability of long-term unsupervised safe storage of radwaste;
- assimilation capabilities of environment type 2 (technical complex):
    - ability to compensate the changes of energy source capacity – availability of reserves, global network, or energy accumulation in an energy-capacious product;
    - conformity of the general technical level with the requirements of safety culture and energy system management (social & cultural resource).

For complete accounting of the radioactive materials threat we use the next formula, which includes the activity of nuclides and reliability of safety barriers:

$$\frac{1}{G_0}\sum G_i \cdot \left(\frac{\lambda_i+\Delta}{\lambda_{U(Th)}+\Delta}\right)\omega_i \le 1 , \qquad (1)$$

Where: G_0 is the amount of the consumed uranium (thorium); G_i is the production of artificial nuclide of *i-th* type; ω_i is the probability of penetration through barriers and drawing of harm; λ_i is a constant of natural disappearance of nay artificial nuclides of *i-th* type; $\lambda_{U(Th)}$ is a constant of disintegration of the raw nuclide; Δ is system factor of discounting (definition and explanation is given later).

The discount coefficient rises upon the recommendation of ICRS on the changing from collective occupation dose to the risks factors (see figure).

Figure 2 basic recommendations on radiation shield evaluation

IAEA and Commission on radiation shield recommend to evaluate the quality of engineering solution by risks and last, in their order, can be discounted as all risks in economics. Therefore in the formula (1) we should add the “discount rate”

The similar resource list characterizes the application of any other technology, thus, we can compare our systems with existed systems of another nature. For example, let consider the biological and artificial objects of different origination (see figure).

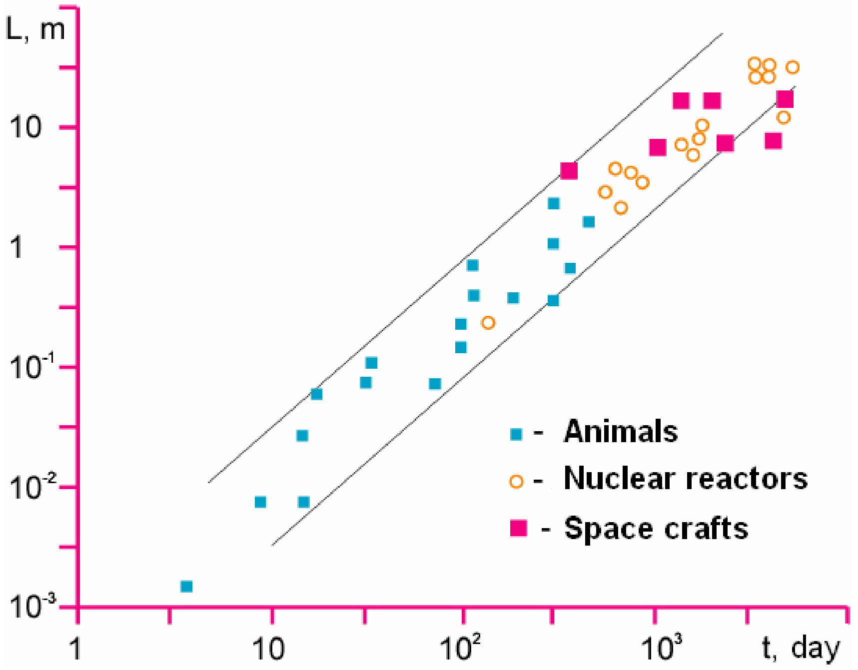

Figure 3 Existed in nature scales of the various objects

The figure describes the scale of various objects but in pour case we can us it as a recommendation what kind of reactor design take into account in the future energy systems.

The next step is to evaluate the proposal number of units and their capacity. The capacity of "battery type" reactors can be evaluated on the base of radiation shield requirements. For example we should substantiate the 12 mkSv per hour on the surface of cask for reactor fuel (or reactor) transportation. From the next hand we should forecast the opportunity of the reactor after shutdown during its transportation.

In the case of lifetime performance about 20 years its capacity should around 120 MW (thermal) to supply the dose and heat removing by natural convection of air.

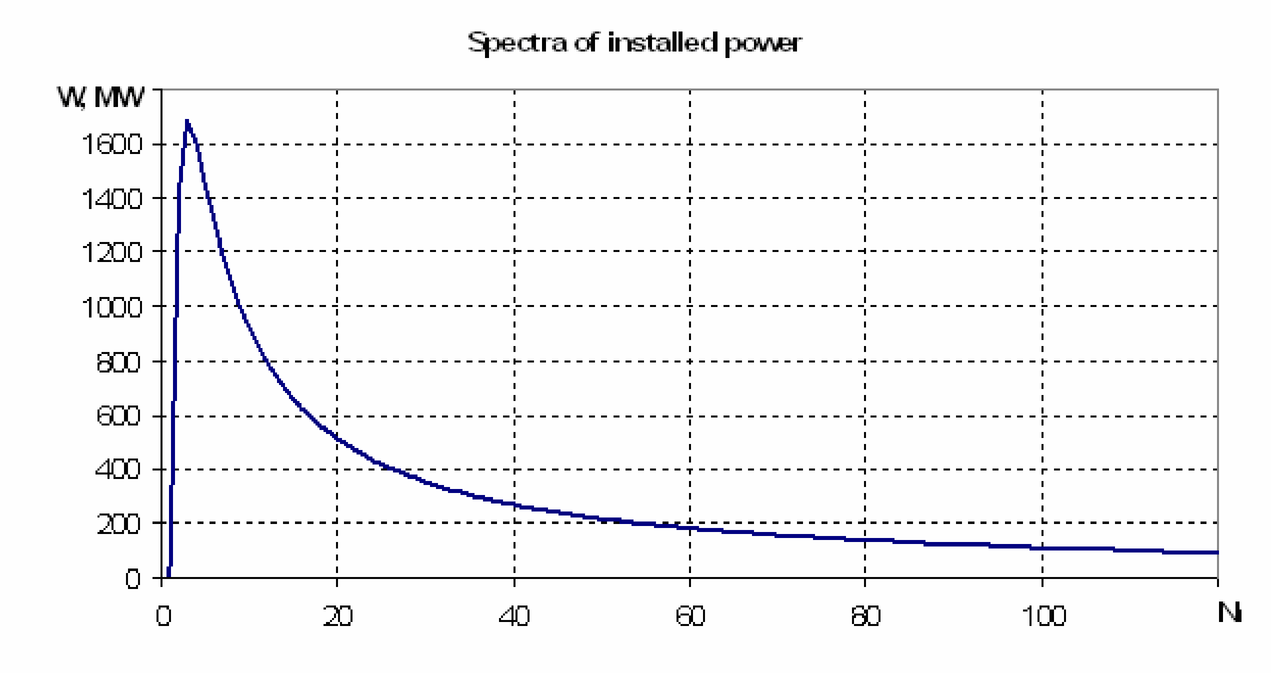

Figure 4 Spectra of nuclear power installations

Spectra of secure and sustainable power installation for electricity production in Russia can be presented by followed curve. In this curve we see two regions for deploy of small power systems. The first one is the field of small numbers of installation and should be recognized as experimental facilities. The second one is the field with expected number of units is about hundred. In our case where we consider "battery types" reactors up to 120 MW their number is about 95-100 units while total installed capacity is 11.5-12 GW.

Governing by presented above curve with lifetime of various specimens we can put the required (for sustainability) company of each battery around 20 years.

Specific of far settlements (where the small power systems are intended for deployment) dictates need to remove the battery not later than after 10 years of complete it's shut down.

Thus we have frames where systems of small reactors are viable.

Brief requirements to and candidates on small power installations

Let described on qualitative level the requirements to building of the small “battery type” reactors systems.

First of all remain the definition of intuitively clear term “battery type”. Battery is a very simple for using but rather complex for production unit, which can be bought on the market and does not require sophisticated and complex procedures on its switch on and off. The one thing is needed is to turn back the spent “battery” on utilization to specialized company.

Thus “battery type” can be qualified as:

- It is simple in operation, switch on and off;
- It is rather cheap (reasonable for the region and condition of application);
- There is service infrastructure for service of “batteries” and their removing and utilization.

The present work is investigation of the last service structure and requirements to small power reactor set by service enterprises.

We know well that there is plenty of the various proposals and designs of the nuclear reactor of the small and medium power [International Conference on Small Power Plants, Moscow, Small Energetics, 2005].

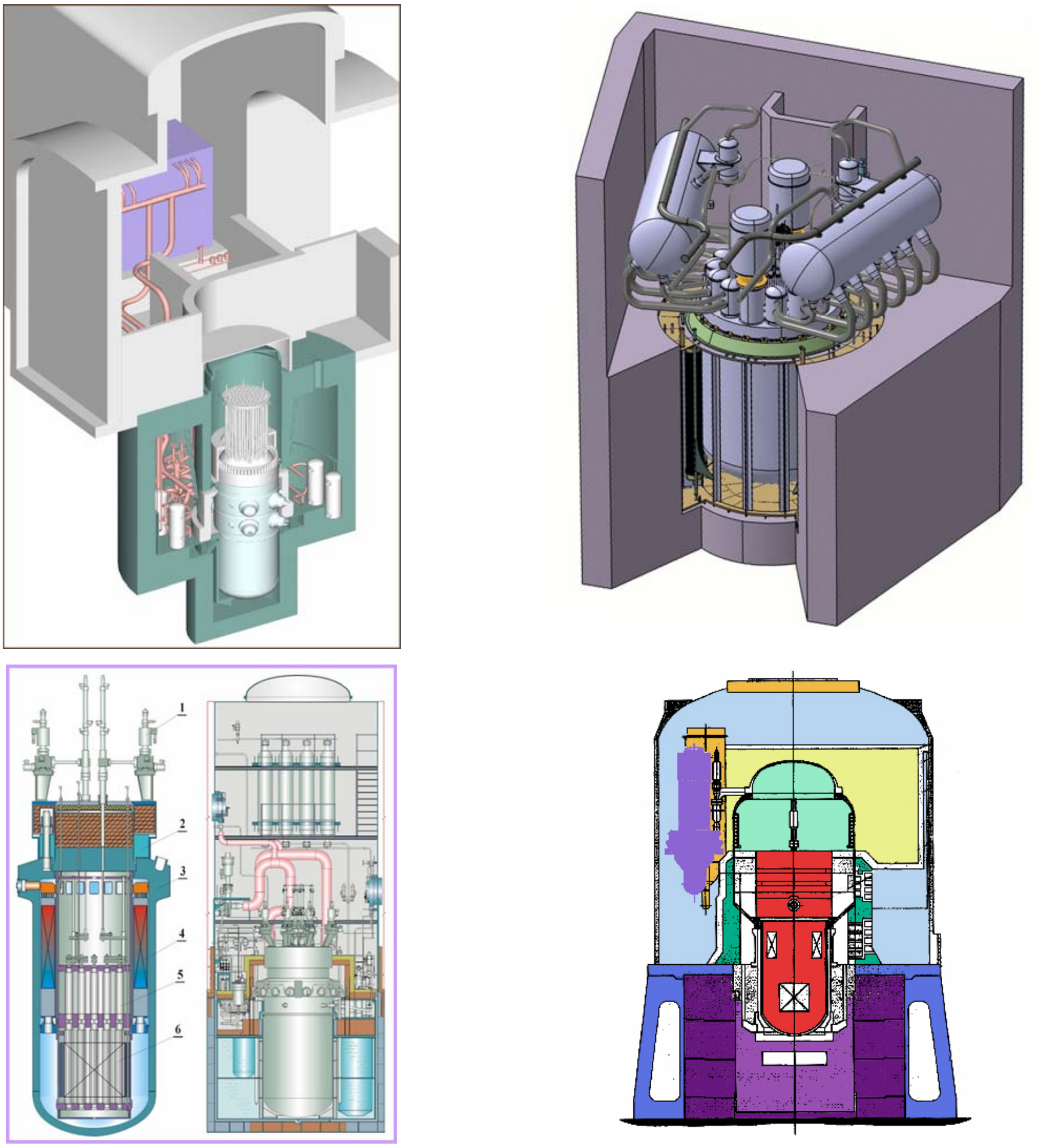

Figure 5 Nuclear reactors of small and medium power (on the material of the recent international meetings [RDIPE, IPPE, OKBM, Gidropress etc])

The main problem is how we can connect them in one network and what kind of requirements could be set by this network to each of elements.

The first restriction is the restriction on the efficiency of the fuel consumption and for

Why we should focused on the fast reactors and long lived autonomic systems. First of the all it is simplification of control because fast reactor has no transient poisons (and Xe or Rh “waves” or

"Sm death" effects). For long time operation it is important to reduce lost of neutrons in the capture on the structure materials and fission products.

Fast neutron spectra allow us to apply the high temperature materials such as nickel alloys or stainless steels with increased part of nickel, molybdenum or molybdenum-rhenium alloys etc.

Where is the application of high temperature materials essentially important? It is important in the hydrogen production high temperature systems.

Moreover, we should repeat, that prospective and viable system of small power nuclear power plants is not small itself and overall installed capacity of proposed system will measured by GW, therefore total consumption of the nuclear fuel and total fluent of nuclear materials in the system will be the same or even greater than in the "big nuclear energy".

In this case all question of fuel supplying are the same as in the case of full scale nuclear power plants and here we also should apply the fuel reprocessing and closing of the nuclear fuel cycle.

Nuclear fuel cycle modeling and consumption of the natural uranium

As it has been mentioned complete system should includes the actors of energy production (small power reactors); manufacturing of the reactors (production of the battery plant);

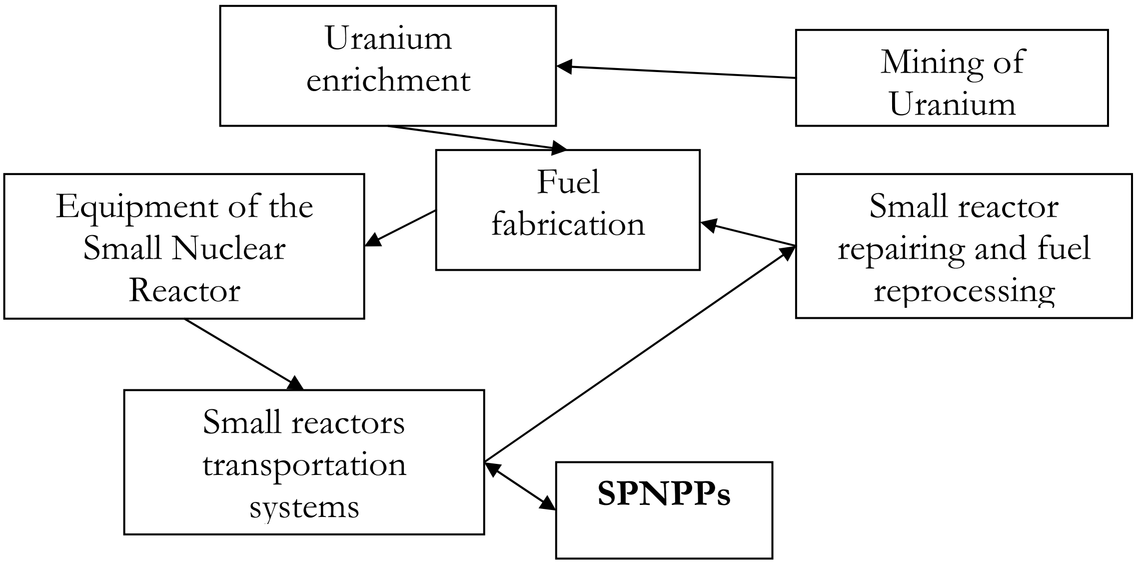

Figure 6 Principle scheme of the engineering structure of the small power installations system

Modeling of the system let evaluate the nuclides spectra that shows that for guarantee the nonproliferation we should use the coupled engineering and organization measures. And centralization of the small power systems service is the one of the organization measure.

Table 1 Fuel composition in equilibrium operation of the power generating system

	Nuclides	Part on mass
Urnium	U^{234}	0.13%
	U^{235}	2.01%
	U^{236}	1.20%
	U^{238}	82.25%

Plutonium	Pu^{238}	0.23%
	Pu^{239}	8.56%
	Pu^{240}	4.19%
	Pu^{241}	0.21%
	Pu^{242}	0.22%
	Np+MA	0.98%

Table 2 Integral parameters of the system and evaluation of the natural uranium consumption

	“Fresh”	SF
		Natural uranium consumption
BR=	87%	
fima=	10%	
x=	12.2%	9.7%

Long lived nuclear reactor required the significant reactivity margins for lifetime performance. Even in the case of fast reactor it is impossible in the small power system make the needs to reduce the initial reactivity.

It is not evident problem because the reactivity evolution through the company depends on the ratio of the condensed cross of the absorber and fuel:

$$\delta k(t) \sim (1-(1-BG)\times q\times t)^{\sigma_A/\sigma_{Pu}-1} \tag{2}$$

And there is only one way to increase the power ratio, it is the concept of thermal trap in molten salt reflector

The main idea of the concept is to divide the neutrons which valuable for chain reaction and the neutrons which are useful only for burning of the absorber (see figures below)

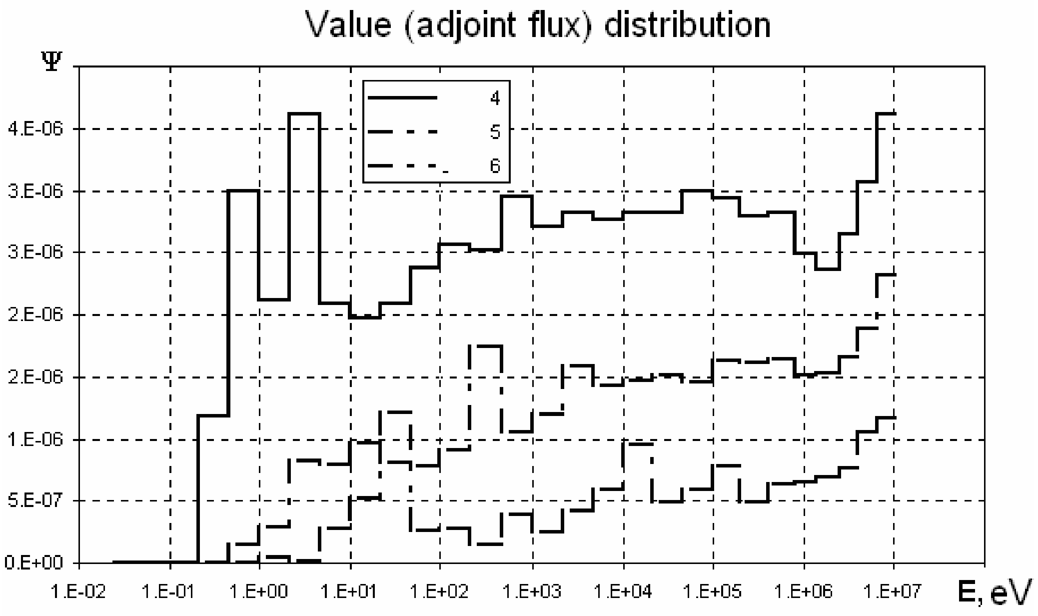

Figure 7 Importance of the neutron spectra per groups in the reflector

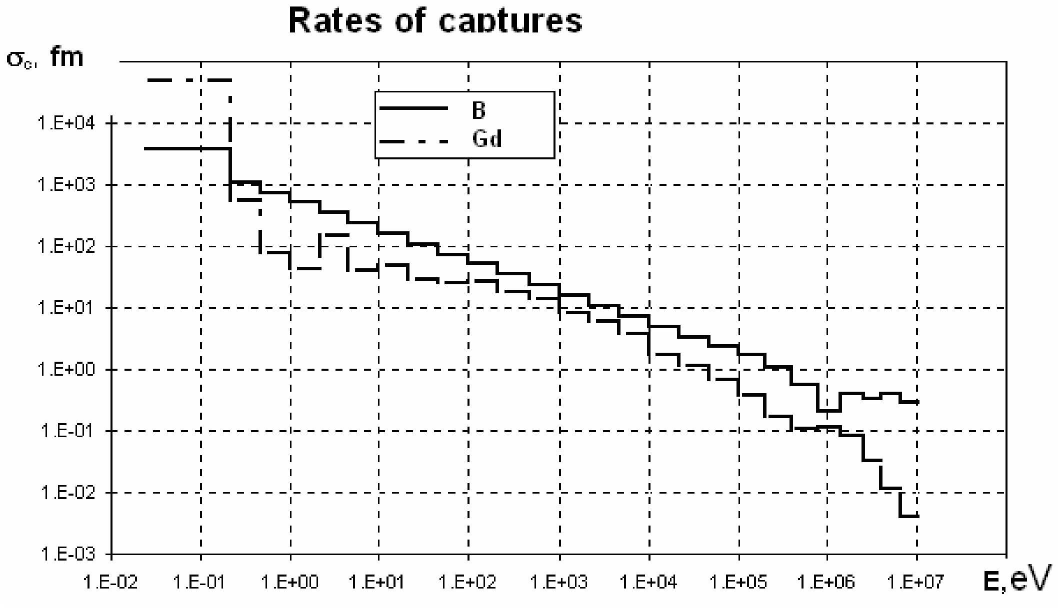

Figure 8 Cross section in the molten salt reflector of small FR

Comparing this figures we can see that for burning of absorbers (captures rates) is “responsible” other neutrons than for criticality (value distribution). Thus moderated in reflector block -in-core-

shield doesn't have an influence on chain reaction sustain but only remove external absorber. In its order absorber by reaction in the epithermal energy region reduce excess of reactivity.
Such technology of reactivity compensation can be used only for so-called physically small nuclear power reactors with:

- the high importance of leak neutrons (the significant weight of the reflector ~ percents in K_{ef});
- the big gap between zero and first eigenvalues of neutron transport operators.

For example, almost all fast neutron reactors with complete capacity up to 300 MW and gaseous or heavy metal coolant can be related to such set.

Expected overall value of the nuclear system service business

Typical cost and turn-over of service and fuel cycle business can be imagined and evaluated in n the base of the cost of Nuclear Submarines Utilization. As write Russian magazine "Energy" in the article "Cost of Utilization" (Vladislav Larin, #9, 2005) the overall cost storage of each nuclear submarine with shut down nuclear power installation on-board is about $100 k per year (in 1998-2000 years). Type, capacity and number of reactors is not sufficient because it is mostly expands on staff and the life-support and housekeeping systems.

The keeping of the engineering systems gives slightly differed estimations of expands from object to object. Thus (as wrote V.Larin) it has been got an information that some designs require complex engineering systems for safe them in safety manner and expands are grown by $ 150 k per year (may be up to $ 120 k per year).

Mr. Larin notes that origin of this difference can be explained not only by differences in design types but by leaks in the complete expands accounting. And in any case the lamp sum on storage of the spent nuclear power installation there is in the range of $ 120-280 k and the appropriate for analysis level could be taken of $ 200 k per year for one installation.

It is well known that average sum on the fuel reprocessing is about $ 1000 per kg of spent fuel.

One cask for fuel transportation has approximate cost about $ 150 k and its storage on the reprocessing plant will be about $ 10 k per year.

Transportation of the one cask with spent fuel takes about $ 260 k (evaluation for Nuclear Submarines by Mr.Larin)

Thus the overall trade-out of the service business in nuclear power systems can be evaluated in the ~ 100× ((10 yr × $200k/yr)+$260+$150+30 yr× $10k/yr+~10000kg/30yr× $1000k/kg) = $3b/yr

Conclusions

Battery type reactor should be simple in operation exploiting, construction (installation) and decommissioning. These properties can be reached by application of systematic approaches in designing of the nuclear reactor, by involving of all innovation in power conversion, such as supercritical heat converters, air turbines in Carnotized thermal cycle etc. Last way require tha the working of gas- turbine machines with gas temperature of 1300°C and using of the blade cooling. It gives the thermal efficiency about 60% and for modern innovative power systems is common technology. But for increasing of the heat conversion efficiency we can use another innovation, first of all connected with the application of supercritical water of carbon dioxide. Regarding to –steam conversion Russia has an engineering solution on the potential of working body about 540°C and efficient rate 50% and more ["Proposals of RRC KI on development of innovative nuclear reactors, fuel cycles and nuclear power systems for International program GENERATION-IV and International project INPRO". RRC KI report, # 35-17/140, 2002].

As the elements of power conversion can considered also the high temperature chemical technology application as hydrogen production or very long distance district heating with application of chemical-thermal transfer of heat by products of conversion reactions.

The system development predicts rising of the great complete installed power with all problems of fuel supplying and radioactive wastes burying. As well as it sits additional problems of nonproliferation guarantee.

Simplification of reactor system makes more acceptable the long lived reactor on fast neutron because it has not complex regimes of start-stop with poisons transients processes and even "samarium death". The fast reactor can keep the reactivity by the breeding of fuel.

Thus the preferable "battery type" reactor is high temperature reactor with fast neutron spectra, and so with gas or heavy metal coolant. Such reactor systems are very convenient for closing of the fuel cycle (because they make enough amount of fuel and can be fuelled by plutonium of second and third and other recycle).

Organization chart of the system includes the nuclear power plants, transport company, enterprises on reactor repairing and reprocessing, waste management and isolation, and governing company. But the governing company is responsible in full state for reliability of energy supplying, safety and radiation shield and for nonproliferation guarantee.

And the projecting (and expected) volume of the business will be around $3 billion/yr per 12 GW installed capacity.

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