WHAT ARE NEUTRONS NEEDED FOR

If you want to see an object, you have to illuminate it. If you want to discern details of an object, you will have to illuminate it with "light" of a wavelength equal to or smaller than the distance between the object details you are interested in. For most solids (or condensed media), such details of interest to physicists (for example, lattice sites, liquids, colloids, plastics, polymer and biological materials, etc.) lie from a few angstroms (10^{-8} cm) to tens nanometers distance from one another. This means that the "light" required for studying the such structures should have a wavelength of the same order. Such light does exist. It is X- and gamma rays, as well as beams of elementary particles, for instance, neutrons.

The exclusive role X- and gamma rays play in scientific research and everyday life is well known. Much less known among nonspecialists are the properties and advantages inherent in neutron radiation. At the same time they are quite significant.

First, neutrons, as particles having a mass, possess an energy much smaller than the X- or gamma rays with the same wavelength, and this energy becomes comparable with the energy of thermal vibrations of atoms and molecules in a substance, which offers a possibility of studying not only the averaged, static atomic structure of matter but the dynamic processes occurring in it as well.

Second, neutron possesses a magnetic moment, and this permits investigation of magnetic structures and magnetic excitations, which has turned out to be very important for understanding the nature of, and the processes occurring, for example, in such new and promising materials as high-temperature superconductors magnetic fluids and magnetic materials with the extraordinary properties, such as multiferroics, manganits cobaltits, ferrits, chiral magnetic structures etc. .

Third, neutrons interact with atomic nuclei rather than with electrons in atomic shells, as X- and gamma rays do, and this factor accounts for their significantly higher "contrast" (sensitivity) in discriminating among neighboring elements in the Periodic Table. This is particularly true for light elements (hydrogen, oxygen etc.), whose identification in solids containing heavy elements by conventional X- or gamma ray techniques meets with staggering difficulties, and which, if present in a material, may dominate its properties. More than that - neutrons can be used to probe even the isotope composition of matter.

Heavy nuclei can be split with neutrons. In this way, a number of still unknown processes which occur during atomic fission can be clarified. Neutrons can also be captured by nuclei. This process releases secondary radiation which can be used to determine the inner structure of these nuclei and also for identifying the element and isotope composition of matter (neutron activation and neutron radiation analisis).

So, neutron elastic scattering on gases, liquids and solid matter gives information about the structure of these materials. Neutron inelastic scattering with excitation of atoms, molecules or collective modes gives unique information about the binding energy within matter. Their property as 'small elementary magnets' makes neutrons an ideal probe for the determination `of structures and dynamics of unknown magnetic matter.

The dynamic properties of the matter are studied using inelastic scattering of the f polarized and nonpolarized neutrons. There are some kinds of devices called spectrometers used for these purposes, such as three-axis, time-of-flight, and high-resolution spin-echo spectrometers. Studies of structure (atomic and magnetic) of the materials are carried out by powder, single-crystal diffractometers, small-angle instruments, and reflectometers

Apart from this, neutrons are electrically neutral, and their interaction with nuclei is weak, which permits neutrons to penetrate deep into matter; this property of neutrons gives them an advantage over the X- and gamma rays, as well as beams of other, charged elementary particles.

These and other, not mentioned here, properties of neutron radiation make it a unique tool for probing condensed matter, and it can be used to advantage in various areas of science, such as physics, chemistry, biology, geology, materials science, to say nothing of its potential in medicine, industry, and other fields.

Note, however, that all these possibilities have not been provided by Nature, so to say, free of charge; indeed, building a good, modem source of neutron radiation is a very expensive endeavor, its cost amounting to hundreds of millions of US dollars.

Nevertheless, neither the trend to progress inherent in science, nor the vital needs of industry and national economy could permit any developed nation to reject the perspectives promised by the use of neutron methods in the investigation of matter, and, hence, the construction of neutron sources.

Now what kind and scale should be the source - that is another question. The answer to it is determined by the specific capabilities of a given country, namely, by the level of its scientific and technological potential, available finances, and personnel, essential not only in the design and construction stage but in the course of using the source as well.

The concept accepted presently universally consists in that each developed region in the world should have at least one high-power (high-flux) neutron source (in a supranational-scale center), complemented by a network of medium-power sources located in national centers of the countries in this region. In Western Europe, such a supranational source is the high-flux reactor HFR at the Institut Laue-Langevin (Grenoble, France), which has been successfully used for many years not only by the European countries but by the World community as well.

The East-European and Asiatic region does not yet have such a source, although medium-power national sources have been already operated successfully and for a long time by different countries in the region. The possibilities offered by these sources are, however, limited.

At the same time the experience gained during the nearly 40 years of HFR operation in Grenoble, and particularly its unplanned shutdown in 1991, have shown convincingly that one high-flux neutron source is certainly too little for the world.

NEUTRON SOURCES: PRESENT SITUATION

The efficiency of neutron methods is determined to a considerable extent by the quality of the available neutron-radiation sources, primarily by their neutron flux density. In this context, it is instructive to analyze the current situation in the world.

The main type of neutron source employed presently is still the nuclear reactor, i.e. a continuous source using the chain reaction of uranium fission for neutron production. The modern spallation-sources based on knocking neutrons out of a heavy target by fast protons have certain advantages in some studies (they operate in pulsed mode and have a very high flux in a pulse), their lower average flux compared with a reactor does not make them really, particularly if one takes into account the comparatively much higher their construction and operating cost. One should consider them as not competitive but complemetary instrument for matter study.

About twenty years ago, there were in the world more than 300 research reactors, which were used primarily in materials science studies, i.e. for sample irradiation, and for production of radionuclides. The number of reactors designed specifically for physical research, i.e. providing neutron beams, did not exceed 100. About 25 of them had a flux density at the level of 10^{14} n/cm^{2}s, and only two (one in USA, in Oakridge, Tennessee, and one in Europe, certainly the best, at the international Institut Laue-Langevin) with a density of ~ 10^{15} n/cm^{2}s.

The 1980s have witnessed a trend to a reduction of the number of reactors through decommissioning of low-power and outdated machines, which have reached the end of their service life. The reactors of a new generation intended to replace them were equipped by modem systems, such as sources of cold, ultracold and hot neutrons and neutron guides, which permit obtaining and leading out beams of neutrons of a given energy.

During last ten years new reactors in Germany, Japan, Korea, Australia and Egypt were commissioned, some reactors in France, USA, Hungary, and Poland were upgraded, and several research reactors in Canada, China, Iran etc. are presently in the stage of design or construction. But all of them are medium-power installations (national sources). Only one high-flux reactor project existed at the time in the fairly advanced stage of development. That is PIK reactor project at the Petersburg Nuclear Physics Institute (Russia), which is presently in the stage of completion.

As we shall see below, the beam parameters and experimental capabilities of the PIK reactor are such that its commissioning would permit us not only satisfy the needs of our country in neutrons, but also set up around it an international center for neutron studies of the type of the ILL facilities which have been used successfully already for more than three decades.

One should notice that the current European Neutron Scattering community expressed a need for additional neutron beam time at High Flux Reactors and Spallation Sources amounting to an increase in demand of 78%. This latter figure is broadly in-line with estimates by ISIS and ILL of an over-subscription factor of approximately two for beam time. A need for a further 18% of beam time at Medium and Low Flux reactors was also identified. So there is an identified need, based on existing demand, for at least a doubling of available beam time on High Flux Reactor and Spallation neutron sources (or pulsed neutron sources, as IBR-2 reactor in Dubna).

PIK REACTOR: CHARACTERISTICS AND POTENTIAL

From the standpoint of its characteristics and experimental capabilities, the high-flux research neutron-beam reactor PIK is not inferior, and in some aspects, even superior to HFR at Institut Laue-Langevin, presently the best research reactor in the world.

The main concepts underlying the technical project were formulated as far back as the late 1960s (practically at the time of the Grenoble project), but its construction was started only in 1976, when the Grenoble reactor was already put in operation.

By 1986, the original project was completed to about 70%, but after this (after the Chernobyl disaster) the construction was practically frozen to bring the project in compliance with the revised nuclear safety requirements. The revised project was approved only in 1990, when our country found itself faced by grave economic problems.

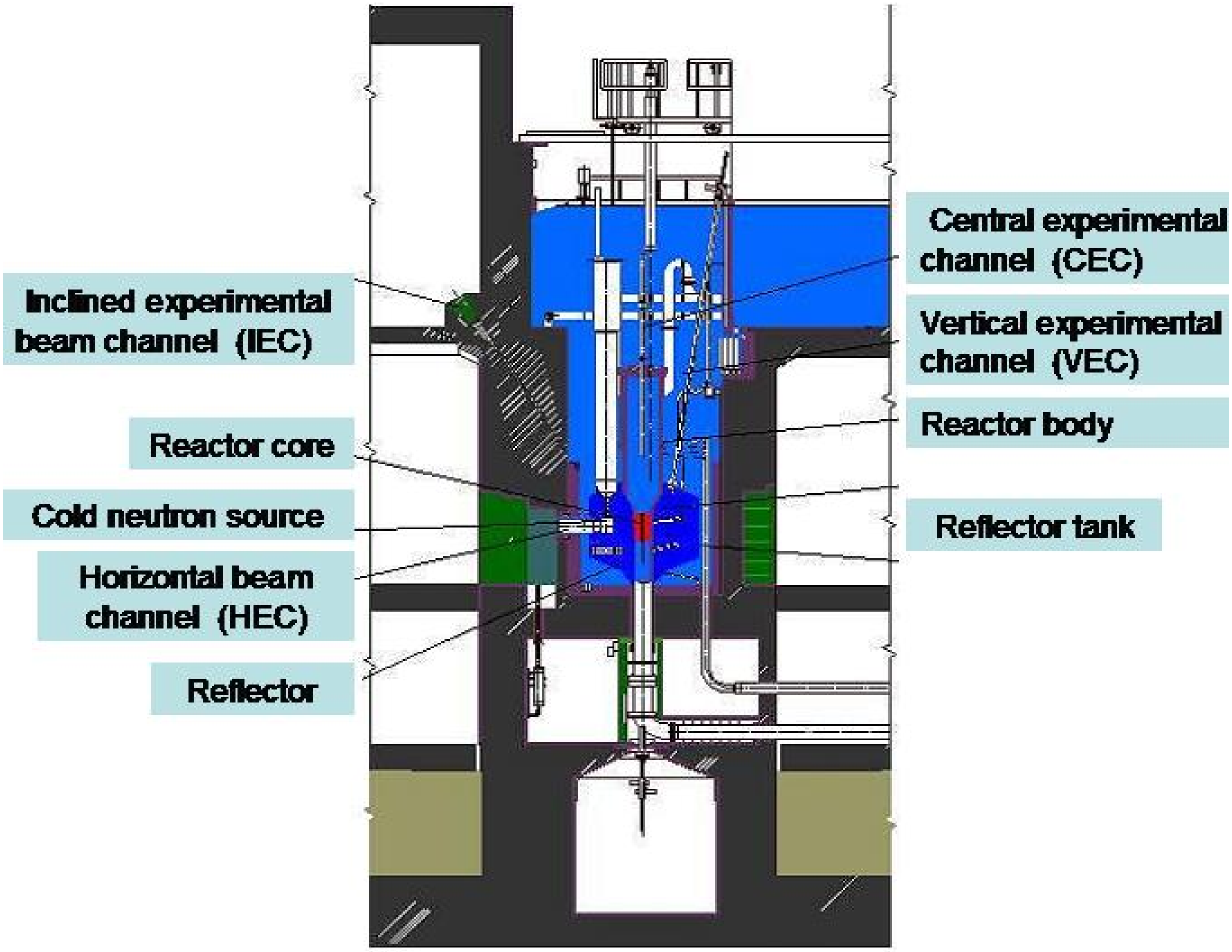
The PIK reactor represents a compact neutron source (core volume 50 l) surrounded by a heavy-water reflector. It is fueled by Uranium-235 (enriched to 90%) of total weight ~ 27 kg. Light water is used both as coolant and as moderator.

The design parameters:

- thermal power 100 MW,
- thermal-neutron flux: in reflector - 1.2x10^{15} n/cm^{2}s, in 10 cm-dia. central channel - 4.5x10^{15} n/cm^{2}s, i.e. four times higher (the Grenoble reactor is not provided by such a channel,
- number of horizontal beam-tubes - 10. Channel diameter - 10 cm, with a possibility of replacement by a 25-cm dia. channel,
- number of inclined beam channels - 6,
- number of vertical thimbles for sample irradiation - 6.

The reactor will by provided by sources of hot, cold (2), and ultracold neutrons to make available neutron beams in different energy ranges.

A low-temperature loop will permit sample irradiation at helium temperatures.

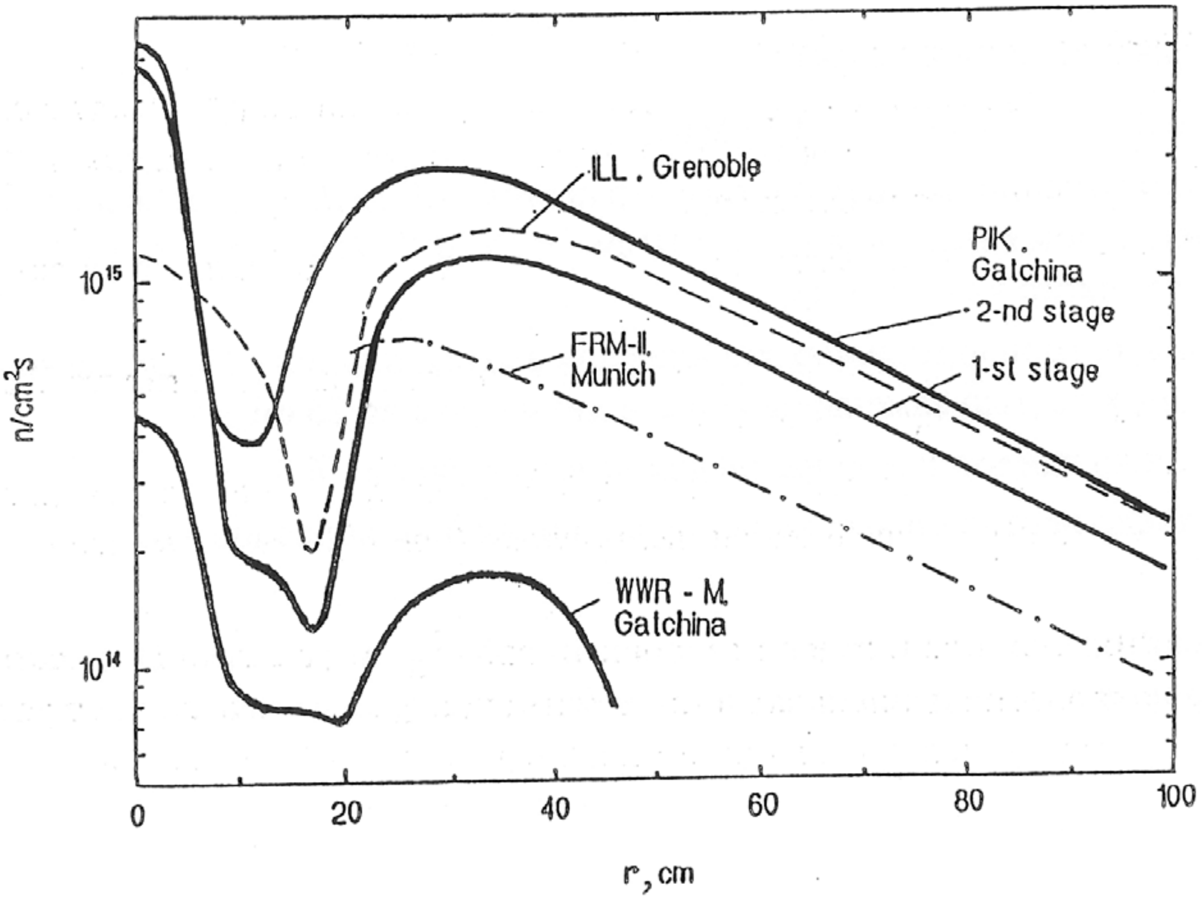


A system of neutron guides (four for the cold, and four for thermal neutrons) of total length 300 m will provide operation with external beams in zero-background conditions of the neutron guide hall adjoining the reactor building.

The total number of work stations for location of experimental setups is as large as 50 (in Grenoble, there are 40 of them presently), which will permit simultaneous operation of 50 groups; in other words, many hundreds of researchers could profit from carrying out their experiments (in Grenoble, more than 800 experiments selected by a scientific review committee are performed annually).

Despite the long period taken up by its construction, the project (after its revision) meets the highest world standards, which has been confirmed by a technical appraisal carried out in 1993 by leading specialists from USA, France, Germany, Great Britain, and EC Committee. The comments of the experts aimed at bringing the project in compliance with the universally accepted nuclear safety requirements have been carefully analyzed, and the corresponding technical solutions implemented. The project has been approved by all organizations exercising State supervision over the construction and operation of objects presenting radiation hazard, including State Committee for Ecology.

Presented below is a graph of thermal-neutron flux-density distribution in the PIK reactor and the HFR reactor in Grenoble. Also shown for comparison are the graphs for the currently operating WWR-M reactor at PNPI and for the FRM-II reactor in Munich (Germany), the best of the new projects approved for building.



PIK REACTOR:

Research program and experimental facilities

From the very beginning, the PIK reactor was conceived as a high-level installation on a state scale (we have in mind the scale of the former USSR), intended to satisfy the needs of research in various areas of science. This can be readily seen from the scientific program below, which was approved by many national and international committees and meetings.

Physics of condensed states:

- crystalline and magnetic structure,
- atomic and spin dynamics,
- phase transitions,
- behavior of matter in extremal conditions,
- (studies on crystals, polymers, amorphous solids, liquids,
- high-temperature superconductors, fullerenes etc).

Structural and radiation biology and biophysics.

Radiation physics and chemistry.

Nuclear and elementary particle physics:

- fundamental properties of the neutron,
- neutrino physics,
- physics of nuclear fission,
- neutron-proton, neutron-neutron, and neutron-nucleus interactions,
- nuclear spectroscopy.

Materials science.

These areas cover the problems of all scientific groups in Russia interested in using neutron methods, and the broad experimental capabilities of the PIK reactor can be adapted to suit scientific interests of our foreign partners.

Everything is determined here by the existence of, and access to, experimental facilities which would be adequate to a given problem. The PNPI, aided by a number of other Russian Institutes, is working on building these facilities.

This relates primarily to the equipment and systems intended for joint use, such as neutron sources for different parts of the energy spectrum (thermal, hot, cold, ultracold), neutron guides, helium ducts, monochromators, polarizers etc.

We have developed and mastered the production of modem neutron optics systems, namely, conventional, focusing, and polarizing neutron guides, neutron spin flip systems, precision, including three-dimensional, polarization analysis. These techniques are currently used in both Russian and foreign laboratories. The nuclear detector and physical electronics departments are capable of equipping experimental setups with high-quality instruments. The instrumentation developed at the Institute is well known to our foreign colleagues who place many orders for instruments at our Institute.

In most research areas in the physics of condensed state, success is determined not by one instrument but rather by a set of instruments (spectrometers, diffractometers etc.) permitting investigation of various characteristics of a sample. Development of such a set comprising about 25 instruments is planned to be pursued during the years left until the PIK is put in operation. Some of them have already been built and are presently being used at our old medium-flux WWR-M reactor and in some foreign centers (France, Germany, Hungary, Egypt etc.).

In the field of nuclear physics, a number of unique installations for operation with ultracold and polarized cold neutrons have been constructed, which permit obtaining, even at the medium-flux levels of the WWR-M, world-class results in studies of the symmetry properties in elementary-particle interactions, and of the fundamental characteristics and decay correlations of the neutron (these studies are well known and widely recognized by the world scientific community).

The general situation in this area is in the stage where, should the PIK reactor be commissioned tomorrow, nearly half of the beam stations could be occupied by the already available installations. The free stations left could be offered to users chosen.

PIK REACTOR:

possibilities for applied work

The unique properties of the neutron and the vast irradiation potential of the PIK reactor can be used to advantage for applied work, as this is illustrated by the examples given below.

I. Production of doped silicon

The demand of electronics industry in doped silicon for production of power valves and large-scale integrated circuits is well known, just as the high efficiency of the use of neutrons for the purpose of doping. The world demand for doped silicon with ingot diameters of 150 mm or more is about 100 tons/y. Setting up industrial-scale production of neutron-doped silicon on a reactor already in use would meet with formidable difficulties for a number of reasons of purely technical nature.

The PIK reactor, with its large-volume reflector, a high and uniform thermal-neutron flux, and a possibility of installing a beam-tube with up to 250 mm in diameter, offers an excellent opportunity for organization of such production. The output could be as high as-50 tons/y.

2. Purification and upgrading of heavy water (D_2O)

Heavy water is used primarily in nuclear power production. Its production from natural raw materials being very energy-consuming, heavy water costs 200-250 USD/kg.

At the same time some countries have accumulated large amounts of D_2O contaminated by tritium and with a low deuterium content. The problem is aggravated by the need of regenerating eliminated nuclear warheads, a process producing heavy-water wastes which are usually contaminated by tritium. Development of a technique of deep purification of heavy-water from tritium and of its enrichment in deuterium, as well as its implementation on an industrial scale promise a significant profit, not to mention the ecological aspects of the problem.

The PNPI has developed an original technique for this process, which has already been tested at pilot plants. An operating project for a large-scale plant of this type has been made. This project is of considerable independent interest and can be analyzed separately from the PIK. Implementation of this project would require capital investments at a level of 12 million USD. The output of such a plant (which is actually a factory) is ~ 60 tons/y of high-quality heavy water with a tritium content of about 4×10^{-6} Curie/kg and D_2O concentration of- 99.8%.

Before the PIK startup and during the first three years of its operation, all this output and, subsequently, after that time about one half of it could be supplied to any Customer on the side.

The funds invested into the construction, including the costs of the raw materials and operation, would be recouped in about three years.

3. Production of radioactive isotopes

The demand for radioisotopes and tagged compounds for medicine and industry is ever increasing while the number of their producers decreases steadily, following the decreasing number of neutron sources suitable for these purposes.

Putting the PIK reactor possessing such a high irradiation potential in operation, the availability at the PNPI site of a cyclotron and of a hot-chamber building, of highly qualified physicists and radiochemists among the personnel of PNPI and of the Radium Institute offer promising prospects for setting up radioisotope production here.

4. Neutron activation analysis

It would be difficult to overestimate the role of neutron activation analysis in ecology, mining industry, production of rare and precious metals, and of all kinds of new materials created by technologists. Specialists believe that any country has to make annually hundreds of thousands of analyses. To be able to do this, however, one has to have neutrons, and the more analyses have to be performed, the more neutrons will be required. The PIK reactor cannot naturally solve this problem alone, but it is capable of providing a very substantial contribution.

The above examples do not naturally exhaust all problems of applied nature that are solvable with neutrons, and were meant simply to illustrate the potential of the PIK. One could add here nondestructive testing and stress study in constructions and materials, neutron therapy in oncology, and many other fields of possible applications.

REACTOR PIK

AS A BASIS FOR AN

INTERNATIONAL NEUTRON RESEARCH CENTER

The neutron beam parameters and the experimental potential of the PIK reactor are indeed unique; as already mentioned, they are comparable only to those of the Institut Laue-Langevin (ILL) at Grenoble, and will not apparently be available anywhere in the world for the nearest 10-15 years.

At the same time the demand for neutrons for both scientific research and applications is growing. This is evidenced by an ever increasing interest in neutron techniques revealed in industrial laboratories all over the world. This is suggested also by the ever more stringent competition reactor experiment proposals meet at Grenoble. By an apt remark of a leading neutron physicist, there are indications of a "neutron drought" in the world, which become increasingly apparent.

Several international meetings on the PIK program held at PNPI and numerous discussions with leading foreign scientists have shown that the PIK reactor simply must be commissioned in a reasonable time (3-4 years).

There are all necessary prerequisites for this, including the available living conditions.

The Petersburg Nuclear Physics Institute is already well known all over the world. It is one of the largest Institutes of the Russian Academy of Sciences, with more than 2000 people on the stuff, including 70 Professors and more than 300 Doctors of science. The research is focused primarily on nuclear and elementary-particle physics, physics of condensed state, molecular and radiation biophysics, and physics of reactors and accelerators. The PNPI was awarded the status of State Research Center of the Russian Federation.

The Institute is located in a beautiful wooded area, three km away from Gatchina.

The closeness to St. Petersburg (43 km), the world-famed center of science and culture, with its numerous research institutes, universities, theaters and museums, its unique palaces provides wonderful possibilities for work and recreation.

The closeness to an International airport (25 km), a well-developed network of railroads, highways, and sea routes provide a convenient answer to any transportation problem.

The Institute has a developed infrastructure, including its own hotel to accommodate 100 guests, a wonderful sporting complex with a swimming pool and game halls, a restaurant-diner, and an outpatient's polyclinic. If this is complemented by a conference center whose project has been completed, and a few cottages for scientists coming with families to stay here for a prolonged period, the living conditions will meet world's standards.

On the other hand, construction of an International center of such a scale and level will be in line with the best traditions of St. Petersburg and the trend of Russia's integration into the world community.

Science, particularly fundamental science, does not recognize state boundaries. Its achievements belong to Mankind. Therefore the proposal to join efforts in constructing a world-class facility for use by all nations appears to conform with the goals of the international scientific community and with the spirit of the world we live in.

First variant was written by V.A.Nazarenko in 1995 and translated by I.A.Kondurov.
Last revised by V.V.Fedorov, 2009