

Atomic Physics and Atomic Industry in Ukraine

Outline of History and Present

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Introduction

In 1920, a young Ukrainian National Republic (UNR) lost its independence and two years later *de jure* became a part of the Soviet Union (USSR). All the time since then and until 1991, when Ukraine regained its statehood after the collapse of the USSR, it was in effect one of the provinces of a huge empire, in which all economic, political, social and other decisions were taken in Moscow, the ultimate goal of these decisions apparently having been USSR world domination. The role of regions - such as Ukraine - was to supply the necessary resources and work force.

USSR's atomic project was at the core of the policy of Soviet hegemony - it was run from Moscow by the omnipotent Central Communist Party Committee (read as Stalin, until his death in 1953) and the KGB, in strict secrecy. The major part of important documents on the Soviet atomic project, stored in archives in Russia, is still classified and will hardly be made public in the foreseeable future. However, general information has been published in recent years, and it is quite sufficient for the writing of this outline of the history of atomic industry in Ukraine.

Soviet atomic industry's scientific and educational potential was (and still is) located mainly in Moscow and its vicinities, and partly deep in Russian territory, near the Urals and in Siberia. However, main research activities on atomic physics in the early years of its development (before WWII) were concentrated in Leningrad (Physical Technical Institute headed by Prof. Ioffe) and partly in Kharkiv. Either due to the Soviet Government's a Russian leaders' gift of foresight, or merely due to the fact that it was easier to hide the atomic project's huge production facilities (with their multi-thousand-people labor camps around them) in Siberia, just a fraction of atomic facilities, and none of the most important ones (e.g. uranium enrichment, plutonium production or warhead design) were located on Ukrainian territory. While reactor production was concentrated in Russia (including the major undertaking of the Soviet epoch - the "Atomash" plant near Volgograd), nuclear power plants were built not only in the Russian Federation (31 reactors on 10 sites are still in operation), but also in several Soviet Socialist Republics (Kazakhstan, Ukraine, Armenia, Lithuania). Many of them are still in operation.

The history of Ukrainian atomic physics was not the same as the history of the Soviet atomic industry. The Academy of Science of Ukraine, which was created in 1918 in Kyiv during the short period of existence of Ukrainian National Republic, was quite independent from the communist government until the early 30ies; only then was it subjected to the rule of the Government and later - to the Academy of Science of the USSR (which was created in 1925 from the Russian Academy, and moved from Leningrad to Moscow in 1936). After that the Academy of Science of Ukrainian SSR played an inferior role, working on the problems which were formulated by the Soviet Government (and the Academy of Science of the USSR) in Moscow. Ukrainian Academy's funding was extremely limited. However, several institutes and a university, which were located in Kharkiv, had better opportunities for staffing and better funding for research in natural sciences, including physics. Kharkiv was a capital of Ukrainian SSR during the period of 1919-1934; Kharkiv is located some 700 km SE of Moscow, very close to the ethnic Russian territory - so it was considered less "nationalistic" than Kyiv.

In this paper we will not discuss the issues of Chernobyl NPP disaster and its consequences, because there are plenty of publications which look at them from perhaps every thinkable angle. Ukrainian atomic industry and science were not independent, so below we put a very brief timeline of the Soviet atomic project and atomic industry. Of course, we pay more attention to events that occurred on Ukrainian territory. We close the table at 1991, when Ukraine declared its independence and the USSR disintegrated.

Timeline: Soviet Atomic Science and Atomic Industry

Information related to Ukraine is in **bold**.

1918	24 September. The State Rentgenological and Radiological Institute founded in Petrograd (Leningrad). The Head of Physical-technical department - Prof. A.Ioffe.
1928	Ukrainian Physical Technical Institute (UPTI) founded in Kharkiv
1932	A special group for investigation of atomic nucleus was created in Leningrad Physical Technical Institute (LPTI). 10 October. A group of UPTI scientists (Leypunsky, Sinelnikov, Valter, Latyshev) for the first time in the USSR split lithium nucleus using a particle accelerator.
1937	The first in Europe cyclotron was started at Radium Institute (Leningrad). The 2.5 MeV (energy of accelerated protons) Van-de-Graaf accelerator launched in UFTI (Kharkiv)
1939	Zeldovich, Khariton, Leipunsky proved the possibility of chain reaction in uranium. Commission on isotopes was created (chaired by V.I.Vernadsky, creator and President of the Ukrainian Academy of Science in 1918-1919). As the first steps, Commission initiated production of heavy water and work on separation of uranium isotopes.
1940	Commission on uranium created (chaired by V.G.Khlopin). Presidium of Academy of Science of USSR approves the program of the first soviet uranium project. Flerov and Petrzhak discover spontaneous fission of uranium nuclei.
1942	Stalin signs a decree "On organization of works on uranium", which resumed uranium-related investigations in LPTI. 27 November. State Committee of Defense orders start of works on geological exploration, production and processing of uranium ores.
1943	11 February. State Committee of Defense orders beginning of works for military use of atomic energy. 14 August. A large group of LPTI physicists (including Kurchatov, Alikhanov, Flerov) are ordered to move to Moscow for permanent work.
1945	20 August. A Special Committee for coordination uranium works created (chaired by NKVD Chief L.Beria). <i>During the year, the Soviet Union signed several agreements with Czechoslovakia, Bulgaria, Germany to create jointly operated uranium mines on territories of these countries. On the Soviet territory, first specialized factories for uranium processing and enrichment were established. The process of creation of huge industrial facilities for military and - later - peaceful atomic programs continued until late 50s.</i>
1946	8 April. A specialized design bureau for nuclear bomb construction is organized in Sarov town (later known also as Arzamas-16) in present-day Nizhegorodskaja oblast. <i>This was the first of at least 10 secret "closed" cities which were founded between 1946-1957 around specialized atomic industrial facilities (uranium enrichment, component manufacturing, plutonium production, weapons design etc.) At that time, workforce needed for these facilities ("numbered factories") and cities (tens of thousand for each one) was supplied by nearby concentration camps. Total population of these cities was over 700,000 in 2002.</i> 25 December. The first Soviet reactor (F-1) became critical at the Laboratory # 2 (currently Kurchatov Institute) in Moscow.
1947	14 August. The Council of Ministers of USSR decrees the construction of hydrometallurgical "Plant # 906" (later Pridneprovsky Chemical Plant) in the city of Dniprodzerzhynsk, Dnipropetrovsk oblast in Ukraine. This plant was intended for

	processing of ore from Pervomaiske and Zhovtorechenske uranium deposits (Ukraine) and uranium-rich blast-furnace slag. Later it processed up to 60 % of uranium ore produced in the Soviet Union.
1948	The first Soviet reactor for production of weapon-grade plutonium was launched at Plant # 817 (in the "closed" Ozersk city, Cheliabinsk oblast). More than 45,000 people (including inmates of concentration camps) worked at its construction site.
1949	27 August. First Soviet nuclear bomb test (20 kilotons) at Semipalatinsk range. In the Institute of Nuclear Problems of Academy of Science of USSR, a 680 MeV synchrocyclotron was launched.
1951	24 July. Plant (<i>Kombinat</i>) # 9 (now Eastern Mining and Processing Complex near Zhovti Vody, Kirovograd oblast of Ukraine) was created on the basis of <i>Pervogo Maya</i> and <i>Zheltaya River</i> mines. Creation of Plant # 586 (from 1966 - Yuzhnyi Mashynostroitelnyi Zavod). A huge tractor factory that was under construction in Dnipropetrovsk was re-oriented towards the production of rockets (ballistic, for nuclear submarines etc). By 1960s, thousands of these rockets were armed with nuclear warheads produced by the Soviet atomic project, and a rough parity between the US and USSR nuclear weapons was achieved.
1952	9 September. Stalin signs the Decree of the Government of the USSR on launching the program for construction of nuclear submarines.
1953	26 June. The Ministry of Medium Machine Building is created (to manage all tasks related to atomic project). July 28 The Council of Ministers of USSR decreed to create two prototypes of ship nuclear reactors: water cooled reactor and liquid metal reactor. 12 August. The first soviet thermonuclear (H) bomb tested.
1954	June 27. The world's first nuclear power plant was launched in Obninsk, 100 km South-West of Moscow. The 5 MW NPP had a water-graphite reactor of channel type. 14 September. A nuclear bomb was detonated over soviet troops at Totsk range in Orenburg oblast during military maneuvers which imitated nuclear war conditions. Many participants of that maneuvers still live in Ukraine. <i>Similar exercise was conducted two years later, in September 1956 at Semipalatinsk range, where 4 bombs, of them one H-bomb, were detonated, and 43 min after the last bomb exploded two companies of paratroopers were parachuted close to the epicenter.</i>
1956	26 March. Representatives of governments of 11 socialist countries signed in Moscow an agreement establishing the Joint Institute for Nuclear Research in Dubna, 120 km North of Moscow. Of 11 founding countries 3 do not exist any more (USSR, GDR, Czechoslovakia), 2 discontinued their membership (Albania, China), 2 new countries joined (Cuba and Vietnam) and 8 former Soviet republics, including Ukraine, joined as independent states. Feb 2 First tests of R-5m rocket with nuclear warhead took place at Kapustin Yar test site
1957	29 September. Major nuclear disaster at Plant # 817 (later known as "Mayak", near present-day Ozersk city in Cheliabinsk oblast) resulted in radioactive contamination of the area of 23,000 sq.km. A plant that was later renamed Hartron was founded in Kharkiv. It's task was to develop and produce control systems for nuclear missiles (such as SS18, SS19 and other). In 1990th the plant started production of electronic equipment and control systems for nuclear power plants. 5 December. The first nuclear-powered ice breaker "Lenin" was set afloat.
1958	17 December. The first Soviet nuclear submarine was accepted for experimental service. At Plant # 816 the first dual-purpose uranium-graphite reactor was launched. It produced plutonium and generated electricity (thermal power 1,450,000 kW). It was designed by the same team (A.P.Aleksandrov, N.A.Dollezhal) that later designed Chernobyl reactor # 4.
1959	January. First kilogram of U₃O₈ produced at Plant # 9 in the city of Zhovti Vody, Dnipropetrovsk oblast.
1961	The first underground nuclear explosion at Semipalatinsk test range.
1964	First two units of energy-generating Beloyarsk NPP (Ekaterinburg oblast) were put into operation. It was equipped with water-graphite channel type reactors.

	First unit of Novo-Voronezh NPP with VVER-type reactor launched
1965	15 January. With underground nuclear blast an artificial lake Chagan of 20 mln.m3 was created in the Semipalatinsk nuclear test site. A world most powerful (at the time) linear electron accelerator for 2,000 MeV was launched in Kharkiv Physical Technical Institute,. The Government of the USSR takes a decision to design a 1000 MWt (el) RBMK reactor.
1967	2 February. The Central Party Committee and the Council of Minister of USSR approve the decision to build a Central-Ukrainian (Chernobyl) NPP near Kopachi village in Kyiv oblast.
1968	1 July. In Washington, London and Moscow a Nuclear Weapons Non-Proliferation Treaty was signed.
1969	Kharkiv Turbine and Generator Plant starts production of turbines for nuclear power plants which were constructed in the USSR and abroad.
1972	An underground nuclear blast of 3.5 kt was used to extinguish a fire on a gas production well in Kharkivska oblast.
1972 - 1974	With the support of Soviet specialists several NPPs launched in socialist countries: Bogunitse, Czechoslovakia; Greifswald, German Democratic Republic; Kozloduy, Bulgaria.
1973	23 December. The first unit of Leningrad NPP with RBMK reactor was launched.
1976	23 February. "Sibir" nuclear icebreaker launched. 19 December. First unit of Kursk NPP with RBMK-1000 reactor launched. Production started at the "Atomash" plant near Volgodonsk, Rostov oblast. The plant produced equipment for civil nuclear power plants. First unit of Armenian NPP with VVER-440 reactor launched.
1977	September. The first unit of Chernobyl NPP with RBMK-1000 reactor launched.
1979	A 0.3 kt nuclear blast was detonated 800 m below surface at Yunyi Kommunar coal mine in Donetsk oblast.
1979 - 1986	9 units commissioned at 5 Ukrainian nuclear power plants
1986	26 April 1986 - catastrophe at unit # 4 of Chernobyl NPP October 1986 - Chernobyl NPP units #1 and #2 restarted
1987	Rivne NPP unit # 3 and Zaporizhzhya unit # 3 commissioned December - Chernobyl NPP units # 3 restarted
1988-1989	At Khmelnytska, Yuzhno-Ukrainska and Zaporizha NPPs four new units commissioned
1990	2 August - the Supreme Council of Ukrainian SSR introduces moratorium on construction of nuclear power plants in Ukraine
1991	24 August - Ukrainian Parliament adopts the Act of Declaration of Independence of Ukraine. The Act establishes Ukraine as an independent, democratic state.

Atomic and nuclear physics in Ukraine

History

The Academy of Science of Ukraine (ASU) was created in 1918 (first President V.Vernadsky), but during it's early years the main focus of the Academy was on humanitarian studies. Only in 1929 the Institute of Physics was founded in Kyiv. There was no research on atomic physics in the Kyiv Institute of Physics until post-World War II period, when A.Leypunsky (who had worked in Leningrad, Kharkiv and Moscow) was it's Director in 1943-1949).

Research on atomic physics during pre-war period was concentrated in the Ukrainian Physical Technical Institute (UPTI), founded in 1928 in Kharkiv (in 1938 it was renamed Kharkiv Physical Technical Institute (KPTI), and in 1993 the the Institute was reorganized into the National Science Center "Kharkiv Institute of Physics and Technology"). In 1930, the Director of Leningrad Physical Technical University Prof. Ioffe initiated transfer of several young talented scientists from LPTI to UPTI, and this

led to outstanding results and establishing of several scientific schools in Kharkiv. Some of these scientist just completed their research work in the best laboratories of England, Germany, Denmark (Sinelnikov, Landau). In October 1932, a group of UPTI scientists (Leypunsky, Sinelnikov, Valter, Latyshev) for the first time in the USSR split the atomic nucleus using a particle accelerator to bombard lithium with protons, thereby repeating the achievement of Cockroft and Walton of half a year earlier.

In 1932, a laboratory of atomic physics was organized in LPTI under the direction of I.Kurchatov. Together with K.Sinelnikov he graduated the same Tavrichesky University in Crimea in 1923. LPTI and UPTI closely cooperated until 1937, when NKVD (KGB) arrested a group of UPTI scientists accused of espionage. Some spent several years in jail, some were shot down, some had to change the job or leave the city. In 1930th UPTI was one of leading Soviet research centers in high-vacuum techniques, development of accelerators, low temperature physics, crystal physics. The department of theoretical physics (L.Landau, E.Lifshyts, I.Pomeranchuk and others) was very strong until the espionage case of 1937, after which many prominent physicists moved to Moscow. In 1938 UPTI was renamed Kharkiv Physical-Technical Institute (KPTI) and subordinated to the Academy of Science. Many UPTI/KPTI's leading physisists (A.Akhieser, L.Landau, I.Lifshyts, K.Sinelnikov) taught at Kharkiv Politechnic and later at Kharkiv University (when it was re-established in 1932-1933), thus educating young researchers not only for UPTI, but for all Soviet Union.

During the World War II both KPTI and Institute of Physics worked in evacuation. When they moved to Ukraine in 1943-1944, the Government planned to merge the Institute of Physics and KPTI into one and move all research to Kyiv, but K.Sinelnikov asserted the independence of KPTI and became it's Director for 1944-1965. The leader of the Soviet atomic project, I.Kurchatov included KPTI in his orbit. A specialised "Laboratory # 1" was organized in KPTI for atomic project works (nuclear physics of medium and high energies, metallurgy for nuclear industry etc.) KPTI received funding, staffing and all resources directly from the *Minsredmash* in Moscow.

In 1947 the Ministry of Education of the USSR approved the new specialty "Nuclear physics" which was taught at Kharkiv University. Students worked on their diplomas at KPTI. Experience of Kharkiv physicists was also used for founding new education institutes in Moscow and other places - e.g. A.Leipunsky was the first Dean of Moscow Engineering Physics Institute.

In 1960-1980th, KPTI retained it's position of the leading Ukrainian center for nuclear science. New research directions were developed, like plasma physics, cryogenic physics, elementary particle physics, radiation material science etc. Several academic institutes were founded on the basis of KPTI's departments.

The Kyiv Institute of Physics also experienced a rapid growth after the war. Academician of the Academy of Science of Ukraine A.Leipunsky was the Head of the Institute's Department of Nuclear Pphysics until 1952. First electrostatic accelerator was launched in the institute in 1947, 120-cm cyclotron in 1957, 10-MW research reactor VVR-M in 1960, Van-de-Graaf accelerator ESG-5 in 1964. However, Institute of Physics was not substantially involved in the Soviet atomic project. The Institute of Nuclear Research of the Academy of Science of Ukrainian SSR was organized (on the basis of several departments of the Institute of Physics) in 1970.

Current status

At present, numerous areas of nuclear physics are investigated at the Ukrainian research institutes of the National Academy of Science of Ukraine. Most of them belong to the Department of Nuclear Physics and Power Engineering of the Academy, headed by Academician I.Nekliudov from Kharkiv Institute for

Solid-State Physics, Materials Science and Technologies). The list of institutes follows (scientific specializations of the institutes are clear from the name):

- National Science Center 'Kharkiv Institute of Physics and Technology' (Kharkiv):
 - Institute of Plasma Physics
 - Institute for High-Energy Physics and Nuclear Physics
 - O. I. Akhiezer Institute for Theoretical Physics
 - Institute for Plasma Electronics and New Methods of Acceleration
 - Institute for Solid-State Physics, Materials Science and Technologies
- Institute for Nuclear Research (Kyiv)
- Institute of Applied Physics (Sumy)
- Institute of Electro physics and Radiation Technologies (Kharkiv)
- Institute of Environmental Geochemistry under NAS and Ministry for Emergencies (Kyiv)
- Research and Training Center 'Physical and Chemical Materials Science' under Kyiv Taras Shevchenko University and NAS of Ukraine (Kyiv)

The Academy approved the Conception of the Program of investigations of the department of nuclear physics for 2007-2011 in November, 2006. The name of the Program is "Fundamental problems in physics of elementary particles and nuclear physics", it covers over 50 research themes. The funding for the Program will come from the state budget - 47.4 mln Ukrainian Hryvna for 5 years. As everywhere in the world, institutes also work on numerous other research programs, which are funded from other sources. Most institutes maintain tight scientific contacts and receive significant funding from foreign research centers.

One institute of the Academy of Science which is directly involved with the work of Ukrainian nuclear power industry, the Institute for Safety Problems of Nuclear Power Plants, belongs to the Department of Physical and Technical Problems of Power Engineering. It was created in 2004 by reorganization of the Inter-departmental Scientific Center "Shelter" of the Academy of Science. Main directions of the Institute's work include: safety and efficiency of NPPs; technologies of nuclear waste management; technologies of decommissioning of NPPs; scientific investigations at the Chernobyl "Shelter" object; technologies of conversion of the "Shelter" object into ecologically safe system.

Of course in this short paper it is impossible to describe the results of the work of Ukrainian scientists during last decades. However, some general problems of the Academy of Science of Ukraine (which are equally acute for the nuclear physics) make prospects for the future not very optimistic. Among these problems - aging of the research personnel (average age of candidate of science in the Academy is 53 years, doctor of science - 62 years), lack of new experimental installations, obsolete equipment etc. Academy is too big (over 44,000 employed, of them 17,000 research staff), state funding is very low and opportunities for external funding (from industry, business, international funds) limited. About 70 % of budget funding is used for personnel's salaries and little is left for other needs. There is ongoing discussion on the ways of reforming of Ukrainian science, but very little has been done so far.

Nuclear Industry in Ukraine: from Atomic Bomb Project to "Peaceful Atom"

Uranium ore mining and processing

An essential problem during the early stage of the Soviet atomic project was the procurement of uranium ore. The first Soviet nuclear reactor was fueled with uranium from the German atomic bomb project. Then the Soviet Union started operating mines in East Germany, Czechoslovakia, Bulgaria and Poland (Soviet Block countries - SBC), and eventually large domestic sources were discovered in Ukraine, Kyrgyzstan,

Uzbekistan and other republics. Supply of uranium during first years of Soviet atomic project (tons):

- 1946 - USSR 50.0, SBC 59.6;
- 1947 - USSR 129.3, SBC 209.8;
- 1948 - USSR 182.5, SBC 451.9;
- 1949 - USSR 278.6, SBC 988.7;
- 1950 - USSR 416.9, SBC 2056.8.

Geologists were the first who started atomic bomb related works in Ukraine. In 1945, Ukrainian geologists discovered uranium ore at Pervomajsky and Zheltorechensky deposits in Dnipropetrovsk oblast. These were the first large uranium deposits discovered in the USSR.

In 1947, the Kirovska Specialized Geological Expedition was created by the order of the Minister of Geology of the USSR. Its role was to explore uranium deposits in Ukraine, Belarus, Moldova, Northern Caucasus and Western provinces of Russian Federation. This organization still exists as a state enterprise Kirovgeologia, with headquarters in Kyiv. It continues exploration of uranium in Ukraine and to a lesser extent abroad.

The ore of Pervomajsky deposit was of iron-uranium type, and it was explored during production of iron ore. The production of uranium ore at Pervomajsky and Zheltorechensky deposits started in 1948 and during following years several mines up to 800 m deep were built. The ore was processed at a hydrometallurgical plant # 906 in the city of Dneprodzerzhynsk. Later, in 1951, a new plant (*kombinat*) # 9 (now the Eastern Mining and Processing Plant (Eastern MPP) near the city of Zhovti Vody) was created (see below). Pervomajsky deposit was exhausted during 1948-1967, and Zheltorechensky during 1948-1989 (production at this deposit exceeded initial estimates).

Meanwhile, extensive exploration of uranium in Ukraine continued, and new deposits were discovered in the same area (Dnipropetrovsk, Kirovograd, Mykolaiv oblasts). Production at the two of them, Devladivske and Bratske, was organized with the use of the technique of bore-hole sulphuric-acid underground leaching (other chemicals were also used). Devlatovske deposit was exhausted during 1964 - 1983, and Bratske in 1970-1990. These areas still suffer from the problems of underground water pollution due to mining operations.

Major achievement of Kirovgeologia was a discovery of Michurinske deposit on the floodplain of Ingul river near the city of Kirovograd in 1964, and later of Vatutinske deposit in 1966. Two most productive mines of Eastern MPP - Ingulska (in operation since 1969, depth 340 m, expected close down 2020-2030) and Smolinska, in Malovysky district of Kirovograd oblast (in operation since 1973, depth 640 m, expected close down 2020-2025) operate on these two deposits. Reported productivity of mines is 20,000 - 25,000 ton/month.

Several more deposits were explored. In accordance with the state program "Uranium of Ukraine", production at these deposits should be started in the near future. Some of them are intended for underground leaching technique (e.g. Safonivske in Mykolaiv oblast) and others for mining. Of these deposits Novokostiantynivske in Kirovograd oblast is considered the largest in Europe. The construction of mines at this deposit was started in 1984 but stopped in 1989. Large investments are needed to complete these mines and start production.

Prydniprovsky Chemical Plant

It was discovered in 1947 that iron ore from Pervomajsky deposit is rich in uranium. During blast furnace production of iron from this ore uranium concentrated in slag. Blast furnace # 6 of Dniprodzerzhynsk metallurgical plant was selected for smelting uranium rich ore, and by a decision of the Council of

Ministers of USSR of 14 August 1957, a special plant for uranium extraction was to be built in Dniprodzerzhynsk. That was Plant # 906, known by its non-secret name as a Slag Fertilizers Plant (by-products of uranium production from slag were reprocessed into fertilizers). More than 16,000 people worked on its construction, many of them inmates of concentration camps which were relocated to the area from the Urals.

In Dneprodzerzhynsk there already existed a plant which produced various chemicals, including acids (present name "Dniiproazot"), so both the raw materials (uranium-rich slag from blast furnace # 6, then uranium ore from Wismut enterprise in GDR, then uranium ore from Ukrainian and Soviet Central Asia deposits) and reagents were at hand. The production of yellow cake in Ukraine was launched. Of course workers of the smelter and plant # 906 did not know what was their product, and the plant was carefully fenced and guarded. At the peak of a "cold war", Plant # 906 processed over 60 % of uranium ore mined in Soviet Union. It also produced other materials needed for Soviet atomic bomb project, like heavy water (5.8 t in 1957 - 25 % of total Soviet production). In 1966 the plant was renamed - it became a "Prydniprovsky Chemical Plant" (PCP). For its own needs it started production of ion exchange resins necessary for new uranium extraction technologies. Later on production of zirconium was launched.

In 1991, when supply of uranium ore and demand for various military-oriented products of PCP dropped, production of uranium concentrate was stopped. In 1990s the plant was divided into several separate plants (production of ion-exchange resins, nonferrous metals, zirconium, hydrometallurgical plant etc) and bankrupted in 2002. Production of ion-exchange resins and zirconium meets the needs of Ukrainian nuclear industry, but PCP does not produce uranium concentrate any more.

A state enterprise "Baryer" was created in December 2000 to manage the PCP's radioactive tailings of uranium production (over 42 mln ton with estimated total activity over $2.7 \cdot 10^{15}$ Bq). One of the storages contains parts of the dismantled blast furnace # 6. The works on the tailings and other objects of the former PCP were carried out in accordance with the State Program of 26.11.03, which was replaced by a new State Program of 30.09.09.

Eastern Mining and Processing Plant

A specialized mining company "Plant (*Kombinat*) # 9" in the city of Zhovti Vody, Dnipropetrovsk oblast, was created on the basis of Pervomaisky and Zheltorechensky mines in July, 1951. Construction of hydrometallurgical production department of the plant was started in 1955, and in January 1959 the first kilogram of U_3O_8 was produced. During the following years the scale of uranium mining and production increased, several deposits were developed with the use of underground leaching, new mines were constructed. In 1989 the plant was renamed Eastern Mining and Processing Complex.

At present, the State Enterprise Eastern Mining and Processing Complex is the only enterprise in Ukraine engaged in the mining of uranium ore and production of a uranium oxide concentrate. It operates two mines, hydrometallurgical plant and other subdivisions. The plant is under the supervision of the Ministry of Energy, and its importance will increase when the state program "Uranium of Ukraine" is implemented.

Construction of nuclear power plants

First soviet atomic reactors were designed for production of weapon-grade plutonium. All of them were located in Russia. Then there was a turn for nuclear reactors for submarines. However, by mid-60s the potential of Soviet nuclear industry exceeded the demand from the military. And so the era of "peaceful

atom" began, and nuclear power plant for electricity and heat generation were built.

In February, 1967 the Central Committee of the Communist Party and the Council of Minister of USSR approved the decision to build a Central-Ukrainian (Chernobyl) NPP near the Kopachi village in Kyiv oblast. This NPP was to be based on graphite-moderated RBMK reactors. Other sites in Ukraine were also investigated and later on more nuclear power plants were constructed. The main problem with siting of Ukrainian NPPs was lack of cooling water and unfavorable geological conditions in many areas. However, by the time of Chernobyl disaster in 1986, four NPPs were in operation in Ukraine, and five other were under construction.

The first unit of Chernobyl NPP was launched in 1977, and the second, third and fourth in 1979, 1982, 1984. Two more units of ChNPP were under construction when the catastrophe on reactor # 4 occurred 26 April 1986. This became a turning point for a growing Ukrainian nuclear energy industry.

On 02.08.1990 the Supreme Council of Ukrainian SSR introduced a moratorium on construction of nuclear power plants in Ukraine. The construction works were suspended and never resumed at four new NPPs (Krymska, Odeska, Kharkivska and Chygyrynska in Cherkasy oblast - see the map). Of them, the degree of completion of Krymska NPP was rather high and the satellite city of Scholkine was already built for its workers. Now the city gradually deteriorates as there are few jobs available for its inhabitants. Negative impacts of cancellation of three other projects (Odessa, Chygyryn, Kharkiv) were lower.

In accordance with international agreements signed by Ukraine, the last operating unit # 3 of Chernobyl NPP was closed down in 2000. More details on the current status of Ukariinian NPPs could be found in the last section of this paper.

Peaceful use of nuclear technologies included underground nuclear explosions. Soviet experiments (published data give the number of 124 peaceful underground blasts) were conducted not only in Siberia or Kazakhstan, where in 1965 an artificial lake Chagan was created by a 140 kt nuclear blast, but also in Ukraine.

In 1972 an underground nuclear blast of 3.5 kt was used to extinguish a fire on a gas production well in Kharkivska oblast. In 1979, nuclear explosion of about 0.2-0.3 kt was used near Gorlivka city in Donetsk oblast, to shake the rock in and around the "Yunyi kommunar" coal mine and thus reduce the concentration of methane gas in the mine. That nuclear blast was detonated on 16 September 1979 at 800 m below the surface, and a glassified capsule of about 100 m³ still exists at the site of the explosion. Unfortunately, none of these blasts produced the expected result - the fire continued, and the level of methane gas in the mine remained high.

Ukrainian industry's input into nuclear energy sector

The work on nuclear weapons, nuclear missiles, atomic submarines and later power nuclear reactors needed huge material and human resources. Whole new industry sectors were created, hundreds of new plants, mines, research and design institutes established. Many of them were located in Ukraine.

Here we cannot provide even a general overview of design and production facilities located in Ukraine, which provided various supplies for the Soviet atomic industry. Most of them were the so called "P.O.Box-organizations" - because there requisites were simply "p.o.box # XXX". Only authorized personnel new where they were located and what did they produce. But several enterprises are now well known all over the world.

The Kharkiv Turbine and Generator Plant was built in 1929-1932. Since 1969 the plant supplied

turbines for many NPPs constructed in the Soviet Union and socialist states. In 1980, by the decision of the Soviet Government it was designated as a main supplier of turbines for nuclear power plants and renamed **Turboatom**. Between 1982-1985, Turboatom's turbines were installed at Yuzho-Ukrainska, Zaporozhzhya, Balakovska and Kalininska NPPs. Turbines for Krymska, Odeska, Kharkivska and Chygyrynska NPPs were also produced. At present Turboatom is the world's fourth largest supplier of turbines.

The plant that now is known as Hartron was established in 1959 in Kharkiv, Ukraine. The main trend of its activity was development and implementation of control systems for ballistic missiles (such as SS18 and SS19, equipped with the nuclear warheads), carrier-boosters and space vehicles. Under a new economic environment, Hartron Corp. has had to adapt to civilian applications, and now its products among others include commercial industrial control systems for fossil-fuel and nuclear power plants, transport, gas and oil pipelines. Hartron is the Ukraine's leading enterprise for reconstruction of instrumentation and control systems for Ukrainian nuclear power plants.

Hartron Corp. includes enterprises located in Kharkiv and Zaporizhzhya, which produce various radioelectronic equipment for nuclear power plants. In 1994, Hartron and Westinghouse established a joint venture, Westron.

Ukrainian Nuclear Industry: Current Status

Ukraine is heavily dependent on nuclear energy - it has 15 reactors generating about half of its electricity. Important weakness of the Ukrainian nuclear industry is the fact that it receives most of its nuclear services and nuclear fuel from Russia. In 2004 Ukraine commissioned two large new reactors. The government plans to maintain nuclear share in electricity production, and this will involve substantial new construction. Plans for this development have been already announced. Here we do not discuss these plans and concentrate on present situation.

On 17 October 1996, the Cabinet of Ministers of Ukraine created a State-owned Enterprise National Nuclear Energy Generating Company (NNEGC) "Energoatom", which merged five Ukrainian NPPs (Chernobylska, Zaporizhzhya, Yuzhno-Ukrainska, Rivne, Khmelnytska). Later on Chernobyl NPP became a separate entity, so at present NNEGC "Energoatom" operates four NPPs and several other separated enterprises (see details below).

NNEGC "Energoatom" is subordinated to the Ministry of Energy of Ukraine, which formulates the state policy in nuclear energy sector, represents interests of Ukraine in IAEA and other international organizations which deal with the nuclear energy issues.

Another government organ with a special status, the State Nuclear Regulatory Committee of Ukraine (SNRCU) performs functions of the national regulatory body on nuclear and radiation safety. It issues licenses and exercise control over all activities related to radioactive materials and sources of radiation, including NPPs. Under the supervision of a Chief State Inspector on Nuclear and Radiation Safety (Deputy Chairperson of SNRCU), the State Nuclear Safety Inspectorates work at all five Ukrainian NPPs. The national policy on radiation protection of population is defined by the National Commission on Radiation Protection appointed by the Parliament of Ukraine.

Chernobyl NPP and the State specialized enterprise "Chernobyl NPP"

After the accident of 26 April 1986 at reactor # 4 of ChNPP, units # 1 and # 2 were restarted already in October, 1986. Unit # 3 was restarted in December, 1987. Three units worked in usual mode until the fire

of 1991 at one of unit # 1 turbines. After the fire, the unit # 1 was stopped and never put in operation again. After the accident of 1986, there was a permanent pressure from Western governments which insisted that ChNPP did not meet nuclear safety requirements and should be shut down. Eventually an agreement between the Government of Ukraine and donor countries was reached to close down Chernobyl NPP. In return, Western countries pledged technical and financial support for solving the problems emerging from this closure (economic, energy supply, radiation safety, social). The agreement between the G7 countries, EU Commission and the Government of Ukraine was signed on 25 December 1995. In accordance with the agreement, four critically important facilities were to be built or completed near the ChNPP:

- completion of the industrial heating plant, IHP (put in operation in 2001, DOE of the USA donated \$22.5 mln);
- liquid radioactive wastes treatment plant (LRWTP);
- spent fuel interim storage facility # 2 (ISF 2);
- Industrial Complex for Solid Radioactive Waste Management (ICSRM).

The last reactor # 3 which was still in operation was shut down on 15 December 2000. After this, Chernobyl NPP is legally in the state of decommissioning. Chernobyl NPP was taken out of NNEGC “Energoatom”. It became a State specialized enterprise "Chernobyl NPP" (SSE ChNPP) with the main task of decommissioning the NPP and transformation of the Shelter object into ecologically safe system. The license for decommissioning works was issued by SNRCU to SSE ChNPP in March, 2002.

The conditions for decommissioning were very unfavorable, because there were no plans, no necessary technical facilities, no accumulated funds. However, significant progress in planning and preparatory works has been achieved since 2002, and the “State Program of Chernobyl NPP Decommissioning and Shelter Transformation into Ecologically Safe System” will come into force on January 1, 2010. It was approved by the law of January 15, 2009.

One of the main responsibilities of SSE ChNPP is management of the Shelter object ("Sarcophagus"). Since its construction in 1986 it underwent a series of repairing, however, the state of construction elements is deteriorating. The nuclear fuel (current estimates show that about 95 % of what initially was in the reactor, with total activity about 16 million Ci is still inside or under the Shelter) undergo destructive processes, and the amount of fine-dispersed fuel increases. This potentially creates a threat of incidents and consequent radioactive contamination. Another problem is possible radioactive contamination of ground water, although on-going investigations show lack of tendency of uranium and plutonium spreading by underground water flow.

By joint decision of the Ministry of Emergencies of Ukraine and National Academy of Science of Ukraine, the responsibility for scientific supervision of the Shelter object and its transformation into ecologically safe object was assigned to the Institute for Safety Problems of Nuclear Power Plants of NASU.

It is assumed that the solution for the problem of Shelter object will be a New Safe Confinement (NSC). The process of designing and preparation works for NSC (funded by the donor countries through European Bank for Reconstruction and Development) is underway. The NSC will have to provide necessary conditions for transformation of the Shelter object into ecologically safe system, including removal of fuel containing materials, radioactive waste management and dismantling of Shelter object structures. So far, the result of joint Ukrainian-international efforts at ChNPP are not very encouraging. Except of IHP, all other facilities are under various stages of construction/completion. Perhaps the worst situation is with ISF 2, which was constructed but could not be put into operation due to various technical faults and problems. At present, new technical conditions and terms of reference for additional works are

considered.

National Nuclear Energy Generating Company “Energoatom”

As of fall, 2009 NNEGC “Energoatom” is a managing company which is in charge of four NPPs and several separated subdivisions. Each NPP and each subdivision is a legal entity with its management, bank account etc. An overview of the four NPPs follows:

- Zaporizhzhya NPP - six VVER-1000 reactors commissioned between 1985-1996, with scheduled close dates between 2015-2026. Zaporizhzhya NPP is the first Ukrainian nuclear power plants where on-site dry storage facility for spent fuel (SFDSF) was built. It was loaded for the first time in 2001. It is expected that the capacity of SFDSF will be sufficient for all life span of the NPP.
- Rivne NPP - two VVER-440 and two VVER-1000 reactors commissioned between 1981-2005, with scheduled close dates between 2011-2035.
- Yuzhno-Ukrainska NPP - three VVER-1000 reactors commissioned between 1983-1989, with scheduled close dates between 2012-2019. To compensate peak loads and secure good operating conditions of YuU NPP, Tashlyk Hydro accumulating Power Plant is being constructed. The first two hydraulic units were put into operation in 2006 and 2007. Upon completion the THAPP is expected to have generating capacity of 906 MW and to work on average 3.1 hour a day (turbining). There exists on-going controversy around THAPP because it will flood valuable ecosystems.
- Khmelnytska NPP - two VVER-1000 reactors commissioned in 1988 and 2005, with scheduled close dates 2018 and 2035. The construction of two other units was started in Soviet period but later stopped.

It should be noticed that at present it is expected that the lifetime of existing nuclear power plants will be extended by about 15 years compared to scheduled close date. The process of necessary checking and licensing of such extension is underway for Rivne-1.

The share of electricity generated by NPPs (percent of total generation) remains high: 2000 - 45.3%, 2004 - 53.2%, 2005 - 52.3%, 2006 - 46.9%, 2007 - 47.5%, 2008 - 46.8%. In December, 2008 NNEGC “Energoatom” issued a statement of intention for completion of two units at existing site of Khmelnytska NPP. Construction works on these two units were started in 1985 and discontinued in 1990. New design and new permits are needed for completion. Currently the preparation of EIA in accordance with Ukrainian legislation is announced.

Since the time of dependence of Ukraine, directly at NPPs a system of personnel training was created. This system is based on the latest legislation framework, IAEA recommendations and international experience. Training centers, created at each NPP, form one of the main components of NPP personnel training. The total staff of these centers comprise 436 persons, of them 160 instructors. Simulator training base was created by joint efforts of specialists from the USA, Russia and Ukraine.

In 1993, the first in Ukraine full scale simulator of the main control room was launched at Zaporizhzhya NPP. In December 1997 a similar simulator was put into operation at Khmelnytsky NPP. In 2001 a full scope simulator for Rivne NPP unit # 3 personnel training was put into operation. At present, 8 simulators work at Ukrainian NPPs. In 2000 Zaporizhzhya NPP received a license for training of the operating personnel. Now all training centers have similar licenses.

Main separated subdivisions of NNEGC “Energoatom” are:

- “AtomRemontService” - improve management and efficiency of maintenance and repair at nuclear power plants; created partly to employ the personnel of Chernobyl NPP after its closure;

- “Atomkomplekt” - supply of materials and services for Ukrainian NPPs;
- "Scientific and Technical Center" - created in 2003 to create in Ukraine a complex and effective system of scientific and technical support of nuclear power industry;
- "Atomenergomash" - manufacturing of equipment for Ukrainian nuclear power plants;
- “Emergency and technical center” - works on the issues of preparedness of Ukraine for quick and effective actions in case of accidents at nuclear power and industrial enterprises;
- "Atomproectenginiring" (created in December 2008) - coordinates investment activities of NNEGC “Energoatom”, especially construction of new and completion of unfinished NPPs.

Services and education for nuclear power plants

It should be noticed that there are numerous enterprises which provide essential services for the nuclear energy industry and which are independent from NNEGC “Energoatom”. Among them, here we will mention Kharkiv Scientific-Research and Design Institute "Energoproekt" (which worked in 1970-80s closely with All-Union Design Institute "Teploelectroproekt", later renamed as Atomenergoproekt, in Moscow) and Kiev Design and Research Institute "Energoproekt" (with two institutes mentioned above, Kiev institute participated in designing of many power plants, among others, Rivne and Khmelnytska NPPs). These design institutes are located in Ukraine and incorporated under Ukrainian law, but their ownership issue is not very clear, as well as their potential after many years of significant work underload.

While there are many universities which have atomic and nuclear physics in their physics curriculum, only three universities teach students in specialty "atomic energy engineering": National Technical University "KPI" (Kyiv), Odessa Polytechnic University (Odessa) and Sevastopol National University of Nuclear Energy and Industry (SNUNEI). For example, students can take this specialty at Kyiv Technical University at a sub-department "Nuclear power stations and engineering thermal physics" of the Heat-and-Power Engineering Department (which was founded back in 1931). SNUNEI is a relatively young university, it was organized in 1996 on the basis of a former Soviet Navy Engineers Higher College, which trained officers for Soviet nuclear submarines since 1964. "Atomic energy engineering" is only one of many specialties at this university, while other specialties related to nuclear industry include dosimetry, radioecology, radioactive waste management. The number of graduates at these specialties in all three universities is not very large.

There is no higher education for reactor personnel in Ukrainian universities, equivalent to the Russian specialty 140305 (070500) - "Nuclear reactors and power plants", which is taught in Moscow, Obninsk, St.-Petersburg, Tomsk. As it was mentioned above, extensive personnel training programs are carried out directly at Ukrainian power plants.

Nuclear fuel and nuclear fuel cycle

Serious problem for Ukrainian nuclear energy industry is a supply of fuel. During the period of Ukrainian independence, nuclear fuel assemblies for Ukrainian NPPs were provided by Russian Corporation "TVEL" (i) as a compensation for nuclear warheads transferred from Ukraine into Russia and (ii) on the basis of contracts between Ukrainian NPPs, NNEGC "Energoatom" and TVEL Corporation. Ukrainian Government works on diversification of nuclear fuel supply, maintaining working contacts with Westinghouse and other Western companies.

No spent nuclear fuel (SNF) processing takes place in Ukraine: spent fuel was exported to Russia. There exists a plan to build a centralized storage for SNF from VVER reactors in the 30-km zone of Chernobyl NPP, but the project is very controversial and its licensing and implementation (if it comes to

implementation) will not be easy.

At present, the State Enterprise Eastern Mining and Processing Complex is the only enterprise in Ukraine engaged in the mining of uranium ore and production of a uranium oxide concentrate. It operates two mines, hydrometallurgical plant and other subdivisions. The plant is under the supervision of the Ministry of Energy, and its importance will increase when the state program "Uranium of Ukraine" is implemented. Currently Ukrainian uranium industry capacity produces about 30 % of uranium that is needed to fuel Ukrainian NPPs. Enrichment of uranium and production of fuel assemblies take place in Russia. There are plans to develop capacities and to introduce some other elements of nuclear fuel cycle in Ukraine, but they are still far from implementation.

Sectoral program "Uranium of Ukraine" (for the period of up to 2030) pays special attention to the increase of uranium production. For this, new uranium deposits should be put into production and the capacity of existing processing plant increased. There are several uranium deposits which are suitable either for underground mining or leaching from the surface technology. The ore is not very rich but the quantities of reserves are large, and this allows for relatively cheap industrial methods of mining and processing. Design works for mining and processing of uranium ore are conducted by the Institute for Industrial Technology in the city of Zhovti Vody in Dnipropetrovsk oblast. The Institute was founded in 1970 to serve the needs of atomic energy industry and it has a significant record of implemented designs.

Ukrainian zirconium production sector includes Vilnogrisk State Mining and Metallurgical Complex in Dnipropetrovsk oblast (ore mining and processing, production of zirconium concentrate) and a State Enterprise "Zirconium" in Dniprodzerzhynsk, which have specialized technological departments for production of nuclear-pure zirconium. A state program "Nuclear fuel of Ukraine". approved 23 September 2009, sets the goal of creating a full cycle of zirconium production at "Zirconium" State Enterprise, which should supply all zirconium rolled products necessary for Ukrainian nuclear industry. According to the Program, some construction elements of fuel assemblies will be produced in Ukraine as well.

Final Remarks

Nuclear physics in Ukraine has quite rich history. It contributed to the success of the Soviet nuclear bomb project - especially during the 1930s-50s, but the field of research and available resources were dictated by the central government in Moscow. At present, there are numerous areas where Ukrainian nuclear physics still has substantial potential. However, it is unclear whether this potential will be converted into a vibrant science. Insufficient funding and neglect by the government of Ukraine, as well as inefficient internal management, soviet-type organizational structure of the Academy of Science, lack of proper cooperation with universities lead to deterioration of Ukrainian academic institutes, especially those which need significant investments to maintain experimental base. Except for some rare occasions, Ukrainian nuclear science and Ukrainian nuclear industry have very limited contacts, and it means that the science cannot count on financial support from the industry.

In Ukraine, the share of nuclear energy in total electricity generation is very high, but the industry is heavily dependent on the supply of equipment, fuel and expertise from Russia. The only improvement that is planned is in-country production of fuel assemblies, but the dependence on enriched uranium will remain. Ukrainian share in production of equipment (like turbines or electronics) for nuclear industry in the former Soviet-block countries is quite high, but the success of this sector depends on Russia's efforts to remain an important player on the world's nuclear industry market.

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Appendix. Map indicating locations mentioned in the text:

