ISSN 1070-3632, Russian Journal of General Chemistry, 2007, Vol. 77, No. 4, pp. 660–675. © Pleiades Publishing, Ltd., 2007.
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Hydrogen Energetics: Past, Present, Prospects

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Received September 28, 2006

Abstract — The deficit of organic fossil fuels and growing global ecological problems has attached increased interest to renewable power sources and hydrogen technologies. A series of major programs are presently in progress, whose ultimate goal is to realize the concept of hydrogen energy systems. The paper considers the dynamics in the development of hydrogen energetics whose concept has been conceived on the background of the global oil crisis of the 1970s.

DOI: 10.1134/S1070363207040299

INTRODUCTION

The deficit of organic fossil fuels together with global ecological problems has attracted considerable attention to hydrogen as a universal energy carrier for stationary and mobile power devices. At present there is a world-wide belief that owing to unlimited resources, high energy capacity, operability, and ecological safety of energy conversion processes involving hydrogen, the latter holds the greatest promise as energy carrier.

The transfer to hydrogen power industry suggests profound changes in the prevailing structure of the fuel and energy complex and is associated with gradual replacement of organic energy carriers (oil, natural gas, coal, and their processing products) by hydrogen generated from water by means of traditional (hydroelectric and nuclear) and renewable (solar, wind, geothermal, etc.) power sources. The new infrastructure which is expected to be completely formed by the end of the present century [1, 2] envisages the use of hydrogen and electric power as major components of the energy component of world economy, including power engineering, industry, transport, agriculture, and municipal sphere.

At present research in the field of hydrogen energetics is being actively supported. This tendency is characteristic of most countries. Beginning with 2002, this process has touched upon Russia, where research in hydrogen energetics and fuel cells (FCs) are given the status of priority and financially supported by governmental and major commercial structures.

The present review provides a brief analysis of the current state of and trends in hydrogen energetics which combines efforts of a great number of scientists, engineers, economists, and politicians. They all are involved in attacking numerous specific problems and, at the same time, for the concept to be realized successfully requires development of a systemic approach to the problem as a whole. The authors invite specialists whose work is associated with hydrogen production, storage, and use to discuss the title problem.

PHYSICOCHEMICAL FEATURES OF HYDROGEN

Hydrogen possesses a unique combination of properties, which predetermines its wide industrial application and, on the other hand, creating a number of technical problems in managing hydrogeninvolving processes [3–6].

Hydrogen is the most widespread element in the Universe (93 at%) and one of the most abundant in the Earth (15.52 at%). The mean hydrogen content of the Earth's crust is 1.4 g kg^{-1}. The major hydrogen

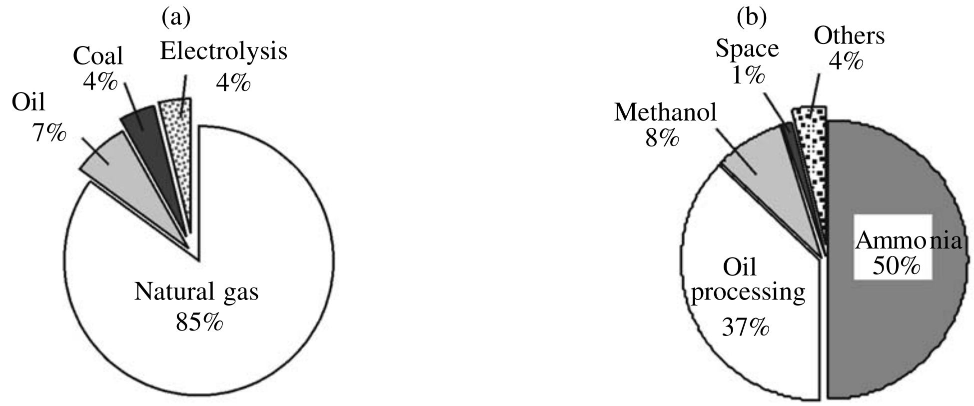

Fig. 1. Structure of world's hydrogen (a) production and (b) consumption.

sources on the Earth are water and organic compounds, including oil, natural gas, and biomass.

The capacity of hydrogen to enter catalytic hydrogenation reactions at elevated temperatures are widely used in chemical (synthesis of ammonia and methanol), oil (hydrocracking), and food (hydrogenation of vegetable fats) industry, as well as a number of other industries. The reductive properties of hydrogen are used in chemical engineering, power metallurgy, metal working, mechanical engineering, and microelectronics.

Hydrogen has the lowest viscosity and highest heat conductivity among the known gases. Thus, the heat conductivity of hydrogen at room temperature and atmospheric pressure is 0.182 W m^{-1} K^{-1}, which is 1.24 times that of helium, 5.9 times that of methane, 7.2 times those of nitrogen and oxygen, and 10.7 times that of argon. Under the same conditions, the dynamic viscosity coefficient of gaseous hydrogen is 8.92×10^{-6} Pa s, which is 2.11 times lower than that of helium [3, 7]. Because of this, hydrogen is used to good advantage for reducing friction and cooling in moving parts of machines (for instance, turbogenerators in heat and nuclear power industry). At the same time, the low viscosity of hydrogen entails enhanced probability of its leakage through seals, which toughens quality requirements for hydrogen gas apparatuses.

Hydrogen is classed with flammable gases with enhanced fire and explosion risk [8]. It has wide combustion and detonation ranges and high flame propagation rate (8 times as high as that of methane), as well as a low (14.5 times as low as that of methane) ignition energy. At the same time, the low density and high diffusion rate of hydrogen results in its fast volatilization in open air and ventilated rooms. Moreover, hydrogen has a fairly high lower detonation limit (2.06 times as high as that of methane), which makes it much less explosive in real conditions.

PRODUCTION OF HYDROGEN AND ITS CONSUMPTION STRUCTURE

Large-scale hydrogen production and processing technologies are presently well developed. According to [9–13], the yearly global hydrogen production by the end of 1990s was 40–45 mln. tons or 450–500 bln. m^3. Other sources [6] give slightly higher values: 60 mln. tons in 1990 and 80 mln. tons in 1998. Anyway, the above volumes comprise 20–25% of the yearly global natural gas production. Most hydrogen is produced by steam reforming or by partial oxidation of hydrocarbon raw materials, largely natural gas (Fig. 1a). It should be noted that as little as 62% of hydrogen is only produced as a target product, and the rest 38% of hydrogen is formed as a by-product in other industries (oil processing, coke chemistry, etc.). The latter percentage also includes almost all electrolytic hydrogen generated during the manufacture of chlorine and sodium hydrate.

The hydrogen consumption structure [6, 12–14] is shown in Fig. 1b. As seen from the figure, the major hydrogen consumers (95%) are chemical industry and oil processing. Hydrogen is the key reagent in the production of fertilizers (synthesis of ammonia) and in organic synthesis. Special role belongs to hydrogen in oil processing (hydrocracking, hydrofining), its application favors more profound crude oil processing and better quality of final products (hydrocarbon fuels). The hydrogen demand of oil processing industry in 1998 was about 1 wt% of the processed crude oil, and this demand steadily grows [14].

More than half the world hydrogen consumption falls on chemical raw material applications. The rest is used in hydrogen-involving engineering processes (hydrogenation, reduction, etc.). The reductive capacity of hydrogen finds use in powder metallurgy, metal working, production of glass and synthetic rubies, etc. (about 2% the total hydrogen consumption). The microelectronics application of hydrogen is largely associated with the production of silicon by $SiCl_4$ reduction.

The major consumer of hydrogen as a fuel is aeronautics. The "liquid hydrogen (fuel)–liquid oxygen (oxidant)" combination provides a maximum energy release per unit weight, which is the key criteria for aerospace applications.

Notably, it is only 5% of the total hydrogen production that is a commercial product. As a rule, major hydrogen consumers provide themselves with a self-produced hydrogen [3, 5], which is caused by economy reasons (high cost of commercial hydrogen), as well as by technical problems associated with storage and transportation of large quantities of hydrogen.

To improve hydrogen technologies, three groups of problems should be solved, specifically development of efficient, economically sound, and safe processes and equipment for hydrogen production, application, and compact storage. Consequently, these are the three priority lines of research and development in the field of hydrogen technologies.

The present-day hydrogen production techniques makes use of water (electrolysis, photolysis, and radiolysis), coal and natural gas (vapor and vapor–oxygen conversion), hydrogen sulfide (chemical and plasmochemical decomposition), and some other compounds as raw materials. The principal way to improve the mentioned hydrogen production processes is via increasing their performance, reducing capital and operation costs, and enhancing reliability and flexibility.

The production of hydrogen from natural organic fuels is presently best mastered. The principal technology is steam methane reforming [13, 15–17]. As seen from Fig. 1a, this process provides about 85% of the world hydrogen production, which is accounted for by its fairly high efficiency (more than 80%), reasonable cost, and well-developed infrastructure of transportation of the raw material. The cost of hydrogen produced by this technology proves to be the lowest compared with other technologies and decreases considerably with increasing efficiency: from \$11.2/GJ (1.3/kg H_2) for fairly small industrial installations 270 ths.m^3 H_2/day up to \$5.5/GJ (0.66/kg H_2) for large (7–25 mln. m^3 H_2/day) [16].

The principal disadvantage of the above technology is that it is dependent on the supply of natural gas whose resources are distributed between several regions (Middle East 40.8%, Russia 26.7%, Iran 15.2%, and Quatar 14.7%). A serious problem is also associated with atmospheric exhausts of large quantities of CO_2, and to utilize it requires substantial capital and operation investments, thus increasing the cost of the final product. Furthermore, the vapor methane reforming technology is poorly adaptable for small-scale devices for decentralized hydrogen production (say, for service stations, autonomous power systems, etc.). One more drawback is the presence of carbon oxide impurities in hydrogen, which imposes additional demands upon its purification, especially for fuel cell applications.

By the above reasons, methane reforming is commonly considered as an intermediate point on the way from the well-developed infrastructure of energy market to future hydrogen economy. Obviously, hydrogen production from organic fuels (natural gas, coal, oil, biomass, etc.) will be replaced by other technologies at some future day.

It should be noted that, from the ecological viewpoint, the strategy of hydrogen production from natural fuels is little different from their direct combustion. In the latter case, harmful atmospheric exhausts are generated on the stage of fuel application, whereas in the former, the same problem arises on the stage of hydrogen production. Therefore, the major components of new technologies of hydrogen production from hydrocarbons are systems for trapping accompanying gases, primarily CO_2. The example is provided by recent developments in steam coal reforming [18]. Furthermore, an important indirect factor here is fuel efficiency. In this respect, hydrogen power technologies offer certain advantages over combustion of fossil fuels.

The future of hydrogen production technologies may lie with water electrolysis, even though presently this method, due to its high cost, contributes no more than 5% into the world hydrogen production (Fig. 1a). The most attractive features of water electrolysis are its ecological purity (provided the primary energy production is not associated with environmental pollution), possibility for creating installations with a wide productivity range (from some liters to hundreds cubic meters of hydrogen an hour), operation easiness and convenience, high purity of produced hydrogen, and presence of a valuable and ecologically safe by-product, viz. gaseous oxygen.

There are presently three electrolytic hydrogen production technologies [16–21], differing from each

Table 1. Principal characteristics of hydrogen production processes in various electrolysers

Type of electrolyser, electrolyte	Electrolysis temperature, °C	Energy consumption for production of 1 m^3 H_2, kW h	Process features	Producers
Aqueous alkaline, 20–30% aqueous KOH (NaOH)	50–100	4–6	Efficiency up to 500 m^3 h^{-1} H_2 (P = 0.1–5 MPa). Admissible load level 20–100% nominal efficiency	Stuart IMET, Electrolyser (Canada); Norsk Hydro (Norway); DeNora (Italy); Uralkhimmash (Russia), etc.
Solid polymer electrolyte (SPE), proton-exchange membrane	80–100	4–6	Efficiency up to 100 m^3 h^{-1} H_2 (P = 0.1–15 MPa). Small size, safety, possible work in nonstationary modes, serviceability, lack of corrosion-active substances. SPE electrolysers are 5–7-fold more expensive than aqueous alkaline with similar characteristics. Stringent requirements for the quality of water	Proton Energy Systems (Canada); Hamilton Substandard (USA); H-Tec (Germany); "Kurchatovskii institut" Russian research Center, "Hydrogen" Research and Development Center (Russia)
Solid oxide electrolyte, Zirconium–yttrium ceramics with oxygen–anion conductivity at high temperatures	800–1000	3.5–4	Can operate in the stationary mode only; sensitive to multiple startup/shutdown cycles associated with cyclic variations in cell temperature. Hold promise for power production in big stationary devices	Experimental and pilot samples

other in electrolyte type and electrolysis conditions (Table 1). The cost of electrolytic hydrogen is largely contributed (70–90%) by expenses for electric power [17]. Unlike the above method for hydrogen production from natural gas, the cost of hydrogen will not decrease considerably with increasing efficiency of the electrolytic cell, and the principal factor responsible for the competitiveness of the latter is its efficiency rather than cost. At the same time, provided the electric power is cheap (as, for instance, in its "collapse" consumption periods), the electrolytic production of hydrogen may well become profitable.

Other hydrogen production methods are now under engineering development. They include, for instance, the following.

Thermochemical water splitting with use of the heat energy ($T \sim 800$ °C) of nuclear reactors or solar devices. A fairly detailed review of the state of these methods by mid-1980s is given in [3]; more recent advances in this field are exemplified in technical papers of the US Department of Energy [22].

Biochemical water splitting (photosynthesis) by specially raised aquatic plants and microorganisms [23].

Photocatalytic water splitting by means of semiconductor materials (mixed oxides, sulfides, selenides, nitrides, and oxynitrides) [24].

Production of power-accumulating substances (silicon and aluminum alloys) followed by hydrogen generation by decomposing them with water immediately before use [6, 25].

HYDROGEN STORAGE, TRANSPORTATION, AND APPLICATION

Compact and safe storage of hydrogen is quite an important problem whose solution predetermines successful realization of the concept of hydrogen energetics as a whole. A review of this problem is given in the present issue [26].

Hydrogen is suggested to be transported largely as a compressed gas via pipeline network. The technical solutions and infrastructure well-developed for natural gas can be adapted, after corresponding modification, for hydrogen. Moreover, the existing pipeline network allows delivery of hydrogen until its concentration in natural gas is below 10% [27], which can facilitate transition to hydrogen energy without profound changes in the prevailing infrastructure.

The use of hydrogen as a fuel is based on the oxidation of hydrogen with oxygen, that occurs at normal conditions (0°C, 0.1 MPa) with strong heat release (120.6 MJ/kg H_2 = 33,5 kW h/kg H_2 = 3 kW h/m^3 H_2). The generation of hydrogen by water electrolysis at a 60–75% efficiency of the electrolytic cell is associated with actual power inputs of 4–5 kW h/m^3 H_2. Combustion of 1 m^3 of hydrogen in a power installation with an efficiency of 15–20% yields 0.45–0.6 kW h, whereas the yield of a fuel cell with an efficiency of 40–60% is 1.2–1.8 kW h. Thus, the total efficiency of the hydrogen energy cycle at finite utilization of mechanic energy and electric power is 10–15% with heat machines and 24–45% at electrochemical hydrogen utilization.

The advantages of hydrogen fuel in internal combustion engines (ICEs), steam generators, and jet engines include its high heating value, complete combustion virtually over the entire range of fuel/oxidant ratios, high flame temperatures and heat efficiency (30–50% higher than that of gasoline ICEs), and lack of hazardous atmospheric exhausts. At present hydrogen is widely used as a rocket fuel. Prototype vehicles with ICEs on hydrogen or mixture of hydrogen with traditional fuels have presently been realized by a series of automobile companies; some of these prototypes are planned to be put into large-scale production in the near future. Hydrogen–oxygen steam generators for peak load electricity generation, as well as for some other purposes [4, 28].

Hydrogen can be converted into various forms of energy (thermal, electrical, chemical) via catalytic combustion, electrochemical conversion, hydrogenation, etc. The efficiency of these processes with hydrogen is higher than with other fuels. Therefore, development of promising hydrogen technologies attracts increased attention.

Particular emphasis is presently put on electrochemical power generators, specifically fuel cells (FCs) [4, 16, 27, 28]. In a FC, the fuel and oxidant are delivered to electrolyte-separated electrodes, and power is generated due to electrochemical oxidation.

Depending on the type of the electrolyte, different types of FCs are recognized. The electrolyte in alkaline FCs is 35–50% aqueous alkali (KOH or NaOH). These FCs are commonly operated at 100–120°C; with concentrated, up to 85%, alkali solutions, the operating temperatures can be raised to 250 °C. Alkaline FCs are best developed and widely used in autonomous power systems in aeronautics and Navy. The most important drawback of such systems is the requirement that the fuel and oxidant be completely free of CO_2.

In FCs with a proton-exchange membrane electrolyte (PEMFCs), the membrane is a thin film made of a fluorinated acid polymers (Nafion is a typical example) with a catalyst (platinum metal) applied on both sides. The operating temperature of FCs of this type is 60–80°C. Even though both the absence of CO_2 in the fuel and oxidant in such FCs is not obligatory, which allows these cells to be operated for a long time with atmospheric air as an oxidant, other admixtures (CO, sulfur compounds) are undesirable. Moreover, the fuel and oxidant should be wetted, since drying of the membrane put is out of operation. Like solid oxide electrolysers, these FCs are fairly expensive, but due to small size and convenience in operation, they can be used to success in small- and mediumscale autonomous power devices, in particular for hydrogen vehicles.

Fuel cells with a phosphoric acid electrolyte comprise a silicon carbide matrix inmpregnated with concentrated (~100%) phosphoric acid. The operating temperature range is 150–220°C. At present such FCs are being replaced by more efficient and economical.

The electrolyte compartment in molten carbonate FCs is a ceramic matrix ($LiAlO_2$) impregnated with a melt of a mixture of alkali metal (lithium, sodium, and potassium) carbonates. These FCs operate at 600–700°C without electrocatalysts. They have similar characteristics as phosphoric acid FCs. In view of the potential low cost, molten carbonate FCs are planned for future use in stationary power devices.

The electrolyte in solid oxide FCs is a zirconium oxide ceramics modified with yttrium oxide. Such FCs operate at 900–1000 °C and hold the greatest promise for large-scale stationary power generation. High-temperature FCs make use of atmospheric air as an oxidant and hydrogen, methane, and other fuels, and, what it important, are quite undemanding in terms of fuel quality. A single drawback of such FCs, like with solid oxide electrolysers, is undesirability of frequent startup/shutdown cycles attendant with heating to operating and cooling to ambient temperatures.

If by the late 1990s there had been near 100 (except for military application) prototype FC power generators [14], presently the research and development in this field has intensified abruptly. Fuel cells of different types are industrially produced on a small and medium scale, including fairly large (1 MW) solid oxide FC power devices (Westinghouse), mobile PEMFC power devices for hydrogen-driven vehicles (Ballard Technologies), etc.

New developments in this field are aimed at increasing the durability and efficiency of FCs and decreasing their cost. Table 2 lists the costs of power generators with different types of FCs by 1999 and prognosis to the middle of the current century [16].

Another perspective direction is development of new technologies on the basis of metal hydrides described in detail in [26].

CONCEPT OF HYDROGEN POWER ENGINEERING SYSTEMS

The production of hydrogen from natural sources is energy-consuming. Therefore, hydrogen should be considered as a secondary (intermediate) energy carrier. The most promising starting material for hydrogen production is water whose Earth's resources are unlimited. On the other hand, hydrogen fuel produces water. Thus, the use of hydrogen as an energy carrier, on the condition that the production of primary energy is ecologically safe, provides a closed ecological cycle. The elements of the power engineering chain, including hydrogen generation from water, its storage, transportation, and consumption, scarcely exert an adverse environmental impact. No greenhouse gas (CO_2 and others) emissions also occur.

The concept of hydrogen power systems envisages large-scale production of hydrogen and further application as energy carrier, fuel, and reagents in fields associated with energy consumption (industry, transport, municipal sphere, etc.). Figure 2 gives a schematic presentation of this concept, according to the Report of the European Commission for Hydrogen Energy and Fuel Cells [29]. Hydrogen is planned to be produced both by traditional methods, including gas and coal conversion, and by newly developed technologies: biochemical, nuclear and solar thermal water splitting, etc. Priority is given to electrolytic hydrogen production from water with use of renewable power sources or nuclear power for electricity generation. At present these technologies are economically noncompetitive compared with those for hydrogen production from hydrocarbon raw material, and the principal problem to be solved is to enhance electrolysis efficiency.

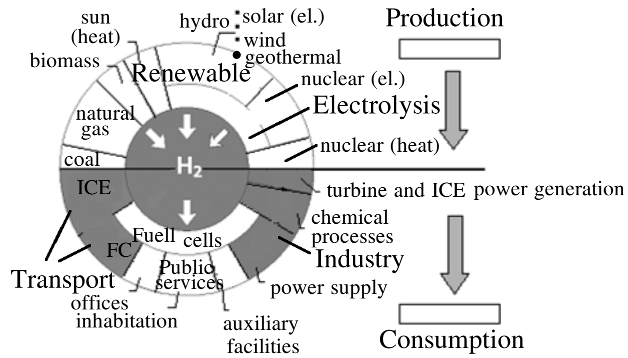

Fig. 2. Schematic representation of the concept of the hydrogen energy system.

To produce power directly at the consumption site, hydrogen is proposed either to combust in ICEs, turbines, and steam generators or to electrochemically oxidize in fuel cells. The latter approach is preferred, since electrochemical power devices are more efficient, compact, and convenient in operation.

Below we give a brief retrospective of the concept of hydrogen energetis, cited largely by [30].

The idea of large-scale use of hydrogen as an artificial fuel generated by water electrolysis was first put forward by Jules Verne in his science-fiction novel "The Mysterious Island" (1874). First attempts to realize this idea date back to 1920–1930s, with the initiation in Canada of industrial production of aqueous alkaline electrolysers and the adoption of the program for development of hydrogen power systems on the basis of the electricity generated by a hydroelectric power station. This program was being fulfilled up to 1936, after which the Canadian market was reoriented to the low-cost natural gas.

In the 1920–40s, the main focus of European hydrogen researchers and engineers was to adapt heat machines, primarily ICEs, for unconventional

Table 2. Cost of hydrogen fuel cell devices, US dollar/kW

FC	1999	Perspective
Alkaline	2000	50–100
With polymer membranes:		
stationary	8000	300
mobile	550	30
Phosphoric acid	3000	1000
Carbonate	5000	600
Solid oxide	1000	600

fuels, including hydrogen. It was shown that the use of hydrogen, after corresponding modification of the fuel system (transfer to internal mixing) allows the engine power to be increased by 10% and even more. Addition of hydrogen to a traditional motor fuel made engines more economic and less environmentally hazardous. During this period, a total of about 4000 vehicles were adapted to use unconventional fuels, including hydrogen, Therewith, the cost of adaptation of one engine, according to later estimates, was no more than several hundreds US dollars in the 1970s prices.

It is interesting to note that during World War II the research and development in this and related fields even intensified. In Germany, a synthetic motor fuel produced by coal hydrogenation was in wide use during the war. In USSR, under Leningrad's blockade conditions, cargo vehicles were reequipped for the hydrogen fuel from exhaust-resource balloons from antiaircraft defense troops [31]. There works were supervised by technic–leutenant B.I. Shelishch.

In 1942, Britain's Navy expressed great interest in hydrogen-fueled autonomous power systems for diesel submarines. The fuel was compressed hydrogen and oxygen obtained by water electrolysis. Australia, being isolated from oil supply during World War II, initiated programs for the development of large-scale production of hydrogen and its application as a motor fuel. The return to cheap oil after the war brought these programs to a halt.

In 1950, the interest in hydrogen was renewed by the progress in FC technologies. Even though FCs had been invented as early as the XIX century, first practically feasible samples appeared in early 1950s in Great Britain and Germany. Later (1970–80s) these developments had a strong impact upon aerospace programs in the USA and USSR. The use of FCs allowed a much more efficient electricity generation at the hydrogen consumption stage.

The vigorous progress in hydrogen energy and technology fell on 1974–1983 and was a direct consequence of the energy crisis involving a great number of industrially developed countries. Beginning with mid-1970s, intense information exchange and international cooperation in hydrogen research was initiated, and at the end of 1974 the International Association for Hydrogen Energy (IAHE) was created. The main line of the IAHE's activities is to provide informational support for research and development in hydrogen technologies and to inform world community about the results of this work. To this end, the Association holds biannual World Hydrogen Energy Conferences and issues the International Journal of Hydrogen Energy. The Association provided support for the establishment of several tens of National associations for hydrogen energy. A brief report on IAHE's activities over 1974–2000 was published in Russia [1].

Changes in global energy market trends in the second half of 1980s slowed down the progress of research in hydrogen energy and technology. This was especially characteristic of the USA, where the Reagan administration cut renewable energy and hydrogen budgets by 80%. The high cost of hydrogen production, especially by electrolysis, disengaged businessmen's and politician's interest in hydrogen energy. A part was also played by certain disappointment of American researchers who pinned before too big hopes on the hydrogen energy concept raised in the rank of panacea and had illusions about its fast realization. The approach of European and especially Japanese research, business, and governmental circles was more realistic. They recognized that the broad introduction of hydrogen technologies would require long and active efforts. It is as far back as 1974 that Japan's 26-year project "Sunshine" started. This was the greatest alternative energy project that compared in scale with the American Apollo space program. A total of $15 billion was spent, including a hydrogen budget of $3.6 billion. Beginning in 1976, the Paris-based International Energy Agency began to support hydrogen programs. In 1978 the IEA's hydrogen budget was about $16 million distributed over several years. At the same time, the general tendencies for expanding use of hydrogen in energetics and technology, while being preserved, became less dynamic.

An important milestone in the development of hydrogen energetics and technology was associated with the results of an economic study by the University of Miami's Clean Energy Research Institute in late 1980s. The authors assessed the environmental costs of industrial and traffic exhausts and suggested a procedure for introducing the corresponding corrections in economic calculations. With these corrections, hydrogen, in view of its ecological purity, proved to be potentially cost efficient in a series of industries [32].

Acting slightly in advance, we give here a diagram showing present-day European prices (in energy equivalents) for hydrogen generated by different methods and attendant CO_2 atmospheric emissions (Fig. 3). The same diagram contains gasoline prices estimated with inclusion of the EU environmental tax (calculated by the above-mentioned procedure) and without it. As seen from the figure, if 50% of hydrogen is produced from natural gas and 50% by means of renewable energy sources, the mean price of hydrogen fuel is close to that of gasoline, including the charge. At the same time, the price of gasoline without the CO_2 tax is half as cheap [33].

In whole, the groundwork for contemporary hydrogen technologies was laid from mid-1970s through late 1990s. Considerable advances were achieved in the field of hydrogen production from renewable hydrogen sources. Basic technical solutions of various-type electrolysers with improved characteristics were perfected and brought up to pilot samples. Concurrently, more efficient, durable, and reliable FCs were being developed. Radically new technical solutions of electrochemical systems on hydrogen appeared (new generation of electrolysers and solid polymer or oxide electrolyte fuel cells). Principally new ecologically pure hydrogen production technologies, such as biochemical and photocatalytic, were developed.

Constructions of hydrogen-burning heat engines and power devices were being dynamically developed. In 1970–1980s, prototypes of cars and other vehicles with ICEs on hydrogen or hydrogen-doped fuel were built in some countries (USA, Germany, Japan, USSR). In 1990s, first examples of automobiles and buses with electric engines powered from mobile FC energy devices appeared.

In that time, a series of big projects on the use of hydrogen as an aviation and aerospace fuel were fulfilled. In the USA (Space Shuttle Program) and USSR (Buran–Energiya Program) large carriers rockets were created, with engines using liquid hydrogen and oxygen as a fuel and an oxidant, respectively. The first successful trial of a hydrogen-fueled aircraft (TU-155 prototype model on the basis of TU-154, with one engine operated on liquid) was performed in the USSR in April 1988. A month later, the USA tried a light (four-seat) aircraft with a hydrogen engine.

Considerable progress was made in solving such an intricate technical problem as compact hydrogen storage. A new generation of high-pressure composite gas cylinders was devised, which allowed the mass and volume densities of hydrogen storage to be much increased. Liquid hydrogen production and storage technologies were also substantially improved. Much success was achieved in physicochemical methods for storage of bound hydrogen, including metal hydride technologies. One of the important results was the creation by early 1990s of high-performance metal–nickel hydride accumulators which are presently widely used in compact chemical energy sources.

At the same time, hydrogen transportation and distribution are still remain a weak spot of hydrogen power technologies and involve a series of technical problems that are to be solved in near future.

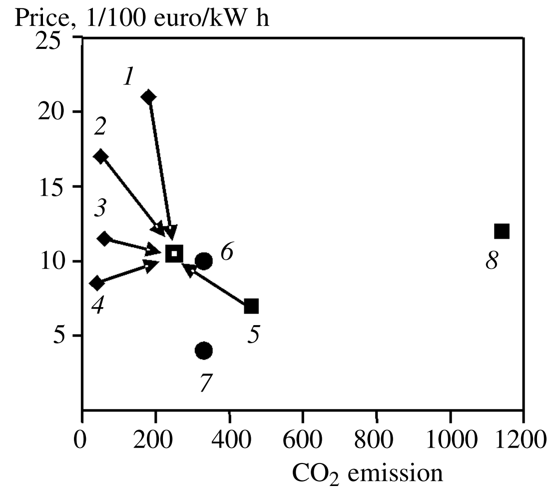

Fig. 3. Prices for hydrogen produced by different technologies and for attendant CO_2 emissions. Hydrogen produced from different energy sources: (*1*) solar (4%); (*2*) wind (24%); (*3*) biomass (14%); (*4*) hydro (8%); (*5*) hydrogen from natural gas (50%); (*6*) gasoline plus CO_2 charges; (*7*) gasoline free of charges; and (*8*) hydrogen from coal.

A great number of new developments deal with household applications of hydrogen (heating, hot water supply, cooking). Catalytic combustion of hydrogen is largely used; prototypes of high-efficiency, economic, and operationally convenient household devices were produced. New technical solutions of industrial and domestic heat devices (heating systems, refrigerators and conditioners, systems for low-potential heat transport, ets.) on the basis of metal hydride technologies were shown to hold promise.

The efforts of international community of researches and engineers in the field of hydrogen power systems in 1970–1990s resulted in that hydrogen energetics passed from research and pilot systems to commercialization. Major commercial companies, primarily motor (General Motors, Daimler-Benz, Toyota, BMW, Ford, Volvo, etc.), petroleum (Royal Dutch/Shell), energy (Norsk Hydro, Tokyo Electric Utility) were involved in this work. Beginning in 1989, development of standards in hydrogen energy and technology was initiated. To this end, by the initiative of the International Organization for Standardization (ISO), a permanent committee was established in Zurich. A series of big international projects for prototyping new hydrogen power devices were

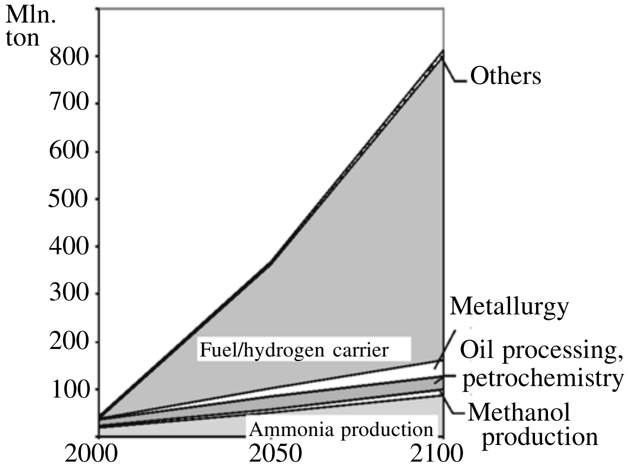

Fig. 4. Prognosis of hydrogen consumption in the XXI century.

fulfilled. The "HYSOLAR" German–Saudi project resulted in putting into operation in 1994 near Riyadh of the first solar-powered hydrogen plant. In the same year, first FC hydrogen powered buses appeared in the Europe. One of the results of the "Sunshine" Japan's project which was reorganized into the "World Energy Network" Project ((WE-NET) with a 2 billion budget up to 2030 was unveiling of one of the first FC power station (11 MW) on the basis of Tokyo Electric Utility.

The progress in hydrogen energy and technology in that period was much contributed by numerous groups from the USSR. Their efforts were coordinated by the Union Commission for Hydrogen Energy, established by the initiative of Academician V.A. Legasov and controlling virtually all facets of this problem.

PRESENT STATE OF THE RESEARCH AND DEVELOPMENT IN HYDROGEN POWER TECHNOLOGIES

Motivation and General Tendencies

The tendency for intensification of research and development in hydrogen power production is presently characteristic of most world's countries and is motivated by energy safety reasons, global ecological and climatic problems, search for commonly accessible energy sources, and demand for investments in modern energy supply infrastructure.

Analysis of the dynamics of the global energy demand [34] shows that, if the present-day energy policy will be preserved, the share of hydrocarbon fuels in the balance of primary energy sources will continuously increase to reach 90% the arbitrary fuel consumption increment by 2030. The above demand will mostly covered by oil, 3/4 of which will be consumed by motor transport. Needs of other consumers (energy, industry) will largely be covered by natural gas and, to a lesser extent, coal. As a result, the volume of the international market of hydrocarbon fuels will double compared to the situation in 2000. This will result in a strongly enhanced economic dependence of importer countries.

Considerable growth of the consumption of hydrocarbon fuels produces enhances the negative environment impact: Atmospheric CO_2 emissions solely are expected to increase by 70% over 2000–2030, whereas, according to data of the Intergovernmental Panel on Climate Change (IPCC), to avoid global warming, over 2020–2050 the atmospheric concentration of CO_2 should be decreased by 50–60% compared to the 1990 level.

Thus, cardinal change of the energy policy and reduction of the consumption of conventional energy carriers, such as oil, gas, and coal, is quite an urgent problem touching upon human interests (climate and ecology) and economical political interests of countries importing hydrocarbon fuels. To solve this problem necessitates development and implementation of energy-saving technologies and structural changes in energetics, aimed at increasing the share of energy whose production does not involve consumption of hydrocarbon fuels and atmospheric CO_2 emissions.

Realization of the concept of hydrogen power systems is the main route to change the energy infrastructure in the desired direction. Figure 4 presents a prognosis of hydrogen market for XXI century [35]. The prognosis envisages a 16–20-fold increase of hydrogen consumption compared with the 2000 level. Therewith, this increase is expected to be mostly (by up to 80%) contributed by the use of hydrogen as a fuel and an energy carrier, and two third of this hydrogen will fall on motor transport.

For success of the concept, hydrogen power technologies should be improved to be competitive technically and economically, having progressed from research and development to a new hydrogen infrastructure: facilities for hydrogen production, storage, transportation, and distribution, high-performance stationary and transport energy devices, etc. Works in this field require thorough planning, coordination, and large investments on the national and international levels. According to expert estimates, in the coming 30–50 years the investments in hydrogen energy will amount \$1–10 trillion [34].

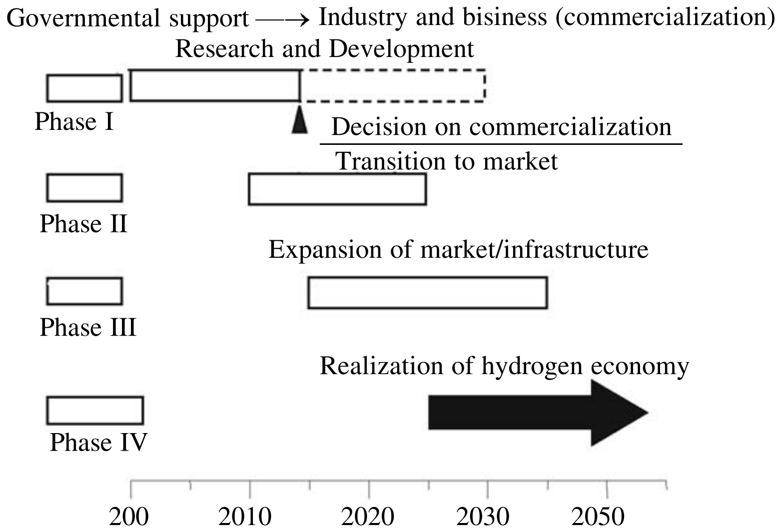

Fig. 5. Strategy of hydrogen economy development in the USA.

National Hydrogen Programs

In late 1990s a number of major international and national programs of commercialization of research and technical developments in hydrogen technologies, fuel cells, renewable energy sources, and other directions were initiated. Along with governmental and nongovernmental funds, works in hydrogen technologies were are invested by a number of commercial structures, primarily motor companies.

Below we give a brief analysis of typical national programs.

USA. The largest scale complex plan of development of hydrogen power technologies on the North American continent is the "Hydrogen R&D Program Rationale, Structure, and Technology Roadmaps" of the US Department of Energy (DOE), accepted in 1999 [36] and amended in February 2004 [37]. The major motivation is to reduce the dependence of the USA from crude oil import two third of which is consumed by motor transport. Therefore, main emphasis is out on large-scale hydrogen use for powering transport. This direction is closely related to the President's Hydrogen Initiative [38] and Freedom-CAR [39] Programs accepted in 2002. The total investments in these projects for 5 years are up to 1.7 billion, of which 1.2 billion were provided by President George W. Bush. It is indicative that the DOE funds and coordinates the above projects together with such major motor companies as Daimler-Chrysler, Ford Motor, and General Motors. The other important components of the DOE complex hydrogen program are research and development on the use of renewable power sources: solar, wind, water resources, geothermal, biomass, etc. The actual hydrogen budgets in the USA were \$92 million in 2003, \$147.2 million in 2004, and \$72.8 million.

The development of hydrogen economy in the USA (Fig. 5) envisages four phases. The first should involve development of critical technologies that will provide for the practical implementation of the stated strategic targets. The works being implemented in this stage by researches and engineers in state and private institutions, should result by 2015 in prototyping technics and equipment; development of comprehensive safety provision rules and corresponding standards and requirement specifications. Thereby, a basis for large-scale investments in hydrogen infrastructure and its commercialization will be laid. Solution on this issue should be made in 2015.

The second phase (2010–2025) involves initiation of commercialization of hydrogen generation and transportation systems, and this work will be implemented under sound governmental support, both via direct investments and via taking political decision to stimulate this market. Beginning in 2015, the third phase of the realization of the hydrogen program will start, which envisages establishment by 2035 of the infrastructure of hydrogen economy and market expansion of hydrogen technology. The start of the third phase will be coordinated with making a decision on the commercialization of hydrogen technologies, primarily, as applied to fuel cell vehicles. The corresponding investments are expected from business under government guardianship.

The introduction of hydrogen technologies during phases I–III will be attended with their further technical and economic perfection (transition to self-repayment and profit return). The latter process is associated with the initiation in 2025 of the fourth phase of the hydrogen program, which envisages for 2040 comletely formed self-sufficient market and infrastructure and, therefore, complete transition to hydrogen economy. As a result, the US oil demand should decrease by 11 mln. barrels per day, and annul`l atmospheric emissions of greenhouse gases, by more than 500 mln. ton.

The US hydrogen program largely addresses the use of hydrogen as a motor fuel, and its main features are the priority given to mobile FC power devices and stringent requirements imposed on characteristics of hydrogen storage systems for transport applications. In particular, the mass capacity (density) of hydrogen storage systems developed by 2005 should comprise 4.5 wt% H_2 (36 kg m^{-3}), by 2010, 6.0 wt% (45 kg m^{-3}), and by 2015, 9.0 wt% (81 kg m^{-3}). The principal result expected from this program is competitiveness of hydrogen-powered automobiles to traditional ICE ones. This, in particular, means that the cost of hydrogen should decrease 3–4-fold and the cost of 1 kW of installed capacity of fuel cells, more than 10-fold compared to the present level.

Japan. Major projects in the field of hydrogen technologies and fuel cells in Japan are administered by the Ministry for Economy, Trade and Industry (METI). The works are aimed at developing the infrastructure and widely introducing both stationary FC power devices and automobiles on hydrogen fuel and fuel cells. The METI program envisages the enhancement of the total capacity of stationary FC devices from 2.2 GW in 2010 to 10 GW in 2020, and 12.5 GW in 2030; the corresponding number of FC vehicles is planned to comprise 50 thousand (2010), 5 million (2020), and 15 mln (2030). Therewith, the annual hydrogen consumption will be 6 (2010), 28.5 (2020), and 46 bln. m^3 (2030) [40].

To this end, the Japanese Government envisages substantial investments in FC and hydrogen projects. Thus, the METI budget for this purpose has increased from $106 million in 2001 to $303 million in 2004 [41]. The METI program comprises three stages. The first (2002–2005) involved comprehensive research with revision of standards and rules on hydrogen production, storage, and use, first pilot works on the introduction of hydrogen infrastructure were performed. Thus, 30 stationary FC hydrogen power devices, 10 hydrogen-filling stations, and about 50 hydrogen-fueled vehicles (in particular, for servicing government) functioned in Japan in March 2004. The second stage (2005–2010) envisages expanding introduction of hydrogen technologies with gradual creation of their full infrastructure. In third stage (2020–2030), the funding source is planned to be transferred from governmental to business structure and natural development of hydrogen economy.

The research and development of hydrogen power technologies in Japan are conducted in state universities and research laboratories, and well as in research branches of major motor (Toyota, Honda, Mitsubishi, Nissan) and metallugrical (Japan Steel Works, Japan Metals and Chemicals etc.) companies.

Considerable attention in Japanese hydrogen programs is given to industrial and household applications of hydrogen technologies, specifically, to the use of metal hydride technologies in heat conversion and delivery [42].

European Union. The initiation of large-scale activities of EU in the hydrogen field [43, 44] dates back to 1999–2001, when the European Hydrogen Energy Thematic Network was set up. This group cooperates representatives of European science and industry (Norsk Hydro, Shell Hydrogen, Air Products, BMW, etc.). Its area of focus is a common strategy in the development of hydrogen energetics in European countries and contributing corresponding suggestions to EU's official structures. In 2002–2003, the group took part in the development of the complex program of the EU (FP6 R&D program) as related to hydrogen, fuel cells, and renewable energy sources [45].

The principal targets of EU's hydrogen programs are to reduce the dependence of the economy of imported Near-Eastern oil, reduction of atmospheric pollution,[1] preservation of the leadership in science-intensive technologies, as well as to increase the share of renewable energy sources in the balance of European countries from 6% in 2000 to 12% in 2010 and 33% in 2020.

The program of the transition of EU countries from an economy based on the use of organic fuels to hydrogen economy is planned to be 50 years long (2000–2050) and includes two main stages. The first (2000–2020) involves development and prototyping of hydrogen power systems and the second (2020–2050), large-scale commercialization of technologies based on hydrogen and fuel cells. The works are performed in two principal directions:

– hydrogen production and distribution;

– hydrogen consumption systems and fuel cells.

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[1] According to the Kyoto Protocol, EU greenhouse gas emissions by December 2008 should by reduced by 8% against the 1990 level.

The first direction involves the generation of hydrogen by gas conversion and water electrolysis, start of formation of regional elements of hydrogen infrastructure (filling stations and distributed hydrogen production for them) and hydrogen distribution pipeline networks. In future plans, organization of hydrogen production from renewable sources, including biomass gasification; modernization of hydrogen production from organic raw materials with trapping CO_2, as well as using nuclear energy.

The first direction involves creation of stationary commercial systems on low-temperature (up to 50 kW) and high-temperature FCs (up to 500 kW) (hydrogen-fueled internal combustion vehicles and concept buses). The next stage should involve reduction of cost and commercialization of mobile FC power devices (portable current sources, motor transport, and big, up to 10 MW, devices), creation of autonomous FC power systems, and use of hydrogen in aviation.

Research and construction projects in the hydrogen field are funded by the EU on a competitive basis. Thus, the FP6 program in 2003 provided 1 mln. euro for hydrogen projects and 1 mln. euro for FC projects. Further investments will comprise 2.8 bln. euro over 2005–2015 for development of technologies for hydrogen and electricity production from hydrocarbon fuels with CO_2 utilization (1.3 bln. euvo), as well as for hydrogen production from renewable energy sources and its stationary and transport use (1.5 bln. euvo). Some projects are funded in part by commercial companies.

The total investments in EU's hydrogen programs are estimated at 4–15 bln. euro. The implementation of hydrogen programs is expected to increase hydrogen production in EU countries from 2.3 bln. m^3 in 2000 to 20.6 bln. m^3 in 2025. By 2020, the number of hydrogen vehicles should reach 2 million (1% of the total vehicle population) at a hydrogen fuel consumption of about 300 thsd. ton/year. The total share of hydrogen in EU's fuel balance should comprise 2% by 2015 and 5% by 2020.

The development of hydrogen technologies in European countries are much contributed by sectoral programs funded and coordinated by the International Energy Agency (IEA), European Space Agency, and a number of other organizations. Of great importance are also bilateral projects of the EU with other countries, in particular, Canada.

North European Countries. These countries, even non-EU member states, take active part in hydrogen programs of the EU, they have a series of own national and international hydrogen programs. The most active in this respect are countries whose energetics is based on renewable energy sources: water resources (Norway) and geothermal sources (Iceland).

In Norway hydrogen programs are largely funded by the Council for Hydrogen Research (Nordisk energiforsking, NEF) having the status of governmental institution. The planned R&D budget of the NEF program is $17–29 million up to 2010 and $7–14 million for 2010–2014. Therewith, the state budget contributes 50%, and the other 50% come from industry and business. The projects are focused on hydrogen production, storage, and distribution, creation of autonomous power systems on renewable energy sources. A number of bilateral Norway–USA and Norway–Japan projects are in progress [46].

At present renewable energy sources (hydro- and geothermal) contribute most in the enegretics of Iceland.

At the same time, the demand for fuel for motor transport and fleet (primarily fishing) is satisfied exclusively by imported oil products. The principal strategic targets of the Iceland's hydrogen [47] are to reduce the dependence on imported fuels via transition of motor transport and fleet to hydrogen fuel produced from renewable energy sources. Beginning in 1998, this program is given priority in national policy, and it is supported by the national government. The hydrogen program is expected to result in that by 2030 Iceland should become the first world's country with completely realized concept and developed infrastructure of hydrogen economy. To this end, in 1999 the Icelandic New Energy (INE) concern was established, whose 51% shares belong to Iceland's governmental structures and private firms and the other 49%, to major foreign companies (Shell Hydrogen, Norsk Hydro, DaimlerChrysler, by 16.33%). At present there is much effort in the framework of this program, in particular, exploitation of hydrogen FC buses on capital's city lines. One of the components of hydrogen transport infrastructure is a filling station in Reikjavik, whose characteristic feature is that hydrogen is produced on-site by electrolysis and then delivered to an intermediate storage system (gas pressure 40 MPa).

China. Much emphasis is put on hydrogen research and development in China [48, 49]. Being among the major word's oil importers (in perspective, natural gas), China is highly interested in restructuring its energy market and reducing consumption of this kind of natural energy carriers. One the ways to such a restructuring might involve expanding use of coal whose share in country's energy balance is as it is considerable (71.5% by 1997). However, this ap-

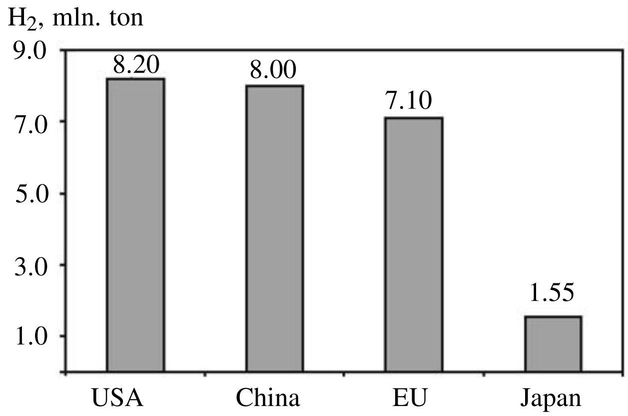

Fig. 6. Hydrogen production (mln. ton) in 2002.

proach necessitates cardinally improved coal processing technologies and reduced environmental impact. Presently China ranks second after the USA in CO_2 emissions and, as state signatory to the Kyoto Protocol, should take measures to reduce these emissions.

The above problems, according to the Chinese government, can be radically solved by gradual transition to hydrogen economy, and China possesses all prerequisites for its building. This country is the second greatest world's hydrogen producer (Fig. 6), has well-mastered technologies for hydrogen production (including electrolysis), purification, and application. In China, such science-intensive technologies, as metal hydride, have already mastered on an industrial level.

In China, tens of universities and research institutes are involved in the R&D activities in the field of hydrogen power technologies. Hydrogen energetics is a separate budget line item in the five-year science and technology plan (Program no. 973 of the Ministry for Science and Technology). The total state investments in hydrogen and fuel cells are presently estimated at $290–460 million. Industry and business are widely involved in these works, and much attention is given to international cooperation. Demonstative is the high activity of Chinese business in the European market of renewable energy sources.

Russian Federation. The present-day economy and budget of Russia are based on the import of Russian oil and gas. Russian governmental and business circles realize that to avoid a depressive country's development model, this dependence should be reduced. Russia possesses a high scientific potential and controls 50% world's production of palladium which is required for a series of hydrogen technologies. This circumstance creates favorable grounds for developing hydrogen energetics. The main target of Russian hydrogen programs is to create by 2010–2012 competitive export-oriented products in this field [50, 51]. The policy in funding these programs envisages investments of major oil, gas, and energy companies, along with governmental moneys.

On November 10, 2003, the President of the RAS Yu.S. Osipov and General Director of the mining-and-metallurgical concern (GMC) "Noril'skii nikel'" put their signatures under an agreement according to which the GMC will invest in hydrogen research 40 million a year. The "Complex Program of Conceptual, Research, and Prototype Works in Hydrogen Energy and Fuel Cells," developed in the framework of this agreement was signed on December 9, 2003. The Program envisages research into expanding industrial use of palladium and perspective technologies for making products on its basis, forming a research and technical, technological, and design reserve for key apparatuses and systems of hydrogen energy and FCs (solid polymer, alkaline, and solid oxide) with characteristics by passing those of foreign analogs; creation of fuel processors for conversion of hydrocarbon fuels and hydrogen production and complexes for hydrogen production, purification, accumulation, storage, and delivery; development of industrial processes for producing the element basis and new materials for hydrogen energetics amd autonomous power devices with various-type FCs; creation of a unified series of high-efficiency ecologically pure power devices and electrochemical hydrogen generators of a broad class on the basis of 1–25-kW fuel cells. The Program also envisages creation of portable FC power sources for household electronic devices and cooperation of research institutions of the Russian Academy of Sciences and industrial enterprises for the production of competitive power devices on the basis FCs and high-tech products and palladium and platinum group metals. The implementation of the Program will result in suggestions on development of the national infrastructure of hydrogen energetics and development of national program for hydrogen energy and FCs, including variants and schemes of funding this work.

There exist a number of other major Russian hydrogen programs. Thus, in spring 2002, a program that subsidizes commercial development of FC power devices (RAS, ISTC, Ministry for Nuclear Industry, Gasprom) was accepted. The total budget of ISTC hydrogen projects is $35 million. Moreover, Russian hydrogen projects are funded by a number of foreign companies.

International Cooperation

The above list of hydrogen programs is far from complete. The concept of hydrogen power systems is being actively realized by many other countries (Canada, Australia, New Zealand, Brazil, India, etc.), as well as all leading motor and transnational oil-and-gas corporations (Royal Dutch/Shell, ExxonMobil, Texaco, British Petroleum, etc.). An important part in the implementation of hydrogen projects belongs to international cooperation in the framework of bipartite and multipartite agreements, programs of major international organizations, such as the above-mentioned IEA, IAHE, and others.

In November 2003 in Washington, 12 countries[2] and the EU (3.5 billion population, 85% world's GDP) established the International Partnership for the Hydrogen Economy [52]. This intergovernmental organization open for new members coordinates current and provides support for new national and international programs for development and introduction of highly efficient hydrogen technologies.

CONCLUSION

Over the past decade hydrogen energy and technology has undergone radical changes. If previously most emphasis was put on engineering and energy aspects, the present focus is ecological, economical, and political facets of the problem of development of intersectoral infrastructure providing large-scale use of hydrogen.

The concept of hydrogen power systems conceived on the background of the global oil crisis of the 1970s has presently transformed into a dynamically developing scientific and technical branch whose support is given priority in the policy of international communities, national governments, commercial companies, and nongovernmental organizations.

At the same time, it should be noted that most efforts has been in concrete directions of hydrogen energetics, technology, and economy, at the lack of a systemic research and correlation of these directions, entailing the lack of balanced strategic recommendations. Economic research into environmental pollution is one of few exceptions. As a result, the economic motivation of hydrogen programs still remains within the province of present-day ideas. This approach is exemplified by an excessive, in our opinion, accent on motor transport. Without due attention to stationary hydrogen devices, primarily those that are technically and economically approved at present, this approach seems hardly realizable.

In our opinion, the concept of hydrogen power systems should be subjected to a comprehensive systemic analysis with subsequent development of a strategy for expanding use of hydrogen in areas where it has already taken its stand and for gradual extension to new fields of energy and technology. In this case, the transition to hydrogen economy will take a longer time, but it may turn to be more organic, and hopes for its realization will eventually come true and not remain a beautiful but utopian dream.

ACKNOWLEDGMENTS

The authors are grateful to B.M. Bulychev (MSU, Chemical Department) and N.A. Shteinberg (Ukrainian Ministry of Energy) for initiation of a discussion which prompted us to write this paper.

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