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PERSPECTIVES OF ELECTRONUCLEAR METHOD OF ENERGY GENERATION AND NUCLEAR WASTE TRANSMUTATION

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The studies of feasibility of electronuclear method of energy generation are overviewed as well as a current research program in this direction at the Synchrophasotron — Nuclotron accelerator complex. The results may be applied for development of new technique of nuclear waste transmutation.

The investigation has been performed at the Laboratory of High Energies, JINR.

Перспективы электроядерного метода генерации энергии и трансмутации радиоактивных отходов

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Дан обзор исследований осуществимости электроядерного метода генерации энергии, а также перспективной программы в этом направлении на ускорительном комплексе синхрофазотрон – Нуклотрон. Результаты могут быть использованы для разработки новых методов переработки радиоактивных отходов.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

The problem of energy source is one of the most important problems to be solved by the mankind. According to the International Energy Congress, during the next century electric power production is expected to increase up to about $50 \cdot 10^{12}$ Watt. As one can see in Fig.1, coal, oil and gas will play the most important role in energy production, but this role will decrease rapidly after the turn of the century: about 60% of the electric power is anticipated to be produced in nuclear plants. Even in 2100, the contribution of all solar energy sources will be still relatively small (20%). Figure 2 illustrates the harmful effects of the current trend in energy production upon people and environment. In the book «Nuclear Energy, Mankind and Nature» [1] the authors have shown that the total harm to people from coal stations is 400 times greater than it is from atomic stations, including all operations from mining to the final storage of reactor waste. Analogous conclusions are presented in other papers.

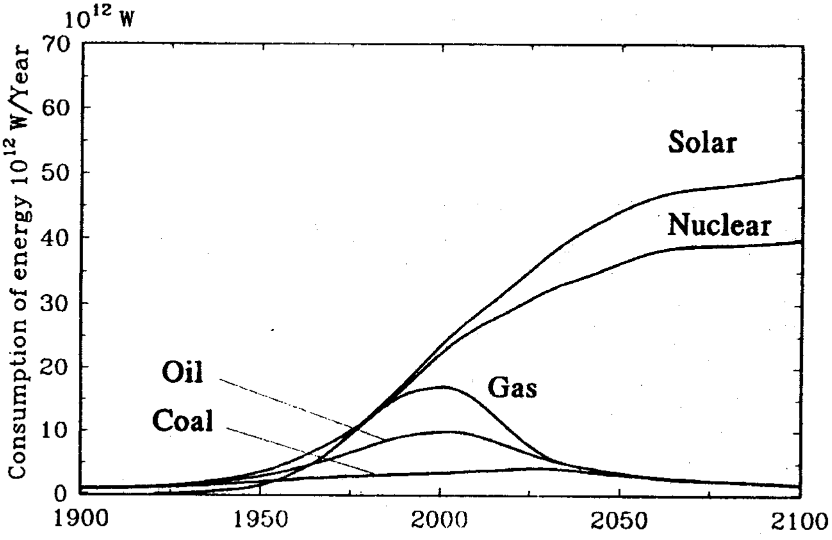


Fig.1

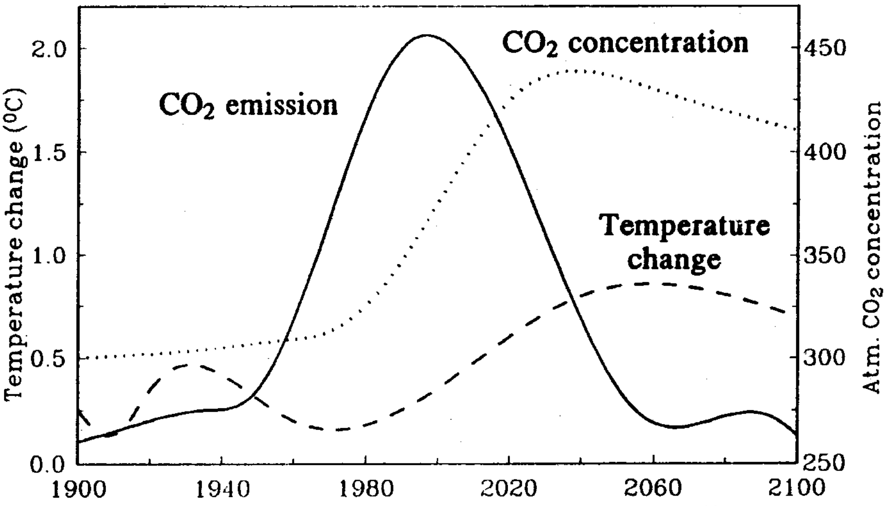


Fig.2

Indeed, coal ashes contain on the average 400 g of uranium per ton. In other words, in 1990 in the former USSR alone, the amount of uranium in coal ashes was $90 \cdot 10^3$ tones, i.e., four times greater than the annual extraction of uranium in the entire world.

The radon discharged into atmosphere is causing more than half dose of natural radioactivity. It should be noted that population is directly exposed to radon only if it leaks into the houses. The radon from ashes does not necessarily mean any further radon exposure of population.

Unfortunately, the public has too little information about all this stuff. The Chernobyl disaster and the incomplete and distorted information provided by the less competent authors and media led to a strong opposition to the use of nuclear energy. At the 1992 Russian Energy Congress some examples were given when people had laid on rails to prevent the construction of atomic power plants.

Thus, to change public opinion, the safety of atomic stations must be guaranteed, especially with respect to the protection of reactors from an unlimited power ramp. If the probability for accidents to the running reactors is estimated to be about 10^{-4} reactor years, and even the intent to improve this by a factor of 10—100 is pushed, then ordinary citizens do not want to consider in probability categories, preferring a binary system («yes» or «no») and no game of probability calculation will satisfy them.

An unlimited increase of reactor power will be prevented by a subcritical reactor with the coefficient of neutron multiplication: $C_{\text{eff}} < 1$. In such a reactor, a chain reaction cannot proceed independently and an external source of neutrons is requested. For this purpose, the accelerator-breeding method (ABM) was proposed in the USA and Canada more than 30 years ago. The method is based on using of accelerated protons for generation of neutrons in nuclear interactions. Thus the chain reactor is supported at $C_{\text{eff}} < 1$.

To realize the ABM it is necessary to combine an accelerator with a reactor and also to obtain nuclear data which permit to optimize the efficiency of the chain reaction. In the first projects [2] and their further modifications, high-current accelerator and «depleted» uranium, i.e., natural uranium from which most of ^{235}U has been extracted, were mostly used.

One of impacts to develop high current accelerators is due to the programs of the generation of tritium for neutron weapon and the transmutation of reactor wastes. For this purpose a conceptual study of the transmutation of actinium series members has been made [3]. The proposed plants consist of a sodium cooled subcritical reactor core with actinide fuel and tungsten target. This system would transmute about 250 kg actinides annually to produce 246 MW of electric power using a 1.5 GeV proton beam with current of 39 mA. The proposed plant based on the Phoenix concept is intended for the construction of a linear accelerator with a proton energy of 1.6 GeV and a current of 104 mA [4]. Figure 3 from [5] gives the data on operating and designed accelerators.

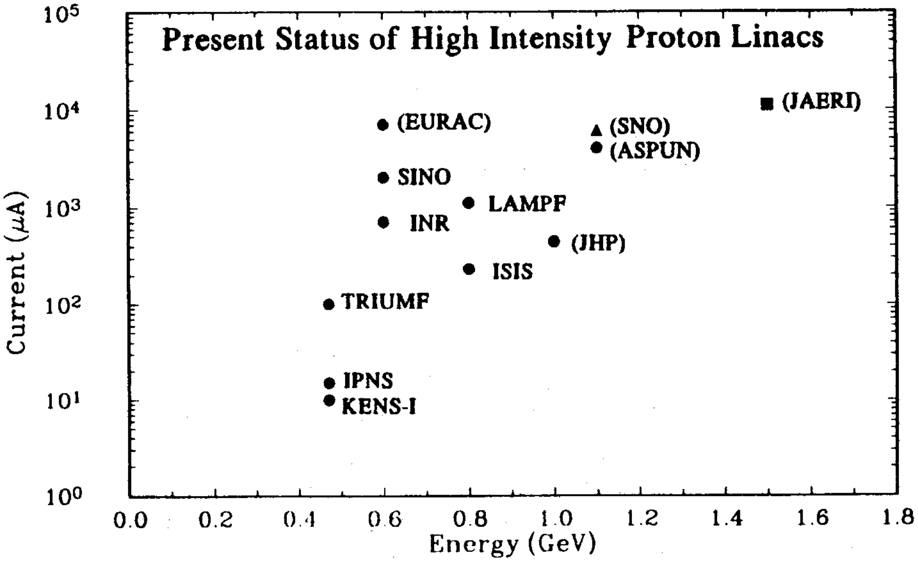


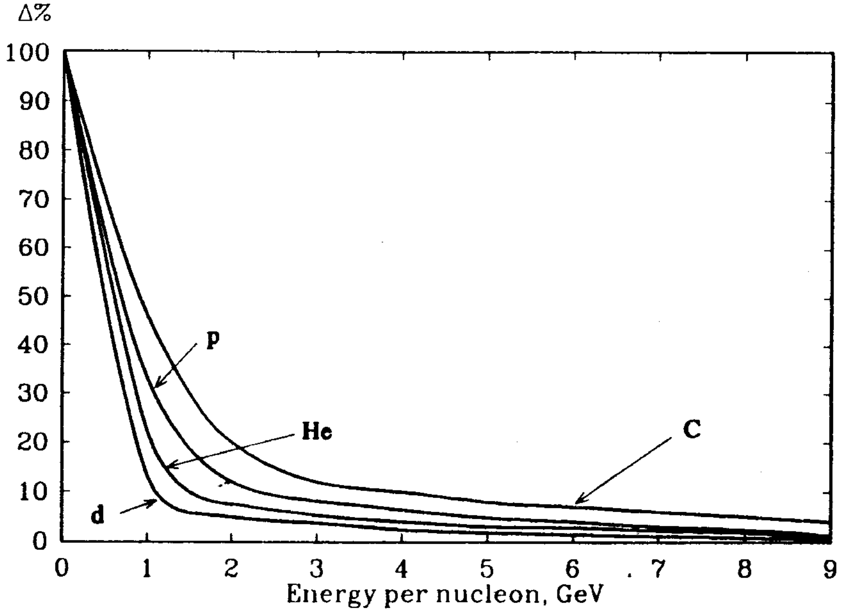
Fig.3

Another ABM possibility is decreasing the beam power by increasing C_{eff} of the subcritical reactor by a prior enrichment of the fuel with ^{235}U or ^{239}Pu. This advantage can be also achieved by accelerating light nuclei instead of protons.

A first conclusion of how this idea might work could be drawn from our investigation of proton and nuclear collisions with silver and bromide nuclei as shown in table 1. As one can see, with an increase of a projectile atomic mass the spectrum of the target produced nucleons becomes harder, and the probability of a complete breakdown of nuclei mainly into nucleons rises. Consequently, a larger number of neutrons will be generated in secondary collisions in the reactions (*n*, 2*n*) and the consumption of energy for the generation of one neutron by light nuclei will be smaller than it is for protons.

Table 1

Projectile	*p*	*d*	^{4}He	^{12}C	^{22}Ne
Probability of complete destribution of Ag and Br nuclei	3%		6	17	
Mean number of fast neutrons	13	21	25	28	30
Mean energy of neutron (MeV)	120±12	110±3	138±3	148±5	156±4
Probability of complete distribution of Pb nuclei	6%	10	22		
Mean number of nucleons	30		45	43	52



The relative ionization losses

Fig.4

It is necessary to take into account the relative ionization losses of energy according to the formula:

$$\Delta = -\frac{1}{E_0}\int_0^{X_{max}} \frac{dE}{dx}\exp(-x/\lambda)dx,$$

where E_0 and X_{max} are the kinetic energy and the maximum path of the projectile, λ is the mean free path.

Figure 4 presents the results of the calculations according to [6]. From this figure it follows that for ^{4}He nuclei the losses are smaller than for protons. Thus, it is more efficient to use lighter and faster nuclei for the ABM implementation. An experimental test of this conclusion has been performed in cooperation with our colleagues from the Kharkov Physical-Technical Institute (Ukraine) at the Dubna synchrophasotron. This test consisted in an investigation of the interactions of protons and light nuclei with a $50\times50\times80$ cm^3 lead target. Beam particles were injected into the lead target through a $10\times10\times20$ cm^3 channel. The fission chambers (KNT-8) were 7 cm in diameter with an effective uranium mass of 1.5 mg [7]. The uranium detectors were 8 mm in diameter and 1 mm thick. They were installed inside the target. The chambers recorded the number of fission while the detectors registered the reaction (n, γ) using γ-spectroscopy method.

Table 2

	p		d	^{4}He	^{12}C
	Energy (GeV)		Energy per nucleon (GeV)		
	3.65	8.1	3.65		
Relative energy deposition for generation of one neutron	1	0.92	0.89	0.72	0,81
The ionization energy losses (%)	8	4	4	6	11
The decrease of energy in comparison with proton of 3.65 GeV (%)		8	11	28	19

Table 3

Projectile	Energy per nucleon (GeV)	Energy for generation of one neutron (MeV)		
		n, γ	n,F	Mean
d	1.5	34.7±3	30.0±4	32.4±3
^{4}He	2.2	30.6±10	27.5±6	29.0±8
^{7}Li	2.2	31.0±8	34.7±5	32.1±6
^{12}C	1.87	31.5±5	32.7±4	32.1±4
		Mean value 32±5 MeV		

The projectile particles were monitored by the aluminium detectors. A method combining KNT-8 chambers and movable nuclear emulsions was developed. The experimental results are published in [9—12]. The data on relative efficiencies of neutron generation are given in table 2. According to this table the amount of energy spent by the ^{4}He nuclei for the generation of one neutron is ~30% less than for protons. The absolute value of energy of one neutron has been determined by the detection of neutrons flying out of the target. They were slowed down in a water bath mounted on the upper side of the target. Neutrons were registered by KNT-8 and the uranium detectors. The experiments were carried out with d, ^{4}He, ^{7}Li, and ^{12}C nuclei in an energy interval of 1.5—2.2 GeV per nucleon. The results from [13] are given in table 3. Both methods gave close results, and the mean value of energy necessary to generate one neutron is $E_n = 32\pm5$ MeV. This value is smaller than that from [2], where $E_n \cong 50$ MeV was found. Later [14] and the references in [14,15,16] described corrections which have to be applied to the reactions (n, $2n$) by the Monte-Carlo method which finally gave $E_n \cong 30$ MeV.

Our data on E_n are important for the ABM as well as for the neutron protection of accelerators and satellites, the construction of neutron generators and the transmutation of reactor waste. For further investigation the project «Investigation of Physical Aspects of the Electronuclear Method for Atomic Energy Production» called «Energiya» is included in the program of the Laboratory of High Energies, JINR, Dubna. Positive conclusions of the project were given by the Ministry of Atomic Energy of Russian Federation, Scientific Center of Kurchatov's Institute, Physics and Energetics Institute and the Institute of Nuclear Energy.

Accoding to the project, the 2 year program is proposed:

- to determine the energy consumption to generate one neutron in massive targets of different nuclear composition and to obtain an increase of energy yield in the target with fissionable nuclei with beam energy;
- to determine energy and mass of the projectile for the optimization of the efficiency of a chain reaction and the construction of an appropriate accelerator;
- to specify the composition of a perspective fuel in both homogeneous and heterogeneous versions;
- to estimate the running time without fuel change or when ^{238}U, Pb and Bi are added to the fuel cycle;
- to determine the spectrum of neutrons inside the target and the spectrum of neutrons flying out of the target.

These data will allow one to start the construction of a subcritical reactor.

A linear dependence of reactor power on beam intensity and $C_{\text{eff}} < 1$ will provide the reactor safety. The beam-off reactor power will be limited by delayed neutrons. The yield of these neutrons is ~0.6% and their decay times are shorter than one minute. Averaging over the groups of delayed neutrons we obtain the following formula for the time dependence of reactor power:

$$W(t) = W_0 \frac{0.0064}{0.0064 - \rho}\, e^{\rho t/0.08},$$

where ρ is reactivity $\rho = C_{\text{eff}} - 1$. If $C_{\text{eff}} = 0.98$,

$$W(t) = W_0 0.242\, e^{0.25t},$$

at $t = 1$ sec $W(1) = 0.19 W_0$; $W(10) = 0.02 W(0)$.

The second goal of nuclear energetics lies in the improvement of its economic efficiency by using more ^{238}U and allowing a prolonged reactor operation without refueling. At present ^{239}U is mainly used by the reactors and, hence it has to be extracted from natural uranium to produce energy. In

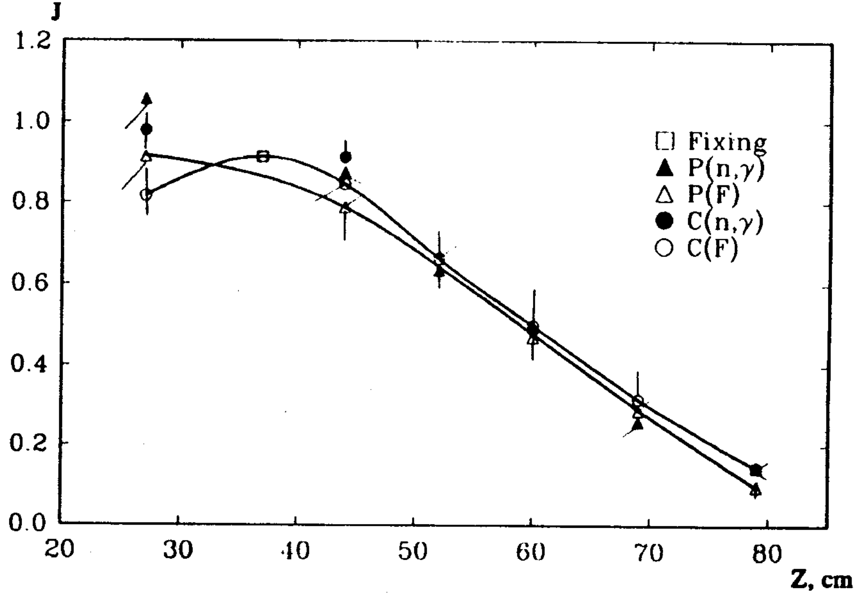


Fig.5

the ABM the neutron spectrum will be harder leading to increase of fission of ^{239}U while the absorbtion of neutrons by fission products will decrease. As a result, the reactor operation becomes more efficient.

Let us now consider the use of the ABM for the reactor waste transmutation. As is shown in [17] the transmutation by protons or γ-quanta isn't promising, because it requires an amount of energy ten times greater than that received from the reactor.

The transmutation by neutrons requires the use of high intensity neutron fluxes or since the required time would be too long. But the intensity of neutron flux in the running reactor is $10^{15}\,cm^{-2}\,s^{-1}$, and a stream of $\sim 10^{16}\,cm^{-2}\,s^{-1}$ in the project [41] demands an accelerator with a very high beam current density.

Our experiment has determined the neutron density inside the lead target. According to Fig.5, neutron density decreases by a factor of 10 at a distance of 50 cm along the beam and by a factor of 5 at 25 cm across the beam (Fig.6). It follows therefore that about half the neutrons and consequently half the energy is released in central zone of the target within a volume of ~100. In the fast neutron reactor BN-600 [18] the neutron density was $10^{16}\,cm^{-2}\,s^{-1}$. So, if the power of the ABM reactor is equal to that of BN-600, the power in its central zone would be 10 times higher and the

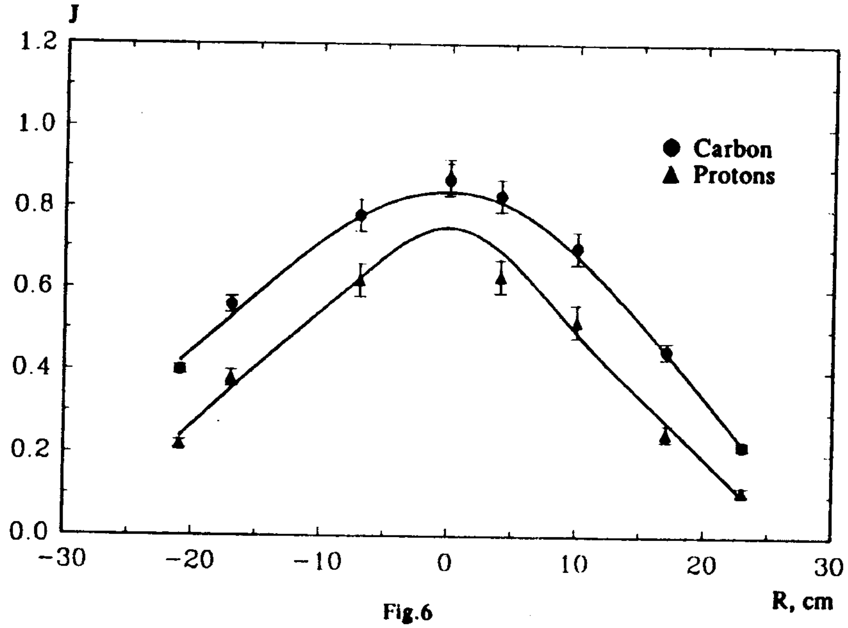


Fig.6

neutron density would be ~ $10^{17}\,cm^{-2}\,s^{-1}$. Consequently, if neutrons are extracted from the reactor core, then the realization of a faster transmutation becomes possible.

The possibilities for the ABM development at the JINR are really unique. The Institute has the beams of protons and light nuclei with enough energy and intensity to allow the determination of the necessary for ABM parameters. Also, the JINR laboratories have the groups of specialists needed for the construction and operation of accelerators. For example the project «Mingen» [19] devoted to the acceleration of deuterons with energies up to 2 GeV and a current of 10 mA is carried on by the Laboratory for Nuclear Problems (JINR). The work on the nuclei acceleration project «Nuclotron», with a superconducting magnet system is under comissioning in the LHE. It will give an opportunity to accelerate light nuclei up to 6 GeV/c per nucleon and heavy nuclei up to uranium of appropriate energies. As it was mentioned above, the methods for the measurement of the parameters necessary for the ABM have already been developed and tested. The reactor IBR-2 available in the Laboratory of Neutron Physics would enable us to perform all the necessary studies. The V.S.Barashenkov group has a solid experience in Monte-Carlo calculations of the processes that occur in reactor systems. Thus, the Institute researchers participating in the project «Energiya» have everything to fulfil this program.

We would like to emphasize that our program is aimed at building a reactor with a long term use without changing the fuel and extracting plutonium, i.e., only for a peaceful utilization of atomic energy.

Following are the estimated operating parameters of an accelerator — breeding reactor for the production of the 10 MW electrical power, i.e., two times larger than that of the first world atomic station built in Obninsk in 1956.

Current, charge units	I
Number of ^{4}He nuclei per second	$I/2$
Energy per nucleon	$\varepsilon = 1.5$ GeV
Beam energy	$E = 3\cdot I$ GeV
Energy for generating one neutron	32 MeV
Number of neutrons	$n = \frac{3\cdot10^9 I}{32\cdot10^6} = 94I$
If $C_{eff} = 0.98$ than the number of neutrons is	$N = \frac{94\cdot0.98}{1-0.98} = 4600$
Number of neutrons per fission	2.44
Number of fissions	$m = 4600/2.44 = 1885$
Energy per fission	~ 200 MeV
Power	$W = \mathrm{Im}\cdot200 = 37700I$ MeV $W = 6\cdot10^{-8}\,IW(t)$

If the electric power of the reactor $W = 10\,MW$ 10 and the coefficient of heat transformation $K = 0.35$, then the heat power is $W = 2.84\cdot10^7$ Watt. Hence, $W = 6\cdot10^{-8}$, $I = 2.8\cdot6\cdot10^7$ Watt $I = 4.8\cdot10^{14}$ charge units. The number of ^{4}He nuclei: $N_{\mathrm{He}} = I/2 = 2.42\cdot10^{14}\,\mathrm{s}^{-1}$. The beam power: $W_{\mathrm{B}} = 2.42\cdot10^{14}\cdot6$ GeV = 230 kW_t. The beam intensity: $I_{\mathrm{B}} = 4.8\cdot10^{14}\times$ $\times\,1.6\cdot10^{-19}$charge units, $I_{\mathrm{B}} = 0.08$ mA.

In conclusion I would like to quote the words by Academician V.I.Veksler, the founder of the Laboratory, USSR State Prize laureate and the USA «Atom for Peace» Prize laureate: «Show that it is possible and necessary and technology will find the means for its realization».

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