STEADY-STATE FUSION FISSION REACTOR CONCEPTS BASED ON STELLARATOR-MIRROR AND MIRROR MACHINES

O. Ågren[1], V.E. Moiseenko[2], K. Noack[1], S.V. Chernitskiy[2]

[1]Uppsala University, Ångström Laboratory, Uppsala, Sweden;
[2]National Science Center ''Kharkov Institute of Physics and Technology", Kharkov, Ukraine

Neutron sources and hybrid reactors offer a possibility for application of fusion in a not too distant future. Steady-state operation on a time scale of a year without interruption is essential for such applications. In response to this need, our studies are focused on concepts which are not limited by pulsed operation. Special attention is put on mirror machines and a stellarator-mirror concept with localized neutron production. Reactor safety, magnetic coils, power amplification by fission, plasma heating, a radial constant of motion which provides a bounded radial motion in the collision free approximation are some of the issues addressed.

PACS: 52.65.Cc, 52.55.Hc, 28.50.Ft

INTRODUCTION

The stellarator and straight field line mirror (SFLM) hybrid reactor studies aim to identify a concept where the safety of fission power production could be enhanced. A fusion neutron source could become a mean to achieve this. The studies address critical issues such as reactor safety, natural circulation of coolants, steady-state operation for a year or more and means to avoid too strong material loads by a proper geometrical arrangement of the reactor components. A key result is that power production may be possible with a fusion Q factor as low as 0.15. This possibility arises from the high power amplification by fission, which within reactor safety margins may be larger than a factor of 100. The requirements on electron temperature, which is a critical issue for mirror machines, are dramatically lower for a fusion hybrid compared to a stand-alone fusion reactor. This and several other factors are important for our choice to select a stellarator-mirror or a mirror machine for the fusion hybrid reactor studies. The basic design in our mirror-machine studies (Fig. 1) is for a 1.5 GW_{th} reactor with a 25 m long plasma confinement region, 40 cm plasma radius and only 10 MW fusion power [2, 3]. The stellarator-mirror concept is outlined in Fig. 2.

In several ways (material loads, demands for plasma confinement, size of fusion device and cost) a hybrid reactor offers increased flexibility for power production compared to a fusion reactor [1]. A disadvantage is the substantial amount of radioactive materials in a hybrid reactor.

The SFLM concept is outlined in Fig. 1. The stellarator-mirror concept is shown in Fig. 2. A local mirror can be created by turning off a toroidal field coil, providing a local mirror field. The intention is to confine hot ions in this mirror region. An advantage with a toroidal device is the possibility to avoid longitudinal losses, which is a serious obstacle for open devices.

A first goal with the hybrid reactor concepts are [2, 3] to develop a fast reactor concepts with enhanced reactor safety and incineration capacities. A second goal is to define a concept where the demands on plasma confinement, technical feasibility etc. are reachable. A third goal is to define a concept where material loads are tolerable. Finally, energy production in steady-state (for a year or more) would be necessary from technological and economic considerations.

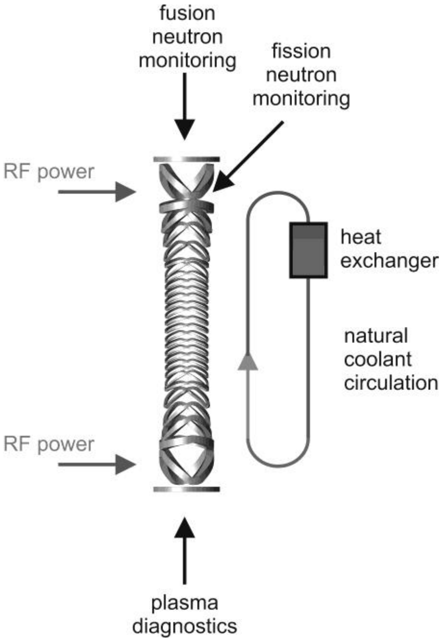

Fig. 1. Outline of an SFLM hybrid reactor. Feeding for RF heating, plasma diagnostics and fusion neutron monitoring is through holes in the end openings. Magnetic coils are shown, and the fission reactor is located in between the coils and the vacuum chamber for the fusion plasma

A magnetic configuration of a stellarator with an embedded magnetic mirror has been arranged in the Uragan-2M experimental device, which has separate feeding for the helical and toroidal fields. Switching off one toroidal coil or lowering the electric current in the pair of neighboring coils creates a magnetic mirror section with a mirror ratio around 1.5. Regions with nested magnetic surfaces exist under certain conditions in such a combined magnetic trap.

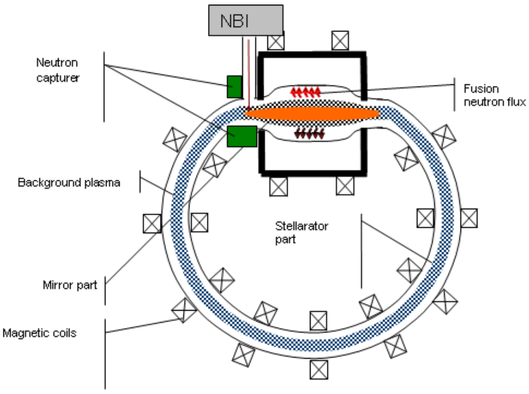

Fig. 2. Outline of the stellarator-mirror neutron source with a fission reactor mantle. Fusion neutron production is localized to the mirror part. All sensitive equipment are also in this concept protected from strong neutron bombardment

NUCLEAR SAFETY

An external neutron source added to a fast reactor could contribute to reactor safety for several reasons: in a driven system, the fission production can quickly be turned off. For the SFLM, passive circulation is furthermore adequate to remove decay heat [3, 6]. There are also other features which could be favorable and make a driven system less vulnerable to hazardous events.

The sub-criticality defines margins towards hazardous events where the criticality for some reason is increased. The SFLM safety has been tested against loss of coolant scenarios (LOCA), void of coolant and partial replacement of the eutectic lead-bismuth by water [4, 5]. In all cases studied, an SFLM reactor is predicted to remain subcritical if the criticality k_{eff} in normal operation is equal to or less than 0.97 (k_{eff} is the effective neutron multiplication coefficient). If k_{eff} would be closer to unity, the power from fission would be increased for a given fusion power, but at the cost of a reduced margin for nuclear safety [5].

PLASMA CONFINEMENT

A first requirement on any plasma device is that the collision free motion is restricted to a region with the confining magnetic field. A net radial drift out from the confining field would lead to a rapid loss of particles. In general quadrupolar mirrors, we have shown that radial confinement could be assured by the existence of a radial drift invariant in the form [7],

$$I_r = r_{gc} + r_{osc}, \qquad (1)$$

where the first term is the guiding center radial coordinate and the second terms represents oscillatory banana excursions from the mean magnetic surface (these banana widths are zero in a perfectly axisymmetric mirror). The freedom to use biased potential endplates is a key for radial confinement in open systems. The net radial drift in quadrupolar mirrors can be eliminated in this way by introducing a slow $\mathbf{E}\times\mathbf{B}$ plasma rotation around the axis, which can be controlled by the biasing potentials of the end plates. Longitudinal confinement is assured by the constancy of the energy ε and magnetic moment μ. The existence of these three constants of motion provides an excellent basis for confinement of particles in mirror machines.

Small field errors (which could be associated with the discrete nature of coils or other disturbances) could produce a radial magnetic drift and an unbounded radial motion. Such radial loss could be cured by a radial electric field. This favorable mechanism could be active in both stellarators and mirror machines. An advantage with the open mirror geometry is that the radial electric field can be controlled by sectioned biased endplates.

No fusion device is yet close to the requirements of a Q factor or 15 or more (which is necessary for commercial power production). In a hybrid reactor, the plasma confinement could be reduced dramatically, if the power amplification from fission is high enough. The geometrical arrangements of the SFLM are intended to optimize the power amplification, without jeopardizing nuclear safety. For nuclear waste burning [5], the prediction for power amplification in the SFLM is

$$PAF \equiv \frac{P_{fis}}{P_{fus}} \approx \frac{4.5}{1-k_{eff}} \leq 150, \qquad (2)$$

where the upper bound is for k_{eff} =0.97, which is our choice for upper bound on reactor safety. This suggests that it could be possible to achieve a design where fission exceeds the fusion power by more than 100 times with a sound margin for reactor safety.

During a full year operation, k_{eff} can slowly decrease from its initial value 0.97. An average power amplification around 100 is still plausible. For power production, the demands on plasma confinement can be reduced correspondingly, and a Q factor as low as 0.15 could be sufficient for power production [2, 4, 5]. This is welcoming news for mirror machines, which are known to struggle with the difficulty to reach sufficiently high electron temperatures [8]. For a mirror hybrid, an electron temperature as low as 800 eV (but preferably somewhat higher, in the 1 keV range) can be sufficient for power production [2-4]. Results in recent years (for GOL-3 [9], GDT [10] and Gamma10 [11]) indicate that electron temperatures in this range could be reached in mirror machines.

Plasma stability is also addressed for the SFLM [2, 3]. The average minimum B field (even without expander tanks) provide gross MHD stability and sloshing ions contribute to stability. Unlike the axisymmetric GDT (Gas Dynamic Trap) the expander tanks are not required for stability, since the quadrupolar field in the SFLM is sufficient for that purpose. The expander tanks with their 4 m radii are merely included to provide a sufficiently large area to withstand and distribute the heat from leaking plasma. A power load less than 1 MW/m^2 is expected for the SFLM “divertor” plates.

MATERIAL LOAD

The mirror machine and stellarator-mirror concepts offer a geometrical flexibility to achieve material loads within tolerable bounds. Diagnostic windows and other sensitive equipment could be avoided in the neutron rich region since the plasma column is accessible beyond the fission mantle. The plasma heating has been selected with care to avoid too strong material loads. Antennas for ion cyclotron heating can be placed near the maxima of the magnetic field, with good coupling to the plasma. This enables shielding and feeding of the antennas with due consideration of material load limitations.

With a 10 MW fusion power and a Q factor of 0.15, the expander tanks need to withstand a power around 60 MW, assuming a predominantly longitudinal plasma loss. With an expander tank area of 100 m^2 (both sides counted for), a power density of 0.6 MW/m^2 is well below critical values. A representative ion gyro radius in the weak field of the expander tanks is 0.5 m. The heat will therefore be evenly distributed in the expander tanks.

Neutron bombardment on the first wall would pose some problem if the buffer region in the fission mantle would not have been included (this action increases the wall life time by a factor of 4). With a buffer, the 200 dpa threshold for the first wall requires more than 30 years for its accumulation [4].

Monitoring of plasma and fusion neutrons is intended with top view installations [12] (see Fig. 1). This choice is made to avoid critical material loads. Monitoring of fission neutrons is possible by detectors inside the fission blanket surrounding the fusion device [12].

STEADY-STATE PLASMA MACHINES

Perhaps the most important reason to consider a mirror machine or a stellarator-mirror device is that there is no need for inductive current drive, whereby steady state operation (for a year or more) may be feasible.

A better plasma confinement than in mirrors is expected in a toroidal device, but a price is added complexity. To avoid strong material loads, it is however necessary to come up with a toroidal device proposal where the neutron production is localized in a similar manner as in the SFLM. For this reason, ideas have been put forward for a stellarator-mirror hybrid [13]. The intention is to achieve a fusion production localized to the mirror segment of the device and to connect the mirror ends with a stellarator tube [13] (a difference from the toroidally linked mirror proposal in [14] is that the stellarator part has a rotational transform).

Our designs consist of a comparatively small fusion neutron sources (only about 10 MW fusion power), aimed for 1.5 GW_{th} power production, where the dominant part comes from fission [1-3]. The role of the fusion part is only to enhance reactor and nuclear safety and be able to burn spent nuclear fuel, including minor actinides [2-4]. Some extra cost will arise from the fusion neutron source, but the price would be dramatically lower than for a fusion reactor. With such a small fusion device, the cost for the power production would come closer to that of conventional fission power.

GEOMETRICAL ARRANGEMENTS

A plasma with 40 cm radius is confined inside a vacuum tube (radius 90 cm and length 25 m). The first wall (3 cm wide) and a blanket with a buffer (15 cm wide), the fission reactor core with fission fuel and liquid lead bismuth eutectic coolant, core expansion zone neutron radial reflector (60 cm wide) and a tritium reproduction zone are located radially outside the vacuum chamber, as indicated in Fig. 3. For the nuclear waste burning application, the fuel consists mainly of plutonium and minor actinide isotopes. To avoid generation of minor actinide isotopes, the U238 isotope is (apart from very small amounts) not present in the blanket, and therefore the Doppler broadening (which is of vital importance for the reactor safety of fast reactors without an external neutron source) is almost negligible. The blanket is surrounded by superconducting coils with an inner radius of 210 cm.

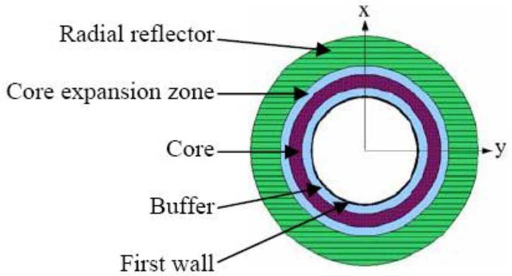

Fig. 3. Radial structure of the blanket model

The plasma losses are expected to be mainly axial, and a sufficiently wide plate area is needed for taking care of the losses. For this reason, flux tube expander regions are located on each side beyond the 25 m long confinement region. With a 10 MW fusion power and Q around 0.15, the expander wall should be capable to handle a power load in the range 60 MW. The 4 m wide expander tank radii provide wide margins for the power load on the expander plates.

RF antennas and their power feed can be located in the high field region, where the neutron flux is low. The ends of the confinement region could be used for diagnostic purposes, refueling, ash removal etc, and the geometry is selected to avoid holes in the fission mantle. The geometry and the minimization of holes in the fission core imply that most of the fusion neutrons contribute to fission. Our concepts have in this respect a better scaling than tokamaks.

Expander regions with favorable curvature add to interchange stability, which is the key element for stabilization of the axisymmetric GDT device, where a stabilizing plasma flow into the expanders is required. In the quadrupolar SFLM case, the expanders are not necessary for MHD stability. The sole purpose of the wide expander tanks is to provide margins for the power load on the wall from leaking plasma.

A design with superconducting 3D coils has been carried out with a mirror ratio of 4 for the vacuum field. The compact coil set has 3 m outer radius and 2.1 m inner radius. The coil inner radius is sufficiently large to provide the required space for the fission mantle. The coil computations take into account the average minimum B stability criterion and the transition to expander regions [15]. Particle orbits, with emphasis on existence of nested magnetic surfaces and radial confinement with closed mean drift surfaces, have also been carried out for the stellarator case. As already mentioned, a radial electric field can have a favorable effect on confinement.

In the SFLM, the vacuum field lines [16, 17] correspond to straight nonparallel lines (thus zero curvature). The magnetic drifts are zero in the vacuum field, but an azimuthal drift is present at finite beta, and there is also a possibility to arrange a radial rotation (which has a positive influence on confinement [10, 11] by radial control plates in the expanders outside the confinement region. Computations with compact 3D superconducting coils have reproduced the SFLM field with high accuracy. The coil computations also provide "trumpet-like" expanders on each side of the confinement region.

PLASMA HEATING

RF heating studies with fundamental ion cyclotron resonance heating on minority deuterium ions predict efficient heating with good coupling between the antenna and the plasma [18]. Tritium ions can be heated with second harmonic heating [19]. Antenna frequencies are matched to cyclotron resonance conditions at a magnetic field strength equal to half the maximum field strength, corresponding to locations of sloshing ion density peaks. The antennas for deuterium and tritium heating can be located at opposite ends of the mirror machine. The RF heating waves propagates from the strong field side towards weaker field. Conversion between fast magnetosonic wave and compressional Alfven wave occurs at a conversion surface and resonant absorption occurs at cyclotron harmonics.

Geometrically, the RF heating option has the advantage that no holes (except at the longitudinal ends of the confinement region) are introduced in the fission mantle [18]. Shielding of the antennas as well as steady state heating are possible with ICRH.

NEUTRON AND COOLING COMPUTATIONS

In Monte Carlo simulations for the neutrons [4, 5], the geometry and materials in the fission mantle is designed to have an initial neutron multiplicity of $k_{eff} = 0.97$. This number is selected with the expectation that the reactor would remain in a subcritical state even in "worst case scenarios" [4, 5]. This has been confirmed by detailed Monte Carlo simulations modeling of scenarios with loss of coolants, void of coolants and partial replacement of the lead-bismuth coolant by water (this could increase fission production by the moderation of neutrons). A connection of the coolant tubes in the buffer and reactor core region is a mean to avoid a reactivity increase when water is entering the coolant tubes. With this arrangement the increase in k_{eff} is below 2% in all cases studied, which suggests that a blanket design with $k_{eff} = 0.97$ initially would retain the reactor in a subcritical state even for a worst case accident [4, 5].

The buffer reduces the neutron load on the stainless steel first wall. For the 1.5 GW thermal power case, the 200 dpa limit for the first wall is predicted to correspond to more than 30 years, with 311 days of steady state operation at fixed power each year. The fuel is slowly burned out, resulting in a lowered k_{eff}. In the 1.5 GW thermal case, k_{eff} decreases to about 0.95 in a one year operation. The power amplification multiplication at the beginning of the cycle is PAF = 147 (with k_{eff} =0.97) and is reduced at the end of the cycle by about 40% in a scenario where control rods or burning absorbers are not used to maintain the core at a constant k_{eff}. A constant power output has in such a case to be maintained by increasing the neutron intensity from the fusion neutron source.

The blanket is designed for tritium reproduction [4]. The computed tritium breeding ratio is around 1.8 in a one year power cycle (this overproduction of tritium can easily be adjusted down to lower values). Empty spatial locations within the blanket which could be used to increase the neutron shielding. Neutron heat load on the superconducting coils been calculated, and an effective shielding of superconductors and antennas can be made with boronized layers.

The vertical orientation of the mirror device could be favorable for self-circulation of the coolant, which is a safety arrangement to remove decay heat [6]. At full 1.5 GW_{th} power production, pumping at a moderate pumping power (less than 50 MW) is predicted [2, 6].

SUMMARY

A power producing reactor has preferentially to operate in steady state (for a year or longer). Geometries with local neutron production seem well suited for a steady state hybrid reactor, and a high power amplification by fission is possible with reactor safety demands satisfied. Sufficient space is available between the vacuum chamber and the magnetic coils to introduce a buffer (for first wall protection against neutron bombardment), fission fuel, neutron reflectors, coolant tubes, shielding, tritium breeding zones and other necessary components. Plasma heating in ion cyclotron range of frequencies has been considered in the studies, and a beneficial feature is that this choice of heating does not split the fission reactor core into two separate parts, as in Ref. 20. Monte Carlo simulations predict that the reactor remains subcritical in reactor safety events (loss and boiling of coolants) with a tolerable load on the first wall (the 200 dpa limit corresponds to more than 30 full power years). Load associated with longitudinal plasma loss could be taken care of with large expanders beyond the confinement region.

Plasma stability is a threat for the efficiency of the system. Large scale plasma activity is not foreseen with an average minimum B field. A "semi-poor" confinement is adequate in the hybrid case, making the hybrid less vulnerable to small scale plasma activity.

Biased potential endplates is in mirror machines a mean to improve radial confinement. A recent study [20] has shown the existence of a radial invariant in the collsion free approximation, where magnetic radial drift leakage (due to field errors or other disturbances) could be cured by creating a slow drift around the magnetic axis. In this way a radially bounded motion could be arranged for all guiding centers when collisions are neglected. The situation is more complex in stellarators, where existence of nested flux surfaces in practice is a necessary condition for radial confinement. Magnetic drifts may still cause radial leakage, even in regions with nested flux surfaces. However, recent studies has shown that a weak radial electric field can restore radial confinement for a majority of such particles where the radial magnetic drift is a threat for their confinement.

The electron temperature is a critical parameter for mirror machines. Means to achieve an electron temperature in the range of 1 keV or more [3], which could be sufficient for power production in a mirror hybrid device, are addressed. Power production in the hybrid reactor concepts are predicted with a fusion Q as low as 0.15, which is one order smaller than predicted critical Q factors for tokamak hybrids. Similar limits on the Q factor is expected for the stellarator-mirror concept [21].

REFERENCES

1. O. Ågren et al. On Fusion Driven Systems (FDS) for Transmutation: SKB Report R-08-126, ISSN 1402-3091, (Oct 2008).
2. O. Ågren et al. // *AIP Conf. Proc.* 2012, v. 1442, p. 173.
3. O. Ågren et al. // *Fusion Science and Technology*. 2010, v. 57, p. 326.
4. K. Noack et al. // *Annals of Nuclear Energy*. 2011, v. 38, p. 578.
5. K. Noack et al.// *AIP Conf. Proc.* 2012, v. 1442, p. 186.
6. H. Anglart et al.// *AIP Conf. Proc.* 2012, v. 1442, p. 208.
7. O. Ågren et al. // *Eur. Phys. J. D.* 2012, v. 66, p. 28.
8. J. Killeen // *Methods of Computational Physics*. 1976, v. 16, p. 389.
9. A.A. Ivanov // *AIP Conf. Proc.* 2012, v. 1442, p. 139.
10. A. Beklemishev et al. // *AIP Conf. Proc.* 2012, v. 1442, p. 147.
11. T. Cho et al. // *Phys. Rev. Lett.* 2006, v. 97, p. 055001.
12. J. Källne et al. // *AIP Conf. Proc.* 2012, v. 1442, p. 281.
13. V.E. Moiseenko et al. // *J. Fus Energ.* 2010, v. 29, p. 65.
14. V.P. Pastukhov et al. // *Nucl. Fusion.* 1993, v. 33, p. 1471.
15. A. Hagnestål et al. // *J. Fusion Energy*. 2011, v. 30, p. 144.; See also A. Hagnestål et al. // *AIP Conf. Proc.* 2012, v. 1442, p. 217.
16. O. Ågren et al. // *Physics of Plasmas*. 2004, v. 11, p. 5041.
17. O. Ågren et al. // *Phys. Rev. E* 2005, v. 72, p. 026408.
18. V.E. Moiseenko et al. // *Phys Plasmas.* 2005, v. 12, p. 102504.
19. V.E. Moiseenko et al. // *Phys Plasmas.* 2007, v. 14, p. 022503; See also V.E. Moiseenko et al. // *AIP Conf. Proc.* 2012, v. 1442, p.199.
20. O. Ågren et al. // *Plasma Phys. Control. Fusion*. 2014, v. 56, p. 095026.
21. V.E. Moiseenko et al. // *Plasma Phys. Control. Fusion*. 2014, v. 56, p. 094008.

Article received 25.12.2014

КОНЦЕПЦИИ СТАЦИОНАРНЫХ ЯДЕРНО-ТЕРМОЯДЕРНЫХ РЕАКТОРОВ НА ОСНОВЕ СТЕЛЛАРАТОРА-ПРОБКОТРОНА И ПРОБКОТРОНА

O. Ågren, В.Е. Моисеенко, К. Ноак, С.В. Черницкий

Источники нейтронов и гибридные реакторы предоставляют возможность применения термоядерного синтеза в не слишком отдаленном будущем. Стационарный режим работы без перерывов необходим для таких устройств. В ответ на эту потребность наши исследования сосредоточены на концепциях, которые не ограничиваются работой только в импульсном режиме. Особое внимание уделяется пробкотронным устройствам и концепции стелларатора-пробкотрона, которые характеризуются локализованным излучением нейтронов. Рассмотрены вопросы безопасности реактора, формы магнитных катушек, усиления мощности за счет реакции деления, нагрева плазмы и роли радиального инварианта движения ионов, который обеспечивает удержание ионов при их радиально колебательном движении в бесстолкновительном приближении.

КОНЦЕПЦІЇ СТАЦІОНАРНИХ ЯДЕРНО-ТЕРМОЯДЕРНИХ РЕАКТОРІВ НА ОСНОВІ СТЕЛАРАТОРА-ПРОБКОТРОНА І ПРОБКОТРОНА

O. Ågren, В.Є. Моісеєнко, К. Ноак, С.В. Черницький

Джерела нейтронів і гібридні реактори надають можливість застосування термоядерного синтезу в не занадто віддаленому майбутньому. Стаціонарний режим роботи без перерв потрібний для таких пристроїв. У відповідь на цю потребу наші дослідження зосереджені на концепціях, які не обмежуються роботою тільки в імпульсному режимі. Особлива увага приділяється пробкотронним пристроям і концепції стеларатора-пробкотрона, які характеризуються локалізованим випромінюванням нейтронів. Розглянуті питання безпеки реактора, форми магнітних котушок, посилення потужності за рахунок реакції ділення, нагріву плазми і ролі радіального інваріанту руху іонів, який забезпечує утримання іонів при їх радіально коливальному русі в беззіштовхувальному наближенні.