Annex 4.

Project report form

APPROVED

Director of Laboratory

_____/ _____/

"____" _____ 202_

REPORT ON PROJECT (INFRUSTRUCTURE PROJECT)
IN FIELD OF RESEARCH WITHIN
THE TOPICAL PLAN FOR JINR RESEARCH

1. General information on the Project
1.1. Scientific field: applied research at NICA complex

1.2. Name of the Project: ADSR

1.3. Project code: 07-1-1107-1-2011/2027

1.4. Theme code: 02-1-1107-2024

1.5. Actual duration of the Project: 2024-2027

1.6. Project Leader(s): M. Paraipan

2. Scientific report
2.1. Annotation

Theoretical studies performed in the frame of ADSR (accelerator driven subcritical reactors) projects at JINR Dubna, underlines the advantages of subcritical reactors as efficient source of energy, with energy gain G>15. A value of the effective multiplication factor k_{eff} in the range 0.985-0.988, maintained during exploitation with control rods, is low enough to avoid reaching the criticality during unprotected transients and ensures a safer exploitation in comparison with fast reactors. The choice of larger configuration of the active zone give the possibility to realize the needed value of k_{eff} with lower enrichment, realizing longer cycle with deeper actinides burning (2-3 times more than in fast reactors). One of the most interesting conclusions concerns the possibility to use ion beams as ^{7}Li or ^{9}Be at low energy (0.25-0.3 GeV/n) instead of 1-1.5 GeV protons, with the same net electrical power but 2 times shorter accelerator, that improves the efficiency diminishing the costs for building and maintenance.

The analysis of possible experiments meant to check the results of theoretical work demonstrates that measurements of the neutron yield from the converters, or measurements of the fission distributions only on the surface of the converter cannot realize a correct comparison of the energy efficiency of different beams used in ADSR. The most reliable comparison is obtained by measuring the fission distribution inside an extended target. Various configurations and materials for the extended target (uranium, lead, graphite, with and without fuel rods) were analyzed. Based on these conclusions, the extended lead target LETASUR was designed.

2.2. A detailed scientific report

The research activity was oriented in the following directions:

- the investigation of experiments that could clarify the best beam-converter combination for ADSR.
- the design of a suitable target and experiment planning
- the study of factors influencing the performance of ADSR.

1. Experimental approach

The main task of the project was the design of a suitable target for experiments meant to realize a correct comparison between the energy efficiency of different beam-converter combinations. The task is fulfilled.

A detailed analysis of the possible experiments was performed. Usually, such experiments can be oriented in two directions. One concerns the measurement of the neutron yield from the converters. But we demonstrated that the neutron multiplicity is not conclusive because is not correlated with the energy released in the core. It is necessary to compare the total energy carried out by the neutrons, that means to registered and integrate the double differential neutron yield. The main contribution of the total kinetic energy is given by the neutrons with energy above 100 MeV, more than 70 % from the total kinetic in the case of 0.3 GeV/n ^{7}Li ions interacting in Be converter, and 53% in the case of 1.5 GeV protons interacting in Pb converter.

Measurements of the double differential neutron spectra from thin and thick targets were realized by many groups, but there are significant differences between the reported data, especially with respect to the high energy part of the neutron spectra. The measurements of the neutron spectra from extended targets rise more difficulties. TOF is difficult to use due to the uncertainties in the interaction point along the target.

The use of different threshold reaction for the characterization of the neutron spectrum is also not possible, due to the very scarce experimental data about the excitation functions for isotopes with threshold energy above 100 MeV.

The second experimental direction consists in registration of the overall effect by measuring the fission or temperature distribution. The measurements are realized inside extended targets, as in experiment FEAT at CERN, or in experiments with Quinta target at LHEP, Dubna. Such experiments are the most suitable for the comparison of the energy efficiency of different beams, under the condition that the target has dimensions large enough to contain inside the most part of the produced neutrons. A limitation of measurements only at the surface of the converter must be avoided, because it does not allow a correct comparison between beams and conduce to false lower values registered with proton beams.

The target design must mainly fulfill two conditions: to allow a correct comparison between different beams, and to realize neutron spectra as close as possible to the ones obtained in an ADSR cooled with LBE.

The dimensions of the target must be large enough to diminish the leakage, and to stop or to ensure the interaction of more than 99 % of the beam inside the target. Various geometries were studied. Finally, a parallelepiped with dimensions 80x80x150 cm, surrounded by a steel

blanket with thickness 10 cm was chosen, presented in figure 1. The target has a central hole with radius 10 cm and length 120 cm for the placement of the converter. Cylindrical converters with length 110 cm, from various materials are positioned inside the central channel in such way to realize a beam window with length 10 cm. Horizontal and vertical holes with radius 2 cm, are positioned at 4 radii (15, 20, 25 and 30 cm), for the placement of the detectors. Lead, graphite and natural uranium were considered as material for the target. Variants with and without fuel rods were analyzed. In the variant with fuel rods, metallic rods (U-10%Zr) with radius 1 cm are inserted as it is shown in figure 1b.

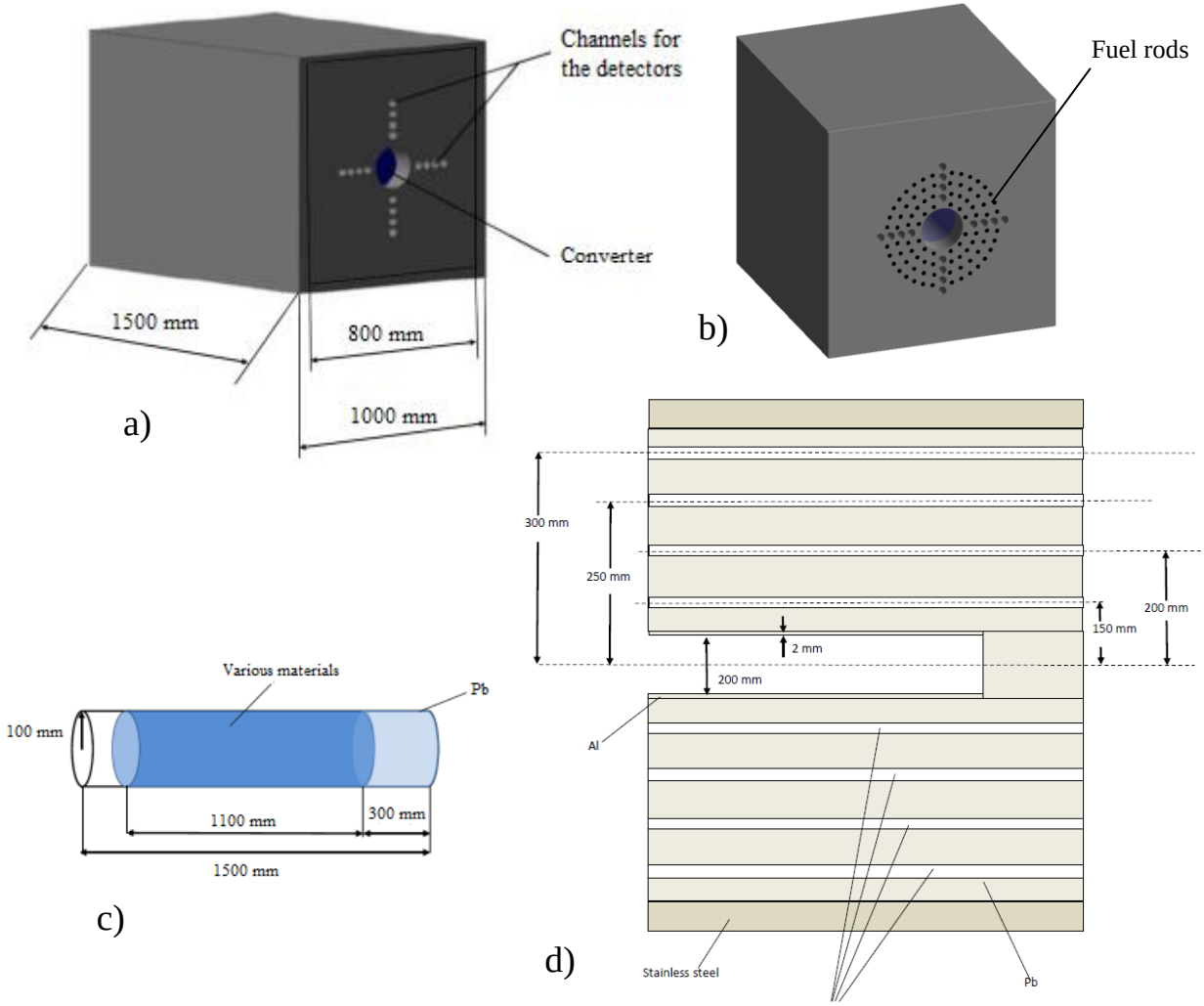

Fig. 1 The scheme of the target without fuel rods (a), with fuel rods (b), the converter (c), and the sectional view of the target LETASUR (d).

Since the design of the target must reproduce the situation from a real ADSR, the first choice would be a target with fuel rods inserted in Pb as substitute for LBE coolant. The use of converters from different materials changes the shape of the neutron spectrum, and consequently the k_{eff}, but a correct comparison of different beams imposes measurements of the fission distributions in target with the same k_{eff}. As the highest k_{eff} is obtained with Be converter, the correction of k_{eff} is obtained in the following manner: converters from other material than Be have a combined structure, with the internal cylinder from the investigated material, surrounded by a layer of polyethylene. The needed thickness of the external layer of polyethylene is determined through simulation. Using such target is costly and raises issues regarding the necessary approval; therefore, we also analyzed a simplified version, without fuel rods. The neutron spectra registered through simulation with Geant4 for different constructive variants of the target are illustrated in figure 2. The target was irradiated with ^{7}Li 0.3 GeV/n, interacting in Be converter.

In a Pb target without fuel rods, the neutron spectrum is softer that the spectrum registered in the presence of fuel rods. The influence of various shapes of the neutron spectrum on the breeding capability is illustrated in table 1 using the ratio of the neutron capture in ^{238}U to the fission in ^{239}Pu. This ratio will be experimentally used to estimate the breeding characteristic of neutron spectra. When the fuel rods are eliminated from the Pb target, the neutron spectrum becomes softer, and the breeding ration decreases with 20%.

A graphite target with fuel rods can be also used to estimate the efficiency of different beams. In such target, the softer neutron spectrum realizes a breeding ratio with 30 % lower than the value realized in a Pb target. But when the fuel rods from a graphite target are removed, the neutron spectrum becomes very soft, close to the spectrum in thermal reactors, and the breeding ratio falls down 6 times. In conclusion, a graphite target without fuel rods is not suitable for our experiments.

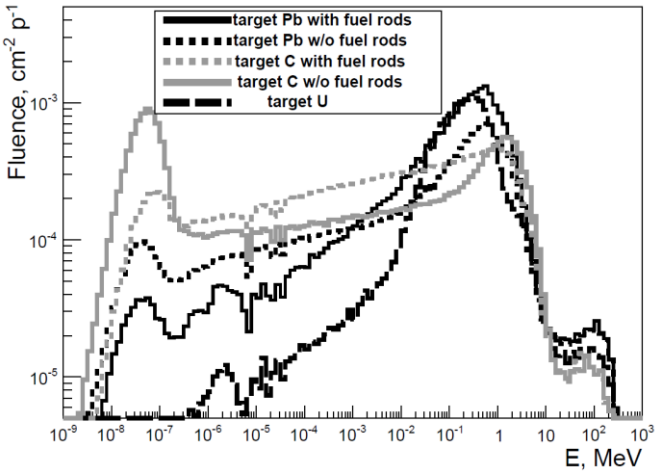

Fig. 2 The mean neutron spectra in detectors for different target configurations.

Table 1. The ratio capt^{238}U/fis^{239}Pu for different shapes of neutron spectrum.

	Pb target with fuel rods	Pb target withuot fuel rods	Graphite target with fuel rods	Graphite target without fuel rods	^{nat}U target
Capt^{238}U/Fis^{239}Pu	0.09	0.074	0.062	0.014	0.116

When ^{nat}U is used as target material instead of Pb, neutron spectra become harder, but the ratios of the integral fission values are similar with those realized in ADSR. The main disadvantage of the U target consists in lower neutron fluences, with faster radial decrease, generated by the neutron absorption in the target material. The measurement of the fission rates at large radii becomes difficult.

On the other hand, a target from Pb without fuel rods allows a correct reproduction of the ratio between the numbers of fissions obtained with different beams specific for a LBE cooled ADSR. The target without fuel rods has also another advantage: the fluence in the channels for the detectors is higher in comparison with the variant with fuel rods. That makes easier the measurements at high radius and represents a relevant factor for experiment planning, since one can count on beam intensities on the order 10^8 p/s.

The design of the target LETASUR (**LE**ad **T**arget for the study of **A**ccelerator driven **SU**bcritical **R**eactors) was approved, the target is under realization.

2. Factors influencing the performance of ADSR

Various factors that influence the efficiency of ADSR were investigated through simulation and theoretical calculation: factors related with the core structure, the particle type

and energy and the accelerator type. The energy released, the particle fluence, and the k_{eff} were obtained through simulation with the code Geant4. The reactor was simulated as an assembly of fuel rods surrounding the converter and immersed in a bath of lead-bismuth eutectic (LBE) coolant. The isotopes evolution and the temperature distribution were calculated with programs realized in the frame of toolkit ROOT.

Cores with k_{eff} in the range 0.985-0.988, LBE converter for protons and Be converter for ions, ensure G ~ 15 for protons, and G>20 for ions. We underlined the possibility of producing the same net electrical power using ion beams as ^{7}Li or ^{9}Be at low energy (0.25-0.3 GeV/n) instead of 1-1.5 GeV protons. That allows shortening the accelerator more than 2 times, and improves the efficiency diminishing the costs for building and maintenance.

Another relevant factor for the efficiency of ADSR, besides the type and the energy of the particle beam used to drive the subcritical reactor, is the beam intensity. ADSR requires beam intensity above 10^{16} particle/s to operate efficiently. G increases with the increase of the beam intensity, depending also on the efficiency of the power transmission in radio frequency (RF) cavities. However, the beam intensity and consequently the maximum power produced depend on the shape of the power distribution and on the type of the fuel. The use of Be converter, preferable in the case of ion beams conduces to power distributions with few times higher peaking factor (PF) in comparison with the situation when LBE is used as converter. In reactor with uniform enrichment and LBE converter PF has a value of ~2. The use of Be converter necessitates a core with gradual enrichment, with lower values in the layers situated in the proximity of the converter.

The maximal power that can be achieved in the reactor is determined by the cooling capability. An ADSR cooled with LBE allows building a subcritical reactor core with pitch to diameter ratio higher than in a fast reactor. In this way, the reactor can accommodate power distributions with higher PF than a critical reactor.

The values of PF determine the temperature in the hottest channel and limit the power that can be achieved. The behavior of different fuels (metal, oxide, nitride, carbide) during various unprotected transients was analyzed. The most solicitant from the point of view of the temperature evolution in the hottest channel is an unprotected beam overpower transient (UBOP). The temperature distribution is calculated using the control volume approach for the discretization of the heat transfer equations and a fully implicit scheme. For each investigated fuel, the temperature evolution during UBOP was calculated for different beam intensities, and the maximum allowed beam intensity was determined. The results are given in table 2.

Table 2. Maximum beam intensity I_{bmax}, electrical power P_{el}, G for different fuels and value of η_b.

Fuel	I_{bmax}, p/s	P_{el}, MW	G, $\eta_b = 0.7$	G, $\eta_b = 0.9$
metal	8×10^{15}	154	15	16.5
oxide	1.5×10^{16}	282	20.5	23.3
carbide	3.6×10^{16}	677	28	33.5
nitride	4×10^{16}	752	29.2	35

Metallic fuel, in spite of its highest thermal conductivity has the lowest melting temperature (1390 K) and can accommodate the lowest power density. The maximum electrical power obtained in ADSR with metallic fuel is ~150 MW. Oxide fuel has high melting temperature (3023 K) but low thermal conductivity and the maximum power is below 300 MW. Metallic and oxide fuels are suitable for small power ADSR. Nitride and carbide fuels allow higher reactor power, due to their both high melting temperature and high thermal conductivity, and they are preferable for ADSR. They can be used for medium-power reactors, with electrical power 650 – 750 MW in a core with pitch-to-diameter ratio ~2, power distribution with peak

factor 2, and maximum velocity of the LBE coolant 2 m/s. The highest electrical power can be reached with nitride fuel, ensuring G~30.

We realized memorandums of collaboration with the Institute of Nuclear Physics of the Academy of Science from Uzbekistan, the Joint Institute of Energy and Nuclear Research Sosny, from Belarus, the Erevan State University from Armenia, the Institute of Nuclear Physics from Almaty, Kazakhstan.

List of publications

- M. Paraipan, V. M. Javadova & S. I. Tyutyunnikov, "Influence of Particle Beam and Accelerator Type on ADS Efficiency", Nucl. Sci. Eng., **198** 1, 109-120 (2024)

- M. Paraipan, A. Abduvaliev, A. Balabekyan, O. V. Belov, F. H. Ergashev, V. M. Javadova, S. V. Korneev, L. K. Kostov, J. H. Khushvaktov, S. A. Kulikov, A. A. Solnyshkin, V. V. Sorokin, T. N. Tran, S. I. Tyutyunnikov, "Extended lead target for studying the perspectives of accelerator driven subcritical reactor", *Nucl. Sci. Eng.*, **1**, 1-13 (2025)

- M. Paraipan, O. V. Belov, V. M. Javadova, T. N. Tran, "The Influence of Fuel Type and Beam Intensity on the Performance of ADSRs", Eng. Proc., 160 (1), 52 (2026)

List of papers presented at international conferences and meetings

- M. Paraipan, O. V. Belov, V. M. Javadova, L. K. Kostov, S. A. Kulikov, V. N. Shvetsov, T. N. Tran, S. I. Tyutyunnikov, "Lead target for the study of accelerator driven subcritical reactor with ion beams"**,** V International Scientific Forum Nuclear Science and Technologies, 7-11 October 2024, Almaty, Kazakhstan

- M. Paraipan, O. V. Belov, V. M. Javadova, L. K. Kostov, T. N.Tran, S. I. Tyutyunnikov, "Perspectives of accelerator driven subcritical reactors", XXXI International Seminar "Nonlinear Phenomena in complex systems", June 24-28, 2024, Minsk

- M. Paraipan, O. V. Belov, V. M. Javadova, L. K. Kostov, T. N.Tran, S. I. Tyutyunnikov, "The influence of the fuel type and enrichment distribution on the ADSR performance", April 22-25, 2024, Samarkand

- M. Paraipan, A. Abduvaliev, A. Balabekyan, O. V. Belov, F. H. Ergashev, V. M. Javadova, S. V. Korneev, L. K. Kostov, J. H. Khushvaktov, A. A. Solnyshkin, V. V. Sorokin, T. N. Tran, S. I. Tyutyunnikov , "Status of ADSR project. The design of the target LETASUR", THE XI International Conference Modern Problems Of Nuclear Energy And Nuclear Technologies, Tashkent, 2025

- M. Paraipan, O. V. Belov, V. M. Javadova, T. N. Tran, S. I. Tyutyunnikov, "Accelerator driven subcritical reactors: status and perspectives", Proceedings RuPac 2025, 137 (2026)

- M. Paraipan, A. Abduvaliev, A. Balabekyan, O. V. Belov, F. H. Ergashev, V. M. Javadova, S. V. Korneev, L. K. Kostov, J. H. Khushvaktov, A. A. Solnyshkin, V. V. Sorokin, T. N. Tran, S. I. Tyutyunnikov, "Assessment of variants for experimental investigation of the efficiency of proton and ion beams for accelerator driven subcritical reactors", Neutron Physics and Radiation Materials Conference (NPRM 2025), October 27-31 2025, Yerevan

- T. N. Tran, M. Paraipan, A. Abduvaliev, A. Balabekyan, O. V. Belov, F. H. Ergashev, V. M. Javadova, S. V. Korneev, L. K. Kostov, J. H. Khushvaktov, S. A. Kulikov, A. A. Solnyshkin, V. V. Sorokin, , S. I. Tyutyunnikov, "Lead target for the study of accelerator driven subcritical reactors", Hanoi, Vietnam 2025

- J.H. Khushvaktov, "Research of Accelerator Driven Systems at JINR", ARIADNA collaboration meeting, September 5-6 2024, Dubna

- M. Paraipan, O. V. Belov, V. M. Javadova, L. K. Kostov[1],of the perspectives of accelerator driven subcritical reactor and planning experiments, ARIADNA collaboration meeting, September 5-6 2024, Dubna

- T. N. Tran, M. Paraipan, O. V. Belov, V. M. Javadova, L. K. Kostov, S. A. Kulikov[1], V. N. Shvetsov, S. I. Tyutyunnikov, "LETASUR target for ADSR project, ARIADNA collaboration meeting", September 5-6 2024, Dubna

- M. Paraipan, "Status of ADSR project", ARIADNA collaboration meeting, September 30- October 2 2026, Dubna

- A. Abduvaliev, "Preliminary study on the design of the lead targetfor experimental investigation of ADSR", ARIADNA collaboration meeting, September 30- October 2 2026, Dubna

- A. Balabekyan, "Research in the field of nuclear physics at Yerevan State University, ARIADNA collaboration meeting", September 30- October 2 2026, Dubna

- T. N. Tran, "Theoretical and experimental investigation on the optimization of accelerator driven subcritical reactors", Nucleus 2026, September 21-26, Khabarovsk, Russia

- M. Paraipan, A. Abduvaliev, A. Balabekyan, O. V. Belov, F. H. Ergashev, V. M. Javadova, S. V. Korneev, L. K. Kostov, J. H. Khushvaktov, S. A. Kulikov, A. A. Solnyshkin, V. V. Sorokin, T. N. Tran, S. I. Tyutyunnikov, "Experimental approach for studying the energy efficiency of various beams in subcritical reactors", ISINN 2026

2.3. Status and stage (TDR, CDR, ongoing project) of the project (including percentage of implementation of the declared milestones of the project *(if applicable)*

2.4. Results of related activities

2.4.1. Research and education activities. List of defended dissertations.

2.4.2. JINR grants (scholarships) received.

- grant JINR order 462/12.05.2026, p.1

2.4.3. Awards and prizes.

2.4.4. Other results (expert, scientific-organisational, scientific-propaganda activities).

3. International scientific and technical cooperation.

Actually participating countries, institutions and organisations

Organisation	Country	City	Participants	Type of agreement
YSU	Republic of Armenia	Yerevan	Balabekyan A. Gaginyan S. Hovhannisyan G.	Cooperation Agreement
INP AS Uz	Republic of Uzbekistan	Tashkent	Ergashev F. Abduvaliev A.	Cooperation Agreement

«JIPNR – Sosny» of the NASB	Republic of Belarus	Minsk	Sorokin V. Korneev S.	Cooperation Agreement
INP-ME	Republic of Kazakhstan	Almaty	Zholdybayev T.	Cooperation Agreement
INR-RAS	Russian Federation	Moscow	Sidorkin S.	
SPbPU	Russian Federation	Saint-Petersburg	Sadeghi H. Perez Quintos M.	
INRNE	Bulgaria	Sofia	Zhivkov P.	

4. Plan/actual analysis of resources used: human (including associated personnel), financial, IT, infrastructure

4.1. Human resources (actual at the time of reporting, total number of participants)
(total number of participants)

№№ п/а	**Categoryof employees**	**Core staff Amount of FTE**	**Associated personnel Amount of FTE**
1.	Scientific staff	6.1	7.2
2.	engineers	2	0
3.	professionals	0.5	0
	Total:	**8.6**	**7.2**

4.2. The actual estimated cost of the project

Names of costs, resources, funding sources		**Cost (thousands of dollars) resource requirements**	**Proposal from the laboratory for allocation of funding and resources**				
			1st year	2nd year	3rd year	4th year	5th year
	International cooperation (IC)	40	10	10	10	10	—
	Materials	60	20	20	10	10	—
	Equipment and third-party services	600	200	200	100	100	—
	Commissioning work	40	10	10	10	10	—
	Services of research organisations	40	15	15	5	5	—
	Acquisition of software	0	0	0	0	0	—
	Design/construction	0	0	0	0	0	—
	Service costs (*planned in case of direct project affiliation)*	0	0	0	0	0	—
Resources required Normo-hours	Resources						
	– The amount of FTE,	83,7	19,1	20,5	21,1	23,0	—
	– accelerator/installation,	100 h.	25 h.	25 h.	25 h.	25 h.	—

		– reactor, ...						
Sources of funding	**Budgetary resources**	JINR budget *(budget items*	780	255	255	135	135	—
	Extrabudgetary (supplementary estimates)	Contributions by co-contractors Funds under contracts with customers Other sources of funding	0	0	0	0	0	—

4.3. Other resources

Computer resources consumed MICC	**Distribution by year**				
	1st year	**2nd year**	**3rd year**	**4th year**	**5th year**
Data storage (TB) - EOS - Tapes	0	0	0	0	—
Tier 1 (core-hour)	0	0	0	0	—
Tier 2 (core-hour)	0	0	0	0	—
SC "Govorun" (core-hour) - CPU - GPU	0	0	0	0	—
Clouds (CPU cores)	0	0	0	0	—

5. Conclusion

The main tasks of the project envisaged within the proposed timeframe have been completed. The project had the adequate human and material support as well as other resources for implementation.

6. Proposed reviewers

- N. I. Zamiatin, VBLHEP, JINR
- S. V. Artemov, INP AS Uz, Uzbekistan

Theme Leader

_____/_____/
"_____"_____ 202_

Project Leader

_____/____ _____/
"_____"_____ 202_

Laboratory Economist

_____ _____/_____ _____/
"_____"_____ 202_