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Approaches to Reduce the Use of Radioisotope Sources in the Logging of Oil and Gas Wells in Ukraine and Kazakhstan within the Framework of the Policy of Reducing Radiation Hazard

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Abstract. *During the preparation of the scientific project «Technology Status Report on Radioactive Well Logging Source Risk Mitigation (ISTC / STCU)», information was collected from industry experts in Ukraine and Kazakhstan. Active radionuclide sources of radiation used in logging tools are Cs-137 and Pu-238. They used to determine the formation density and neutron porosity. They also help to determine oil-water contact, gas-liquid contact and to isolate oil-and-gas-saturated formations. The article analyzes the possibilities of alternatives for replacing logging technologies with ampoule sources of ionizing radiation (IRS) with technologies that use, albeit more expensive, but safer controlled deuterium-tritium pulsed neutron generators. It is concluded that at this stage, the complete replacement of well logging tools with ampoule IRS by tools with controlled neutron generators is impractical. The latter can be a significant addition to traditional radioactive logging technologies. The main steps towards the implementation of the policy of reducing radiation risks when performing radioactive well logging have been developed.*

Keywords: *radionuclide, radioisotope sources, radiation, logging, oil-and-gas-saturated formation.*

Introduction

The most common using mobile radioactive sources is oil geology along with medicine, test equipment, technical diagnostics et cet. The potential dangers of mobile radioactive sources lead to permanent correct requirements and regulatory norms, decreasing level of activities of sources, and to attempt various non-nuclear tools. Policies to reduce radiation hazard need to maintain government regulatory and/or enhance requirements ot activity with mobile sources and emphasize decreasing the probability worker radiation exposure, widespread adoption of managed sources instead radionuclide-based sources and increasing the total radiaton security.That is the reason for modernization of nuclear sources and substantial financial resources. How is this transfer to execute in an economical manner that for all provider and operators is key issue of State Regulatory policy. They must face the facts inherent in diversity and complexity of radiation safety tasks in oil geology. Namely, simultaneously meeting geological challenges for commercial needs and ensuring radiation safety means that logging operations using nuclear physics tools must simultaneously be accurate, safe and cost-effective. Any changes in these factors could become sensitive for operators and logging service providers. For example, geophysical well survey (GIS) data are critical to the determination of porosity, lithology, and subsurface dissection. Considering the rather high cost of drilling (some wells can cost more than $ 100 million), the significance of well logging results in establishing the physical characteristics of reservoir rocks, type of fluid, pressure, etc. no doubt. An error in determining porosity even in one unit for highly porous (~20%) reservoirs with low reserves (up to 100 million barrels) causes a loss in monetary terms up to $ 3.33 million, and for low-porosity reservoirs these losses will increase several times [16].

The incident with the loss of the ^{137}Cs radioactive source in September 2014 and the attempted illegal sale of ^{137}Cs [https://www.caravan.kz/gazeta/yadernyjj-sklad-v-vashem-dvore-cezijj137-i-drugie-podarki-radiacii-79722] stimulated expert discussions on the issues of potential threats and damage associated with mobile IRS, as well as the transparency of user handling practices [10] and ways to reduce the use of radioisotope sources.

The operations of well logging service providers and designers are governed by stringent regulations (state safety standards and departmental guidelines) concerning all the stages of handling radionuclide-based logging tools, including site storage, transport, use, tracking, inventory, removal upon completion of job, disposal, dealing with lost or missing sources, dealing with stuck source incidents, and the regulatory regime followed by the source licensees.

Respect for the principle «Risk Mitigation without losing benefits» is no alternative and may some approach to achieve the goal.

1) enhancing of Government regulations and/or requirements;

2) decreasing of activities of used radionuclide-based sources in logging technology;

3) increasing use nuclear alternatives simultaneously with decrease use of the conventional radionuclide-based logging tools.

The possible replacement of radionuclide-based logging technology by managed sources in frame of mitigation policies radiation security in Ukraine and Kazakhstan is analyzed in our study.

Activities and risks of radiation sources used in radioactive logging (RL) of oil and gas wells in Ukraine and Kazakhstan.

To study a geological section, traditional logging technology uses radioactive logging, which consists in studying the natural gamma radiation of rocks (gamma-ray logging – GK) and the effects of interaction of radiation from a gamma-source (gamma-gamma-ray logging – GGK) and neutrons (neutron logging – NK) with rock. Radioisotope instruments and neutron generators are used as sources of ionizing radiation (IRS). Usually these are ampoules, therefore such methods are called «ampoule». The term «stationary» is also used for neutron generators. They are used in neutron gamma-ray logging (NGK), thermal neutron-neutron logging (NNK-T) and epithermal neutrons (NNK-NT).

Another type of neutron source is a neutron generator, the main part of which is a neutron tube, which contains a titanium or zirconium target with a hydrogen isotope, tritium, dissolved in it. Radiation of the neutron flux occurs only when the power is turned on to the neutron tube. A neutron generator of this type can operate in a pulsed mode. An important advantage of «pulsed» neutron sources is the ability to turn them off, which increases the safety of work and allows the intensity of the sources to be increased to 10^8-10^9 neutrons/sec. With their use, it becomes possible to study the total age of the medium and its neutron characteristics, such as the neutron diffusion coefficient, the average lifetime of thermal neutrons and the slowing down length of neutrons in the medium, which subsequently makes it possible to determine the oil saturation coefficients of rocks. At the same time, the cost of such a source significantly exceeds the cost of ampoule sources. There are also technological problems, since the guaranteed service life of neutron tubes in the operating mode is from 50 to 120-150 hours. In addition, the presence of tritium in the tubes requires the same safety measures as when using radiation sources.

The relative simplicity and profitability of using ampoule sources is accompanied by the need to solve a number of problems associated with maintaining the required level of radiation and physical safety at all stages of the life cycle. Radioactive sources in logging tools, as a rule, belong to the 2-4 category of radioactive materials in terms of their potential radiation hazard (Table 1). Their radiological effects on human health can result in injury or death. In the general case, logging radiation sources are characterized by the average values of the ratio of the source activity (A) to the conditional hazard value (D): $10 > A/D \geq 1$. Note that the conditional hazard value depends on both the deterministic radiation exposure to human organs and the type of radionuclide [18].

Radiological risks when using ampoule sources in GIS arise both within the framework of operational activities and during unauthorized irradiation. Structurally, radioactive sources have a double casing made of steel or lead, resistant to external influences. Therefore, during technological operations with IRS, they do not pose a significant threat and, as a rule, the exposure of personnel at the drilling site, during transportation or in stationary storage does not pose a significant radiation threat. The specified group of risks, as a rule, is well standardized and has fairly accurate guidelines for expected radiation doses.

The second group of risks is associated with various unauthorized factors and interventions – accidents, losses and theft of sources, with outside interference or unauthorized access. The vulnerability of ampoule sources of radiation sources is associated with this group of factors, since all ampoule sources are removable, have a miniature size and a small mass.

The second group of risks has recently been given increasing attention both by the IAEA directives [17-18] and by national regulators. Regulatory support for the safety of the activities of companies in Ukraine and Kazakhstan has a multi-level structure and consists of laws, rules, state standards, regulations and departmental orders covering the manufacture, use, export / import, commissioning and decommissioning, transportation, accounting, control, formation IRS registers, as well as the Procedure for ensuring radiation safety [4-5, 7-9, 11-15].

Currently, in Ukraine and Kazakhstan, radioisotopes are used as ampoule radiation sources:

- Cs-137 in DL, with source strength ranging from 1.2×10^{10} to 1.2×10^{11} Becquerel (Ukraine), $9,25\times10^{10}$ Bq (Kazakhstan); Co-60 in GGRL, with source strength of 1.5×10^{8} Becquerel (Ukraine); $^{238}Pu/Be$ with source strength of $2,4\times10^{11}$ Becquerel (Ukraine, Kazakhstan);

- stationary neutron generators used in neutron gamma-ray logging (NGK), neutron-neutron logging (NNK), two-probe neutron-neutron logging (2NNK)

Table 1 – Application and categorization of the hazard of radioisotope sources during logging and well operation in oil and gas geology

Isotope (/ targed)	Operator of source	IAEA category [16]	A/D	$T_{1/2}$, year	Typical activity, $\frac{TBq}{Cu}$	Practice
$^{241}Am/Be$	Kazakhstan	2 – 3	12	433	$\frac{>0,74}{>20}$	NL
		3 – 4	12			Frack-pack monitoring
	Kazakhstan	4	0,031		$\frac{0,0019}{0,05}$	DL
^{75}Se		2	15	~0,33	$\frac{3}{80}$	pectrometric gamma-gamma ray log
^{60}Co	Ukraine	3 – 4	3,71	5,27	$\frac{0,00015}{0,04}$	DL
$^{238}Pu/Be$	Ukraine Kazakhstan	3	1,9	24360	$\frac{0,11}{3}$	NL
^{137}Cs	Ukraine Kazakhstan	3 – 4	0,74	30	$\frac{0,037-0,074}{1-2}$	DL
^{252}Cf		4	0,056	2,55	$\frac{0,0011}{0,03}$	NL
$^{210}Po/Be$	Ukraine	4	0,019	0,39	$\frac{0,0011}{0,03}$	NL
^{226}Ra		4	0,019	1620	$\frac{0,000074}{0,02}$	DL
^{85}Kr		3 – 4	0,0012	10,7	$\frac{0,037}{1}$	tracer analysis

use 238Pu (target – Be) with an activity from 6.1×10^{10} Bq to $2,4\times10^{11}$ Bq (Ukraine), 5.92×10^{10} Bq (Kazakhstan).

Based on the results of logging studies, lithological dissection of the section is performed, determination of oil-water contact, gas-liquid contact (GLC), contacts between oil and gas-saturated formations – methods of NGK, NNK, 2NNK, GGK-P, as well as determination of such parameters as porosity (porosity coefficient) – methods of NGK, NNK, 2NNK; density (bulk density of the rock) – GGK-P method; lithological composition – NGK method.

Density logs have a vertical resolution of 45 cm with a density determination accuracy of 0.01-0.02 g/cm^3 at a logging probe speed of 550 m/h. With an increase in speed to 1100 m/h, the accuracy decreases to 0.025 g/cm^3.

Methods of NGK, NNK, GGK, GK allow to determine the main reservoir properties of terrigenous and carbonate sections [2-3] (Table 2): clay content; porosity; identification of reservoirs and main lithotypes; assessment of oil and gas saturation; assessment of the nature of reservoir saturation; separation of oil-water (OWC) and gas-liquid (GLC) contacts.

Alternative to nuclear geophysical methods with ampoule IRS. In the field of geological problems, for the solution of which ampoule logging tools are used, we will consider the applicability of alternative technologies based on controlled neutron generators. First of all, these are various modifications of pulsed neutron methods (pulsed neutron-neutron logging – INNK, pulsed neutron gamma-ray logging of radiation capture – INGK-RZ, neutron gamma-ray inelastic scattering – INGK-NR), which have high efficiency and an extended range of tasks to be solved. oil and gas geology [1, 3, 6, 9, 16-18]. INNK in the GIS complex (together with NGK, GGK) makes it possible to determine the set of reservoir properties and the structural characteristics of the sections: the volume of the skeleton, the volume of the clay fraction, the structure of the pore space, etc.; reliably determine contacts in cased wells.

A brief summary of the possibilities of alternatives for replacing well logging technologies with ampoule IRS is as follows:

- the transition to low-level ampoule sources will not allow to confidently solve the problems of determining density (GGK-P), neutron porosity, determination of mineralogy and lithology (NC), porosity in clay-free formations (NGK);
- the transition to low-level sources will require an increase in research time, which will lead to additional downtime of wells and economic losses for companies;
- the use of deuterium-tritium neutron generators makes it possible to monitor productive formations, and a high logging speed significantly reduces the likelihood of accidents and reduces the total time of work on the well; the cost of deuterium-tritium neutron generators is much higher than ampoule

<table>
<tr><th colspan="8">Table 2 – Possibilities of nuclear physics methods for solving problems of oil and gas geology</th></tr>
<tr><th colspan="2" rowspan="2">Parameter/Method</th><th colspan="4">Conventional geophysical complex</th><th colspan="2">Nonnuclear and alternative logging tools</th></tr>
<tr><th>DL</th><th>NGRL</th><th>NLI</th><th>TNL, ENL</th><th>NNLL</th><th>PNGL-RC, PNGL-IS</th></tr>
<tr><td colspan="2">Clay content evaluation</td><td>Does not depend on salinity of formation water and mud</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Porosity evaluation</td><td></td><td></td><td>+</td><td>1. C_{H2}
2. at C (formation water) ≤ 100 г/л
3. together with DL</td><td>C_{H2}</td><td>+</td></tr>
<tr><td colspan="2">Reservoir identification</td><td>with respect to consolidated rocks, high porosity and clay particles presence</td><td></td><td></td><td>+</td><td colspan="2">low value $\frac{Si}{Ca}$ – carbonated reserv.,
high $\frac{Si}{Ca}$ – terrigenous reserv.</td></tr>
<tr><td colspan="2">Lithotype determination</td><td></td><td>According to hydrogen content</td><td></td><td>+</td><td>high vertical resolution (to h=30-40 cm)</td><td></td></tr>
<tr><td colspan="2">Evaluation of oil and gas saturation</td><td></td><td></td><td></td><td>including via casing</td><td>C/O proportion</td><td>+</td></tr>
<tr><td colspan="2">Evaluation of the nature of reservoirs saturation</td><td></td><td></td><td></td><td>elements with high thermal-neutron capture cross-section</td><td colspan="2">Does not depend on salinity of formation water;
C/O of oil-saturated formation > C/O of water-saturated formation</td></tr>
<tr><td colspan="2">Oil-water contact determination</td><td></td><td>+</td><td>salinity > 50 g/l</td><td>including disbanded zones</td><td>including gas-fluid contact</td><td>+</td></tr>
<tr><td rowspan="3">Depth of investigation, cm</td><td>Cs-137</td><td>4</td><td></td><td></td><td></td><td>120</td><td></td></tr>
<tr><td>Co-60</td><td>10-15</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Pu+Be</td><td></td><td>~20-30 cm (depend on hydrogen content)</td><td>12-15 (thermal neutrons.)</td><td>120 (for dry sand)</td><td></td><td>for 10% > PNNL</td></tr>
<tr><td colspan="2">Notes</td><td>Large caverns influence (20-25 cm)</td><td></td><td></td><td></td><td></td><td>Less-common</td></tr>
<tr><td colspan="2">Combinations of methods</td><td></td><td>EL, SL, geochemical methods</td><td></td><td>DL</td><td></td><td></td></tr>
</table>

Methods: AK – acoustic logging; PNNK – pulsed neutron-neutron craotage (P3 – radiation capture, HP – inelastic scattering); NAC – neutron activation logging; NNK-T – thermal neutron neutron logging; NNK-NT – epithermal neutron neutron-neutron logging; EC – electrical logging.
Abbreviations: C/O, carbon to oxygen ratio; SSS – formation water salinity; Ref – salinity of the flushing fluid; CH2 – hydrogen content; rel. – attitude.

sources and they have small resources of use;

• INNK (in comparison with the methods of NOC and OGK) has a larger research radius, which makes it possible to more reliably determine the water-oil and gas-liquid contacts, especially at long delays;

• the research area with pulsed neutron instruments reaches 30 cm, which exceeds the research area with ampoule instruments (NGK ~ 20 cm, HHK-NT ~ 10 cm).

• studies with pulsed neutron instruments are characterized by high vertical resolution (20-50 cm) and approximately the same (in comparison with ampoule instruments) measurement ranges for hydrogen content.

• the undoubted advantage of logging tools with controlled neutron generators, in comparison with ampoule analogs, is a decrease in the level of exposure of production personnel and complete radiation safety (neutron fluxes are generated only when the tool is turned on).

It should be noted that pulsed neutron methods at the present stage have limited application due to the high cost of the corresponding nuclear geophysical equipment and, as a consequence, the high cost of logging studies by these methods. In particular, such methods as INGK-RZ and INGK-NS in Ukraine have not received wide application in the practice of geophysical surveys of wells (GIS).

The experience of manufacturing companies and comparative analysis shows that a complete replacement of logging tools with ampoule radiation sources for tools with controlled neutron generators is impractical. The latter act as a significant addition to traditional RK technologies, in particular, for the determination of neutron porosity. Such nuclear methods of geophysical surveys in wells (for example, using controlled deuterium-tritium neutron generators) are, with a single exception, a significant addition to the traditional methods of RK both in Ukraine and Kazakhstan. Most customers are satisfied with the level of accuracy provided by ampoule nuclear technology.

The widespread use of alternative technologies using neutron generators is limited by the following reasons (in decreasing order of importance): high cost; cost of maintenance and service; limited use of existing logging tools [1] at temperatures above 120°C and pressures above 80 MPa.

Directions for the development of nuclear logging technologies in the framework of the policy of reducing radiation exposure. The main steps towards the implementation of such a policy, in our opinion, will be as follows.

1. Consensus development by the Regulator, together with service companies, a series of normative documents, including:

• to recommend that the State Nuclear Regulation Committee of Ukraine, jointly with the well logging service providers, develop a set of requirements and regulatory norms on using radiation sources in well logging operations (source mounting/dismounting, transportation etc.);

• to recommend that the State Nuclear Regulation Committee develop a methodology for approving the use of radiation sources in well logging operations based on risk assessment criteria, including the use of alternative technologies, and radiation source risk mitigation measures.

2. Improving departmental protocols:

• Updating in-house safety and security regulations on source handling and bringing them in compliance with the IAEA recommendations concerning permanent and on-site storage and transportation of mobile radiation sources;

• notification procedures as a result of an emergency at the well (in case of loss of radiation sources);

• termination of technical measures to overcome an emergency, the timing of notification of the regulator, provider, in case of theft – appeal to law enforcement agencies.

3. Technology:

• Designing and introducing an electronic system of mobile radiation source monitoring;

• Designing and introducing an improved system of control over authorized personnel access to radiation sources (for example, an Access Authorization Program).

4. Organizational measures to reduce the risks of unauthorized use:

• It is necessary to develop and implement incentive systems for the use of alternative methods in production, in particular, the creation of a fund for the provision of concessional loans to replace logging equipment with radioisotope sources with an alternative one, which is especially important for small logging companies;

• the social aspect is also important, consisting in raising awareness of reducing the risk of radiation exposure when using alternative logging technologies (specialized universities in Ukraine and Kazakhstan);

• optimization of the physical protection of radiation sources in accordance with the IAEA recommendation during stationary storage (organization of video surveillance, as well as an electronic system for fixing the intervention) and transportation (GPS-monitoring of the movement of special vehicles, radiation monitoring of radiation sources, reliable packing of containers and their labeling, installation of protective covers and chains, alarm signal via mobile communication).

Results

Compliance with existing safety measures and minimization of radiation exposure risks during logging with IRS and, as a result, the practical absence of emergency situations (the absence of lost IRS in Ukraine and Kazakhstan over the past 5 years and a small number of incidents with jamming of IRS logging probes) do not create additional operating costs for logging companies, accordingly, do not induce them to abandon or reduce the use of radioisotope (ampoule) sources.

An obstacle to the widespread involvement of the latest alternative logging technologies is their high cost and high cost of maintenance, respectively, the demand for the introduction of non-radioisotope alternatives is hampered by a shortage of funds from service companies. The difference in the landscape of the logging services market in Ukraine and Kazakhstan is likely to affect the pace of modernization of nuclear logging tools. In Ukraine, logging services are provided by various large and small companies: state, corporate and private, as well as companies with foreign capital. Estimated in the segment of geological exploration for oil and gas, large and small companies keep parity, covering 50% of the market, respectively. Currently, there are 10 leading oil producing and 6 world logging companies operating in Kazakhstan. In the near future, the situation in Ukraine may change dramatically, since the largest state-owned company Ukrgazvydobuvannya (Ukrgazvydobuvannya) has achieved the abolition of fixed prices for service work in geophysical well surveys and is guided by world standards in this area. Increasingly, the leaders of the world market – Schlumberger, Weatherford, Hallibarton, Baker Hughes – are involved in performing geophysical works in wells, which support high corporate incentives and have a wide range of modern downhole tools for radioactive logging. This will force both Ukrainian state and private companies to switch to modern equipment.

The regulatory frameworks in Ukraine and Kazakhstan are generally very similar and tend to adapt to IAEA directives and recommendations and to follow current practices for handling mobile IRS.

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***Аңдатпа.** «Technology Status Report on Radioactive Well Logging Source Risk Mitigation (ISTC/STCU)» зерттеу жобасын дайындау барысында Украина мен Қазақстандағы салалық мамандардан ақпарат жиналды. Тіркеу құралдарында қолданылатын радиоактивті сәулеленудің белсенді радионуклидтер көздері Cs-137 және Pu-238 болып табылады. Олардың көмегімен резервуардың тығыздығы және нейтрон кеуектілігі анықталады. Сондай-ақ олар мұнай-су контактісін, газ-сұйықтық байланысын анықтауға және мұнай мен газдың қаныққан бөліктерін айқындауға көмектеседі. Мақалада қымбаттырақ, бірақ қауіпсіз, басқарылатын детерий-тритиия импульстік нейтронды генераторларды қолданатын технологияларға иондаушы сәулеленудің ампулалық көздерімен (ІІІ) күнбағыс технологияларын ауыстырудың баламалы мүмкіндіктерін талдайды. Осы кезеңде реттелетін нейтрондар генераторлары бар аспаптарға арналған ампула ІІІ-нің тіркейтін құралдарын толық ауыстыру ұсынылмайды. Соңғысы дәстүрлі радиоактивті материалдарды өңдеу технологиясына елеулі қосымша болуы мүмкін. Негізгі қадамдар ұңғымаларды радиоактивтік тіркеу кезінде радиациялық қауіптерді азайту жөніндегі саясатты жүзеге асыру бағытында жасалды.*

***Кілт сөздер:** радионуклид, радиоизотоп көзі, сәулелену, каротаж, мұнайгазбен қаныққан қаба.*

Пути к сокращению использования радиоизотопных источников при каротаже нефтяных и газовых скважин в Украине и Казахстане в рамках политики снижения радиационной опасности

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***Аннотация.** Во время подготовки научного проекта «Technology Status Report on Radioactive Well Logging Source Risk Mitigation (ISTC/STCU)» была собрана информация от специалистов отрасли в Украине и Казахстане. Активными радионуклидными источниками радиоактивного излучения, применяемыми в каротажных инструментах, являются Cs-137 и Pu-238. С их помощью определяются плотность пласта и нейтронная пористость. Также они помогают определять контакт «нефть-вода», газожидкостный контакт и выделять нефтегазонасыщенные пласты. В статье выполнен анализ возможностей альтернатив замены каротажных технологий с ампульными источниками ионизирующих излучений (ИИИ) на технологии, использующие хоть и более дорогостоящие, но более безопасные управляемые дейтерий-тритиевые импульсные генераторы нейтронов. Сделан вывод о том, что на данном этапе полная замена каротажных инструментов с ампульными ИИИ на инструменты с управляемыми генераторами нейтронов нецелесообразна. Последние могут выступать существенным дополнением традиционных технологий радиоактивного каротажа. Разработаны главные шаги в направлении реализации политики снижения радиационных рисков при выполнении радиоактивного каротажа скважин.*

***Ключевые слова:** радионуклид, радиоизотопный источник, излучение, каротаж, нефтегазонасыщенный пласт.*

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