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February 24, 2014

ENDING HEU USE IN MEDICAL ISOTOPE PRODUCTION: OPTIONS FOR RUSSIAN-U.S. COOPERATION*

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Great progress has been achieved in recent years in minimizing civilian use of highly enriched uranium (HEU) as part of the international efforts to reduce the nuclear terrorism threat.[1] In particular, the leading global suppliers of the molybdenum-99 (Mo-99) isotope, which is widely used in medical diagnostics, are taking steps to reduce and, in the medium time frame, completely eliminate the use of HEU in the production of medical isotopes. Major new steps towards phasing out HEU use in medical isotopes production could be announced at the Nuclear Security Summit that will take place in The Hague on March 24-25, 2014. Several countries believe it should be possible to develop a road map towards that goal, with clear deadlines, by the time the heads of state meet in the Netherlands.

The Russian nuclear industry has set for itself an ambitious goal of becoming one of the three top global suppliers of Mo-99, which is used in 80 per cent of the medical procedures involving isotopes. Russia aims to win a 20-per-cent share of the global market for Mo-99. It is therefore important to identify mechanisms that could enable Russia to achieve that goal, while at the same time facilitating the Russian industry's transition to new market requirements for producing Mo-99 without HEU.

The Mo-99 and Tc-99m markets[2]

Every year, medical professionals worldwide carry out more than 30 million procedures using the medical isotope technetium-99m (Tc-99m), near half of these in the United States *(see Fig. 1 for more details on global market demand breakdown).*[3]

A radioisotope that decays over six hours, Tc-99m is injected into the human body to assess the presence and progress of ailments such as heart disease and cancer.[4] In a hospital setting, Tc-99m is derived from special generators that incorporate its parent, Mo-99.[5] But because Mo-99 has a relatively short half-life of 66 hours, these generators cannot be stockpiled and must be replaced on a weekly basis, and even more often for some hospitals.

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* This study was commissioned by the Nuclear Threat Initiative (NTI). The views expressed in this report are entirely the authors' own and do not reflect those of NTI or its Board of Directors. For more information, see the NTI website: http://www.nti.org/.

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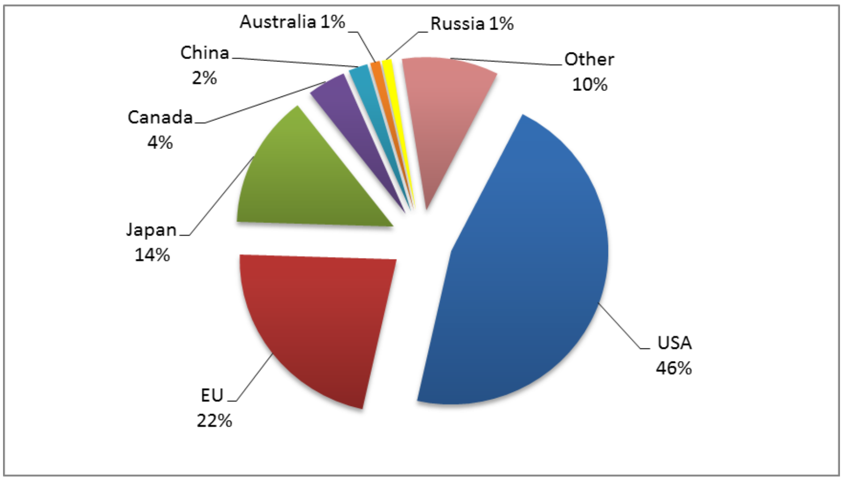
Fig 1. *Breakdown of Global Mo-99 Demand by Country/Region*



Sources: The Global Mo-99 Crisis: Australia's Unique Leadership Role. ANSTO. http://www.oecd-nea.org/med-radio/docs/ARI%20Newsletter%20on%20Mo-99_FINAL_02Dec09.pdf (Retrieved on November 11, 2013); Roy W. Brown. Covidien's Progress in Conversion from HEU to LEU Production of Mo-99. 2012, October, 2. http://www.iaea.org/OurWork/ST/NE/NEFW/Technical_Areas/RRS/documents/mo99/Peykov1.pdf (Retrieved on November 11, 2013); E-mail correspondence with OECD Nuclear Energy Agency expert. December 10, 2013.

At this time, however, the key Mo-99 manufacturing facilities (except Canadian) are situated very far away from the largest market, the United States, where that isotope is not currently produced. Most of the world's Mo-99 is produced in other countries (Australia, Canada, the EU, and South Africa), through fission using uranium in a handful of research and test reactors. Several of these reactors (or irradiators) are powered by HEU fuel and/or irradiate HEU targets, and acquire the estimated 40-50 kilograms required annually for isotope production targets.[6] Isotope production facilities then process the HEU targets to extract and purify Mo-99. The Mo-99 is then shipped to generator manufacturers and the generators to radiopharmacies at hospitals or independent vendors who mix the Tc-99m into particular formulations for radiopharmaceuticals.

The industry is highly concentrated. Eight reactors now provide the bulk of irradiation services to meet the global estimated demand of about 10,000 six-day curies per week (*Table 1*). In order of capacity they are Belgium's BR2, the Dutch HFR, the Canadian NRU, the South African SAFARI, the Czech LVR-15, the Polish MARIA, the French OSIRIS, and the Australian OPAL. All of these reactors can produce 1000 or more six-day curies per week of Mo-99 and all except for the BR2 and OSIRIS reactors have converted from HEU to LEU fuel.[7] Nearly all of these however still irradiate HEU targets (the SAFARI reactor irradiates both HEU and LEU targets), given the fact that most of their processors either do not plan to convert to LEU (Nordion for NRU)[8] or are in the process of doing so (Mallinckrodt and IRE for the European irradiators).

Table 1. *Current Irradiators*

Reactor/ Location	Targets	Normal operatin g days	Normal available capacity per week (6-day Ci)	Potential annual production (6-day Ci)	Estimated stop production date
BR-2 (Belgium)	HEU	140	7,800	156,000	2026
HFR (Netherlands)	HEU	280	4,680	187,200	2022
LVR-15 (Czech Republic)	HEU	200	2,800	80,000	2028
MARIA (Poland)	HEU	165	1,920	42,500	2030
NRU (Canada)	HEU	300	4,680	200,600	2016
OPAL (Australia)	LEU	290	1,000	41,450	>2030
OSIRIS (France)	HEU	200	1,200	34,300	2018
RA-3 (Argentina)	LEU	336	400	19,200	2027
SAFARI-1 (South Africa)	HEU /LEU	305	3,000	130,700	2025

Source: A Supply and Demand Update of the Molybdenum-99 Market. OECD Nuclear Energy Agency. 2012, August, Appendix 1. P.9. http://www.oecd-nea.org/med-radio/docs/2012-supply-demand.pdf (Retrieved on December 5, 2013).

The processor market (*Table 2)* is more concentrated with five firms capable of processing 1000 or more six-day curies per week. In order of capacity, they are Nordion (Canada), Mallinckrodt (Netherlands), NTP (South Africa), IRE (Belgium), ANSTO (Australia).[9] The Tc-99m generator market is dominated by two firms: Mallinckrodt, with operations in the Netherlands, and U.S-based Lantheus Medical Imaging who together control more than 80% of the global Tc-99m generator market.

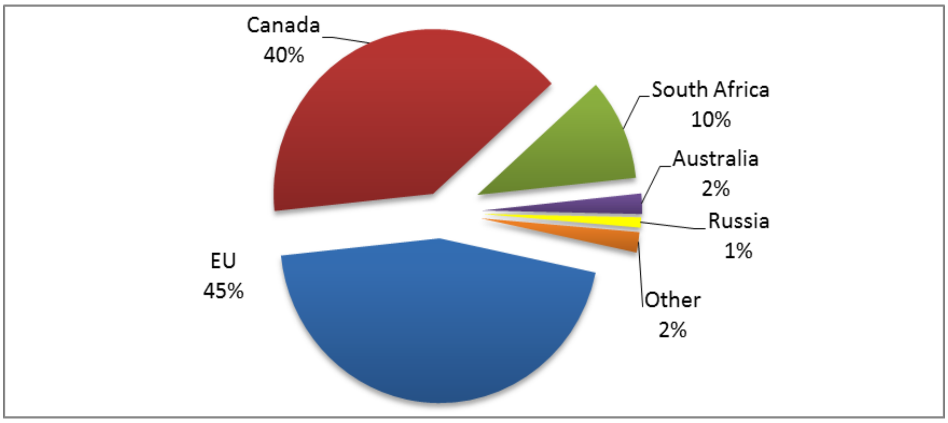
Table 2. *Current Processors*

Processor	Targets	Capacity per week (6-d Ci)	Available annual capacity (6-d Ci)	Expected date of conversion to LEU targets
AECL/NORDION (Canada)	HEU	7,200	374,400	Not expected
ANSTO HEALTH (Australia)	LEU	1,000	52,000	Started as LEU
CNEA (Argentina)	LEU	900	46,800	Converted
Mallinckrodt (Netherlands)	HEU	3,500	182,000	2015
IRE (Belgium)	HEU	2,500	130,000	2015
NTP (South Africa)	HEU/LEU	3,500	156,000	2013

Sources: A Supply and Demand Update of the Molybdenum-99 Market. OECD Nuclear Energy Agency. 2012, August, Appendix 1. P.9. http://www.oecd-nea.org/med-radio/docs/2012-supply-demand.pdf (Retrieved on December 5, 2013); E-mail correspondence with OECD Nuclear Energy Agency expert. December 19, 2013.

Taking into account the utilization ratio of the installed Mo-99 production capacity, as well as production at smaller facilities, this is what the breakdown of global production by country/region looks like in *Fig.2.*

Fig. 2. *Global Mo-99 Production*[10]



Sources: Molybdenum and Technetium from Obninsk. *AtomInfo.ru*. 2013, September 14. http://www.atominfo.ru/newsf/m0378.htm (Retrieved on November 11, 2013); Logan Michael Scott. Incentivizing Domestic Production of Molybdenum-99 for Diagnostic Medicine. American Nuclear Society. Oklahoma State University. 2013, August. http://www.wise-intern.org/journal/2013/documents/LMS_WISE_2013paper.pdf (Retrieved on November 11, 2013).

Eliminating HEU from research reactors and Mo-99 production: global trends

For over three decades, Washington and Moscow have aimed to minimize the use of HEU in the civilian sphere because of proliferation and nuclear terrorism concerns. In the past decade Russia and the United States, generally in cooperation with IAEA, have worked to convert Soviet-built research reactors overseas from HEU. And in recent years the two countries have cooperated on feasibility studies for the conversion of some Russian domestic research reactors.[11]

More recently, the U.S. government has advocated the development of new Mo-99 production capabilities that utilize LEU or alternative non-HEU-based technologies. The United States has taken several domestic policy initiatives to support the move away from HEU technologies including congressional support for the development of a domestic non-HEU-based industry and government incentives to put non-HEU Mo-99 on an equal market footing with HEU and stimulate demand for them.[12]

It has also supported the efforts of some foreign producers to convert away from HEU. In 2010, the National Nuclear Security Administration (NNSA) announced its support for producers from Australia and South Africa to supply LEU-based Mo-99 to the United States.[13] This support included approval by the FDA of Tc-99m derived from the new LEU-based Mo-99. Australia and South Africa have, at times, supplied as much as a third of the Mo-99 market for diagnostic procedures in the United States (when other major reactors have been shut down).[14] The IAEA (with NNSA support) has also worked to develop small-scale regional production capabilities based on alternative technologies in Eastern Europe, Latin America, and elsewhere.[15]

These efforts have been given strong backing at the Nuclear Security Summits. *Table 3* below summarizes the commitments undertaken by the Mo-99 producer countries with regard to the phasing out of HEU use.

Table 3. *Commitments by Participating States at the 2012 Seoul Nuclear Security Summit*[16]

Countries	Commitments
Belgium	participating in a joint project to qualify high-density LEU fuel to replace HEU fuel in research reactors; converting a research reactor and a processing facility for medical radioisotopes from using HEU to LEU
Canada	exploring an alternate method to replace HEU in the production of medical radioisotopes
France	working on a joint project to replace HEU targets with LEU targets in the production of medical radioisotopes; participating in a joint project to qualify high-density LEU fuel to replace HEU fuel in research reactors
The Netherlands	working on a joint project to replace HEU targets with LEU targets in the production of medical radioisotopes
Poland	completing the conversion of MARIA reactor in the first quarter of 2014
Republic of Korea	Participating in and championing a joint project to develop high-density LEU fuel to replace HEU fuel in research reactors
Russia	assessing the economic and technical feasibility of converting six research reactors from using HEU fuel to LUE fuel jointly with the US
South Africa	successfully converted Mo-99 production from the use of HEU to LEU

Source: Highlights of Achievements and Commitments by Participating States as stated in National Progress Reports and National Statements. The Seoul Nuclear Security Summit Preparatory Secretariat. The 2012 Seoul Nuclear Security Summit. https://www.nss2014.com/sites/default/files/documents/highlights_of_the_seoul_nuclear_security_summit120403.pdf (Retrieved on December 6, 2013).

Yet this effort has occurred simultaneously with rising public health concerns about the stability of Mo-99 (and thus Tc-99m) supplies. Between 2005 and 2013, lengthy irradiator outages and several other incidents caused severe shortages of Mo-99 for medical procedures worldwide, demonstrating the fragility of the radioisotope's supply chain. In the short term, these concerns have been dealt with through increasing coordination among suppliers. But amid likely rising global demand,[17] these stopgaps are not expected to hold within the next few years when the NRU and OSIRIS reactor intend to shut down permanently and the BR2 reactor is expected to be offline for more than a year. At the same time, continuing effective subsidies for these and other aging reactors have deterred new investment in production capacity. The result could be a new severe shortage by 2015 or 2016.

Mo-99 production in Russia

On the global scale, Russia is currently a very small producer of medical isotopes. In recent years the country's share of the global market was at or below 1 per cent.[18] That contrasts sharply with the situation on the market for other types of isotopes. For example, Rosatom accounts for 20 per cent of the global production of industrial isotopes and has earned itself a reputation as a reliable supplier. Russia is also the sole global supplier of such isotopes as helium-3, nickel-63, and americium-241.[19] There is, however, great potential for a stronger Russian presence in the international market for Mo-99 since many of the aging reactors that currently account for the bulk of global Mo-99 production are sometimes halted for maintenance and will soon be decommissioned altogether. Russia can make up for much of that soon-to-be-lost production and can contribute to ensuring that the global system has sufficient "outage reserve capacity." This goal, sought by the OECD Nuclear Energy, seeks to ensure that there is sufficient surplus production capacity to ensure that a temporary shutdown does not affect supplies to medical providers.

The Presidential Commission for the Modernization and Technological Development of the Russian economy has initiated a project to build new Mo-99 production facility at the NIIAR nuclear center in Dimitrovgrad, Ulyanovsk Region; construction began in 2010. The overall cost of the project is 1 billion roubles ($30 million). The first processing line as part of the new Mo-99 facility at NIIAR was launched on December 18, 2010, adding 250 to 400 six-day curies of weekly production capacity. On June 26, 2012 engineers completed construction and installation of irradiated targets processing equipment as part of the second processing line - but as of November 1, 2013, that additional capacity had yet to be launched. Once both lines of the new facility are up and running, their combined weekly output will reach 1,200 six-day curies.[20]

The goal of the project is to achieve a greater stability of supply in Russia and meet growing domestic demand, as well as to cater to foreign markets. At present, cancer is the second-biggest cause of death in Russia. More than 60 per cent of cancer patients in Russia are diagnosed at Stage 3 or 4 of the disease, i.e. when their cancer has already become very advanced. The government wants to change the situation through early diagnostics, which often requires the use of isotopes. Up until recently, most of the Russian demand was supplied by a branch of the Karpov Research Institute of Physical Chemistry, NIFKhI (Obninsk, Kaluga Region, Central Federal District). There were no other major producers with a similar output capacity. Whenever the reactor used by NIFKhI for irradiation was halted for maintenance, the company had to import molybdenum from South Africa so as to maintain an uninterrupted supply of the isotope to its own customers.[21] But creating a network of radiation medicine centers will take time. Given that Russia's own domestic demand for Mo-99 remains fairly limited (up to 100 six-day curies), in the short and medium term most of the NIIAR output will be destined for exports.[22]

In addition to NIAAR there are three other current Mo-99 production facilities in Russia, including:

- The Nuclear Physics Research Institute at the Tomsk Polytechnic University, TPU (city of Tomsk, Tomsk Region, Siberian Federal District);
- The Khlopin Radium Institute, KRI (St Petersburg, Northwestern Federal District);
- A branch of the Karpov Research Institute of Physical Chemistry, NIFKhI (Obninsk, Kaluga Region, Central Federal District), which was already mentioned.

For more details about Mo-99 producers, please see *Annex A*.

Tc-99m generators are currently made at three Russian facilities: NIFKhI, the Leypunsky Institute for Physics and Power Engineering (IPPE), and the TPU (the last one is a small producer, and all of its output is used to supply the institute's own demand for Mo-99)[23].

The largest of the existing Russian Mo-99 production facilities is at the NIFKhI Karpov Institute. At has output up to 170 six-day curies a week[24], but there is room for expansion up to 500 curies.[25]

Three of the four Russian Mo-99 facilities (NIIAR, TPU and NIFKhI) rely on irradiators (i.e. reactors) that use HEU fuel; two of the four (NIIAR and NIFKhI) use HEU targets. *Table 4* below summarizes the use of HEU in irradiator fuel and targets for Mo-99 production in Russia and the rest of the world. In percentage terms, Russia relies less on HEU targets compared to the rest of the world, but it is more reliant on HEU fuel.

Table 4. *Use of HEU in the Fuel of Irradiator Reactors and in the Targets for Mo-99 Production in Russia and the Rest of the World*

	Use of HEU in reactor fuel (% from the total number of reactors)	Use of HEU in targets (% from the total number of producers)
Russia	75%	50%
Rest of the world[26] (as of June 2011)	25%	87%

The two processing lines of the new Mo-99 facility at NIIAR were originally designed to use HEU targets and the existing research reactor (RBT-10-2), which also relies on HEU fuel. That choice appears to have been made without an in-depth study of the latest market trends, given that the project was supposed to cater to foreign as well as domestic demand. The decision failed to take into account the ongoing global transition towards minimizing HEU use, including legislation and regulations that provide incentives for customers to consume non-HEU based Mo-99 instead of Mo-99 made from HEU targets. As a result, marketing any HEU-based Russian Mo-99 made at NIIAR will be more difficult.

Two of Russia's four Mo-99 producers (KRI and TPU) supply their output only to the domestic market, and don't have any substantial spare capacity for exports at this time. The output of the NIFKhI and NIIAR facilities, which as noted above, currently rely on HEU fuels and targets, can be used for the domestic as well as the global market.

At this time NIFKhI makes regular Mo-99 deliveries to Iran.[27] Several Mo-99 deliveries have been made on a trial basis to Canada, India, Philippines, Poland, and Saudi Arabia.[28] Once both processing lines of the new facility at NIIAR reach their expected output, the Russian production capacity will be enough to cover up to 15 per cent of the global demand.[29]

Global and Russian incentives for non-HEU Mo-99 production

Growing Russian production could help stabilize the global Mo-99 market, which faced severe shortages on several occasions in 2005-2013. In 2009-2010 the shortages resulted from lengthy maintenance of the NRU reactor in Canada; to make matters worse, the irradiator reactors in the EU could not be used to their full capacity at the time.[30] According to some estimates, in 2010 during a six month period medical facilities around the world were unable to perform diagnostic procedures for several million people due to the shortage of Mo-99; the shortfall was estimated at 7 million doses.[31] In November 2013 three reactors used by the largest Mo-99 suppliers for target irradiation (the HFR reactor in the Netherlands, the NRU in Canada, and the Safari-1 in South Africa) were shut down almost simultaneously for technical reasons. In particular, exports of Russian Mo-99 could help make up for the shortfall on the global market that is likely to follow the end of production at Canada's NRU and France's OSIRIS reactors in 2016 and 2018, respectively.

In addition, the lack of clarity about future market developments, including Russian production has proved an important obstacle (among others) to financing. In the United States, four companies received research and development cost-sharing funding from NNSA to support non-reactor-based technologies for producing Mo-99. Only one of these companies, Northstar, is expected to enter into production soon (2014) using a neutron-capture technology. The company is expected to produce 750 six-day curies in 2014 and 3000 curies—or about half of current U.S consumption — in 2016.[32] The other three funded projects as well as another half-dozen commercial ventures are either stalled or in early licensing stages, having yet to receive sufficient financing.

Clearly, increased certainty and supply diversity would benefit the Mo-99 market and patients. Given the large number of reactors in operation in Russia (with three suitable reactors at NIIAR alone), and the availability of independent processing lines to extract Mo-99 from the targets, an increase in the Russian share of the global Mo-99 market would translate into greater supplies and reliability of Mo-99, and help to avert any future supply crises resulting from fluctuations in production. That would obviously be in the interests of the United States, which is the world's largest consumer of medical isotopes (every year, over 17 million patients are diagnosed and/or treated in the United States, using radiopharmaceuticals and radioisotopes)[33], and which is currently the main consumer of isotopes produced at Canada's NRU reactor.

Despite the lack of ability for an immediate shift in production away from HEU due to lack of funding and in some cases appropriate technology, Russian officials and producers have shown a growing willingness to consider a medium-term efforts to phase out HEU use. In 2012 the Rosatom nuclear corporation developed a program of converting reactors and targets from HEU to LEU.[34] As a first step, Russia is considering a conversion to LEU targets; such a step is less costly that conversion to LEU fuel, and the necessary technologies are easier to develop. Among the measures announced to an international audience later that year were a pilot project that would test the feasibility of using LEU targets for Mo-99 production at the NIFKhI facility— and the conversion of the reactor. The NIFKhI top management regards the conversion to LEU targets as one of the company's development priorities.[35] It was also noted that the VVR-K reactor in Kazakhstan which has already been converted with U.S. government assistance used similar fuel assemblies so there did not appear to be significant technical obstacles to developing and qualifying the fuel.[36]

The Novosibirsk Chemical Concentrates Plant (NZKhK), which supplies the targets to NIIAR, is considering development of a uranium-based target with a 19.75-per-cent enrichment ratio, as a key step to facilitate Russian exports of molybdenum to the Western markets.[37] Development of new LEU targets began as part of the Ministry of Education and Science grant "Comprehensive modernization and development of national production of radioactive isotopes at NIIAR to sustain the development of nuclear medicine and radiation technologies" awarded on December 27, 2012.[38] According to NIFKhI and NIIAR plans, a pilot batch of Mo-99 from LEU targets could be made in 2014 at the former facility, and in 2015 at the latter. A complete transition to the use of LEU targets could be made in 2016, provided that the upgraded Mo-99 production technology proves effective, and that there are economic incentives for ending the use of HEU in the production of medical isotopes.[39]

Russia and the United States also agreed on a series of six feasibility studies on HEU-LEU conversion which have since been completed, including one which studied the feasibility of converting the TPU reactor to LEU fuel and determined that further work was needed to develop appropriate high-density LEU fuel.

A transition of medical isotope production to LEU-based targets will require a whole number of issues to be resolved, including the provision of financing; development of LEU-based targets technology; and disposal of larger amounts of liquid waste produced when Mo-99 is processed from LEU targets.

Despite the research funding, it appears unlikely that the Russian government will allocate more funding in the short term to convert the production facility at NIIAR to the use of LEU targets, absent other incentives After all, the facility was only launched recently and engineers are still working to improve the technology of Mo-99 production.[40]

Moreover, direct U.S. or other foreign funding for conversion is also unlikely. On the whole, projects undertaken in Russia as part of the Global Partnership Against the Spread of WMD and the Nunn-Lugar Program have been completed. There is an understanding in Moscow that new Russian nuclear projects should not depend on foreign funding allocated for nonproliferation programs. That is why the financing of the projects to convert Mo-99 production to non-HEU technologies should rely on commercial instruments, including measures to stimulate demand for the output of the Russian companies transitioning to such technologies. That would enable these companies to invest in upgrading their production facilities so as to achieve compliance with the new market demands and legal requirements in certain countries. One example of these mechanisms in action is NIFKhI. The company quadrupled its Mo-99 output in 2008-2011 (thanks in part to securing export contracts). That has enabled it to upgrade and launch a new filling facility for technetium generators in September 2013 in line with internally accepted "good manufacturing practices"(GMP), helpful in gaining approval from foreign regulators. The project was funded by the company itself as part of its strategy of securing greater access to Western Mo-99 markets.[41]

Given the potential benefits to public health and preventing nuclear terrorism, Russia and the United States share an interest in accelerating the development of the Russian transition away from HEU targets and fuels in order to align Russia with other leading global suppliers in this regard.

Options for Russian-U.S. cooperation

Let's try to answer the question "What can be done to harmonize the Russian producers' plans to win a share of the global market, and the Western countries' (especially the United States') aspiration to convert the entire global production of Mo-99 to LEU while encouraging sufficient investment in new Mo-99 production to safeguard public health?"

To begin with, the United States and Russia must continue their current efforts to develop appropriate LEU fuels for NIFKhI and TPU reactors and seek to develop them for NIIAR as well. But other incentives should be considered to encourage Russia to convert the facilities in NIIAR and NIFKhI to the use of LEU targets. In particular, the United States, the world's largest Mo-99 consumer, should consider providing several, commercial-type, incentives that would encourage Russian suppliers to convert swiftly to LEU by easing access to the U.S. market after conversion. By doing so, the United States would allow Russia to increase its future exports and quickly recoup some of its conversion expenses while shoring up global non-HEU supplies.

The United States could consider some or all of the following commitments:

- To carry out bulk purchases of pharmaceuticals that use Russian non-HEU based Mo-99 when available, for an agreed period and to an agreed amount. A particular focus could be purchases by U.S. government agencies, such as the Veterans Health Administration and the Defense Department. This could begin with NIFKhI.
- Assistance in winning expedited licensing approval from the FDA for Tc-99m pharmaceuticals based on Russian LEU-based Mo-99.
- Cost-sharing support for converting NIFKhI and NIIAR to the use of LEU targets through co-funding of related R&D work done jointly by Russian and US scientists.
- U.S. informal assistance to Russian LEU research reactor fuel producers to spur competition in exports to third country research reactors.
- Continued joint research on high-density LEU fuels.

Russia could consider the following commitments:

- Committing to a timetable-based road map to end HEU-based Mo-99 production.
- An agreement that in the meantime HEU-based production would be only be used for Russia and Russia's existing customers, except for any requests by the United States or other states for emergency shipments of isotopes in the event of an interruption of supply from other sources.
- Revenue from bulk sales to the U.S. government would go to finance the conversion of the targets and later the fuel at the irradiator reactors, where technologically feasible.

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Coordination of Russian-U.S. cooperation in this area should be done via the Working Group on Nuclear Energy and Nuclear Security of the bilateral Russian-U.S. Presidential Commission. Also, it would be more appropriate to approach this issue within the context of the development of nuclear science and technology cooperation between the two countries rather than the nonproliferation context. It would therefore make sense to create a new Subgroup for Non-Energy Applications of Nuclear Technologies, which would take over this remit from the Subgroup on HEU Minimization.

Annex A. *Russian Mo-99 Producers.*

Subordinated to	Producer	Production method/ irradiator reactor	Use of HEU in fuel/targets	Production began	Market orientation	Comments
Ministry of Education and Science	Nuclear Physics Research Institute at the Tomsk Polytechnic University (TPU), city of Tomsk, Tomsk Region, Siberian Federal District	Activation/ IRT-T[42]	Yes/ No [43]	1985 [44]	Domestic	The reactor is one of six Russian research reactors that are subject of the technical feasibility of the conversion to LEU as part of cooperation between Rosatom State Corporation and the U.S. Department of Energy. The feasibility of conversion of IRT-T reactor was confirmed.[45]
Rosatom State Nuclear Energy Corporation	The Khlopin Radium Institute (KRI), St. Petersburg, Northwestern Federal District	Activation/ RBMK-1000[46]	No/ No	1997[47]	Domestic	KRI works in cooperation with the Leningrad NPP, where Mo-98 is irradiated in a RBMK-1000 reactor.
	A branch of the Karpov Research Institute of Physical Chemistry (NIFKhI), Obninsk, Kaluga Region, Central Federal District	Fission/ VVR-ts[48]	Yes/ Yes	1985[49]	Domestic/ Export	NIFKhI cooperates with Leipunski Institute of Physics and Power Engineering (IPPE), which manufactures Mo-99/Tc-99m generators.
	The Research Institute of Nuclear Reactors (NIIAR), Dimitrovgrad, Ulyanovsk Region, Volga Federal District	Fission/ RBT-10-2[50]	Yes/ Yes	2010 [51] (first processing line) 2012 [52] (second processing line)	Domestic/ Export	The new Mo-99 production facility is being built as part of a project of the Presidential Commission for the Modernization and Technological Development of the Russian Economy.[53] The project implementation is scheduled for 2010-2013. [54] As of December 1, 2013, the facility has yet to launch commercial production of Mo-99.

Notes

[1] HEU is uranium which has been altered to increase the share of the fissionable isotope U-235 to levels greater than 20 percent. By contrast, natural uranium has less than 1 percent U-235 while low enriched uranium (LEU) has less than 20 percent U-235. HEU can be used to produce nuclear weapons; LEU cannot. Typically, weapons designers use HEU enriched to as much as 90 percent U-235. HEU is also seen as particularly vulnerable to terrorists.

[2] This section and other portions of this paper draw from Anya Loukianova. What the Doctor Ordered: Eliminating Weapons-Grade Uranium from Medical Isotope Production. Monterey Institute for International Studies. *Nuclear Threat Initiative (NTI)*. 2012, September 5. http://www.nti.org/analysis/articles/what-doctor-ordered-eliminating-weapons-grade-uranium-medical-isotope-production/ (Retrieved on December 5, 2013). ; Miles A. Pomper. The 2012 Nuclear Security Summit and HEU Minimization. US Korea Institute at *SAIS*. 2012, January.

[3] John J. Szymanski and Parrish Staples. Ensuring a Reliable Supply of Medical Radioisotopes. Office of Science and Technology Policy. 2012, March 27. http://www.whitehouse.gov/blog/2012/03/27/ensuring-reliable-supply-medical-radioisotopes (Retrieved on December 5, 2013).

[4] Radioisotopes are unstable forms of elements that emit radiation during their decay process. More than 100 different radioisotopes are used in various sectors of the U.S. economy today. See Jeff Norenberg, Parrish Staples, Robert Atcher, Robert Tribble, Jack Faught, and Lee Riedinger. The Nation's Needs for Isotopes: Present and Future. Department of Energy workshop. 2008, August. P. 29. http://science.energy.gov/~/media/np/pdf/program/docs/workshop_report_final.pdf (Retrieved on December 5, 2013).

[5] The radioisotope is eluted from the Tc-99m generator using procedure-specific kits supplied by manufacturers.

[6] Parrish Staples. Chairman's Summary. Mo-99 Topical Meeting. Chicago. 2013, April. The NRU reactor uses U.S.-origin HEU, European producers usually use U.S. origin HEU, but have used Russian HEU in the past, and South Africa relies on South African HEU when it uses HEU targets.

[7] A Supply and Demand Update of the Molybdenum-99 Market. OECD Nuclear Energy Agency. 2012, August, Appendix 1. P.9. http://www.oecd-nea.org/med-radio/docs/2012-supply-demand.pdf (Retrieved on December 5, 2013).

[8] Nordion can technically convert its facilities to processing LEU targets, but does not plan to do so as it will no longer have the NRU reactor to provide irradiation services and AECL's planned MAPLE reactors were never finished. With the anticipated 2016 closure of the NRU reactor, Nordion has been "actively investigating options around the world for a long-term secure supply of medical isotopes" such as from Russian reactors and processors and from domestic non-reactor (cyclotron) production that does not involve using uranium targets or require Nordion's processing line. However it acknowledged sufficient "uncertainty regarding the Company's ability to source a viable long-term supply of medical isotopes" to form part of the rationale for the company suspending its quarterly dividend and share buyback programs in 2012. See Global Experience, Global Opportunity: Nordion Annual Report 2012. Nordion. P. 4-5. 13, 22. http://www.nordion.com/reports/2012_engannual.pdf (Retrieved on December 5, 2013).; Jill Chitra (Nordion). Mo-99 Supply: LEU Conversion Outlook and Activities. Nuclear Security Side Event Meeting. Buenos Aires. 2010, November 4.

[9] A Supply and Demand Update of the Molybdenum-99 Market. OECD Nuclear Energy Agency. 2012, August, Appendix 1. P.9. http://www.oecd-nea.org/med-radio/docs/2012-supply-demand.pdf (Retrieved on December 5, 2013).

[10] For the purpose of this graph, Mo-99 production is defined as the Mo-99 production process starting from the processing of irradiated targets. The three largest producers in the EU are the Netherlands (25%), Belgium (10%), and France (10%). The MARIA reactor in Poland and LVR-15 reactor in the Czech Republic irradiate targets that are then sent for processing and Mo-99 purification to the Netherlands and Belgium accordingly. Source: The Medical Isotope Crisis. http://www.euronuclear.org/1-information/news/medical-isotope-crisis.htm (Retrieved on November 12, 2013).

[11] For details, see 'Joint Statement of the Co-chairs of the Nuclear Energy and Nuclear Security Working Group of the bilateral Russian-U.S. Presidential Commission'. 2013, June 27.

http://energy.gov/articles/joint-statement-co-chairs-nuclear-energy-and-nuclear-security-working-group-bilateral-us (Retrieved on August 20, 2013).

[12] See: Encouraging Reliable Supplies of Molybdenum-99 Produced without Highly Enriched Uranium. The White House Office of the Press Secretary. 2012, June 7. http://www.whitehouse.gov/the-press-office/2012/06/07/fact-sheet-encouraging-reliable-supplies-molybdenum-99-produced-without- (Retrieved on December 5, 2013); the American Medical Isotopes Production Act passed as part of the Fiscal 2013 National Defense Authorization Act. Public Law 112-239; presentation by Jeff Chamberlin. The Role of International Cooperation Programs in International HEU Minimization. The Second International Symposium on HEU Minimization in Vienna. Austria. 2012, January. As part of stimulating demand, Veterans Health Administration offices have been encouraged and are beginning to purchase HEU-free Tc-99m.

[13] In 2010, South Africa received a commitment of up to $25 million from NNSA to cover the costs of converting to LEU production and winning licensing approval for the LEU-based Mo-99. See *NECSA/NTP*. NECSA Consortium Wins United States Radioisotopes Contract. 2010, October 27. A Belgian Mo-99 processor has also received U.S government assistance for conversion but an eligible Dutch producer has declined it.

[14] Record Levels of Non-HEU-Based Mo-99 Supplied to the United States. National Nuclear Security Administration. 2011, June 2. http://nnsa.energy.gov/mediaroom/pressreleases/nonheumo996211 (Retrieved on December 5, 2013).

[15] See 'CRP on Production of Mo-99 from LEU or Neutron Activation'. *IAEA* Research Reactor Section. International Atomic Energy Agency. http://www.iaea.org/OurWork/ST/NE/NEFW/Technical_Areas/RRS/mo99.html (Retrieved on December 5, 2013).

[16] During the 2010 Nuclear Security Summit in Washington, Participating States agreed to collaborate "[…] to research and develop new technologies that require neither highly enriched uranium fuels for reactor operation nor highly enriched uranium targets for producing medical or other isotopes, and will encourage the use of low enriched uranium and other proliferation-resistant technologies and fuels in various commercial applications such as isotope production;" and "[…] will provide assistance to those States requesting assistance to secure, account for, consolidate, and convert nuclear materials". See 'Working materials. Consultancy on conversion planning for Mo-99 production facilities from HEU to LEU'. International Atomic Energy Agency. Vienna, Austria. 2010, 24-27 August. http://www.iaea.org/OurWork/ST/NE/NEFW/Technical_Areas/RRS/documents/mo99/WORKINGMATERIALSmo99CM.pdf (Retrieved on December 6, 2013).

[17] A Supply and Demand Update of the Molybdenum-99 Market. OECD Nuclear Energy Agency. 2012, August, Appendix 1. P.9. http://www.oecd-nea.org/med-radio/docs/2012-supply-demand.pdf (Retrieved on December 5, 2013). Some of the expected increase in demand does not appear to be materializing. The NEA is expected to producer an updated supply-demand analysis early in 2014.

[18] Presentation by SC Rosatom deputy director-general Vyacheslav Pershukov. Current State of Isotope Production in Russia. 7th International Conference on Isotopes (ICI7). Moscow, Russia. 4-8 September 2011; authors' estimates based on Russian Mo-99 production and global production.

[19] Presentation by SC Rosatom deputy director-general Vyacheslav Pershukov. Current State of Isotope Production in Russia. 7th International Conference on Isotopes (ICI7). Moscow, Russia. 4-8 September 2011; Consolidated Sources. *Vestnik Atomproma*. 2010, № 4. P. 12.

[20] Initially, the plan was to build two processing lines with an output of 900 and 1,800 six-day curies (2,700 Ci in total). The plans were later revised to 400 and 800 Ci (1,200 Ci in total for the two lines). There were three reasons for that: 1) Technological difficulties; the technology acquired for this project had not been previously used for industrial-scale Mo-99 production, and trial runs had shown that the technology could not sustain the originally expected output; 2) A fall in the global demand for Mo-99; 3) A lack of confirmed contracts for the Mo-99 isotope, which cannot be stockpiled for later deliveries due to its short half-life. See: NIIAR launches Mo-99 Production. 2010, December 19. http://www.niiar.ru/?q=arh_news/2010 (Retrieved on December 7, 2013); Moving Forward Step by Step. *Izvestiya*. 2012, January 18. http://www.proatom.ru/modules.php?name=News&file=article&sid=4071 (Retrieved on December 7, 2013.); Ovchinnikov Daniil. Targeting the Target. *Vpered* (OAO NZKKh corporate newspaper) 2013, No 5. P. 2. http://www.nccp.ru/upload/iblock/9f4/9f4dd8f423974b8f1b71b027c8bf54e9.pdf (Retrieved on December 7, 2013); Hot Testing of the Second Mo-99 Production Stage Commences at NIIAR.

Nuclear.Ru. December 21, 2012. http://www.rosatom.ru/journalist/atomicsphere/f18742804de380dea2acbfdcac52bcd5 (Retrieved on December 5, 2013).

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