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A. Travelli, L.L. Gaines, V. Minkov, A.P. Olson, and J. Snelgrove

Arms Control and Nonproliferation Program
Argonne National Laboratory
Argonne, Illinois, 60439, USA

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CONSTRAINING POTENTIAL NUCLEAR-WEAPONS PROLIFERATION FROM CIVILIAN REACTORS¹

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Arms Control and Nonproliferation Program
Argonne National Laboratory
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ABSTRACT

Cessation of the Cold War and renewed international attention to the proliferation of weapons of mass destruction are leading to national policies aimed at restraining nuclear-weapons proliferation that could occur through the nuclear-fuel cycle. Argonne, which has unique experience, technology, and capabilities, is one of the US national laboratories contributing to this nonproliferation effort.

INTRODUCTION

The prevention and control of proliferation of weapons of mass destruction is a goal stated by the Congress and the Administration of the United States and reaffirmed in pending legislation. One publicized concern has been that "...the clandestine production of enough fissile material to make tens or even hundreds of warheads could probably be hidden in the background 'noise' of activities associated with civilian nuclear power."²

So far, nations that have developed nuclear weapons have all devised dedicated -- sometimes clandestine -- programs to produce only high quality fissile materials (highly enriched uranium [HEU] or weapons-grade plutonium). Nevertheless, because civilian reactors could at least in theory form a pathway to fission weapons, prudent preventative actions are an integral part of national and international nonproliferation policies. What are some of the possible elements of such policies?

First, one must safeguard the mounting accumulations of reactor-grade plutonium at facilities for spent fuel storage, processing, and waste disposal. Second, wherever possible, fuels in existing reactors (research, test, naval and power reactors such as breeders) need to be kept sufficiently dilute to be unattractive for use in weapons.

Third, the broad umbrella of domestic and international safeguards could be applied to the entire civilian nuclear fuel cycle in both nuclear- and nonnuclear-weapons states. Materials accountancy and control for all transactions, transfers, and storage of sensitive materials would be involved.

Fourth, trade of all equipment, processes, and expertise usable to produce high-grade fissile materials illicitly could be subject to a strengthened international control regime. Nuclear materials and

¹Work supported by the U.S. Department of Energy, Office of Arms Control and Nonproliferation, under Contract W31-109-ENG-38.

²Frank von Hippel, "Nuclear weapon elimination: fissile material and warheads", Chapter 7 in Security Without Nuclear Weapons? Different Perspectives on Non-Nuclear Security, R.C. Karp (Ed.) Oxford University Press (1992).

related facilities and software are presently controlled by member states via COCOM, the London Group, and the Nuclear Suppliers Group.

In each of the foregoing areas of restraint, contemporary factors need to be considered. Chief among them is the end of the Cold War, which brought about the need to demilitarize huge quantities of weapons-grade fissile material and to deal with nuclear reactors formerly under COMECON standards for materials control and accountancy. Reactors and associated fuel-cycle facilities in the FSU pose special problems for materials control, accountancy, security, and safety. The US Department of Energy (DOE) has agreed to purchase Former Soviet Union (FSU) uranium in massive quantities.

Finally, the imminence of the 1995 Extension Conference on the Nuclear Non-Proliferation Treaty (NPT) impels consideration of reciprocal, possibly burdensome measures on nuclear-weapons states, including the United States.

ARGONNE'S ROLE

DOE has a pivotal role in the United States' compliance with the NPT and in preventing proliferation; Argonne National Laboratory (ANL) is one of several national laboratories with unique experience and technical capabilities, authorized to pursue a variety of important programs that support the constraint of proliferation from the nuclear fuel cycle.

ANL has a long history of major contributions to nuclear reactor technologies (CP-1, CP-5, EBWR, EBR-I, EBR-II [now the IFR], TREAT, ZPPR, ...). In addition, Argonne has comprehensive expertise in enrichment, fuel fabrication, and fuel reprocessing. This experience in the reactor fuel cycle, as well as related experience with proton-spallation neutron sources such as the IPNS, has been applied to the new problems posed by the demise of the Soviet Union, and to the attempts by various countries to acquire the technologies necessary for special nuclear material production.

For example, ANL has led the Reduced Enrichment Research and Test Reactor (RERTR) Program for about 16 years, in order to reduce proliferation risks by reducing or eliminating the need for highly-enriched uranium ($\geq 20\%$ ^{235}U) in over one hundred research reactors worldwide. The program mission was just recently extended to include reactors in the FSU; ANL is tasked to carry out this work.

ANL also performs many specific arms control and nonproliferation projects. For instance, assistance is provided in developing and implementing international and US export control policies and regulations, domestic and international safeguards, and arms control technologies applied to nonproliferation. The following sections highlight some of ANL's contributions.

RERTR PROGRAM

When research reactors were first exported from the US under the Atoms for Peace program in the 1950s, only fuel containing low-enrichment uranium (LEU, $<20\%$ -enriched) was allowed. By the late 1960s, however, HEU became widely available, and many reactors began to use it without real need. Because of concern about the possible diversion of HEU by nations, subnational groups, or terrorists, the US RERTR Program was started in 1977-78. At that time, HEU was used by more than half of the world's research reactors, requiring annual exports of approximately 600 kg from the US. Because some reactors have been closed or are operating on reduced schedules, current annual exports would have been nearly 500 kg without the program.

The objective of the RERTR Program is to provide the technical means to reduce the enrichment of a reactor's fuel without compromising safety and without a noticeable penalty in performance or economics. Significant progress has been made by:

1. Developing high-density fuels that will accommodate the extra ^{238}U needed to reduce the enrichment. Fuels containing up to 4.8 Mg U/m^3 , suitable to convert 90% of the existing research and test reactors, have been developed, demonstrated, and qualified.
2. Assisting in developing qualified fuel suppliers throughout the world. Six fuel fabricators are currently marketing LEU fuels, and another five are developing the capability.
3. Encouraging suppliers of research and test reactors to design and market only LEU-fueled reactors. All research reactors built or committed in Western countries since 1980 have been designed for LEU cores.
4. Encouraging and providing technical support to convert existing reactors to LEU fuel use. Of the 42 foreign research reactors using HEU with power of at least 1 MW, eleven reactors in 11 countries have completed their conversion to LEU, removing the need for exporting approximately 160 kg of HEU each year. Seven more reactors have either begun conversion or have ordered LEU fuel elements for conversion, removing the need for exporting another 70 kg of HEU each year. Therefore, an approximately 50% reduction in the need for HEU exports has been achieved to date. Five additional reactors are irradiating or have irradiated prototypes, and 13 either are planning to convert or are believed to be technically capable of converting.

Conversion of three reactors in Europe, with annual HEU requirements of 100 kg, is not currently feasible because they need higher-density fuels than are available. The RERTR Program is not actively developing the very-high-density fuels needed for these remaining reactors; however, the US Congress is considering funding for such work. Work on very-high-density fuels would include refinement of fabrication techniques to achieve higher fuel volume fractions in a dispersion fuel meat, use of high-density fuel compounds, and possible use of matrix materials other than aluminum.

During the past several years the RERTR Program has concentrated on providing technical assistance for conversions using the already-qualified fuels. The program is currently receiving increased emphasis and funding. A major new initiative is collaboration with the FSU to complete the reduced-enrichment program they began in 1978. Their program was very similar to the US program. When work was stopped in 1989 due to lack of funding, the Soviet program had developed, tested, and qualified a medium-density (2.5 Mg U/m^3) fuel. This fuel is currently being exported with 36% enrichment. A higher-density fuel (5.0 Mg U/m^3) was in the early stages of testing. Under a cooperation agreement recently signed by ANL and the Reactor Development Institute for Power Engineering (RDIPE) in Moscow, a higher-density fuel will be qualified and used in whole-core demonstrations. Upon completion of this five-year project, the Russian Federation will be capable of supplying LEU fuels to its research reactor customers as new fuel is needed in existing reactors and as new reactors are built in Russia or abroad. We are seeking to establish similar cooperation with the People's Republic of China.

Another thrust of the RERTR Program is the development of the technology to produce fission-product ^{99}Mo using LEU targets. This material is used in generators for ^{99}Tc , a widely-used radioisotope for medical diagnostics. We plan to develop, test, and qualify irradiation targets and

demonstrate a suitable chemical separation technology. This work was begun earlier, but was inactive for several years due to lack of funding.

INTEGRAL FAST REACTOR

ANL's principal reactor development project, the Integral Fast Reactor (IFR) has a major nonproliferation component. The IFR is a metal-fueled, sodium-cooled reactor with an integral fuel cycle, that is, the fuel is reprocessed, removing only the major fission products, and refabricated on site. The IFR fuel cycle has strong proliferation-resistant characteristics: the fuel never leaves the site; the IFR process does not produce a pure plutonium product stream; and the product is highly radioactive and would still need conventional aqueous reprocessing for anything but IFR usage. The IFR has been designed to meet the IAEA criteria for "the timely detection of diversion of significant quantities of nuclear material" through the use of near-real-time monitoring for the entire process stream. The IFR has the additional advantage of being able to effectively and efficiently burn weapons stockpile plutonium.

Strange as it may seem, the IFR, with its closed-cycle pyrometallurgical fuel processing, could help phase out worldwide dependence on the proliferation-prone PUREX process. Pyrometallurgical processing always keeps the metallic fuel in a highly-radioactive state and the plutonium diluted with weapons-spoiling actinides. If the reactor is operated without a breeding blanket, it can be used to consume the world surplus of reactor- and weapons-grade plutonium.

ISOTOPE CORRELATION TECHNIQUE

Any activity involving nuclear material irradiation transmutes and/or creates actinides and fission products. The irradiated material carries with it (in its isotopic composition) an integral of its neutron irradiation history. Mathematically, it is not a well-posed problem to discover the initial state of the material or the conditions under which the irradiation took place. But practically speaking, it may be possible to deduce them with high precision, given the ability to model the expected conditions accurately.

The Isotope Correlation Technique (ICT) is simply a numerical analysis of relative isotope concentrations, with indicators chosen to best discriminate between likely scenarios of irradiation. The indicators may be numerical ratios such as Pu/U, or $^{235}\text{U}/^{238}\text{U}$. Given reliable nuclear fuel-cycle analysis models, it is possible to calculate normal and abnormal (i.e., diversion) fuel-cycle scenarios and to discover the tell-tale markers (signatures) associated with a given reactor type and a given fuel cycle.

ANL has the nuclear analysis tools to generate realistic fuel cycle models. The ICT has recently been investigated for a variety of fuel cycles; in FY93, work concentrated on the Soviet RBMK-type graphite-moderated, water-cooled reactors and their fuel cycle. Three-dimensional models were created of a supercell of 25 fuel channels, occupied by normal (2.0% enriched in ^{235}U) and target (natural uranium) fuel elements. The purpose is to discover the sensitivity limits of the ICT, knowing that even in normal operation, isotopics vary with control rod presence and the extent of coolant channel voiding. We expect to characterize the normal variability range of spent fuel, and to identify the signatures for spent fuel irradiated in company with special diversion (target) elements for weapons-grade plutonium production.

As an example of fuel isotopics in RBMK-type reactors, we compared a normal fuel cycle to a special fuel cycle in which target elements are made of natural uranium and are discharged after only

120 days irradiation versus 1080 days for 2.0% enriched standard elements. The special fuel cycle consists of two cases: (a) one in which just 1 out of 25 elements is a target element; (b) one in which 4 out of 25 are target elements.

We assume that the target elements are not available for monitoring; however, their presence creates noticeable effects upon the isotopes of the normal discharge fuel, which we assume is available. The effect obvious in Table I is that the presence of natural uranium targets increases the burnup of the nearby normal fuel, because the target elements have less fissionable material than even a fully-burned normal element. It is also clear (see Table II) that the higher isotopes of plutonium accumulate at different rates, and in different proportions. In particular, the isotope ratio: $^{239}\text{Pu}/^{241}\text{Pu}$ is reduced by 7% in scenario (b). This change should be detectable, indicating that an RBMK reactor operated with 16% or more of its elements replaced by target elements should be identifiable as a diversion cycle. We expect to show more explicitly the connection between diversion scenario, isotopic changes, and measurement sensitivity as this work progresses.

TABLE I. RBMK FUEL CYCLE ISOTOPICS FOR 2 DIVERSION SCENARIOS
(Masses in kg per fuel element)

ISOTOPE	BASE CASE	1 OF 25 (a)	4 OF 25 (b)
^{235}U	1.1462	1.1364	1.0825
^{236}U	0.2582	0.2594	0.2675
^{238}U	126.85	126.86	126.78
^{239}Pu	0.4318	0.4274	0.4364
^{240}Pu	0.1522	0.1526	0.1634
^{241}Pu	0.0450	0.0444	0.0485
^{242}Pu	0.0106	0.0104	0.0123
^{241}Am	0.0014	0.0014	0.0017
^{237}Np	0.0092	0.0092	0.0102

TABLE II. RBMK FUEL CYCLE MASS RATIOS FOR 2 DIVERSION SCENARIOS

MASS RATIO	BASE CASE	1 OF 25 (a)	4 OF 25 (b)
$^{240}\text{Pu}/^{241}\text{Pu}$	3.38	3.44	3.37
$^{239}\text{Pu}/^{240}\text{Pu}$	2.84	2.80	2.67
$^{239}\text{Pu}/^{241}\text{Pu}$	9.60	9.63	9.00

FSU-RELATED STUDIES

ANL has assessed the general situation in the FSU as it affects the development and implementation of nonproliferation measures. Some of the studies are briefly described below.

Related Management Systems: This study compared elements in FSU and US management systems that may influence the development and implementation of nonproliferation measures, including those directly and indirectly related to manufacturing nuclear materials and systems. Examples are transportation and guarding entities with their own rules and practices, safeguarding enterprises with

their own quality standards for nonproliferation monitoring equipment, and trade organizations with their own rules on international equipment sales.

Cultural, Business and Engineering Traditions: This study identified different US-FSU traditions and practices, for example in designing equipment of possible proliferation interest. Among the most pertinent are different perceptions of the need to follow the law strictly (this may necessitate non-traditional accounting and controlling mechanisms) and different perceptions of the value of human life (this may create different acceptance of the risk involved in proliferation activities).

Assessment of the Management of Russian/Ukrainian Nuclear Reactor and Mine Safety: This study found that much greater risk is accepted in the FSU in dealing with dangerous situations. A level of risk which may lead Western experts to conclude that certain proliferation actions are impossible may be accepted by certain elements of the FSU population. Similarly, what may be considered a possible event in the FSU may in reality be impossible in the US.

Construction Management System for Storage Facilities: This study compared construction and operation of facilities where materials and equipment of proliferation interest may be stored and safeguarded; specifics may affect the control and accountancy measures. A similar study was completed for railroad transportation.

Economic Incentives on Arms Control Matters: This study investigated possible economic incentives that could be presented to individuals or groups in charge of performing accounting and controlling nonproliferation procedures.

CONCLUSIONS

Much of the burden of confirming nonproliferation within the civilian nuclear-fuel cycle -- and even of restraining proliferation -- devolves upon the IAEA inspection process. US DOE laboratories continue to provide better tools for measuring, monitoring, detecting, analyzing, and predicting nuclear fuel-cycle data. At ANL, we have been concerned about what to measure, where, and with what devices; we also have been concerned with simulation and modeling. Through improvements to the tools, together with enhanced training in their use, we hope to significantly increase the effectiveness of the IAEA. Through the RERTR Program, we have already considerably reduced the proliferation risks associated with HEU in western countries by curtailing the need for its use in research reactors. The extension of RERTR to the FSU will further reduce the availability of HEU.

As we move toward the 21st Century, we must mitigate proliferation risks from existing stockpiles of plutonium and from plutonium accumulating in irradiated power-reactor fuel. One possibility is a dedicated burner reactor to produce electricity while consuming plutonium in a closed fuel cycle. This reduces proliferation risks while the plutonium is in fuel form and gradually reduces the stockpiles already in existence. ANL has investigated with General Electric Co. the characteristics of a fast spectrum liquid-metal-cooled reactor with enhanced safety performance, based on the IFR technology. Technically, there is much merit in this concept, as it also features the ability to transmute long-lived isotopes into shorter-lived fission products. The economics, technological options, and politics of plutonium burners versus long-term storage of high-level waste are subjects of intense concern in countries with large installed nuclear capacity.

Argonne's future work will materially assist the DOE in formulating US policy for the nuclear fuel cycle in the 21st Century.

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