# HOW CAN THE AVAILABILITY OF SAFE AND SECURE RESEARCH REACTORS BE ASSURED IN FUTURE?

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## ABSTRACT

*As the world's non-power reactors age, questions of decommissioning, life extension, safety and security are increasingly problematic. The 245 disparate research reactors operating around the world today are used for a wide range of purposes, from materials analysis and testing and radioisotope production to environmental science, nuclear medicine, and fusion research, among others. Their heterogeneity extends to reactor and fuel types, power levels, and other physical characteristics, as well as utilization, safety measures, and security practices. Given the increasing reliance of users on reactors located outside of their own countries, as well as the importance to the global community of maintaining installations online to provide for the needs of future scientists, medical patients, industry, and other users around the world, planning for the future of the global reactor park should be a coordinated, not an ad-hoc, effort.*

*The safety and security of these facilities today is uneven as well. Although nuclear safety culture has improved significantly over the past two decades, aging reactors are an increasing challenge for government agencies, particularly nuclear regulators. The issue of nuclear security culture has only recently begun to come into focus, and is still not sufficiently widely understood. Methods to train reactor personnel in security culture are yet to be institutionalized. In this regard, the International Atomic Energy Agency's (IAEA) forthcoming nuclear security guidelines are an important basis upon which to build. However, detailed international agreements that spell out minimum security requirements, as well as better coordination between safety and security requirements (which are sometimes contradictory), are still needed, as is national legislation to implement the IAEA security guidelines and other measures that may be recommended. Today, great variation in security procedures and requirements is found even in locations with comparable threat assessments. This evidence supports the contention that there is a real need to focus international attention on maintaining at least minimum standards in both established and new facilities. Although there are bilateral and multilateral programs working to help research reactor operators—to facilitate coordination, improve security training, and remove vulnerable materials such as HEU fuel, for example—to date these efforts are not well coordinated, and can even work at cross-purposes (particularly where security and safety measures are concerned).*

*In order to assess research reactor needs on a global basis, this paper begins with a systematic overview of non-power reactors. It then focuses on several uses that are of particular relevance when considering future needs: production of Molybdenum-99 (Mo-99) and uses related to future nuclear power plant design and operation. The author uses the case of Mo-99 production to examine how the ongoing production crisis came about and why neither market mechanisms nor individual governments were able to prevent it. The possible solutions to this crisis, as well as their potential pitfalls, are analyzed. The second area assessed in the paper is the use of research reactors for the development of future power reactors. This topic is of special interest as many governments have argued that they are maintaining installations or unutilized nuclear materials because they believe these will have value in future. In order to examine this assumption, the author reviews the future reactor types that have been proposed for* *development in the next 2-3 decades, and assesses the likely testing needs in terms of research reactor type and fuel. This review makes it clear, for example, that HEU fuels are not being planned for any future power reactor design and HEU material of no more than 35% enrichment may only be needed at 1-2 facilities for the testing of future power reactor fuel. These "mothballed" facilities and materials are of particular concern, since the lack of current value to operators or governments means they are often not adequately secured. This review of current capacities and future needs suggests that installation decommissioning and nuclear materials removal is the most responsible course of action in such cases, whereas there is an insufficient number of reactors for the education and training of new power reactor operators in some areas of the globe.*

*The final section of this paper evaluates the current mechanisms for coordination and cooperation between reactor owners and operators, national authorities, multinational users, and the IAEA in three areas: ensuring the provision of and access to key reactor services, providing for the security of reactor facilities and fissile materials, and preventing proliferation of weapons-usable materials. The overview of today's reactor utilization, current and key future reactor services, and remaining safety and security risks are used to derive conclusions regarding the need for better coordination worldwide. The paper concludes with some possible solutions, including providing the IAEA with additional authority to promote stricter security measures and the minimization of HEU use. Additionally, the author argues that governments must play a new role in ensuring that key reactor services, such as medical isotope production, are provided, including oversight of corporate plans to cooperate during times of unplanned reactor shutdowns. Non-power reactors provide key services to the global community, which must be safeguarded by government and nuclear officials to ensure continued operation in a safe and secure manner.*

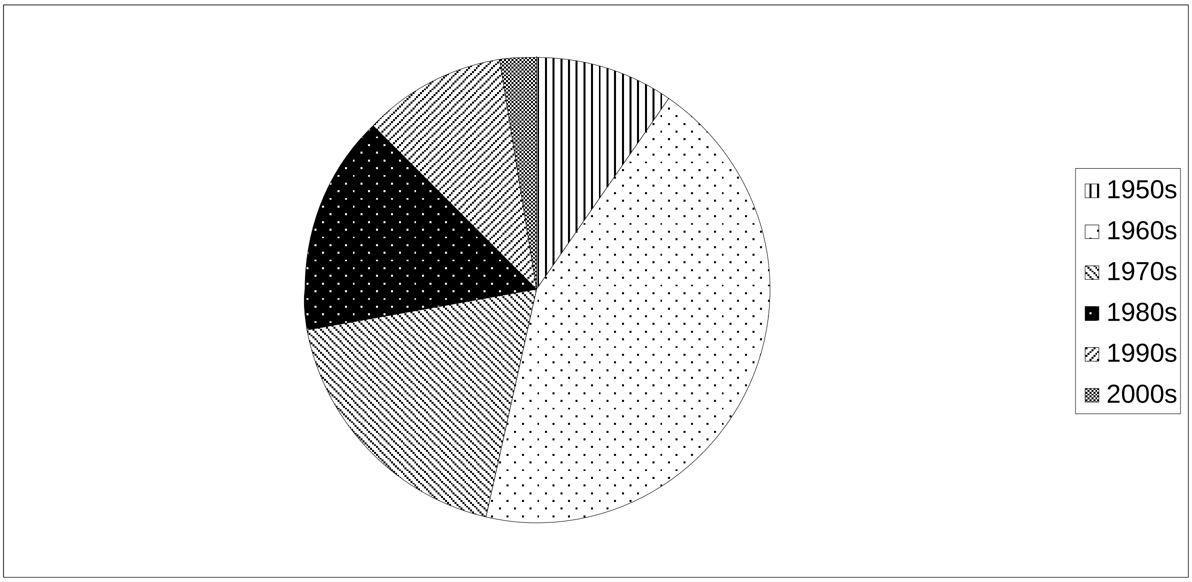
**Keywords**: Nuclear security, nuclear safety, safeguards, nonproliferation, research reactor, terrorism, Material Testing Reactor, isotope production, nuclear power

## 1. INTRODUCTION

There are currently 245 research reactors listed in the IAEA research reactor database (RRDB) as operational, with uses varying from education and training to solid state physics research, radioisotope production, and biological experiments, to name but a few of the great variety of roles research reactors play at present. The variety of reactor types, levels of neutron flux, and core size is also quite extensive. It is far from self-evident that these reactors meet the needs of reactor users today; in future, the availability of appropriate facilities is an even greater question.

Many of today's operational reactors are quite old (see Figure 1), whereas few reactors are currently under construction. While a large portion of shut down reactors to date were employed for military uses, some facilities shut in the 1950s and 1960s appear never to have been needed (a few even shutting within a few years of start-up), and construction in the 1960s in particular may well have been excessive, it is nevertheless remarkable that about 63% of the reactors constructed to date have already been shut down. Meanwhile, construction costs are higher than ever and likely to climb further. For example, when adjusted for inflation costs of constructing a TRIGA Mark I in 1960 were still less than half the cost of constructing a TRIGA Mark II today.[1] Even greater cost increases appear at the high-end research reactors (though it is not clear what costs the IAEA research reactor database captures, and the degree to which reactor costs given in the database are comparable): construction of the high-flux reactor MURR was nearly 20 times cheaper, when adjusted for inflation, than the FRM II or Australia's OPAL, while Oak Ridge's HFIR cost about four times less.[2]

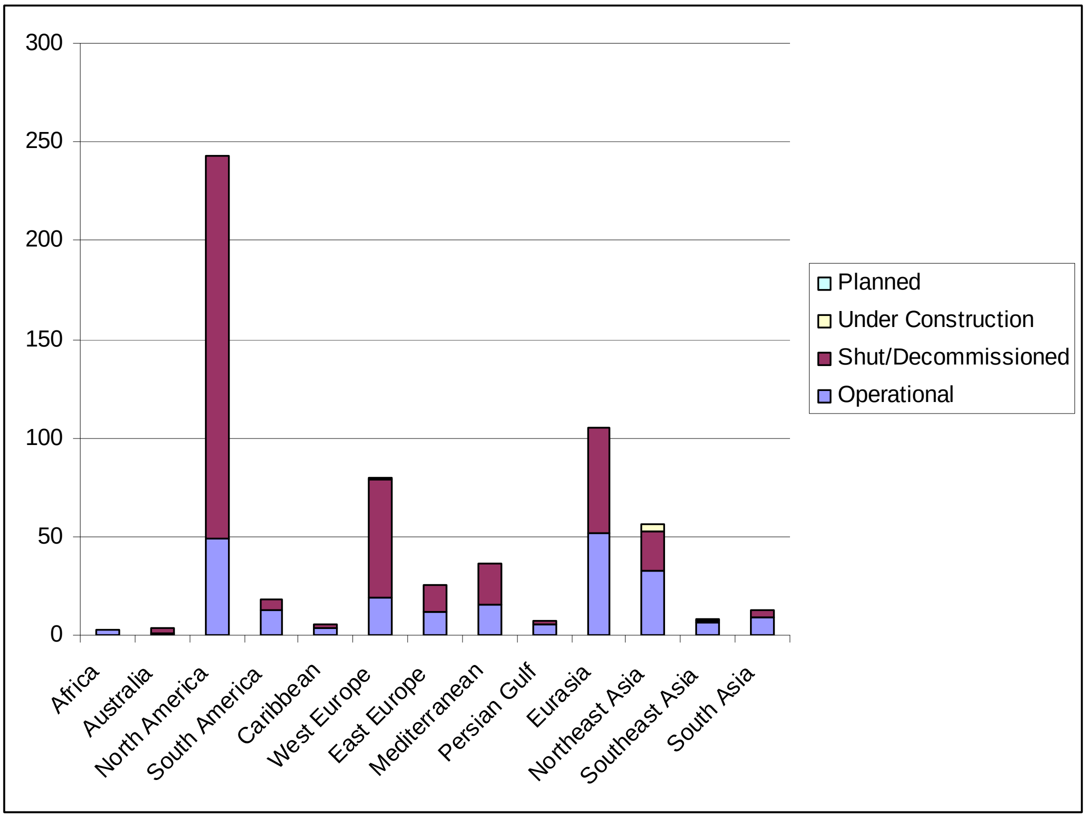
**Figure 1. Age of Operational Research Reactors, by Criticality Date[3]**




As noted by Tohoku University researcher Tatsuo Shikama, "Materials irradiation studies utilizing fission reactors are becoming more and more expensive and time consuming. Collaboration among organizations participating fission-reactor materials irradiation will be inevitable."[4] This is particularly true for researchers in locations lacking appropriate reactors—a problem exacerbated by the uneven geographic distribution of reactors (see Figure 2). Given the importance of access to nuclear reactors for uses from basic scientific and applied research to isotope production, education and training, etc., planning for the future of the global reactor park should be a coordinated, not an ad-hoc effort. The production of the isotope Mo-99 is particularly illustrative of the problem of relying on national facilities as well as market mechanisms to ensure the sufficiency of reactor availability. Further, this paper argues that safety, security, and nonproliferation concerns could best be met through a multilateralization of reactor facilities.

The final section of this paper notes some of the mechanisms that have been used to facilitate cooperative use of research reactors. Coordinated planning, though, appears to be hampered by a lack of information. Not all research reactor operators duly report data to the voluntary IAEA research reactor database (some entries have not been updated in decades, while others are incomplete), while not all of the necessary information is collected by the database. For example, more details on the specifics of reactor utilization, including the distribution of reactor uses and demand for reactor time, would help to determine where there is underused capacity or where facilities have difficulties meeting user needs.

**Figure 2. Number of Research Reactors Worldwide**[5]




## 2. MO-99 PRODUCTION

Current global supplies of metastable technetium-99 (Tc-99m), the daughter product of molybdenum-99 (Mo-99), are in crisis. The four major Tc-99m producers employ just five reactors worldwide, and several of them have faced unplanned shutdowns or outages in the past couple of years. This section briefly reviews the importance of this isotope, examines the development of the current production system, and suggests reasons for why market mechanisms and individual governments have been unable to ensure availability. Some possible solutions to today's crisis, as well as potential pitfalls, are then analyzed.

### 2.1 The Importance of Tc-99m

Tc-99m is a critical product—the most important isotope used in nuclear medicine today, used in approximately 80% of all nuclear medicine procedures worldwide. While there are alternative diagnostics and treatment for some conditions, for others, Tc-99m is by far the best choice. It is particularly important for oncologists and heart specialists, for example. Radiation oncologists employ Tc-99m to determine the presence and severity of cancers, especially in the bones, and have few good alternative diagnostic tools. For cardiac stress testing, for example, there are no good alternatives. Without Tc-99m, doctors could turn to Thallium-201, but it provides lower resolution images (meaning missed cancer cases) and results in higher radiation doses to patients.

Another alternative, stress echocardiography, is a less sensitive test that has a higher rate of false negative results and is not useful for patients with previous heart attacks. Stress testing with PET scanning or MRI is possible, but availability of these devices is limited and few physicians have the relevant expertise.[6] The final alternative option is the invasive angiogram (cardiac catheterization), which is invasive, expensive, and risky (~1 in 1000 patients die from the procedure).[7]

**2.2 Mo-99 Supply Today**

Today, over 90% of the Mo-99 used to produce Tc-99m generators is supplied by just four producers, relying on five research reactors: the NRU reactor in Canada, HFR, BR2, and Osiris reactors in Europe, and the SAFARI reactor in South Africa. As can be seen in Table 1, these reactors are aging and have suffered several unplanned shutdowns over the past 18 months. HEU targets are irradiated in these reactors, and the Mo-99 is extracted first by dissolving either the entire plate or pin or by dissolving the UO2 and then performing a series of extraction and purification steps. The targets used today are not standardized, and both acid and basic dissolutions are used, with each producer using its own special process.[8]

Additionally, Australia's OPAL reactor has begun Mo-99 production and plans to become a major producer.[9] Mo-99 is produced on a smaller scale via fission in Argentina (in the RA-3 reactor), Indonesia (Siwabessy), and Russia (processed by the Karpov Institute of Physical Chemistry, Obninsk, with targets irradiated in the VVR-Ts reactor in Obninsk as well as the RT-T reactor in Tomsk), with additional states such as Iran planning fission production in future. Mo-99 is also produced using neutron activation (gel generators) to meet local needs in India, China, Iran, and Kazakhstan; Brazil and Egypt too may start up production of gel generators.[10]

**2.3 The Historic Origins of the Tc-99m Supply Crisis**

The medical uses of Tc-99m have been under development since the 1960s, when its use was pioneered at the University of Chicago.[11] The isotope's short half life (just over six hours) makes it an ideal tracer in the human body—long enough for examinations yet short enough to avoid radiation damage to bodily organs; yet the short half life of its parent isotope, Mo-99 (66 hours) means that the useful lifespan of a Tc-99m generator is just one week, making a constant and reliable supply critical for nuclear medicine. Due the demand for Tc-99m, production was transferred from the U.S. national laboratories to commercial enterprises in the mid-1960s. Soon, four North American reactors were employed: two in the U.S. and two in Chalk River, Canada. However, three of the reactors have since been decommissioned (the General Electric Test Reactor in Pleasanton, California in 1977, the Cintichem Test Reactor in Tuxedo, New York in 1990, and the NRX Reactor in Chalk River, Canada in 1992), leaving only the NRU reactor at Chalk River still producing Mo-99. Although the U.S. Congress was concerned about relying on a single facility, establishing the Isotope Production and Distribution Program to run all DOE isotope production activities in 1990, and ensure "a stable supply of Mo-99 to the U.S. medical community," the U.S. Congress wanted supplies to be provided on a commercial basis. Yet isotope irradiation has never been a lucrative business—today, production of the Tc-99m generators appears to generate far more income that irradiation services—and the efforts in the 1990s to develop a Mo-99 production reactor in the U.S. came to naught.[12]

**Table 1. Major Mo-99 production reactors**

| Reactor | NRU[13] | BR-2[14] | HFR[15] | SAFARI[16] | OSIRIS[17] |
|---|---|---|---|---|---|
| **Location** | Chalk River, Canada | Mol, Belgium | Petten, Netherlands | Pelindaba, South Africa | Saclay, France |
| **Owner** | Atomic Energy of Canada, Ltd (AECL) | Centre d'Etude de l'Energie Nucleaire (S.C.K./C.E.N.) | European Commission (EU) | South African Nuclear Energy Corporation (NECSA) | CEA/CEN-Saclay |
| **Operator** | Chalk River Laboratories | S.C.K./C.E.N. | Nuclear Research and consultancy Group (NRG) | NECSA | DEN/DRSN, Service d'Exploitation du Réacteur OSIRIS |
| **Criticality Date** | 1957/11/03 | 1961/06/29 | 1961/11/09 | 1965/03/18 | 1966/09/08 |
| **Thermal Power, Steady** | 135 MW | 100 MW | 45 MW | 20 MW | 70 MW |
| **Maximum Thermal Flux (n/cm2-s)** | 4.0E14 | 1.0E15 | 2.7E14 | 2.4E14 | 2.7E14 |
| **Utilization** | **Hours/Day** 24 **Days/Week** 7 **Weeks/Year** 39 **MW Days/Yr** 32300 | **Hours/Day** 24 **Days/Week** 7 **Weeks/Year** 15 **MW Days/Yr** 6500 | **Hours/Day** 24 **Days/Week** 7 **Weeks/Year** 44 **MW Days/Yr** 12640 | **Hours/Day** 24 **Days/Week** 7 **Weeks/Year** 44 **MW Days/Yr** 6060 | **Hours/Day** 24 **Days/Week** 7 **Weeks/Year** 36 **MW Days/Yr** 15000 |
| **Isotope production** | Mo-99, I-125, Co-60, C-14 | Mo-99, Ir-192 | 99Mo-99, Ir-192, Sr-89, others. | Mo-99, I-131, etc. | Mo-99, I-131 |
| **Recent develop-ments** | Shut down November – December 2007; May 2009-present | In August-November 2008, associated isotope production facilities in Fleurus shut after 40 GBq of I-131 gas unexpectedly released to environment. (NAS, p. 59) | Shut down August 2008 – February 2009; will be shut for extensive renovations beginning March 2010 | Has increased Mo-99 production to maximum & shortening planned maintenance shutdown August 30-September 4, 2009.[18] | Increased production. Note that as targets different from those at Petten, Covidien had to alter processing and receive regulatory permission to employ Osiris. |

Given the short half life of the generators, distribution networks set up by pharmaceutical companies are critical. These often involve long-term contracts—which though good for consumer and supplier when production difficulties do not arise, make new entry into this market exceedingly difficult. The only potential market for new reactor services comes either from pharmaceutical companies wishing to ensure back-up supply, or during times of crisis, when supplies are not available.

It is the short half-life of Mo-99 that has led to large-scale distribution systems, since timelines and reliability of supply are so very critical in the use of this product. Yet the scale needed has made it difficult for new competitors, and resulted in the current supply system of just four major processors, who have agreements on mutual back-up yet jealously guard their markets (and have lost market share to each other in past crises), relying on five aged reactors. The processing and distribution companies recognize that additional reactors are necessary, yet they have not attempted to engage other reactors in production. By contrast, some have reportedly acted in an oligopolistic fashion to prevent new market entry.[19]

### 2.4 The MAPLE Reactor Project

The world's largest producer, Nordion of Canada, did work to ensure its continued viability through the construction of new reactors, but has faced a raft of difficulties in this regard and has recently acted in ways that are less than constructive. In 1996, AECL committed to the construction of two dedicated isotope-production reactors—the Multipurpose Applied Physics Lattice Experiment reactors, or MAPLE-1 and MAPLE-2, on the basis of new designs. However, after construction was completed in 2000 tests determined that the reactors, which were supposed to have a negative coefficient of reactivity, exhibited positive reactivity instead. Much effort—by U.S. national laboratories and others, alongside AECL—went into studying the problem, and Argentina's INVAP finally was able to understand how to model the reactor.[20] However, even this success would not be enough safely to operate the reactor: its safety case was designed to handle a negative coefficient, and would therefore have to have been completely altered. Alternatively, a new core would need to be built in the MAPLE—a solution mooted in a U.S. National Academies of Sciences study,[21] and supported by an Argentinean expert familiar with the reactor who noted core replacement would be better than altering the safety systems, given cost and difficulty (to say nothing of the current lack of trust between the regulator and the operator in this particular case). Unfortunately, while the question of the MAPLEs—each of which were supposed to have the capacity to meet the worldwide demand for Tc-99m at the time—drags on, investment in any alternative production reactor would be inordinately risky. Sadly, even the May 2008 AECL decision to discontinue the MAPLE project has not led to clarity for would-be investors: as of August 2009, MDS Nordion was suing to restart the project, and had filed a $1.6 billion Canadian claim against AECL and the government of Canada, arguing that the reactors could safely be started (without explaining how to ensure their safety).[22]

### 2.5 The Terrorism Risk Posed by Highly Enriched Uranium

For a quarter century, governments have joined together to convert reactors from the use of highly enriched uranium (HEU) fuels to low-enriched fuels, out of the concern that the HEU, considered a direct-use material by the IAEA, could be used for nuclear weapons. Concern about the HEU targets used by Mo-99 producers has also been of concern, but little progress has been made towards conversion of major production facilities, despite the fact that targets and target waste pose substantially greater risks than irradiated fuel. As Vandegrift et al have noted, irradiated target waste can be contact-handled (and converted into uranium metal) without shielding after a cooling period of just three years, exposing the perpetrator to doses hazardous to long-term health but not sufficient to disable the person handling the material.[23] While two decades ago quantities of Mo-99 target waste were dwarfed by research reactor fuel amounts, this calculus is slowly shifting as fuel is removed and target waste accumulates. The fissile solution storage tank at Chalk River, for example, is likely to contain well in excess of 100 kg of HEU today.[24] Moreover, the failure to develop a disposition pathway for this material sets a negative precedent, effecting other efforts to remove HEU—both fuel and other materials—at other sites around the globe. As long as any site continues to house HEU materials, it erodes the norm against use and storage of these materials in the civil sphere.

### 2.6 Solutions for the Future

There are a variety of options available to develop new, more secure Mo-99 production capabilities. However, ensuring more than enough supply capacity and the ability to deliver Mo-99 where needed in a timely fashion may not be possible without government support and/or some alteration to the current production and distribution system. To ensure that Tc-99m generators be delivered to hospitals on time, as needed, by a system with sufficient excess capacity to weather any future reactor outage that does not employ risky materials such as HEU, is both necessary and possible. Nevertheless, it will take vision, funding, and some time to achieve.

#### 2.6.1 Existing Reactors That Could Be Used for Mo-99 Production

There are several reactors that could easily prove more reliable Mo-99 producers than the current five currently in use by major producers. One of these reactors, Argentina’s RA-3, already produces best-quality Mo-99 but has been kept out of the North American market to date. Only with the crisis of the past year has production increased from once a week to twice, as INVAP has begun to service some of the Brazilian market. In the past, all attempts to enter new markets have been pushed back by competitors. RA-3, nearly a decade younger than the other five Mo-99 production reactors, could increase production if brought into the supply chain, but this has not happened to date. It should be noted that ANSTO experts noted as recently as fall 2008 that they had no plans to enter the U.S. market due to the extremely low prices for irradiation services here—prices some experts have argued are kept at or below cost (with profits made through generator sales, not irradiation services).[25] Only after the NRU shutdown has Lantheus Imaging begun to engage Australia’s OPAL in serving North America—the first pharmaceutical company to do so.[26]

Additional reactors that could become Mo-99 producers are listed in Table 2. All of them have been exploring such production, as noted in the table. Two of the reactors with highest flux, South Korea’s Hanaro and Japan’s JMTR, have initiated efforts to produce Mo-99 in the near term due to the current shortages. In the case of Japan, it has made the commitment to employ LEU targets, as has the University of Missouri in the United States. However, it will take a minimum of two years to begin production at Missouri, including the time to obtain product licenses. Missouri has been working on obtaining an agreement with a Tc-99m generator producer and distributor for several years, an indication of just how difficult it is to break into the market (despite MURR’s strong experience producing other types of medical isotopes). Of the other reactors in Table 2, only OPAL has an agreement with a major distributor, as noted above.

**Table 2. Other High Flux Reactors with Major Mo-99 Production Potential**[27]

| Reactor | Criticality Date | Thermal Power, Steady/ Maximum Thermal Flux (n/cm2-s) | Utilization | Mo-99 Work |
|---|---|---|---|---|
| **MURR**<br>(University of Missouri, USA) | 1966 | 10 MW/<br>6.0E14 | **Hours/Day** 24<br>**Days/Week** 6<br>**Weeks/Year** 52<br>**MW Days/Yr**<br>3285 | Working on LEU targets; part of IAEA CRP;[28] plans to begin major Mo-99 production (meeting up to 50% U.S. demand) as early as 2012 |
| **HANARO**<br>(S. Korea) | 1995 | 30 MW/<br>4.5E14 | **Hours/Day** 24<br>**Days/Week** 3<br>**Weeks/Year**<br>**MW Days/Yr**<br>3248 | In January 2009, it was announced that Hanaro would be used for Mo-99 production on an emergency basis[29] |
| **Japan Materials Testing Reactor (JMTR)**<br>(Oarai, Japan) | 1968 | 50 MW/<br>4.0E14 | **Hours/Day** 24<br>**Days/Week** 7<br>**Weeks/Year** 26<br>**MW Days/Yr**<br>9000 | July 2009 announcement that Mo-99 production without HEU would be demonstrated [30] |
| **MARIA**<br>(Poland) | 1974 | 30 MW/<br>3.5E14 | **Hours/Day** 24<br>**Days/Week** 5<br>**Weeks/Year** 40<br>**MW Days/Yr**<br>3000 | Joined IAEA CRP in April 2007 |
| **TRIGA II Pitesti**<br>(Romania) | 1980 | 14 MW/<br>3.3E14 | **Hours/Day** 24<br>**Days/Week** 7<br>**Weeks/Year** 40<br>**MW Days/Yr** | IAEA CRP member, working on foil targets, LEU-modified Cintichem process |
| **OPAL**<br>(Australia) | 2006 | 20 MW/<br>3.0E14 | | Planning to become major Mo-99 producer; employs LEU fuel and targets |
| **ETRR-2**<br>(Inshas, Egypt) | 1997 | 22 MW/<br>2.8E14 | **Hours/Day** 24<br>**Days/Week** 1<br>**Weeks/Year** 48<br>**MW Days/Yr**<br>920 | Turn-key Mo-99 separation/purification facility constructed by INVAP[31] |
| **Siwabessy MPR**<br>(Serpong, Tangerang, Indonesia) | 1987 | 30 MW/<br>2.52E14 | **Hours/Day** 24<br>**Days/Week** 7<br>**Weeks/Year** 21<br>**MW Days/Yr**<br>2160 | Produced Mo-99 from HEU since 1996; engaged in development of LEU-based Mo-99 production through RERTR since 1992; part of IAEA CRP |
| **IRT-T**<br>(Tomsk | 1967 | 6 MW/<br>2.5E14 | **Hours/Day** 24<br>**Days/Week** 5 | Produces Mo-99 for regional market, employing HEU fuel and |

| | | | | |
|---|---|---|---|---|
| Polytechnic University, Russia) | | | **Weeks/Year** 30 **MW Days/Yr** 900 | HEU targets |
| **IRT-1,** Tajoura Nuclear Research Center, Libya) | 1981 | 10 MW/ 2.0E14 | **Hours/Day** 20 **Days/Week** 1 **Weeks/Year** 14 **MW Days/Yr** 55 | IAEA CRP member, working on foil targets, LEU-modified Cintichem process |
| **VVR-Ts** (Karpov Institute, Obninsk, Russia) | 1964 | 15 MW/ 1.8E14 | **Hours/Day** 24 **Days/Week** 5 **Weeks/Year** 42 **MW Days/Yr** 1900 | Produces Mo-99 for regional market, employing HEU fuel and HEU targets |
| **PARR-1** (Pakistan) | 1965 | 10 MW/ 1.7E14 | **Hours/Day** 12 **Days/Week** 1 **Weeks/Year** 23 **MW Days/Yr** 150 | IAEA CRP member, working on foil plate targets, LEU-modified Cintichem process |
| **RP-10** (Peru) | 1988 | 10 MW/ 1.21E14 | **Hours/Day** 6 **Days/Week** 3 **Weeks/Year** 52 **MW Days/Yr** 156 | Produces Mo-99 |
| **RECH-1** (Chile) | 1974 | 5 MW/ 7.0E13 | **Hours/Day** 24 **Days/Week** 1 **Weeks/Year** 50 **MW Days/Yr** 250 | Part of IAEA CRP, exploring Cintichem process modified for LEU |

### 2.6.2 Alternative Mo-99 Production Methods

There are several other processes that can be used to produce Mo-99. As was mentioned above, small-scale production is already ongoing employing gel generators. Babcock and Wilcox (B&W), in Lynchburg, Virginia, have been working on the development of a solution reactor system, in February 2009 announcing an agreement to collaborate with pharmaceuticals giant Covidien on an Aqueous Homogeneous Reactor employing LEU for Mo-99 production. This system would not employ separate targets, as is the case in conventional reactors, but would instead derive the Mo-99 from the fuel itself. B&W has stated it could meet 50% of U.S. demand for Mo-99. A solution reactor in Russia successfully demonstrated Mo-99 production in 2002-2003, albeit employing HEU fuel.

## 2.7 Conclusion: Government Intervention is Necessary and Likely to Be Forthcoming

Guaranteeing Mo-99 supply means ensuring that sufficient reactors are committed to isotope production. The market has failed to provide this guarantee: reactor services are not highly paid, while the oligopolistic distribution system—though it ensures quick distribution of available product—makes entry into the market by new players difficult. This factor is further exacerbated by government subsidies of construction and operation in some countries but not in others. Though doctors are willing to pay a premium to ensure reliability of supply, the market has yet to offer such a service. Instead, government must play a role in ensuring irradiation services, as well as demanding that isotope production does not involve turning on unsafe reactors (such as the MAPLEs) or result in stockpiles of risky HEU target waste.

The recent medical isotope shortages have caused governments to seek answers. In addition to the existing plans for new isotope production reactors (such as the Pallas, to replace the aging HFR in the Netherlands, and the Jules Horowitz to replace the Osiris in France), national governments are seeking short term solutions through the utilization of additional existing reactors (such as the Hanaro in Korea and TRR in Iran). Yet these facilities are not likely to become major producers, while current major production reactors (the NRU in Canada and BR2 in Belgium) are likely soon to shut down. Thus, a few states have begun to look at ways to incentivize the start-up of new producers. The United States, in particular, has seen government action: the U.S. Congress is considering legislation (the American Medical Isotopes Production Act of 2009) which directs the Secretary of Energy to "support projects for the production in the United States, without the use of highly enriched uranium, of significant quantities of molybdenum-99 for medical uses," providing $163,000,000 for FY 2010 through 2014 for that purpose. Additionally, the act would set a 10-year limit on exports of HEU from the United States.[32]

## 3. THE DEVELOPMENT OF FUTURE POWER REACTORS AND THE IMPLICATIONS FOR RESEARCH REACTORS

Another research reactor use of particular concern to governments today is the role reactors play both in the development of new power reactor types and their role in the education and training of power reactor operators. Determining the possible needs of the power reactor industry are of critical importance to nuclear security, since some governments have argued that they are maintaining underutilized reactor installations or unutilized HEU materials because they believe these will have value in future.[33] A review of power reactors types proposed for development in the next two to three decades—in national programs as well as through the Generation IV international forum[34] and the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)[35]—reveals, however, that none involve the use of HEU. Indeed, only research associated with MOX fuel may involve the use of highly enriched uranium—though the enrichment level need not exceed 35% percent—to mock up MOX fuel assemblies at 1-2 critical facilities.[36] Thus, it does not appear likely that "mothballed" reactor facilities and materials will be useful for the development of power reactors and power reactor fuel within the next decade or two. These facilities are of particular concern, since the lack of current value to operators or governments means they may not be adequately secured. A review of current capacities and future needs suggests that installation decommissioning and nuclear materials removal is the most responsible course of action in such cases.

While fuel development is not likely to require more than a few new research reactors and no HEU material, there will likely be an insufficient number of reactors in the right locations for education and training. Of 38 countries WNA lists as potentially acquiring power reactors, 15 do not have research reactors.[37] Reactors for education and training worldwide have decreased dramatically over the past two decades, with many universities shuttering their facilities.[38]

**Table 3. Research Reactors in Potential Nuclear Newcomer Countries**

| Country | Number of Research Reactors | Comments |
|---|---|---|
| Albania | None | May embark upon feasibility study jointly with Croatia.[39] |
| Algeria | 2 | Aims to build NPP in 2020. 2008 agreement with China on sharing training, research and human resources; has nuclear agreements with Argentina, France and the United States and in talks with Russia and South Africa.[40] |
| Azerbaijan | None, but construction planned.[41] | Construction of an NPP may begin in the next year or two. |
| Bangladesh | 1 | Education and training reactor being upgraded, financed by the Government of Bangladesh.[42] |
| Belarus | None operational | Sosny has decommissioned education & training reactor. |
| Bosnia | None | May cooperate on NPP with Albania and Croatia.[43] |
| Chile | 1 operational, 1 shut down | NPP construction under consideration. |
| Croatia | None | May embark upon feasibility study jointly with Albania. |
| Egypt | 2 | Plans call for NPP to go online by 2017.[44] |
| Estonia | None (former naval training reactors dismantled) | Parliamentary decision on whether to build an NPP expected in 2014; NPP could be introduced in 2025.[45] |
| Ghana | 1 MNSR | Plans NPP by 2018.[46] |
| Indonesia[47] | 3 | Plans NPP by 2016.[48] |
| Israel | 2 operational[49] | NPP site chosen, but no current construction plans. |
| Italy | 4 operational, 5 shut down, 5 decommissioned. | Government has passed legislation and intends to build new nuclear power plants by 2013.[50] |
| Jordan | Planned[51] | Aims to have NPP in operation 2017/2018. |
| Kuwait | None | Formed nuclear commission to study NPP construction. |
| Latvia | None operational (2 shut down) | In talks on construction of replacement for Ignalina NPP in Lithuania. |
| Libya | 1 | Seeking NPP for desalination and electricity production. |
| Malaysia | 1 | Undertaking NPP feasibility study; 2023 target date for possible NPP.[52] |
| Mongolia | None | Undertaking NPP feasibility study. |
| Morocco | 1 | First NPP may be in operation 2016/2017.[53] |
| Namibia | None | Government policy: nuclear power by about 2018.[54] |
| Nigeria | 1 MNSR | Plans for up to 5000 MWe of nuclear capacity by 2017; June 2009 agreement with Russia to explore construction of NPP and new research reactor.[55] |
| Norway | 2 | Studying feasibility of thorium-fueled reactors. |
| Philippines | None in operation (1 shut down, 1988) | 600 MWe projected on line in 2025; conducting feasibility study of bringing Bataan 1 (621 MWe Westinghouse PWR completed 1984) online. |
| Poland | 1 (2 shut down, 2 decommissioned) | NPP planned by 2020; may cooperate on construction of replacement for Ignalina NPP in Lithuania. |
| Portugal | 1 | No current plans. |
| Thailand | 1 operational, 1 under construction (on hold?) | NPP construction to begin 2014, plans call for first of 4 NPPs online by 2020. |
| Tunisia | None; 2 MW Triga Mark II feasibility study, 2001; alternatives: bilateral/multilateral cooperation[56] | |
| Turkey | 1 (2 shutdown) | First NPP expected to come on line in 2016, others in 2017, 2018 and 2019.[57] |
| Uganda | None | Undertaking feasibility study. |

| | | |
|---|---|---|
| United Arab Emirates | None | UAE has published plans for three operational nuclear power plants by 2020.[58] |
| Venezuela | None (one shut); may construct[59] | May construct with Russian assistance.[60] |
| Vietnam[61] | 1 (may construct additional high-power RR[62]) | First NPP expected to be commissioned in 2017. |

Whereas the complex and expensive instrumentation and reactor types required for advanced scientific research argues for multinational research reactors for these purposes, the training of power reactor operators requires regular access to simpler training reactors at regional universities or industrial facilities. Here too, however, thought should be given to construction of appropriate reactor types, which are relatively simple to safeguard and do not raise proliferation concerns unnecessarily. As noted below, the safeguarding of research reactors is an important nonproliferation and confidence-building measure that should be facilitated when planning new facilities.

### 3.1 Security

Research reactors vary widely when it comes to their security implications, from facilities presenting extremely few risks to those posing significant proliferation and security concerns. While power reactors generally employ large fuel rods that are traditionally employed to a very high burn-up level,[63] the size of rods, type of fuel, enrichment level, and level of burnup varies considerably among research reactors. Over the past three decades, efforts to reduce the use of highly enriched uranium in research reactor fuel, along with the closure of many HEU-fueled reactors, have reduced the risks posed by HEU stocks at such facilities. Data on stockpiles is not publicly available, though it would appear that some critical facilities continue to house significant quantities of unirradiated or lightly irradiated HEU, presenting significant security risks. To reduce these risks in future, minimization of HEU is warranted, as is the formulation of minimum security standards, security training, and the sharing of "best practices" in security.

Security training and the spread of security culture among reactor personnel has yet to be institutionalized to the degree of safety culture. In this regard, the IAEA's forthcoming nuclear security guidelines are an important basis upon which to build. However, detailed international agreements that spell out minimum security requirements, as well as better coordination between safety and security requirements (sometimes contradictory), are still needed, as is national legislation to implement the IAEA security guidelines and other measures that may be recommended.

Of further concern, the IAEA and the Convention on the Physical Protection of Nuclear Material (CPPNM) only provide general physical protection recommendations, not specific guidance or minimum standards. The concept of a minimum design basis threat (DBT) has been mooted by Scott Sagan[64] as a way to help ensure minimum standards. Currently, CPPNM call for basing physical protection on "the state's current evaluation of the threat," though states have different perceptions, and can be harmed by threats emanating from inside other states. Furthermore, even in locations with similar threat assessments great variation in security provisions and requirements has been found.[65] This evidence supports the contention that there is a real need to focus international attention on maintaining at least minimum standards in both established and new facilities. Although there are bilateral and multilateral programs working to help research reactor operators—to facilitate coordination, improve security training, and remove vulnerable materials such as HEU fuel, for example—to date these efforts are not well coordinated, and can even work at cross purposes (particularly where security and safety measures are concerned). Ensuring that safety and security practices are mutually complementary is a difficult, but important task. Design and construction of facilities to facilitate both safety and security measures, and the avoidance of accumulation of nuclear materials of particular concern, should be a main focus of planners developing the global research reactor park.

### 3.2 Nonproliferation and Safeguards

As noted above, research and test reactors vary widely when it comes to quantity and quality of nuclear material. While policymakers worldwide have focused considerable attention on the proliferation resistance of power reactors, relatively little attention to date has been paid to research and test reactors outside of programs to convert from HEU to LEU fuel. Yet were nuclear power to expand to new countries, additional research reactors would be needed for education and training, if not other purposes. New power and research reactor facilities will tax IAEA implementation of safeguards through the increase of facility numbers alone; new reactors should be designed to facilitate safeguarding in order to ensure continued confidence that they are not contributing to proliferation risks. Technical equipment to improve monitoring capabilities, so-called “safeguards by design,” can help to alleviate concerns but are not a substitute for minimization of weapons-usable materials.

### 3.3 Conclusion: Nonproliferation Efforts Must Involve Research, as Well as Power Reactors

The spread of nuclear power has resulted in many studies into how to reduce related proliferation risks, but little attention has gone into research reactors. Yet the spread of nuclear power reactors will mean construction of research reactors for training purposes in newcomer states as well. These facilities can be designed to minimize security and proliferation concerns, while facilitating safeguards. Education and training reactors should not need to employ weapons-usable material or have design features making them difficult to safeguard.

Reactors employed for the development of new power reactor designs are of greater concern. In particular, critical assemblies have traditionally been associated with large stockpiles of very lightly irradiated highly enriched uranium materials, which are difficult to account for and inherently of proliferation concern. Other research reactor types have employed highly enriched uranium for research purposes, though new power reactor development should not require such materials. However, consideration should be given for how to minimize the production of weapons-usable plutonium in fuel test reactors, an issue that does not appear to have been a focus of reactor developers to date. While much thought has been given to developing power reactor designs that are “proliferation resistant,” the research reactors involved in such development projects also should not contribute to proliferation risks.

## 4. COORDINATION MECHANISMS

Traditionally, national governments and/or industry have constructed non-power reactors on an independent basis, with little coordination between facilities. Only a few reactors, such as the Institut Laue-Langevin’s HFR reactor in Grenoble, France, have been constructed by a consortium of nations for shared use. A handful of others, like the new OPAL in Australia, were designed with multinational users in mind. More typically, however, reactors have been nationally funded and designed for local users, not international access to key reactor services. As research costs increase, however, this model would not seem to be sustainable. Instead, basic education and training should be done at smaller, university and industry reactors while scientific and other uses that require higher flux and/or specific instrumentation should be done at shared, multilateral facilities. This would have the additional benefit of helping to ensure the full utilization of facilities, increase the security of reactor facilities and fissile materials, as well as facilitate transparency and thereby make more difficult the proliferation of weapons-usable materials.

Levels of reactor utilization today vary widely, from a few hours per week to 24 hours per day 7 days per week, with some users facing difficulties obtaining reactor time while other reactors suffer from underutilization. Clearly, better coordination worldwide is needed. The IAEA would seem best placed to help facilitate such cooperation, and indeed has initiated so-called “research reactor coalitions” with this idea in mind. While welcome as a way to improve reactor utilization, the concept has yet to involve cooperation in running facilities or investing in new construction or upgrades. Nevertheless, it may prove to be a first step towards deeper cooperation.

### 4.1 Research Reactor Coalitions

There are currently several research reactor coalitions that have been established with the assistance of the IAEA and ongoing efforts to facilitate additional cooperative groupings. The East European Research Reactor Initiative involves reactors in Austria, the Czech Republic, Hungary, Romania, Poland, and Slovenia. The Eurasian Research Reactor Coalition brings together research reactors in the Czech Republic, Kazakhstan, Ukraine, and Uzbekistan along with isotope and other organizations in Hungary and the U.S., and is focusing on the production of Mo-99 from Enriched Mo-98. The Caribbean Research Reactor Coalition includes research reactors in Austria, Colombia, Jamaica, and Mexico. A fourth arrangement, the Mediterranean Research Reactor Utilization Network, was established without a formal agreement. It is based on on-going IAEA efforts to promote regional networking and utilization between research reactors and users in Azerbaijan, Egypt, Greece, Montenegro, Syria, Tunisia, and the IAEA. Meetings have also been held on the formation of coalitions of Russian facilities, on formation of a neutron scattering reactor coalition, on a coalition centered at Australia’s OPAL reactor, as well as on the possible formation of a North-South America Research Reactor Coalition and a Baltic Research Reactor Coalition. Some countries and individual facilities have been involved in more than one of the cooperative efforts.

## 5. CONCLUSION

To ensure the future contribution of research reactors to science and technology, energy, medicine, as well as industrial and environmental applications, more effective, coordinated management strategies are needed. As the world’s non-power reactors age, questions of decommissioning, life extension, safety and security are increasingly problematic, with international effects. This paper has argued that attention to minimizing proliferation and security risks cannot be confined to power reactors, but should involve the facilities at which power plant designs and fuels are being tested as well. Minimum security requirements would seem prudent, as current recommendations have not resulted in adequate physical protection measures at all sites. Nor have current mechanisms proven adequate at ensuring access to reactor services;

international government oversight appears to be necessary, as the recent crisis in availability of Mo-99 has shown. The increasing price of reactor construction also argues for new cooperation in this area. Policymakers have proposed multinational nuclear facilities for the enrichment of uranium or reprocessing of spent fuel. Multinational research reactor facilities would also appear warranted, as the would make possible the pooling of resources, improved utilization, direct sharing of best practices, and levels of transparency that should facilitate safeguarding—especially important at facilities that employ nuclear materials of concern.

Coordination could also be improved through better sharing of information, including through the IAEA research reactor database. On the one hand, not all facilities update the database on a regular database (some individual entries are over a decade old) or provide all of the required information. Further, planned research reactors are only reported in a handful of cases. On the other hand, the current database questionnaire does not include all of the data needed to analyze the global reactor situation. For example, reactor age statistics do not necessarily provide information on reactor quality or upgrades (or potential decommissioning dates). Instrumentation is often not specified; nor is there indication of the proportions of various reactor services. For those interested in civilian reactor uses, it would also be useful to indicate which reactors are strictly military, or the proportion of utilization that is devoted to weapons research. Even where a reactor is strictly civilian, effectiveness of reactor utilization remains difficult to determine, as the only data given are hours of use but not proportions of various services. The IAEA database, thus, is a good tool but could clearly be improved. The Agency should also be given permission to collect safety and security information, to be kept in-house only, for the purpose of developing improved safety and security recommendations.

Non-power reactors provide key services to the global community. Failures at a single facility, however, could have global repercussions, either for existing research and power reactors or for the construction of new nuclear facilities. It is in the interest of governments worldwide that research and test reactors be managed safely, securely, and in ways that minimize proliferation risks. New cooperative reactor ventures should be considered, in order to improve funding for top-flight machines and instrumentation, maximize utilization, and increase transparency.

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[1] Brazil's IPR-RI, a TRIGA Mark I, cost $250,000 in1960 ($1.8 million in today's dollars when adjusted for inflation), while Morocco's MA-R1, a TRIGA Mark II, cost $4.2 million in 2007.
[2] MURR cost $3.5 million in 1966 ($23.3 million in today's dollars) vs. $435 million for FRM II; HFIR initially cost $14.6 million ($100 million today) vs. an estimated $400 million for OPAL (note that no initial cost is listed under the OPAL in the IAEA RRDB).
[3] Data taken from IAEA RRDB.
[4] Tatsuo Shikama, "Study of irradiation effects in materials with high-neutron-flux fission reactors," Proceedings of IAEA Technical Meeting TM-34779, Vienna, 17-21 November 2008, http://www-naweb.iaea.org/napc/physics/meetings/TM34779/Papers%20PDF/shikama-Japan.pdf.
[5] Status as reported in IAEA RRDB.
[6] About 240,000 MRIs and just 36,000 PET scans are performed each year in the United States. Andrew Einstein, Columbia University Medical Center, "Why America Needs Technetium-99m," presentation at U.S. Senate outreach event on "Ensuring U.S. Medical Isotope Supply and Minimizing Risks of Nuclear Terrorism," October 6, 2008.
[7] Ibid.
[8] Snelgrove, Hofman, et al, "Development and Processing of LEU Targets for Mo-99 Production—Overview of the ANL Program," RERTR-1995, Paris, September 18-21, 1994, <http://www.rertr.anl.gov/MO99/JLS.pdf>. The varying target configuration also makes altering current procedures difficult. When the Petten reactor was shut down in late 2008/early 2009, Mallinckrodt Medical/Covidien had to turn to the reactor in Saclay. Due to differences in the targets, however, Mallinckrodt Medical/Covidien had to modify its normal procedures and receive regulatory

authorization to amend the European Drug Master File of Mo-99 held by Mallinckrodt Medical/Covidien in order to employ the Osiris targets. European Medicines Agency, "Report to the European Commission on the Supply Shortage of Radiopharmaceuticals (Status as of 24 October 2008)," London, March 5, 2009, <EMEA/51183/2009http://www.emea.europa.eu/pdfs/human/press/pus/5118309en.pdf>.

[9] In July 2009, Australia's Australian Nuclear Science And Technology Organisation received approvals to sell Tc-99m generators in the U.S. and Canada. "Lantheus Medical Imaging Announces FDA And Health Canada Approval Of Australian Nuclear Science And Technology Organisation (Ansto)-Supplied Key Medical Isotope To Manufacture Technelite(R) Generator"
Biospace website, <http://www.biospace.com/news_story.aspx?NewsEntityId=149493>, July 9, 2009.

[10] For more information, see "CRP on Production of Mo-99 from LEU or Neutron Activation," IAEA website, <http://www.iaea.org/OurWork/ST/NE/NEFW/rrg_Mo99.html>.

[11] For more on the development of Tc-99m, see Cristina Hansell, "Nuclear Medicine's Double Hazard: Imperiled Treatment and the Risk of Terrorism," *Nonproliferation Review*, July 2008, <http://cns.miis.edu/npr/pdfs/152_hansell_nuclear_medicine.pdf>.

[12] For more details, see Hansell, op. cit.

[13] IAEA Research Reactor Database. NRU data last updated 2002/10/22.

[14] IAEA Research Reactor Database. BR-2 data last updated 2008/12/04.

[15] IAEA Research Reactor Database. HFR data last updated 2009/05/10.

[16] IAEA Research Reactor Database. SAFARI data last updated 2009/06/18.

[17] IAEA Research Reactor Database. OSIRIS data last updated 2008/12/17.

[18] <http://www.world-nuclear-news.org/RS_Medical_community_eyes_reactor_shutdowns_2808082.html>.

[19] Latin America and India have reportedly encountered cases of MDS dramatically lowering its prices or refusing to provide short-term back-up Mo-99 supplies.

[20] Author's interview with Argentinean nuclear specialist, June 2009.

[21] Committee on Medical Isotope Production Without Highly Enriched Uranium, National Research Council, "Medical Isotope Production Without Highly Enriched Uranium" (Washington: The National Academies Press, 2009).

[22] See, for example, "MDS Commences Arbitration against AECL over Cancelled MAPLE Project and Files $1.6 Billion Court Claim against AECL and the Government of Canada," MDS Nordion website, July 9, 2008, <http://www.mdsnordion.com/documents/news-releases/2008/AECL_Arbitration_FINAL.pdf>and "MDS Nordion Urges Government of Canada to Complete MAPLE Project to Address Current Medical Isotope Supply Shortage," MDS Nordion website, June 1, 2009, <http://www.mdsnordion.com/documents/news-releases/2009/MDSN_Urges_Government_to_Complete_MAPLE_June_2009.pdf>. Notably, the latter deceptively quotes the U.S. National Academies study, saying "The National Academy of Science Committee states that 'AECL could probably contract with another organization to fix the MAPLE reactors…if it does not have the necessary in-house technical expertise or resources to do the work itself'" without explaining that the statement in question was in reference to gutting the reactor and installing a new core (the letter appears to suggest the current core could be fixed in short order).

[23] George Vandegrift, Allen J. Bakel, and Justin W. Thomas, "Overview of 2007 ANL Progress for Conversion of HEU Based Mo-99 Production as Part of the U.S. Global Threat Reduction—Conversion Program,'' paper presented at RERTR 2007, Prague, September 23-27, 2007. According to the calculations in this study, the dose rate per gram of HEU irradiated for five days at a flux of 1x1014 neutrons per square cm per second drops by nearly five orders of magnitude from the day the target is processed until the end of three years in storage. Calculating dose rates after three years for the two types of processing methods used by major producers, it was determined that for acid-dissolution waste, the dose rate after three years of storage is 1.5 mrem per hour per gram of HEU at 100 cm, with no shielding. For alkaline-digested HEU, the dose rate is 0.5 mrem. Any shielding would considerably lower this dose rate.

[24] Committee on Medical Isotope Production Without Highly Enriched Uranium, National Research Council, "Medical Isotope Production Without Highly Enriched Uranium" (Washington: The National Academies Press, 2009), p. 160.

[25] Author interviews with experts from ANSTO, Argentina, India and elsewhere, October 2008.

[26] See "Written Testimony of Michael P. Duffy on behalf of the Lantheus Medical Imaging, Inc. (Lantheus) and Council on Radionuclides and Radiopharmaceuticals (CORAR) Before the United States House of Representatives Committee on Energy and Commerce Subcommittee on Energy and Environment," September 9, 2009, http://www.radiopharm.com/Mo99SupplyUpdate/pdf/M.%20Duffy%20testimony%20--%209-9-09%20final.pdf.

[27] Criticality, thermal power, thermal flux, and utilization data from IAEA RRDB.
[28] Coordinated Research Project (CRP) on "Developing Techniques for Small-scale Indigenous Production of Mo-99 using Low Enriched Uranium or Neutron Activation," International Atomic Energy Agency, http://www.iaea.org/OurWork/ST/NE/NEFW/rrg_Mo99.html.
[29] "Korea reactor to produce Mo-99 on trial basis," HealthImaging website, January 29, 2009, <http://www.healthimaging.com/index.php?option=com_articles&view=article&id=16050:korea-reactor-to-produce-mo-99-on-trial-basis>.
[30] "JRIA Discusses Stable Supply of Mo-99 at Annual Meeting in Tokyo," Atoms in Japan website, July 21, 2009, <http://www.jaif.or.jp/english/aij/member/2009/2009-07-21c.pdf>.
[31] For details, see INVAP website, <http://www.invap.net/nuclear/etrr-2/data-e.html>.
[32] HR 3276, "American Medical Isotopes Production Act of 2009" (Introduced in House), July 21, 2009, Library of Congress, http://thomas.loc.gov/cgi-bin/query/z?c111:H.R.+3276:.
[33] See, for example, William C. Potter and Robert Nurick, "The Hard Cases: Eliminating Civilian HEU in Ukraine and Belarus," in William C. Potter and Cristina Hansell, *The Global Politics of Combating Nuclear Terrorism: A Supply-Side Approach* (London: Routledge, 2009).
[34] The Generation IV forum is considering the following technology concepts: Gas-Cooled Fast Reactor (GFR), Lead-Cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Sodium-Cooled Fast Reactor (SFR), Supercritical-Water-Cooled Reactor (SCWR), Very-High-Temperature Reactor (VHTR). Gen IV website, http://gen4.inel.gov/.
[35] INPRO research is focused on similar reactor concepts as Gen IV, as well as thorium-fueled reactors. INPRO is also examining safety issues associated with combining advanced high temperature reactors and hydrogen producing plants, proliferation resistance, and implementation of reactors in newcomer countries. INPRO webpage, http://www.iaea.org/INPRO/collaborative_projects.html.
[36] MOX fuel is currently mocked up using both plutonium and HEU. However, no more than 35% enriched uranium is needed for this purpose. See M. Salvatores (CEA, Cadarache, France), H.Khalil (ANL, USA), G. Bignan (CEA, Cadarache, France), R.Hill (ANL, USA), R.Jacqmin (CEA, Cadarache, France), J. Tommasi (CEA, Cadarache, France), "Advanced Fast Reactor Development Requirements: is there any need for HEU?" Cadarache/Argonne, April 2006, http://www.nrpa.no/symposium/abstracts/Massimo%20Salvatores.doc.
[37] Mycle Schneider, Steve Thomas, Antony Froggatt, and Doug Koplow, "The World Nuclear Industry Status Report 2009," http://www.bmu.de/files/english/pdf/application/pdf/welt_statusbericht_atomindustrie_0908_en.pdf, p. 117.
[38] For example, of 22 argonauts constructed, only 3 are in operation today; of 40 solid homogenous reactors, 14 are in operation; and of 48 TRIGAs, 29 are in operation. IAEA RRDB, accessed October 2009.
[39] Phil Cain, "Albania Nuclear Reactor Reports Premature," *World Politics Review*, April 28, 2009, http://www.worldpoliticsreview.com/article.aspx?id=3663.
[40] Reuters, "Algeria to build nuclear power plants from 2020," *Mail & Guardian* online, February 24, 2009, http://www.mg.co.za/article/2009-02-24-algeria-to-build-nuclear-power-plants-from-2020.
[41] The IAEA has concluded a preliminary agreement to support construction of a 10-15 megawatt research reactor outside of Baku; construction is expected to begin in 2012. "Emerging Nuclear Energy Countries," World Nuclear Association Website, updated August 26, 2009, http://www.world-nuclear.org. The reactor is to be used for radioisotope production, nuclear medicine and personnel training, materials development, environmental pollution control, as well as for the development of nuclear energy. "Planning and implementation of research reactor in the Republic of Azerbaijan," http://www-naweb.iaea.org/napc/physics/meetings/TM-34781/pdf-presentations/Azerbaijan%20%20-%20Vienna-February%2019%202008.pdf.
[42] S. M. Hossain, M. A. Zulquarnain, I. Kamal and M. N. Islam, "Current Status and Perspectives of Nuclear Reactor Based Research in Bangladesh," http://www-naweb.iaea.org/napc/physics/meetings/TM34779/Papers%20PDF/Hossain_Bangladesch.pdf.
[43] "Emerging Nuclear Energy Countries."
[44] Ibid.
[45] "Estonia to prepare a decision in principle for nuclear power plant," *Helsingin Sanomat*, July 9, 2009, http://www.hs.fi/english/article/Estonia+to+prepare+a+decision+in+principle+for+nuclear+power+plant/1135243574541.
[46] Daily Guide, "Ghana Goes Nuclear 2018," Modern Ghana website, January 8, 2008, http://www.modernghana.com/GhanaHome/NewsArchive/news_details.asp?menu_id=1&id=VFZSVmVVNXFZek09.
[47] Indonesia has agreements on cooperation in the peaceful use of nuclear technology with Argentina, Australia, USA, Canada, Frances, Germany, Italy, Japan and South Korea as well as Westinghouse, General Electric, USNRC,

DOE, Nucleonic Medical, AECB, AECL, KFA Julich, Siemens, Amersham, UKEEA, ENEEA, JAERI, JA'IF, Mitsubishi, Newjec, TIT, KAKEN Co.Ltd, KEK, KAERI, KHNP and KIRAMS. National Nuclear Agency of Indonesia (BATAN) website, http://www.batan.go.id/en2008/coorporate.php.

[48] BATAN website, http://www.batan.go.id/en2008/landmark2.php.

[49] IAEA RRDB. Note information on heavy water reactor noted as "unverified."

[50] World Nuclear Association website, http://www.world-nuclear.org/info/inf101.html.

[51] A 5MW plant is to be built at the Jordan University of Science and Technology. Ned Xoubi, "Jordan's Planned Nuclear Research Reactor," presentation on February 16, 2009, http://www.docstoc.com/docs/10630689/Jordans-Planned--Nuclear-Research-Reactor; Taylor Luck, "JAEC to name consultant for nuclear project next month," *Jordan Times*, September 7, 2009, http://www.jordantimes.com/?news=19719.

[52] "Emerging Nuclear Energy Countries."

[53] R. Sekkouri Alaoui, "Summary of the First Moroccan Nuclear Power Plant Feasibility Study," IAEA-CN-153/4/P/30, http://www.iaea.org/inisnkm/nkm/documents/nkmCon2007/fulltext/ES/IAEA-CN-153-4-P-30es.pdf.

[54] "Uranium in Namibia," World Nuclear Association, last updated September 2009, http://www.world-nuclear.org/info/inf111.html.

[55] "Emerging Nuclear Energy Countries."

[56] The National Center of Nuclear Sciences and Technologies of Tunisia has cooperation agreements with CEA, France; CNESTEN, Morocco; BHABHA Atomic Research Center, India; NECSA, South Africa; CEA, Argentina; and Atom Institute, Austria. Additionally, many Tunisians have been trained abroad. http://www-naweb.iaea.org/napc/physics/meetings/TM-34781/pdf-presentations/Tunisia%20Reguigui%20RR2008.pdf.

[57] "Emerging Nuclear Energy Countries."

[58] "Kuwait to form nuclear energy commission," World Nuclear News, March 3, 2009, http://www.world-nuclear-news.org/newsarticle.aspx?id=24761.

[59] "Russia, Venezuela discuss nuclear research reactor plans," RIAN website, August 5, 2009.

[60] "Emerging Nuclear Energy Countries."

[61] See Vietnam Atomic Energy Commission, http://www.vaec.gov.vn/News/main.php?iddomain=34&EV=0.

[62] Vietnam Atomic Energy Commission, http://www.vaec.gov.vn/Userfiles/file/RD.pdf.

[63] Heavy water reactors are an exception in this regard, as they result in relatively high levels of Pu-239 in spent fuel. As has been noted by Harmon Hubbard, LWRs can also be used to produce Pu-239 if unloaded after one cycle instead of three. See Harmon Hubbard, "Plutonium from Light Water Reactors as Nuclear Weapons Material," in Victor Gilinsky, Marvin Miller and Harmon Hubbard, *A Fresh Examination of the Proliferation Dangers of Light Water Reactors* (Washington: Nonproliferation Policy Education Center, October 22, 2004), pp. 55-62.

[64] Scott Sagan, "New Ideas for Strengthening the Design Basis Threat (DBT) Process," presentation at International Symposium on Nuclear Security, Vienna, March 31, 2009.

[65] George Bunn, Chaim Braun, and Fritz Steinhausler, "Nuclear Terrorism Potential: Research Reactors vs. Power Reactors?" (Proc. EU-High Level Conference on Physical Protection, Salzburg, Sept. 8-13, 2002).