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# JNMM Journal of Nuclear Materials Management



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# JNMM Journal of Nuclear Materials Management

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The Institute of Nuclear Materials Management is dedicated to the safe, secure and effective stewardship of nuclear materials and related technologies through the advancement of scientific knowledge, technical skills, policy dialogue, professional capabilities, and best practices.

INMM INSTITUTE OF NUCLEAR MATERIALS MANAGEMENT

# President's Message

*By Cary Crawford*
*INMM President*

**INMM Community,**

Welcome to this issue of the *Journal of Nuclear Materials Management*. At the time of this writing, we have just come from the INMM 60th Annual Meeting in Palm Desert, California, as well as PATRAM 2019 in New Orleans, Louisiana. Both meetings were very successful, and you can expect a summary in the next issue of *the JNMM*. It was certainly good to see everybody again and interact both personally and professionally!

We were finally able to announce that the INMM 2021 Annual Meeting will be our first one outside of the United States. We will hold that meeting at the Austria Center in Vienna, August 21–26, 2021. The leadership sees this as a strategic step in reaching our larger international membership, and we are looking forward to working with our technical divisions and other international partners to create a compelling and enriching program. In the meantime, don't forget about our 2020 Annual Meeting in Baltimore!

Because this is the introduction to the *JNMM*, I would like to remind you that this publication is your opportunity to publish in a peer-reviewed journal. We are always looking for the next topic or special issue, so if you have ideas, please don't hesitate to contact Markku Koskelo, chair of the *JNMM* committee. Below is additional information for submitting to the *JNMM*; I encourage you to share with others if you have any topics you would like to submit for future publications.

Finally, it always seems like coming off the annual meeting is a time to relax, but just around the corner will be our call for abstracts for INMM 2020. Now is the time to be thinking of special sessions, papers, posters, etc. We are also always open to new ideas for improving your experience at the annual meeting, so please send any ideas you have to me or to any executive committee member or annual meeting chair.

As always, thanks for your ongoing support of the INMM. Enjoy this edition of the *JNMM*.

Sincerely,
Cary Crawford
President, INMM

## Why Publish In The JNMM?

The *Journal of Nuclear Materials Management (JNMM)* is the only international scholarly journal in the field of nuclear materials management. The JNMM provides a forum for the exchange of ideas and information related to the technical divisions of the Institute.

Specific areas of interest include facility operations, international safeguards, materials control and accountability, nonproliferation and arms control, packaging, transportation and disposition, and nuclear security and physical protection.

Refer to our **submissions guidelines** or contact **dbright@inmm.org** to submit a manuscript.

# From Advanced Nuclear Fuels to State Level Non-Proliferation

*By Markku Koskelo*
*JNMM Technical Editor*

Two more contributed manuscripts have made it through the peer review process and are included in this issue.

The first one is the winning student paper from the 2018 annual meeting. It takes a fresh look at the idea of designing nuclear reactor fuel that has intrinsic safety features and offers proliferation resistance characteristics. The paper specifically explores reducing the weapons usability of used fuels by mixing the fuel with impurities using the proposed advanced metallic fuel as an example. Various advanced nuclear fuels have been proposed before as noted in the references of the paper. However, in the wake of Fukushima and Chernobyl, they have more commonly concentrated on the safety aspects of such redesigned fuel. It is nice to see a paper addressing the issue of proliferation resistance for these types of efforts.

The second paper discusses a tool to evaluate the nuclear latency of a state. Nuclear latency is defined as "the expected time to be taken by a non-nuclear weapons state to develop a conventionally deliverable nuclear weapon given the state's position on a path toward or away from a nuclear weapon and accounting for the state's motivations and intentions". Given the recent efforts to establish a state level concept, it would seem that a tool of this kind might well have its use. The paper includes an extensive list of references to put the tool in perspective.

In his column, Taking the Long View in a Time of Great Uncertainty, Jack Jekowski, Industry News Editor and chair of the INMM Strategic Planning Committee, discusses the current efforts by the U.S. NNSA to modernize the U.S. Nuclear Stockpile. Some of us might prefer that there were no nuclear stockpiles to worry about. However, for as long as they do continue to exist, efforts to take care of the stockpile safely and responsibly should be welcome.

In his book review, Mark Maiello gives an overview of the two volumes of the book *Doomed to Cooperate*. The book is an important and little-told story of the immediate post-Soviet era of how the former adversaries found a way to cooperate in the face of concerns that nuclear weapons materials and technology would fall into the hands of proliferators and terrorists. It includes many first person accounts of what happened during those years. This is not a scintillating cover-to-cover read. Instead, expect a very competent account of a particular slice of history of superpower collaboration.

Should you have any comments or questions, feel free to contact me.

*Markku Koskelo*
*JNMM Technical Editor*

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# Innovative Fuel Design to Improve Proliferation Resistance

**Taylor Britt, Braden Goddard, and Manit Shah**
*Virginia Commonwealth University, Richmond, Virginia*

## Abstract

This research uses an existing innovative fuel design (IFD) that has intrinsic safety features and enhanced economics over the current uranium dioxide ($UO_2$) light water fuel design and evaluates its proliferation resistance capability by doping the fresh IFD with select actinides. The most robust approach for proliferation resistance is to denature these materials by adding a uranium or plutonium (Pu) isotope that hampers the usability of the materials in weapons. The proposed modifications to the IFD use this approach through elevated fractions of $^{238}$Pu. $^{238}$Pu generates large quantities of heat and neutrons through its radioactive decay and has been estimated to create a proliferation firewall at concentrations as little as 9%. Proliferation firewall nuclear materials have properties that create substantial technical barriers that would take significant resources and time to use these materials as the fissile component in a nuclear weapon. The IFD consists of an advanced metallic fuel design for use in current light water reactors. Due to the high fission density of this metallic fuel and the proposed uranium enrichment, the plutonium produced by irradiating this fuel has promising isotopic content for proliferation resistance. This proliferation resistance can be further increased by adding $^{237}$Np, $^{238}$Pu, or $^{241}$Am to the initial fresh fuel composition that will result in increased $^{238}$Pu content in the used fuel.

## Introduction

There are two main approaches to help prevent nuclear materials from being used for weapons purposes. The first method is to monitor and assay these materials to ensure they are fully accounted for. This is the approach taken by the International Atomic Energy Agency (IAEA) pursuant to the Treaty on the Non-Proliferation of Nuclear Weapons.[1] An alternative approach is to reduce the weapons usability of these materials by mixing them with impurities. This approach is often referred to as *proliferation resistance* and has the goal of either strengthening the international nonproliferation regime or reducing the burden on IAEA safeguards activities.[2] Although proliferation resistance has many attractive features, it should be noted that any chemical and physical modifications to nuclear materials have limited potential because any modification of this type can be undone without significant difficulty.[3]

This work is focused on the proliferation resistance approach for plutonium in used fuel by investigating an innovative fuel design (IFD) and denaturing this fuel further by adding $^{238}$Pu or $^{238}$Pu producing actinides to the fresh fuel. By adding these actinides, the plutonium vector in the used fuel can be altered to improve its proliferation resistance. $^{238}$Pu generates large quantities of heat and neutrons through its radioactivity decay (half-life of 87.7 years) and is estimated to create a proliferation firewall at concentrations of as little as 9% to 18%, depending on the specific hypothetical nuclear explosives device model.[4,5,6] Proliferation firewall nuclear materials have properties that create substantial technical barriers that would take significant resources and time to use these materials as the fissile component in a nuclear weapon.

The IFD being used for this work is based on an advanced metallic fuel design for applications in commercial pressurized water reactors (PWRs). Each fuel rod has a cruciform shape with a central displacer made of a zirconium alloy that houses burnable poisons. The fuel consists of a 50 weight percent (wt.%) zirconium-uranium (Zr-U) alloy and has a nonuniform thickness zircaloy-4 cladding.[7] The IFD has a helical twist throughout the length of the fuel rod.[8] Figure 1 shows the fuel geometry that this research is based on.

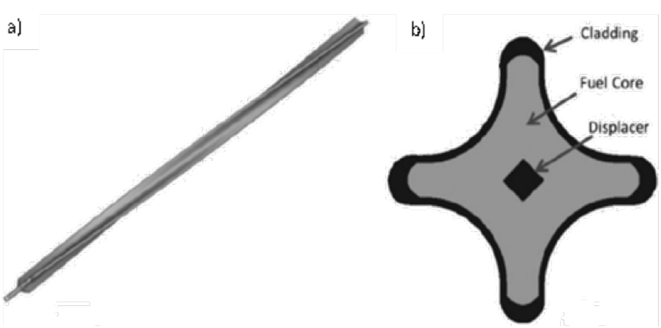


**Figure 1.** Innovative fuel design (IFD): (a) axial rod showing helical twist; (b) cross-section showing the displacer, fuel core, and cladding.[8]

This fuel rod will be enriched to 19.7% $^{235}$U and has a proposed burnup of 190 gigawatt-days per metric tons of uranium (GWd/MTU).[8] The high fission density of this metallic fuel will decrease the $^{239}$Pu concentration and promote the growth of less fissile nuclides such as $^{242}$Pu.[9] The proposed uranium enrichment of 19.7% will increase the number of $^{235}$U atoms that become $^{238}$Pu through neutron capture reactions. Both of these mechanisms will result in the production of plutonium with a proliferation-resistant isotopic composition. This proliferation resistance can be further increased by adding $^{237}$Np, $^{238}$Pu, or $^{241}$Am to the initial fresh fuel composition that will result in increased $^{238}$Pu content in the used fuel.

This research will serve as a proof of concept where the proliferation resistance for the irradiated non-doped IFD will be quantified along with actinide-doped IFD cases. This assessment has not considered some aspects, such as efforts required to separate the actinides from the used fuel at a technical, safeguards, economic cost, and manufacturing challenge level. These topics are relevant, but in this preliminary research, the focus is to assess improvement in the proliferation resistance capability of the irradiated metallic-based IFD against the traditional PWR fuel. Note that while the work presented here exclusively focuses on proliferation resistance of plutonium, concurrent work is being done evaluating innovative methods to increase the proliferation resistance of uranium in fresh and used fuel.[10]

## Methodology

To determine the plutonium vector of a freshly burned fuel rod, a model was created using the Monte Carlo N-Particle Radiation Transport Code (MCNP) version 6.1. The specific dimensions of the IFD fuel rod is proprietary information, but it is known that this rod is a replacement for PWR fuel rods.[11] Using this knowledge, a PWR fuel rod was first modeled in MCNP to determine its initial and final $k_\infty$ values. Using the known enrichment, burnup, and approximate geometrical shape, an MCNP model was made of the IFD fuel rod. The dimensions of the rod and burnable poison concentration were modified until the $k_\infty$ values matched that of the PWR fuel rod. As a verification check, both fuel rods were modeled with the Oak Ridge Isotope GENeration (ORIGEN) code and found to produce used fuel compositions similar to the MCNP models, given the lack of IFD neutron flux distribution values in ORIGEN.[12] Cross-sectional plots of both MCNP models can be seen in Figure 2. While this approach to determining fuel dimensions is not ideal, it is sufficient to demonstrate the proof of principle proposed by this work.

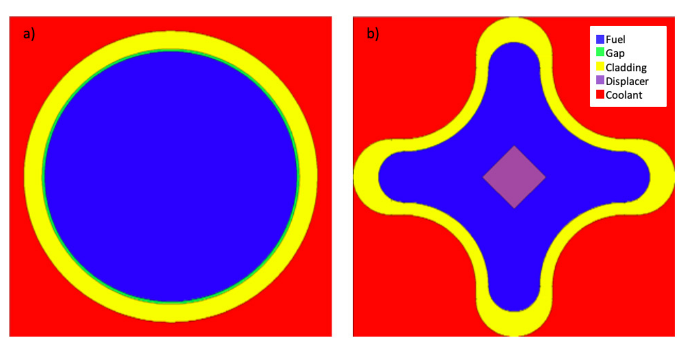


**Figure 2.** MCNP cross-sectional view of the (a) PWR fuel rod and (b) IFD fuel rod

## Results

After matching the $k_\infty$ values, the burnup calculations were performed at a burnup of 190 GWd/MTU to determine the used fuel plutonium vector.[8] This vector was compared to the plutonium vector of a typical PWR fuel rod and a plutonium vector considered to be a proliferation firewall. Table 1 lists these vectors.

**Table 1.** Plutonium vector comparison

| Isotope | IFD | PWR—Ceramic | Proliferation Firewall[6] |
|---|---|---|---|
| $^{238}Pu$ | 14.2% | 1.5% | 18.1% |
| $^{239}Pu$ | 35.5% | 57.7% | 35.7% |
| $^{240}Pu$ | 19.7% | 22.6% | 21.1% |
| $^{241}Pu$ | 14.6% | 13.7% | 13.5% |
| $^{242}Pu$ | 16.0% | 4.4% | 11.6% |

Plutonium from typical PWR ceramic fuel can be used as fissile material in a nuclear explosive device.[9] One of the reasons for this is the relatively small concentration of $^{238}Pu$ and high concentration of $^{239}Pu$. The contrast in these values is significant when compared to the proliferation firewall values, which not only have a smaller concentration of $^{239}Pu$, but also have larger concentrations of both $^{238}Pu$ and $^{242}Pu$, both of which contribute to the unattractiveness of plutonium.[9] The plutonium vector from the IFD can be seen to have a plutonium concentration that is more proliferation resistant than that of the PWR ceramic fuel but is not sufficient to be considered a proliferation firewall, according to Lloyd and Goddard.[6]

In order to reach this proliferation firewall threshold of 18.1% $^{238}Pu$, the IFD was doped with three different actinides: $^{237}Np$, $^{238}Pu$, and $^{241}Am$. Each actinide was added to the fresh IFD fuel at a concentration of 1 wt.% total fuel mass. This is used as a proof of concept to determine if these isotopes would sufficiently enhance the proliferation resistance of the IFD. Each case, shown in Table 2, has a large increase in the wt.% of $^{238}Pu$. This follows with the initial assumption that by denaturing the fresh fuel, the proliferation resistance could be improved upon.

**Table 2.** Plutonium vector of the IFD with actinide doping at 1 wt.%

| Isotope | Original IFD | $^{237}Np$ doped | $^{238}Pu$ doped | $^{241}Am$ doped | Proliferation Firewall[6] |
|---|---|---|---|---|---|
| $^{238}Pu$ | 14.2% | 35.3% | 32.9% | 30.9% | 18.1% |
| $^{239}Pu$ | 35.5% | 30.2% | 30.9% | 30.2% | 35.7% |
| $^{240}Pu$ | 19.7% | 14.1% | 14.8% | 14.5% | 21.1% |
| $^{241}Pu$ | 14.6% | 11.7% | 12.4% | 12.0% | 13.5% |
| $^{242}Pu$ | 16.0% | 8.6% | 9.0% | 12.4% | 11.6% |

From Table 2, it is clear that doping at 1 wt.% with any of the actinides creates a plutonium vector that surpasses this threshold for a proliferation firewall. $^{237}Np$ performs the best with the highest concentration of $^{238}Pu$. $^{241}Am$ has the lowest concentration of $^{238}Pu$, but it does have the highest concentration of $^{242}Pu$. While these results are promising from a proliferation resistance perspective, the amount of denaturing actinides needed for a typical 1,000 megawatt electric (MWe) reactor can be of concern. Each fresh fuel rod will contain at most 15.9 g (1 wt.%) of additional actinide material. A typical PWR core contains approximately 51,000 rods, which corresponds to at most 811 kg of actinide material. Given that the United States has recently started expanding its $^{238}Pu$ production capabilities from 50 g per year to 1,500 g per year,[13,14] denaturing a typical commercial-sized nuclear reactor with $^{238}Pu$ is not currently feasible. There are considerable stockpiles of $^{237}Np$ and $^{241}Am$ throughout the world, but these actinides are contained within used nuclear fuel. To extract these actinides would require used fuel reprocessing, which in itself has proliferation concerns. An additional concern is that separated $^{237}Np$ exhibits some features that could provide a new avenue for proliferation.[9]

## Future Work

While the initial results of this proof-of-concept study are promising, considerable additional work is needed. As stated above, large quantities of $^{237}Np$, $^{238}Pu$, or $^{241}Am$ are not readily available in separated form. This means an innovative method to produce or extract these actinides is needed. In addition to acquiring the raw materials to make the doped fuel, there may be additional complications during the fabrication process. The radiation dose from the doped fresh fuel will be higher than that of uranium and will likely require remote handling, similar to that of mixed oxide (MOX) fuel.

The work presented here shows that 1 wt.% actinide doping is sufficient to create a proliferation firewall; however, additional simulations will need to be performed with varying masses of these actinides in the fresh IFD fuel to better estimate the minimum doping to create plutonium with 18.1% $^{238}$Pu. Simulations are also needed to evaluate the plutonium composition of the fuel at lower burnups to capture the possibility of material diversion before reaching its full burnup of 190 GWd/MTU. Although $^{238}$Pu concentration is the primary attribute in determining the proliferation resistance of plutonium, other isotopes and factors are also important. A rigorous proliferation resistance assessment should be done with established analysis tools.[3,15]

Various conventional reactor performance characteristics (such as flux peaking factors, core reactivity, fuel pin wised power distribution, and fuel and moderator coefficients) should also be modeled for each modified fuel composition. Simulations should be performed to evaluate the impact of introducing separated plutonium with other actinides into the fresh fuel as a mixed metallic uranium/neptunium/plutonium/americium/zirconium (U-Np-Pu-Am-Zr) fuel. Fuel material of this type may be viable in the future depending on which type of advanced reprocessing method is pursued.

## Conclusion

The results of the burnup calculations for a IFD fuel pin showed that it is plausible for this design to be proliferation resistant. The increased levels of $^{238}$Pu (see Table 2) in the doped IFD fuel can generate enough heat to classify the plutonium as having a proliferation firewall. This preliminary analysis shows the proof of concept and lays the foundation for additional necessary in-depth analysis.

## Acknowledgments

The authors thank the Nuclear Regulatory Commission for partially supporting this work (NRC-HQ-84-14-G-0051). Please note that this work is not sponsored by the Lightbridge Cooperation and that all designs and calculations are based on open source information and best estimate assumptions.

## Keywords

Proliferation resistance, proliferation firewall, metallic fuel

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# A Nuclear Weapons Latency Computational Tool

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## Abstract

A novel nuclear weapons proliferation assessment method has been developed to determine a state's *nuclear weapons latency*, the expected time to be taken by a non-nuclear weapons state to develop a conventionally deliverable nuclear weapon given the state's position on a path toward or away from a nuclear weapon and accounting for the state's motivations and intentions. Potential proliferation time is taken as a representation of the latent proliferation capacity of a non-nuclear weapons state. An assessment of proliferation time is critical to crafting an effective policy response within a useful time frame. Current proliferation assessments either have a limited (or nonexistent) treatment of proliferation time or are static case-specific assessments frequently built on restricted information and opaque assumptions.

A nuclear weapons latency computational tool has been developed to determine a state's nuclear weapons latency. It embodies a stochastic Petri net proliferation simulation. The Latency Tool makes three simple assumptions: (1) a decision to proliferate has been made, (2) the proliferation pathway network is known, and (3) the associated pathway activity times are estimable. Beyond the quantification of a state's latency, the Latency Tool provides a transparent, efficient, adaptable, and highly repeatable platform, which allows for extensive sensitivity analysis to better inform the nonproliferation discussion and policy decisions.

Functionality of the Latency Tool was verified and inherent sensitivities determined through historical analysis with the U.S. case of proliferation in the Manhattan Project. Network and operational parameters were found that drove expected latencies high, whereas others increased the latency distribution variance.

Specific sensitivity testing to policy options such as nuclear technology sale or development enables the Latency Tool to characterize the relative proliferation risk of the options. In this manner, the Latency Tool can help fill a void of useful proliferation risk information provided by technical assessments to policy makers identified by the 2013 National Research Council study *Improving the Assessment of Proliferation Risk of Nuclear Fuel Cycles*.

## Introduction

The proliferation of nuclear weapons is a major threat to U.S. and international security today.[1] Substantial attention has been given to the concept of eliminating all nuclear weapons.[2,3,4] The (potential) nuclear threats of North Korea and Iran regularly grab headlines.[5,6] In 2009, President Barack Obama gave a marquee foreign policy speech vowing to address proliferation concerns and pursue full nuclear disarmament.[7] However, to best address nuclear weapons proliferation and prepare for a world without them, one must fully understand the dynamics of proliferation. Paramount among the characteristics of such proliferation are the time (or "latency") and pathway that a state takes to develop its nuclear weapons given its motivations, intentions, and underlying latent capacities.[8,9,10,11]

Nuclear weapons latency has been defined as "the expected time to be taken by a non-nuclear weapons state to develop a conventionally deliverable nuclear weapon given the state's position on a path toward or away from a nuclear weapon and accounting for the state's motivations and intentions."[12,13] A conventionally deliverable weapon is defined as a weapon deliverable by airdrop, missile, or artillery systems. Proliferation pathways refer to the particular choices, steps, and methods that a state pursues to develop a nuclear weapon. To gain a deeper understanding of the dynamics of nuclear weapons proliferation, it is necessary to create a systematic methodology to quantify nuclear weapons latency.

Figure 1 depicts a simplified, abstract graphical representation of nuclear weapons latency. Three general proliferation pathways are shown as linked nodes. The nodes represent sequential stages of development necessary for successful proliferation, beginning with natural uranium, uranium enrichment or plutonium production, and the weaponization corresponding to each weapon type. Time is indicated on the horizontal axis to illustrate that the required proliferation time is dependent on the path taken. It should be noted that the relative magnitudes of the different pathway times indicated in Figure 1 are purely notional and are for illustrative purpose only.

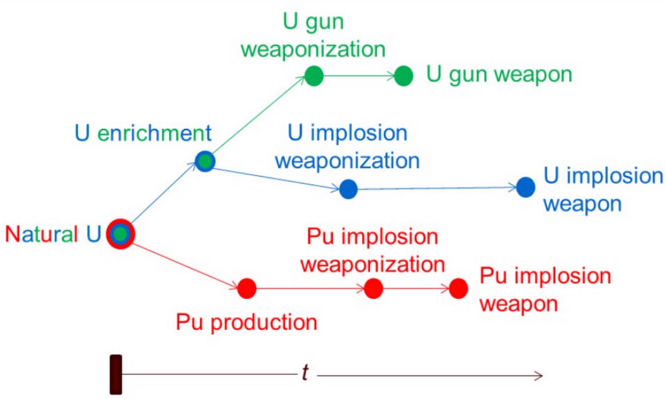


**Figure 1.** Abstract graphical nuclear weapons latency concept representation indicating that uranium (U) gun-type, uranium implosion, and plutonium (Pu) implosion weapons all take different proliferation pathways for production, with potentially different times. (Note: Relative magnitudes of different pathway times are purely notional.)

## The Nuclear Weapons Latency Tool: A Progression of Proliferation Assessments

A nuclear weapons latency computational tool was developed to determine a state's nuclear weapons latency given its current condition, including available resources and motivational environment.[14] Nuclear weapons latency is characterized by an expected time to proliferate and the associated proliferation pathway. It is not a prediction of proliferation; such predictions are perilous.[15] Nuclear weapons latency answers the question, If a decision to proliferate has already been made, how long is it expected to take and what path should the state be expected to follow?

The Latency Tool makes only three simple assumptions: (1) that a proliferation decision has been made, (2) that the network of potential proliferation pathways available to the proliferator is known, and (3) that proliferation network activity times may be reasonably estimated. The first assumption is necessary to limit the scope of the problem to what is tractable. A lack of a clear decision in favor of nuclear weapons development can only slow proliferation. Therefore, the only consequence of this assumption being incorrect is that proliferation times may be underestimated. Expecting proliferation sooner than it might actually occur is a safe and conservative approximation. The other two assumptions are entirely testable. Tool simulations may be run ad infinitum, varying the network and activity time assumptions to quantify their impact. The Latency Tool thus provides a transparent platform to perform repeatable studies using well-defined and variable assumptions that allow for complete sensitivity analysis of the results. In this manner, intuition building by independent users without requiring intensive expert efforts is possible.

### *Proliferation Assessments*

The quantification of nuclear weapons latency as defined above is a type of proliferation assessment that focuses on time and the proliferation pathway. Attempts at assessing proliferation were being made before the first nuclear weapon was even constructed.[16] Modern technical proliferation assessments can be divided into three categories: (1) broad theoretical methodologies focused on assessing the likelihood of proliferation and, in some cases, predicting proliferation that may be applied to any case; (2) proliferation pathway analysis; and (3) specific case-based assessments that apply expert analysis. Closely related to proliferation assessments are proliferation resistance methodologies. These methods focus on evaluating the relative technical difficulty associated with proliferation from specific sets of fuel cycle technology as opposed to assessing state proliferation with different fuel cycle technologies.[17,18,19,20,21, 22,23,24,25,26,27,28,29]

None of the existing proliferation assessment methods provide a complete treatment of nuclear weapons proliferation time that allows for general application and robust sensitivity analysis. Table 1 compares ideal assessment characteristics possessed by the various proliferation assessment methods and the developed Nuclear Weapons Latency Tool. The theoretical methods focus on various metrics, correlations, and indicators to assess proliferation likelihood, sometimes in various stages.[11,30,31,32,33,34,35] Recent special nuclear material (SNM) acquisition pathway analyses use proliferation time as an input criterion for determining pathway attractiveness to a proliferator for allocating International Atomic Energy Agency (IAEA) safeguards resources.[36,37,38] An earlier SNM acquisition assessment by Ford included a deterministic treatment of time as a secondary output based on predefined production learning curves.[39] All SNM acquisition analyses fall short of a complete proliferation assessment by neglecting weaponization and the state's weaponization capability, which should impact policy and resource allocation considerations. A Bayesian pathway analysis method by Freeman involved complete proliferation, including weaponization, but focused solely on pathway likelihood, neglecting proliferation time.[40,41] Case-based proliferation assessments do rigorously address proliferation time, although they are limited by being static, case-specific assessments (real world or hypothetical).[42,43,44,45] These assessments are not generally applicable, require significant expert effort to reproduce or update, and are frequently based on classified information and opaque assumptions.

**Table 1.** Ideal proliferation assessment characteristics

| Proliferation Assessment Types | Proliferation Theory | Pathway Analysis | Specific/ Case-Based | Latency |
|---|---|---|---|---|
| Proliferation Likelihood | Yes | No | Yes | No |
| Pathway Likelihood | No | Yes | Yes | Limited |
| Proliferation Time | No | Limited | Yes | Yes |
| Transparent Assumptions | Yes | Yes | Some | Yes |
| Robust Uncertainty and Sensitivity Analysis | Some | Yes | Some | Yes |
| Easily Reproducible and Widely Applicable | Yes | Yes | No | Yes |

It is clear that despite the substantial contributions of previous assessment methodologies, more development is needed. Thus, a computational tool to determine a state's nuclear weapons latency represents a novel and significant advancement for this field.

Although the latency method treats the actual proliferation decision as an assumption, it does bring distinct advantages. Policy makers and analysts need a reliable method that can promptly provide limits on the window of opportunity they have to influence proliferation and pinpoint the pathway aspects that can be influenced to generate the greatest increase in latency time. This method should also be available in unclassified settings, use transparent assumptions that can be easily adjusted for sensitivity analysis, and be usable by nonexperts to generate valid results. The Nuclear Weapons Latency Tool satisfies these needs.

## Latency Calculation Methodology

The Nuclear Weapons Latency Tool determines a state's nuclear weapons latency by simulating state proliferation through a Petri net model. The problem confronting a decided state proliferator is essentially the well-known resource-constrained scheduling problem (RCSP).[46] Large-scale projects like nuclear weapons development rarely go as planned, and simulations of a proliferator's progress are best represented with a stochastic probability model. Generalized Stochastic Petri Nets (GSPNs) have served well as both an RCSP solution method and a dynamic probability model.[47] Petri nets are highly flexible and also reduce the potential for intractable growth of the probabilistic state-space associated with other probability modeling techniques that could be problematic given the numerous options for proliferation and desired modeling detail. This section describes Petri nets and their application in the Nuclear Weapons Latency Tool, along with inputs and outputs from the Latency Tool.

### *Petri Net Theory*

Petri nets are a simple yet powerful simulation technique for modeling complex systems.[48,49,50] Petri nets are directed bipartite graphs consisting of *places* and *transitions*, represented by circles and bars, respectively. Directional arcs connect places to transitions and transitions to places. Any number of places may connect to a single transition and vice versa. However, places cannot connect directly to other places, and transitions cannot connect directly to other transitions.

Dots located within the places are called *tokens*. The location of these tokens within the network places is known as the *marking* and represents the state or evolution of a Petri net simulation. Tokens may move from an upstream place to a downstream place as the simulation evolves when the transition between the two places fires. Before firing, a transition must first be enabled. A transition is enabled when all places immediately preceding the transition accumulate the number of tokens corresponding to the weight of the arc connecting that place to the subsequent transition. When a transition fires, it removes tokens from all its immediately preceding places and adds tokens to all the places immediately downstream from the transition. The amount of tokens removed from and added to each place corresponds to the weights of the arcs connecting the places and transition.

Figure 2 depicts the simple example of simulating the process of assembling a wagon with a Petri net. Place 1 ($p_1$) represents the number of wagon wheels available. Each token in $p_1$ represents a wagon wheel. Place 2 ($p_2$) represents the number of wagon chassis. Place 3 ($p_3$) represents assembled wagons. Transition 1 ($t_1$) represents the activity of assembling a wagon. The arc weights denoted in Figure 2 dictate that it requires four wagon wheels and one wagon chassis to assemble one wagon.

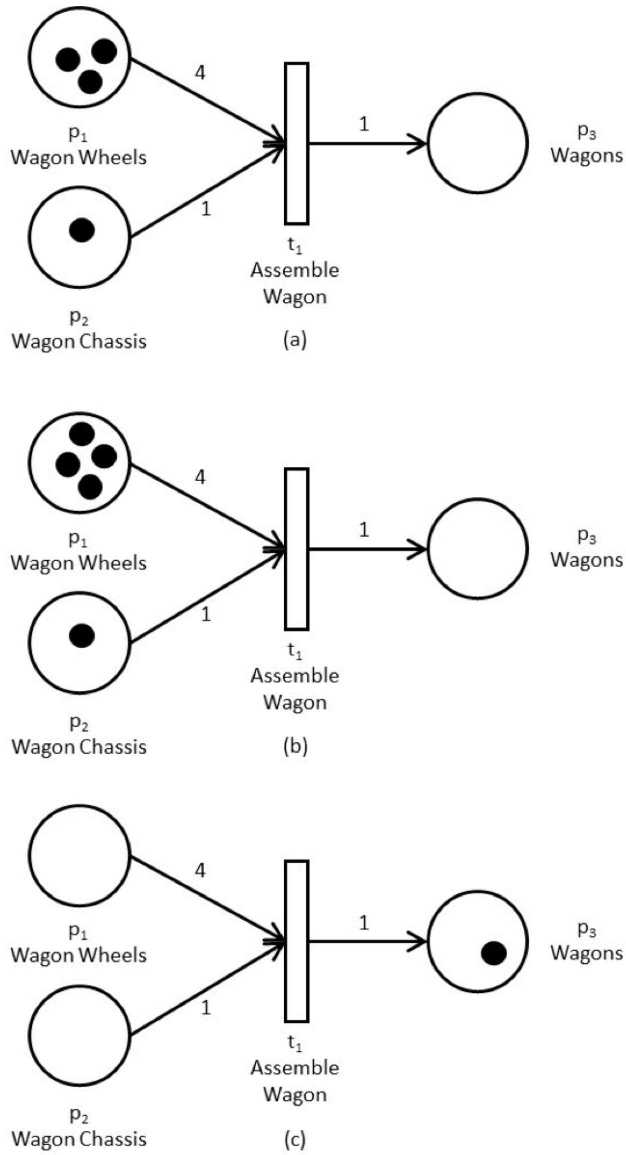


**Figure 2.** Simple Petri net for wagon assembly: (a) transition 1 is not enabled, (b) transition 1 is enabled, and (c) after Transition 1 fires.

Figure 2 illustrates the process of enabling and firing $t_1$—i.e., assembling a wagon. Figure 2(a) shows three tokens in $p_1$ and one token in $p_2$, indicating that there are three wagon wheels and one wagon chassis available, respectively. The $p_1t_1$ arc weight of four dictates that at least four tokens must be present in $p_1$ (four wagon wheels) for $t_1$ to be enabled. In Figure 2(a), $t_1$ is not enabled because there are fewer than four tokens in $p_1$. In Figure 2(b), an additional token has been added to $p_1$, thus enabling $t_1$. Figure 2(c) illustrates the marking after $t_1$ fires. Four tokens from $p_1$ and one token from $p_2$ have been removed, while one token has been added to $p_3$, indicating that one wagon has been assembled.

Inhibitor arcs can add a further degree of control to a Petri net.[49,50] Inhibitor arcs are connected from places to transitions. When the amount of tokens in the place is greater than or equal to the weight of a connected inhibitor arc, the associated transition is blocked from firing, even if the current marking would otherwise enable the transition. Figure 3 shows the net of Figure 2 with $t_2$: enact wagon production moratorium, $p_4$: wagon production moratorium, and $t_3$: remove wagon production moratorium added. Figure 3 also has an inhibitor arc added from $p_4$ to $t_1$ with an arc weight of 1, indicating that one wagon production moratorium will inhibit the production of wagons even if $t_1$ would otherwise be enabled. In Figure 3(a), $t_1$ is enabled. Figure 3(b) has the same marking as Figure 3(a), but an additional token in $p_4$ inhibits $t_1$ from being enabled and subsequently firing.

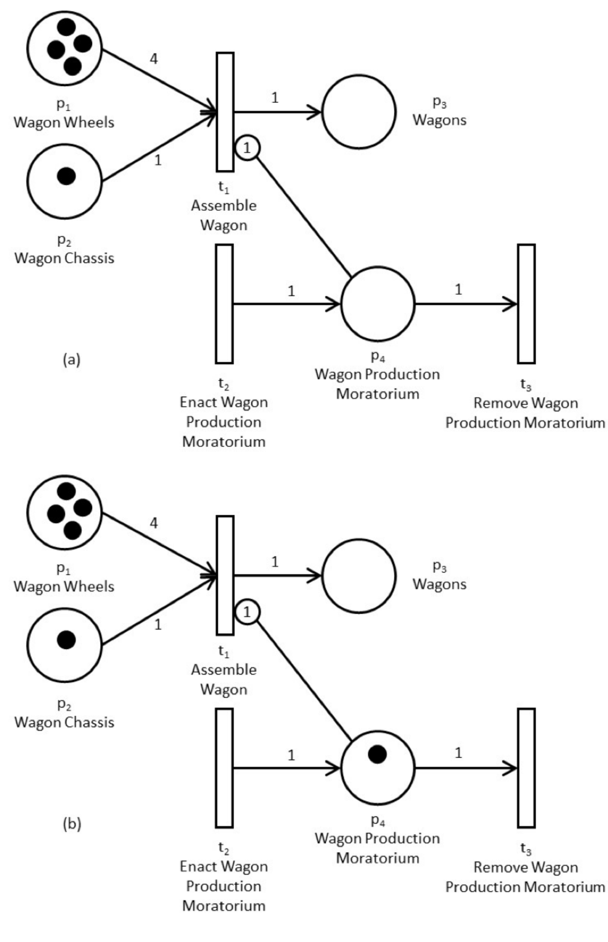


**Figure 3.** The wagon assembly Petri net of Figure 2 augmented with an inhibitor arc representing (a) Transition 1 enabled and (b) Transition 1 inhibited by Place 4, a wagon production moratorium.

The mathematical representation of Petri nets is straightforward.[48,49,50] A Petri net is defined as the following 6-tuple:

$$PN = \{P, T, D^-, D^+, H, M_0\} \quad (1)$$

where

$P = \{p_1, p_2, \ldots, p_r\}$ is the set of $r$ places;
$T = \{t_1, t_2, \ldots t_s\}$ is the set of $s$ transitions, $T \cap P = \emptyset$;
$D^- \subset (P \times T)$ is the set of transition input arcs;
$D^+ \subset (T \times P)$ is the set of transition output arcs;
$H \subset (P \times T)$ is the set of inhibition arcs;
$M: P \to \mathbb{N}$ is the marking that lists the number of tokens in each place with initial marking $M_0$.

Petri nets are functionally represented through matrices. The input, output, and inhibition matrices $D^-$, $D^+$ and $H$ are all $s \times r$ matrices. The matrix element $d_{ij}^-$ is equal to the arc weight connecting place $p_j$ to transition $t_i$. The element  is equal to the weight of the arc connecting transition $t_i$ to place $p_j$. The element $h_{ij}$ of inhibition matrix $H$ is equal to the weight of the inhibitor arc connecting place $p_j$ to transition $t_i$. The incidence matrix is then $D = D^+ - D^-$. For example, the PN of Figure 3 is represented as

$$D^- = \begin{bmatrix} 4 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (2)$$

$$D^+ = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad (3)$$

$$H = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \text{ and} \quad (4)$$

$$D = \begin{bmatrix} -4 & -1 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -1 \end{bmatrix}. \quad (5)$$

The marking in Figure 3a is $M_a = [4\ 1\ 0\ 0]$. If $\vec{e_j}$ is an $r$-dimensional row vector with all elements equal to zero except element $j = 1$, then transition $j$ is enabled to fire when

$$M \geq \vec{e_j} D^-. \quad (6)$$

Furthermore, for transition $j$ to be enabled, it must not be inhibited as

$$M < \vec{e_j} H \text{ if } \vec{e_j} H > 0. \quad (7)$$

When transition $j$ fires, the new marking becomes

$$M' = M + \vec{e_j} D \quad (8)$$

for all transitions $j$ to be fired at that moment. Thus, the marking of Figure 3b after transition 4 fires is $M_b = M_a + [0\ 0\ 0 - 2 - 1\ 1] = [0\ 2\ 0\ 0\ 0\ 1]$. A PN simulation may end when the marking reaches some desired state as $M \geq M_{desired}$.

Figure 4 redefines the places and transitions of the Petri net of Figure 3 to make it more relevant to nuclear weapons proliferation. While keeping the same network structure of the trivial wagon wheel example, the example of Figure 4 represents uranium enrichment with the potential for an agreement to limit highly enriched uranium (HEU) production. Natural uranium, an operational uranium enrichment facility configured for HEU production, HEU, and an HEU production limitation agreement are represented by places $p_1$, $p_2$, $p_3$, and $p_4$, respectively. Enrichment of natural uranium to HEU, negotiation of an HEU production limitation agreement, and withdrawal from an HEU limitation agreement are represented by transitions $t_1$, $t_2$, and $t_3$, respectively.

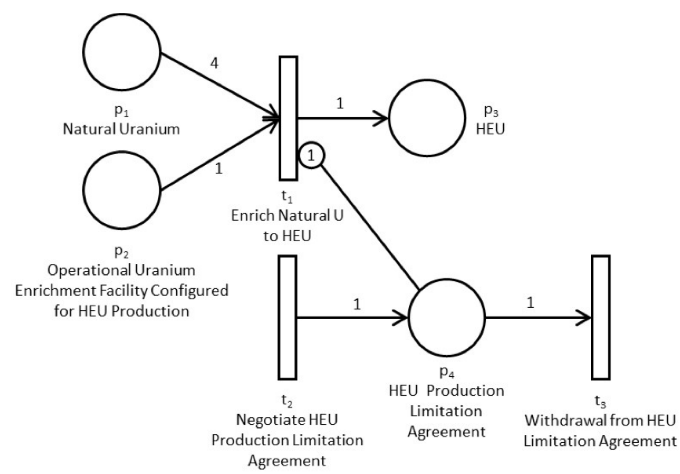


**Figure 4.** Wagon assembly with inhibitor arc of Figure 3 redefined to represent highly enriched uranium (HEU) production with the potential to be blocked by an HEU production limitation agreement. (Note: This is a simplified representation for illustrative purposes.)

It should be noted that Figure 4 is a notional construct for illustrative purposes. It is likely that a more accurate representation of this scenario would be much more complex. In Figure 4, four tokens in $p_1$ representing four units of natural uranium are required to produce one token in $p_2$ representing one unit of HEU using the notional uranium enrichment facility represented by one token in $p_2$. The Petri net will function as defined without regard to reality. It is up to the user to correctly define the appropriate units of measure and quantities represented by one token for each place. Furthermore, the units and quantities represented by tokens are defined relative to that specific place. As illustrated in Figure 2, Figure 3, and Figure 4, the tokens represent different items in each place.

Timed Petri nets require a specific amount of time to pass before the movement of tokens may occur.[51,52] Time in Petri nets may be linked to either the transitions, places, or arcs of the net or to the tokens. For this research, transitions are associated with proliferation activities that may occur. As such, time is associated with the transitions. Once a transition is enabled, the transition time begins counting. Only once the time is complete is the transition fired. The latency net developed is a stochastic timed PN, as the activity times are randomly sampled from user-defined probability density functions (PDFs) each time any transition is enabled. This methodology allows for the dynamic fluctuation of activity times as they may be realized in undefined future events.

### *Main Petri Net Function*

The Latency Tool implements a stochastic timed Petri net using the MATLAB programming language.[53] The primary activity of the Petri net loop is the maintenance of three arrays: the marking, *M*; a list of enabled transitions, *ET* (which is reset to zero after each time step); and a list of timing transitions, *TT* (the remaining times before previously enabled transitions may fire). At the beginning of each simulation iteration or run, *M* is set to the initial marking $M_0$. The Petri net function loop then starts by checking *M* and enabling transitions in *ET*. *ET* is then checked for transition conflicts, and conflicted transitions are de-enabled in random fashion (as described below). Activity times are sampled for the remaining enabled transitions and stored in *TT*. Simulation runtime is advanced by subtracting the time step *TS* from *TT* at the end of each iteration. Transition *j* is fired when $-TS < TT_j \leq 0$. The elements of *TT* are initially set to —*TS* and reset to this value after firing to prevent extraneous transition firing. When the marking is greater than or equal to the user-defined deliverable nuclear weapon marking, $M_{DNW}$, the simulation run is complete. Figure 5 symbolically illustrates the conceptual flow of the latency Petri net and maintenance of the three arrays

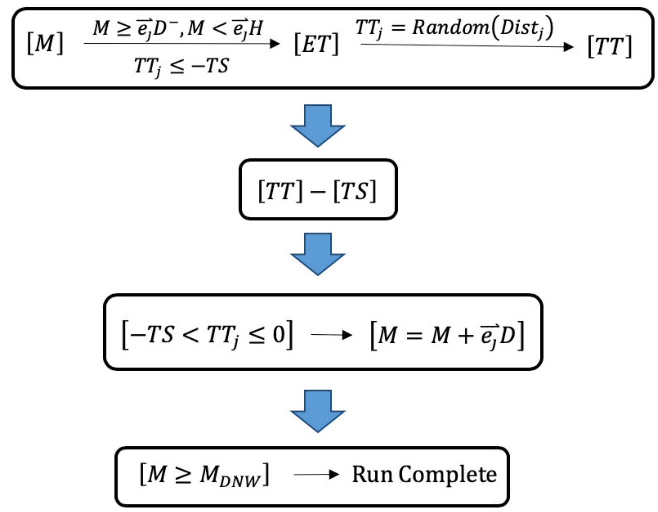


**Figure 5.** Conceptual flow of Latency Tool Petri net simulation.

Figure 6 describes the overall flow of the Nuclear Weapons Latency Tool. The proliferation network available to the proliferator is defined by the transition input, output, and inhibit (and incidence) matrices. However, there are normally multiple independent paths within the full proliferation network from which the proliferator may select a preferred path. These independent paths, defined by the transitions that must fire to complete them, are also input by the user. The Nuclear Weapons Latency Tool has a built in subfunction to generate all possible combinations of the independent paths, allowing the simulation to choose from a complete range of proliferation pathways through the independent paths defined by the user. Without detailed insight of the motivations and intentions of the proliferator, path selection is done randomly at user-specified intervals. Transitions not on the selected path are permanently blocked from being enabled unless those transitions are part of a path selected later in the simulation. Other required inputs are the transition activity time PDFs and associated parameters as well as the initial marking and the deliverable nuclear weapon marking. At the time of this publishing, the Latency Tool is capable of sampling from uniform PDFs and log-normal PDFs. Other PDFs can easily be added.

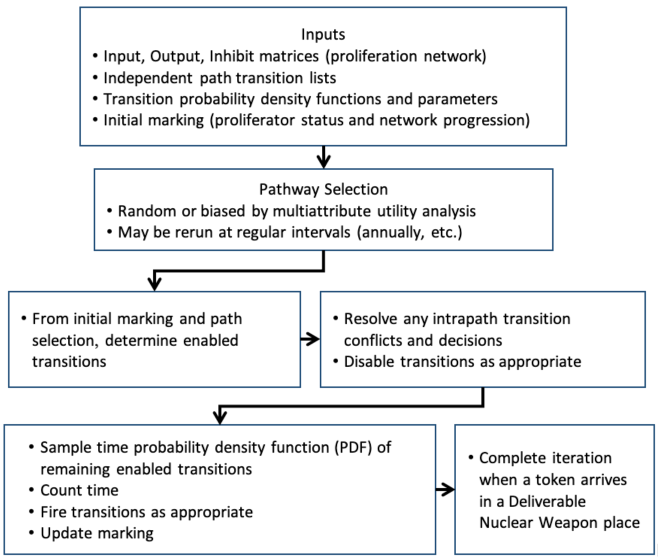


**Figure 6.** Overall flow of the Latency Tool.

The Nuclear Weapons Latency Tool includes several other features to facilitate its operation. It is possible for intrapath conflicts to occur where two or more transitions are enabled by the same tokens in upstream places, even though there are not enough tokens for all the transitions to fire. This scenario is easily envisioned when considering financial resources. Figure 7 shows a hypothetical Petri net with $p_1$: Financial Resources, $p_2$: Enrichment Facility, $p_3$: Nuclear Reactor, $t_1$: Build Enrichment Facility, and $t_2$: Build Nuclear Reactor. As indicated by the arc weights of Figure 7, $t_1$ requires three tokens of $p_1$: Financial Resources to be enabled, whereas $t_2$ requires four tokens from $p_1$. There are five tokens in $p_1$, which is greater than each of the individual arc weights outgoing from $p_1$. Thus, $t_1$ and $t_2$ should both be enabled. However, to successfully fire both $t_1$ and $t_2$, $p_1$ should have at least seven tokens; the sum of both outgoing arc weights from $p_1$. Therefore, $t_1$ and $t_2$ are referred to as “conflicted” because they are competing for the same tokens from $p_1$.

To resolve conflicted transitions, a check for intrapath conflicts is done after the enabled transitions are determined. When conflicts are found, a subfunction randomly disables one of the conflicted transitions, rechecks for remaining conflicts, and repeats the process until there are no remaining conflicts. The remaining enabled transitions will then receive sampled activity times and progress accordingly.

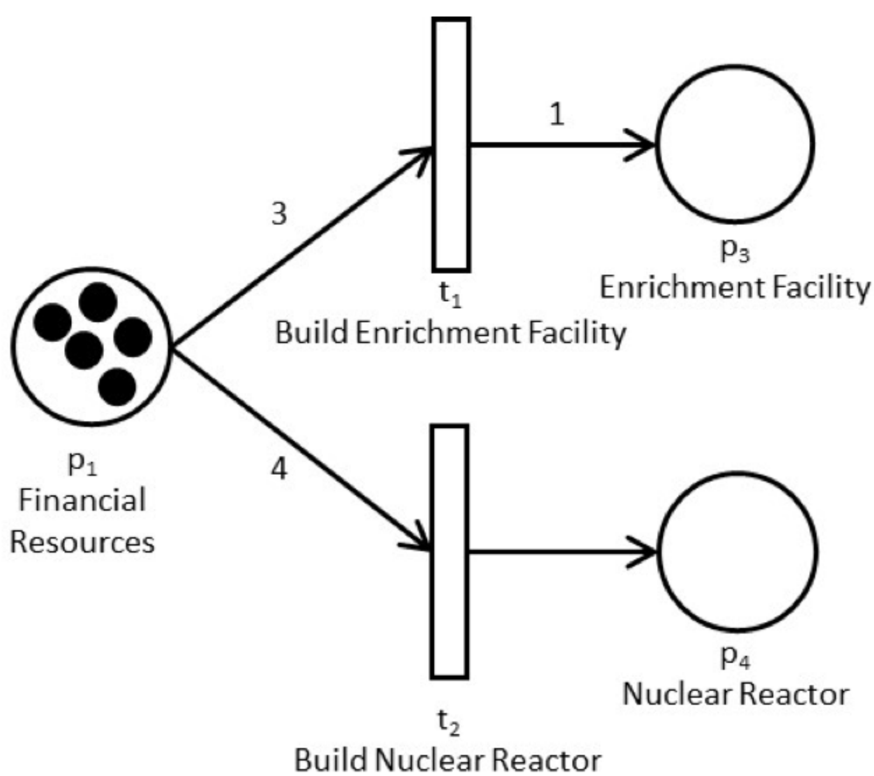


**Figure 7.** Hypothetical Petri net illustrating the concept of two conflicted transitions—$t_1$: Build Enrichment Facility and $t_2$: Build Nuclear Reactor— due to limited financial resources.

Simulation computation time was reduced by switching from a fixed time-step progression to an event-based progression. Instead of advancing the simulation time by one time step for each loop iteration, simulation time was advanced immediately to either the next time a transition would fire or the next time of a pathway selection. This required the inclusion of a separate array to track the progression of simulation time. The savings in computation time were well worth the effort. It should be noted that computation time savings from event-based progression may be lost when using short activity times for transitions that are repeated often during network simulation.

A moderately detailed pseudocode is provided in Figure 8. This pseudocode algorithm itself resides within a loop over the number of desired simulation iterations. Because individual simulations may take hours to days, a batch calling file was also developed.

Operation of the Latency Tool is straightforward. Input matrices are generated graphically using Microsoft Visio and an

$$M = M_0$$
$$TT = -TS$$

Time = 0<br>
For i=1:Max simulation time<br>
    $ET = 0$<br>
    if time ∈ pathway selection interval<br>
        randomly select path<br>
    end<br>
    $M_{dummy} = M - \overrightarrow{e(TT_j)}D^- \ \forall\ TT_j > 0$ % remove tokens reserved for timing transitions<br>
    For all $j$ transitions<br>
        If $M \geq \vec{e}_j H$ & $TT_j > 0$ % a timing transition is now inhibited<br>
            $M_{dummy} = M + \overrightarrow{e(TT_j)}D^- \ \forall\ TT_j > 0$ % release reserved tokens<br>
        Else if $M < \vec{e}_j H$ & $TT_j \leq -TS$<br>
            $ET_j = 1$<br>
        end<br>
    End<br>
    Check $ET$ for and resolve intrapath conflicts<br>
    For all $j$ transitions<br>
        If $ETj$ = 1<br>
            $TT_j = random(dist_j)$<br>
        end<br>
    End<br>
    $\text{Clockadvance} = \min(\text{time to next transition fire, time to next path selection})$<br>
    $\text{TT} = \text{TT} - \text{Clockadvance}$<br>
    $\text{Time} = \text{Time} + \text{Clockadvance}$<br>
    if $-TS < TT_j \leq 0$<br>
        $M = M + \vec{e}_j D$<br>
    End<br>
    If $M \geq M_{DNW}$<br>
        $\text{Iteration Latency} = \text{Time}$<br>
    End<br>
End

**Figure 8.** Latency Tool Petri net pseudocode

associated macro.[14] Furthermore, a batch file was created to facilitate case variation and repeated operations. The primary output from the Latency Tool is the latency time for each simulation iteration. Latency times are also tabulated per path with associated mean or expected values, the standard deviation, and minimum value. Pathway selection probabilities—useful when using the MAUA path selection function, statistical transition firing data, and marking data—are also reported.

## Latency Tool Verification and Historical Analysis with the U.S. Case

Before using any newly developed computational tool, it is necessary to verify and possibly validate its function against experimental results when applicable.[54] Verification is done to ensure that the tool functions as designed and expected. This is accomplished by providing the tool with simple inputs for which the expected results are obvious. Experimental validation requires matching tool outputs to results of actual experiments. The experiment for the Latency Tool is the future. By definition, the results of the future are, and will always be, unknown. As such, it is impossible to experimentally validate the Latency Tool. This does not detract from the Latency Tool's value to build intuition, test sensitivities, and inform decision makers.

In the absence of true experimental validation, historical case analysis is done to build confidence in the verification. It should be noted that while history provides a useful guide to and may impact the future, future cases of proliferation (and the future in general) are new and unique experiments that may vary from history unexpectedly.[55] The best known case of nuclear weapons proliferation is the U.S. Manhattan Project. This case is used as an initial historical analysis to verify code function and test the inherent sensitivities of the Latency Tool.[56]

### *U.S. Network*

For verification, the U.S. Manhattan Project was broken into four cases of materials production, which were modeled as Petri nets and analyzed. Petri nets can determine passage time to any point in the network for any amount of tokens, so analysis can be done on portions of a single historical case of nuclear proliferation. The following four cases were considered:

1. Liquid thermal diffusion uranium enrichment in the S-50 facility
2. Gaseous diffusion uranium enrichment in the K-25 facility
3. Electromagnetic isotope separation uranium enrichment in the Y-12 facility
4. Plutonium production at the W facility at Hanford (along with its pilot X program at the Clinton site)[57]

The full combined case of U.S. proliferation is also included in the analysis, which added a weaponization layer involving weapons and delivery system design and production (which involved retrofitting existing B-29 bombers). The characteristics of each case are given in Table 2, which lists by column the network material production model, the general activities represented by the models, and the target latency quantity desired for simulation completion. Because the completion goal for these partial proliferation cases was not a single deliverable nuclear weapon, substitute latency quantities, established from historical references and given in Table 2, were used as simulation endpoints. A historical timeline of U.S. proliferation builds the U.S. case with transition data with the historical reference times; the place data with initial markings and completion markings (when a latency quantity is filled); Petri net matrices $D^{-}$, $D^{+}$, and $H$ for the S-50, K-25, Y-12, and W&X material production cases; and weaponization. Reference 14 contains the full U.S. case in three levels of network resolution and an appendix containing calculations and tables in detail of the network resolution.

**Table 2.** U.S. case latency network characteristics

| Network Model | Activities | Transitions | Places | Latency Quantity |
|---|---|---|---|---|
| Liquid Thermal Diffusion S-50 | R&D; LTD facility: Lab Scale, Pilot Scale, Full Scale | 29 | 11 | 20,420 kg 0.85wt% U-235[a] |
| Gaseous Diffusion K-25 | R&D; barrier plant: Pilot Scale, Full Scale; Full-Scale GD Plant | 21 | 22 | 210 kg 7wt% U-235[b] |
| Electromagnetic Isotope Separation Y-12 | R&D; Lab Scale; Alpha Track Facility, Beta Track Facility | 21 | 18 | 66 kg 80wt% U-235[c] |
| Plutonium Production W (Hanford) and X (Clinton) | Graphite Reactor: Lab Scale, Pilot Scale, Full Scale; Separations Plant: Pilot Scale, Full Scale; Graphite Production; Fuel Slug Canning | 59 | 55 | 19 kg Pu[d] |
| U.S. Full | All, including a design and weaponization layer | 160 | 133 | 1 deliverable nuclear weapon (HEU or PU) |

[a]S-50 production through July 1945.[58]
[b]Derived from [c] the approximated Little Boy uranium content.[59,60]
[d]Approximated plutonium content of three Pu cores finished July 1, 1945.[59,60]

As a graphical reference for the scale of the networks developed, Figure 9 shows the complete Pu production Petri net built in MS Visio with an inset zoom of Hanford Pile operation and refueling. As shown in the key in the Visio environment, the large circles are places, the tall rectangles are transitions, and the small rounded rectangles (ovals) are used to denote the arc weights between places and transitions. Actual tokens are not shown in the Visio networks because the initial marking is specified as an input directly to the Latency Tool.

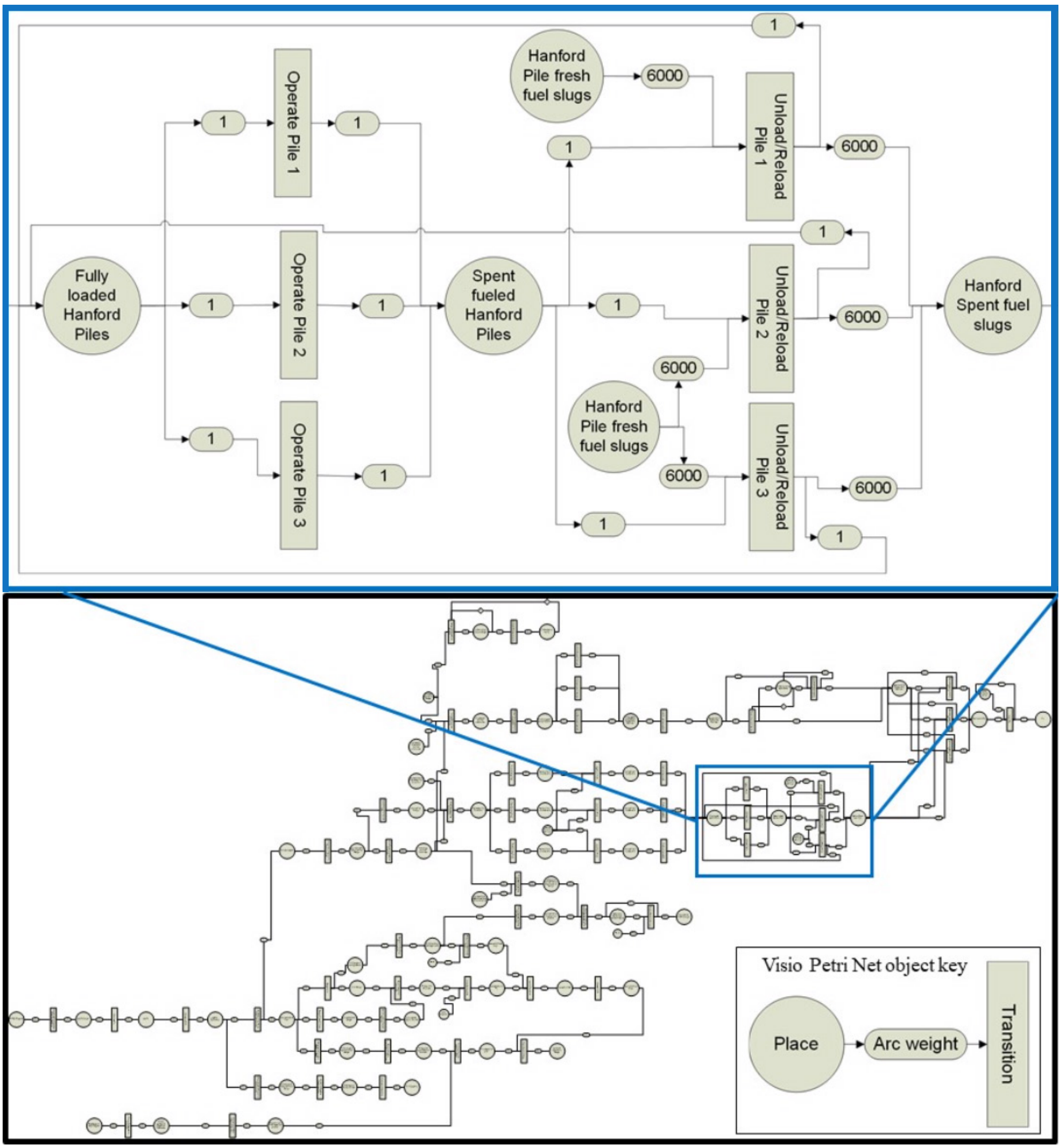


**Figure 9.** Complete U.S. Pu production Latency Petri net with zoom inset above and Visio Petri net object description key in the lower right. Note: The place "Hanford Pile fresh fuel slugs" appears twice in this figure to avoid excessive arc overlap, but it is counted as only a single place in the actual Petri net matrix.

The inset of Figure 9 traces the irradiation of fresh uranium fuel slugs for plutonium production through Hanford nuclear reactors known as "piles" during the Manhattan Project. Starting at the left of the inset, this network snippet begins with the "Fully loaded Hanford Piles" place. Here, "fully loaded" refers to the pile being fully loaded with Hanford fuel slugs. Tokens collected in the "Fully loaded Hanford Piles" place represent the number of fully loaded piles available. Three Hanford Piles were in operation during the Manhattan Project. While these three Hanford Piles are represented by three tokens in the one "Fully loaded Hanford Piles" place, three separate Hanford Pile operation transitions are necessary to allow for simultaneous pile operation. The operation transitions are labeled "Operate Pile 1," "Operate Pile 2," and "Operate Pile 3," where the numbers in the names are more appropriately associated with the transitions than a specific Hanford Pile. It should be noted that if there are not three tokens in the "Fully loaded Hanford Piles" place, the three pile operation transitions could be conflicted because there would not be enough tokens for all three operation transitions to fire. As previously discussed, the Latency Tool algorithm would resolve any conflicts that may occur during the simulation. After pile operation, single tokens flow to the "Spent fueled Hanford Piles" place. One token in the "Spent fueled Hanford Piles" place and 6,000 tokens in the "Hanford Pile fresh fuel slugs" are required to enable and fire transitions "Unload/Reload Pile 1," "Unload Reload Pile 2," and "Unload Reload Pile 3" (the numbers in the transition names are more appropriately associated with the transitions than a specific Hanford Pile). Tokens in the "Hanford Pile fresh fuel slugs" correspond to individual fresh fuel slugs. Hanford Piles were initially charged with 65,000 fuel slugs, but during pile reloading, only 6,000 spent fuel slugs were removed and replaced with fresh fuel slugs, while the remaining 59,000 fuel slugs were rotated in the pile. After each fuel unloading and reloading transition, 6,000 tokens representing individual spent fuel slugs flow to the "Hanford Spent fuel slugs" place, and one token flows back to the "Fully Loaded Hanford Pile" place, indicating that a loaded Hanford Pile is ready to restart the process. Table 3 provides the excerpted transition historical reference timetable for the transitions shown in Figure 9. For the stochastic simulations performed in this study, the transition activity time distributions were used as discussed based on the historical reference times.

**Table 3.** Excerpted transition historical reference timetable for transitions shown in Figure 9. Note: For the stochastic simulations, activity time distributions were used as discussed based on the historical reference times.

| Number | Transitions | Reference Time (days) |
|---|---|---|
| [...] | [...] | [...] |
| 15 | Unload/Reload Pile 3 | 1 |
| 16 | Unload/Reload Pile 2 | 1 |
| 17 | Unload/Reload Pile 1 | 1 |
| 18 | Operate Pile 3 | 21 |
| 19 | Operate Pile 2 | 21 |
| 20 | Operate Pile 1 | 21 |
| [...] | [...] | [...] |

### *Verification with Discrete and Stochastic Simulations*

Verification of the Petri net latency simulation occurred in two steps. First, activity durations were derived from history for the corresponding transitions of the developed Petri nets. These discrete values were then used as constant transition firing times in the latency simulations. The resultant latency time produced for each case with constant transition firing times is taken to be the "latency standard." Because the latency standard was derived using historically accurate data, we expect good agreement between the latency standard and the actual historical proliferation time if the Nuclear Weapons Latency Tool is accurately simulating the nuclear weapons development program.

Figure 10 shows historical target dates along with the percent difference of the associated latency standard time. Dates derive from references given for corresponding Table 2 quantities. The U.S. decision date for proliferation is assumed to be January 19, 1942, when President Franklin Roosevelt approved the third National Academies study on the subject.[57] The Little Boy completion date was assumed when HEU fabrication completed, as the rest of the Little Boy bomb weapon had already been finished.[57] The Fat Man completion date was assumed to be at the successful Trinity test because the Pu pit and explosive lenses required for implosion were already fabricated.[57] The latency standard times very closely agree with the actual historical targets. This was expected because historically accurate details for the individual steps were inserted and then aggregated by the Petri net simulation to determine the completion date. This is a useful verification test that demonstrates that when given accurate inputs, the Latency Tool will produce accurate outputs. The network models and transition times could be further refined to precisely replicate the historical times, but this is not necessary.

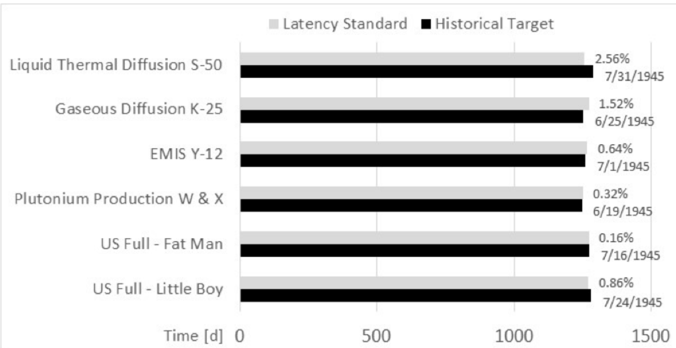


**Figure 10.** U.S. network pathway historical times compared with latency standard. Listed to the right of the bar graphs are the percentage differences between the latency standard and the historical target as well as the actual historical date for the endpoint.

Discrete transition times were replaced with uniform PDFs with bounds 50% above and below the historically derived activity time to complete the verification. Each simulation used 1,000 simulation runs. Each run in a simulation produces a latency time. Frequency distributions of single-iteration latency times will subsequently be referred to as "latency distributions." The single-valued nuclear weapons latency results for a simulation of importance are the expected value or mean and minimum of the latency distribution. These values are referred to as the "expected latency" (time) and the "minimum latency" (time). Note that the minimum latency is the shortest time observed from the simulation; It is not necessarily the absolute minimum that could be calculated deterministically from the network if desired.

Figure 11a–11d illustrates the resulting latency distributions using uniform transition-time PDFs for the S-50, K-25, Y-12, and W&X material production cases, respectively. The shape of the latency distributions resulting from the use of uniform transition-time PDFs consistently appears to be Gaussian. Both the historical and latency standard times of each material production case fall within the associated latency distribution. However, it is also apparent that all the latency distributions of Figure 11 have a shift to the right of the reference times. This shift results in the associated expected latency times being about 200 days higher than the reference times. This discrepancy is due to the transition-time PDF bound and time-step precision. This precision sensitivity is discussed in the next section.

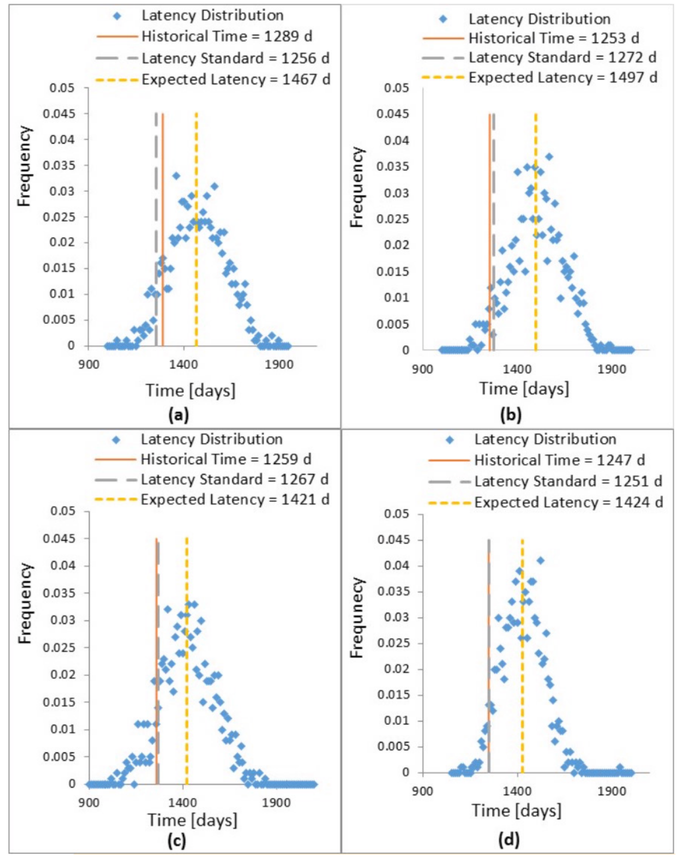


**Figure 11.** Latency distributions from simulations using uniform transition-time probability density functions with bounds +/– 50% of the reference times with historical and latency standard times shown for the U.S. materials production subcases (a) S-50, (b) K-25, (c) Y-12, and (d) W&X.

For the simulation of the full U.S. case, all material production cases were combined with a weaponization (WP) layer. The combinations of these components resulted in seven optional paths through the U.S. proliferation network: (1) S-50, K-25, and WP; (2) Y-12 and WP; (3) S-50, K-25, Y-12, and WP; (4) W&X and WP; (5) S-50, K-25, W&X, and WP; (6) Y-12, W&X, and WP; and (7) S-50, K-25, Y-12, W&X, and WP. Historically, S-50 never produced any uranium above slightly enriched and had use only as a feed for either Y-12 or K-25.[57] Furthermore, K-25 used only the S-50 product as a feed until after the war.[57] Thus, those two material production options do not appear independent of each other as an isolated path for producing an HEU weapon.

Figure 12 shows the latency distribution for the full U.S. case for all paths. Historical completion times for Little Boy and Fat Man, latency standard times for each path, and the expected latency time, including all paths, are shown with the latency distributions of Figure 12. Figure 12 illustrates the same effects from Figure 11. The latency distributions resulting from uniform PDF transition times are mostly Gaussian, the reference times fall within the latency distributions, and the latency distributions and expected values are shifted above the reference times. Additionally, computational time for the full U.S. case of 160 transitions and 133 places run for 1,000 iterations was approximately 8,491 seconds or 2.36 hours. The simulation was run on a Dell Optiplex desktop computer with 16 GB of DDR2 RAM.

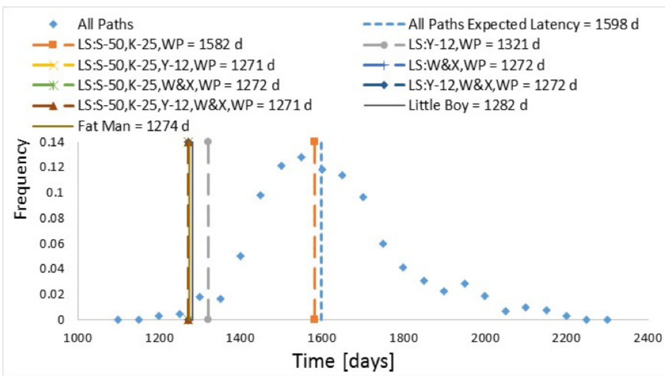


**Figure 12.** Latency distributions for the full U.S. case compared with historical time, pathway latency standard (LS) time, and the expected latency time from all paths. (Note: Some LS times are equal and obscured.)

Together, the results of Figure 10, Figure 11, and Figure 12 verify the function of the Latency Tool. When given accurate, discrete transition times for an appropriate model, the Latency Tool gives accurate results. When transition times are sampled stochastically from PDFs based on accurate reference times, the Latency Tool will simulate results that contain the accurate result, but with the mean systematically biased high. The cause of that bias is discussed in the next section.

### *Input Precision Sensitivity: Transition Activity Time PDF Bounds and Time Step*

The shift of the latency distributions to the right of the latency standard in Figure 11 and Figure 12 can be explained by a bias resulting from the precision in the transition activity time PDF bounds and Latency Tool operation time step. It was initially decided that using uniform PDF bounds with precision less than 1 day would be impractical for approximating multiyear activities, and the input bounds were rounded up to the nearest day. Furthermore, it was also judged impractical to operate the Latency Tool such that it would track time steps of less than 1 day. The impact of these assumptions was tested by varying the precision of the input transition bounds and allowing a time step of less than 1 day.

The results of the input transition bound and time-step precision sensitivity analysis for the S-50 subcase appear in Figure 13. Figure 13a contains the latency distributions determined for S-50 while varying the time step from 1 day, 0.5 day, to 0.1 day while rounding the transition-time bounds to the nearest day and leaving the bounds unrounded. Figure 13a includes the S-50 latency standard and historical time as vertical lines for comparison with the distributions. It was expected that these reference times would occur near the center of a Gaussian latency distribution produced from the S-50 model. In Figure 13a, the simulation with rounded bounds and a time step of 1 day produced the latency distribution farthest to the right. Moving from right to left, the next two latency distributions were from simulations with rounded bounds and time steps of 0.5 days and 0.1 days, respectively. The next three latency distributions all had unrounded transition activity time bounds and occur in order from right to left, with simulation time steps of 1 day, 0.5 days, and 0.1 days. The unrounded bound, 0.1 day time-step latency distribution is nearly centered about the S-50 latency standard in agreement with the initial expectation. Thus, it is clear that the latency distributions shifted left toward the latency standard as bound and time-step precision was increased.

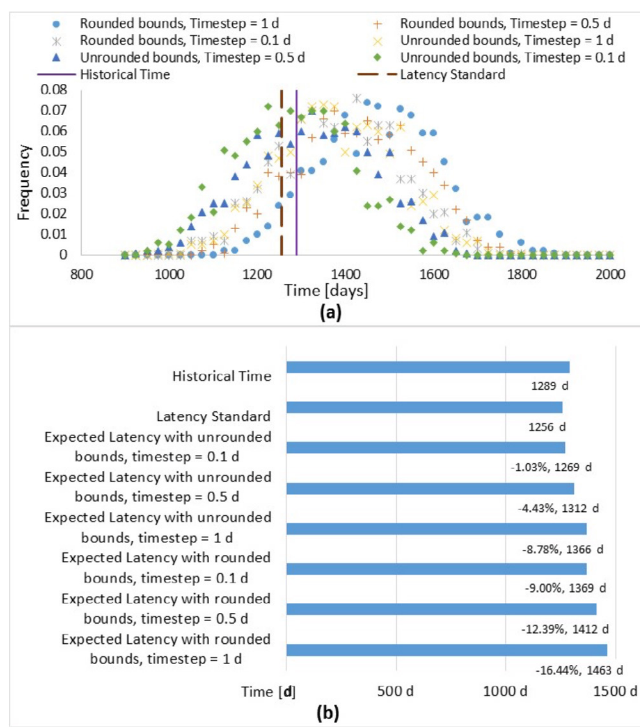


**Figure 13.** Sensitivity to bound and time-step precision for the S-50 subcase showing (a) latency distributions compared to the latency standard and historical time and (b) expected latencies compared to the latency standard and historical time showing percent difference with the latency standard and time value in days

Figure 13b is a bar chart depicting the S-50 historical time, latency standard, and expected latency times for each of the S-50 precision sensitivity cases. Data labels on the bars in Figure 13b show the actual time in days for each of the values as well as the percent difference with the latency standard for each of the expected latencies generated (percent difference with the latency standard is neglected for the historical time). The expected latency for the case with rounded bounds and a time step of 1 day begins at the bottom of the Figure 13b. Moving up Figure 13b, the expected latencies are given while reducing the time step to 0.5 days and 0.1 days. Then expected latencies are shown for unrounded transition-time PDF bound cases while the time step is again varied from 1 day, 0.5 days, and 0.1 days. The latency standard and historical time for the S-50 case are given at the top of Figure 13b. The results of Figure 13b illustrate that by increasing the precision of the bounds and time step, one can reduce the difference between the expected latency and latency about 200 days or 15% for the S-50 case.

Figure 13 demonstrates that the precision of the inputs and time step can bias the resulting latency distributions and expected times high. Figure 13 shows how both the Gaussian latency distributions and expected latencies converge toward the latency standard times as the bound and time-step precision are increased. Figure 13b shows the improved accuracy of the expected latencies expressed as percent difference with the latency standard with increasing precision. It is clear from the analysis that both input precision and time-step size can bias latency results high. Simply rounding those parameters to the nearest day can be expected to increase latency by as much as 15%.

### *Additional Sensitivity Analyses*

Further analyses tested the latency sensitivity to network structure, the type of transition-time PDF used, and the path selection interval used.[14] The network structure analyses investigated the impact of dividing one transition into multiple transitions in series or multiple transitions in parallel as well as the impact of overall network resolution (varied in three levels of network detail: detailed, medium, and coarse). Transition-time PDF variations included uniform and log-normal PDFs. Uniform PDFs were used with bounds 25%, 50%, and 75% above and below the reference activity times. Log-normal PDFs varied the σ value as 0.1, 0.5, and 1 while taking the mean to be equal to reference activity time. Simulation path selection intervals used were 0.5 years, 1 year, 2 years, 5 years, and 10 years (U.S. proliferation took about 3.5 years, so the 10-year selection interval effected a single path selection).

The additional sensitivity analyses revealed several biases and insights. Factors that biased latency times high included parallel transitions and frequent path selection (in addition to the previously discussed time-step precision and PDF bound rounding). Parallel transitions and network flows result in the Petri net taking the maximum sampled time of all transitions or flows in parallel. If the parallel transitions were replaced by a single representative transition, a single time would be sampled and the chances of a shorter time would be greater. Frequent path selection limited the amount of progress that could be made before a path change. The path selection interval impact may be specific to the U.S. network.

Increased amounts of transitions in series, greater resolution networks, tighter transition activity time PDFs, very frequent path selection, and very infrequent path selection contributed to a reduction in simulation latency variance. Representing an activity by many serial subactivities results in a higher resolution network with more transitions in series. The result is that there is more random sampling of shorter time intervals, which drives the macroscopic activity toward the mean. This does not occur when the macroscopic activity is represented by a single transition. Very frequent path selection results in similar progress along all paths, thus eliminating variance. A single path selection (very infrequent) will concentrate latency results around average single path latencies. For the U.S. network, the plutonium and the all-method uranium enrichment path both finished at approximately the same time, which further reduced latency variance.

Several additional insights were learned through the sensitivity analysis. To increase network resolution, it is necessary break down macroscopic activities into subactivities in both parallel and series. This means that greater resolution networks are by definition more sensitive to parallel and series effects. Furthermore, larger or wider bounds on transition activity time PDFs allow for larger time swings during simulations. Simulations using larger transition activity time PDF bounds are thus more sensitive to the other effects.

The initial sensitivity analysis described here is given as an illustrative exercise (and is described in more detail in Reference 14). This analysis does not indicate a preference for less or more of any of the network characteristics discussed. The resulting effects of these sensitivities may accurately capture reality in some instances, whereas in others, the effects may not be realistic. In other instances, the sensitivities may not matter, or there may be other more important sensitivities. It is up to any future user of the Latency Tool to perform further sensitivity analyses on any newly developed model or network.

## Conclusion

A new computational proliferation assessment methodology was developed called the Nuclear Weapons Latency Tool. Given three basic assumptions, the Latency Tool determines a state's nuclear weapons latency, the expected time to be taken by a non-nuclear weapons state to develop a conventionally deliverable nuclear weapon given the state's position on a path toward or away from a nuclear weapon and accounting for the state's motivations and intentions. The Latency Tool uses a stochastic Petri net simulation to estimate latency and was verified using historical case data. Beyond the latency time result, the Latency Tool provides a transparent, efficient, and highly repeatable platform that allows for extensive sensitivity analysis to better inform the nonproliferation discussion.

Sensitivity analysis can determine the impact of varying assumptions, including the nuclear fuel cycle technology available to the potential proliferator. As such, the Latency Tool can provide a characterization of proliferation risk due to the acquisition of different technology to policy makers. This enables the Latency Tool to help fill a void in quantifying proliferation, identified by the 2013 National Research Council study *Improving the Assessment of the Proliferation Risk of Nuclear Fuel Cycles*.[61] The Latency Tool also serves as a foundation for future development that may lead to a more complete characterization of proliferation risk to better support nuclear nonproliferation policy making.

Future development in the area of nuclear weapons latency includes both further refinement of the Latency Tool as well as extension of the application of latency results and concepts to further characterize nuclear proliferation risk. One simple improvement to promote greater ease of use would be the development of a complete stand-alone graphical user interface (GUI) to replace the MS Visio and Macro Petri net development. Regarding latency analysis, further case studies of both historical and current proliferation are expected. Iranian proliferation activity and nuclear interest elsewhere in the Middle East provide relevant opportunities for analysis in an area of continued strategic importance. Latency analyses can also be applied to analysis of vertical proliferation. The networks simply need to be extended and the simulation ending marking altered. Additionally, the latency networks considered were highly specific. It may be beneficial to create and analyze more general networks that would have broader application.


## Acknowledgments

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## Keywords

Nuclear weapons, latency, time proliferation


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# Taking the Long View in a Time of Great Uncertainty

## The New NNSA Strategic Vision to Modernize the U.S. Nuclear Stockpile

**Jack Jekowski**
*Industry News Editor and Chair of the Strategic Planning Committee*

In previous columns, we have discussed the challenges that the U.S. Nuclear Security Enterprise (NSE) faces to ensure a safe, secure, and reliable nuclear stockpile.[1] These challenges include meeting the requirements identified in the U.S. Nuclear Posture Review (NPR) of 2018;[2] revitalizing the infrastructure associated with the NSE National Laboratories and production sites, much of which is decades old; addressing the "gray tsunami"—the significant departure of the baby boomers who represented the first generation of nuclear stewards—an event expected earlier but now being driven by the inevitable aging of the workforce; and the issues addressed by recent critical reviews of the governance and management of the NSE.[3] As all of those challenges are being addressed, the new technologies that are beginning to wrap around the nuclear deterrent—including artificial intelligence, additive manufacturing, cybersecurity, and hypersonics—bring additional uncertainties to the future of deterrence as we know it. In many ways, these challenges intersect with the top-level strategic issues identified by Institute membership at the special "Global Nuclear Materials Stewardship Challenges" interactive session held during the closing plenary of the 2018 Annual Meeting.[4]

### What Is Modernization?

All nuclear states are currently "modernizing" their nuclear deterrents. The traditional definition of modernization includes the following:

- Upgrading, improving, and enhancing nuclear weapons capabilities, to include nuclear weapons, delivery systems (bombers, intercontinental ballistic missiles, and submarines and cruise missiles), and command and control instrumentation;
- Maintenance, repair, and replacement of aging facilities and related infrastructure;
- Educating the next generation of "nuclear stewards";
- Legacy management.

However, in the context of today's complex world, modernization discussions can also include the following:

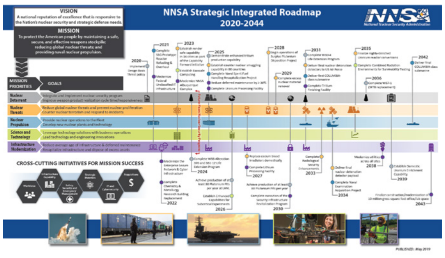
- Adaptation to a new global environment of proliferation and terrorism;
- Diplomacy, arms control treaties, nonproliferation, and counterproliferation;
- Stockpile reductions;
- Humanitarian impacts; and
- The concept of Global Zero.

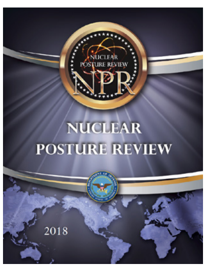
In this complex environment, the pendulum often swings from one extreme to the other, and despite the major reductions in total nuclear weapons in the world from more than 70,000 in 1986 to less than 15,000 in early 2019,[5] the reality of the remaining destructive power in the hands of nuclear-armed nations is difficult to grasp. The overwhelming number of nuclear weapons in the world is still held in the United States and in Russian stockpiles,[6] but the proliferation of nuclear weapons knowledge and the advancement of advanced technologies portend a future to modernization that is more characteristic of science fiction stories where even non-nation states could represent existential threats to nations and even the future of mankind.

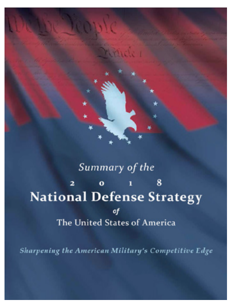
### The New Reality

Nuclear weapons and the threat of using them has taken on a new reality in today's world, amid public discussion of new delivery systems using hypersonic vehicles, large autonomous underwater nuclear torpedoes, and even nuclear-powered cruise missiles.[1,6,7] Unknown, and unspoken, is research that may be occurring in new weapons technologies and effects, despite the current "observed" nuclear test ban.[8] Against that backdrop, the United States has embarked on a modernization plan initiated during President Obama's administration and fully engaged during the current Trump administration. Congressional Budget Office estimates are that $1.3 trillion will be needed over the next 30 years to achieve the goals set by our current NPR.[9]

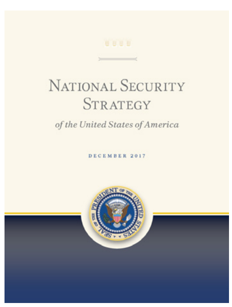
## A New Vision for the National Nuclear Security Administration (NNSA)









NNSA issued a new *Strategic Vision*,[10] *Governance & Management Framework*,[11] and *Strategic Roadmap (2020–2044)*[12] in early May 2019 to address the challenges of modernization and other issues. More than a year in the making, these new documents create a path forward for the NSE, addressing not only the requirements of the NPR, but also the related issues of infrastructure, workforce, governance and management, and risk management. These new strategic documents are driven by U.S. national planning documents, including the *National Security Strategy*,[13] *National Defense Strategy*,[14] and NPR, overseen by the Nuclear Weapons Council (NWC)[15] that serves as the focal point for interagency activities to maintain the U.S. nuclear weapons stockpile. The NWC is a joint Department of Defense (DoD) and Department of Energy (DoE) activity responsible for facilitating cooperation and coordination, reaching consensus, and establishing priorities between the two departments as they fulfill their dual-agency responsibilities for U.S. nuclear weapons stockpile management.

The mission priorities and strategic management challenges identified in these new NNSA strategic planning documents include the following:

### Mission Priorities

- Maintain the safety, security, and effectiveness of the nation's nuclear deterrent
- Reduce global nuclear security threats and strengthen the nuclear enterprise
- Provide safe and effective integrated nuclear propulsion systems for the U.S. Navy
- Strengthen key science, technology, and engineering capabilities
- Modernize the national security infrastructure

### Strategic Management Challenges

- Workforce
- Infrastructure capability
- Safety and security
- Strategic materials
- Emergency management
- Information technology and cybersecurity
- Acquisition

These strategic documents also describe corporate expectations for federal program, functional, and field offices, as well as the contractor partners and corporate parents of the management and operating (M&O) contractors, creating "one NNSA" to achieve the aggressive goals set by the NPR.

## The Future of Deterrence

The intersection of these modernization efforts and the Institute's newly identified strategic priorities can be seen particularly in these areas discussed in last quarter's *JNMM* column[4]:

- Lack of political progress on nuclear disarmament;
- Ability to interfere with safety systems at facilities;
- Connecting policy and technical communities to develop solutions;
- Artificial intelligence/machine learning.

So striking is the change in technologies that the literature has begun to speculate where deterrence might be headed with the intersection, for example, of hypersonics and artificial intelligence,[16] leading to scenarios seen only in science fiction movies, where autonomous systems are justified to ensure a timely retaliatory response. How the nations of the world continue to modernize their nuclear stockpiles in the context of these rapidly evolving technologies is yet to be understood. This is the future the world now faces with more than 13,000 nuclear weapons still in stockpiles.

*This column is intended to serve as a forum to present and discuss current strategic issues impacting the Institute of Nuclear Materials Management in the furtherance of its mission. The views expressed by the author are not* *necessarily endorsed by the Institute but are intended to stimulate and encourage* JNMM *readers to actively participate in strategic discussions. Please provide your thoughts and ideas to the Institute's leadership on these and other issues of importance. With your feedback, we hope to create an environment of open dialogue, addressing the critical uncertainties that lie ahead for the world, and identify the possible paths to the future based on those uncertainties that can be influenced by the Institute. Jack Jekowski can be contacted at jpjekowski@aol.com.*

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# Book Review

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*Book Review Editor*

*Doomed to Cooperate*
*Edited by Siegfried S. Hecker*
*Volume 1: Hardcover, 540 pages, ISBN 978-0-9411232-44-9*
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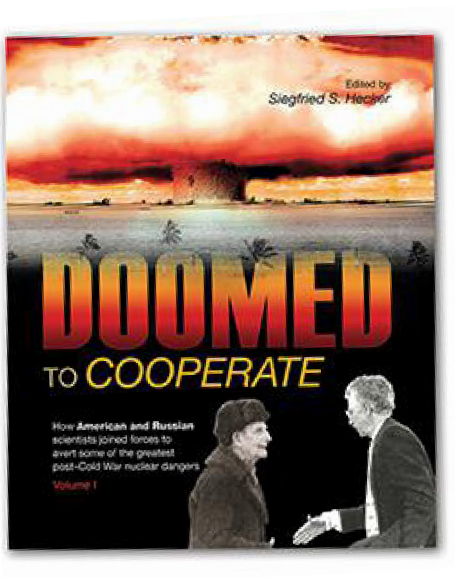
*Bathtub Row Press, Los Alamos, New Mexico, 2016*




This massive undertaking focuses its effort on an important and little-told story that those studying the immediate post-Soviet era of nuclear angst in the United States will no doubt find interesting. Weapons scientists of both nations—one concerned that abandoned Soviet nuclear weapons would fall prey to proliferators and terrorists, the other sanguine about its change of nation-status but still confident in its scientists' ability to protect the nuclear arsenal despite the evolving political climate—came together with a shared sense of accountability to manage the situation. This is how, at least in part, the story arc reads in *Doomed to Cooperate*, a publication of the Los Alamos Historical Society.

The editor and contributors do a very credible job of painting the bleak landscape of the Russian nuclear complex in decline (especially from the U.S. perspective). With thousands of weapons of various designs, the international community felt justified in its fear and concern that the Soviet political upheaval would leave components of the arsenal exposed to terrorism. By 1985, Mikhail Gorbachev had been elected and initiated detente with the United States. Two years later, the first scientific cooperation between the two nations occurred under the Joint Verification Experiment (JVE), a U.S.–Soviet collaboration to measure the explosive yields of both nation's nuclear tests. It resulted in a verification mechanism for the Threshold Test Ban Treaty (1974) to limit testing yields. This initial bridge-building effort was later supplemented by the 1989 Megagauss-V Conference that built a path toward joint scientific research. The very first collaboration was held in Moscow between a delegation from Los Alamos National Lab and the Russian Research Institute for Experimental Physics (VNIIEF) in May 1992. The last such conference was held in 2013. The editor focuses on the personal narratives originating from employees of three U.S. nuclear weapons laboratories—Los Alamos, Lawrence Livermore, and Sandia—and their Russian Federation counterparts—VNIIEF, VNIITF (Russian Federal Nuclear Center All-Russian Research Institute for Technical Physic), and VNIIA (All-Russian Research Institute of Automatics), respectively. These weapons facilities faced the most dramatic changes as the Cold War ended.

Here are the "diaries" of the people living this historical moment of peaceful cooperation. The two volumes record the efforts and impressions of American and former Soviet nuclear weapons scientists collaborating to establish a camaraderie that would serve both nations well during and after the Soviet Union breakup. With at least 120 contributors (mostly men; this reviewer counted eight women contributing to volume 1), the reader will find first-person accounts mixed with interview-style recollections. For reasons mentioned later, such variety of presentation is welcome.

The books are well designed. Volume 1 covers the efforts to safeguard weapons and nuclear materials. Volume 2 focuses on converting a part of the Russian weapons complex into a civilian effort, thereby giving Russian scientists future employment options. The "brain drain" to terrorist organizations so feared in the West was largely averted. There is also a section devoted to joint science projects between both nations—another welcome addition to the read.

The table of contents in both volumes clearly shows the thought that went into the construction of this history. Each major section is a broad technical area. Examples include "warhead safety," "nuclear materials," and "Russian military cooperation." Under each, one encounters chapter headings focusing the reader on one aspect of the section topic. That is followed by a multitude of relevant personal narratives. One complaint: there is no glossary, which I imagine will be regretted by historians wading through the two-volume, 976-page effort in their hunt for ever-elusive facts.

There is an extensive biographical section lauding the accomplishments of the contributors. Two-page maps indicating locations for the USSR/Russia and U.S. nuclear weapons facilities and supporting sites are located on the inside front and back covers. Black-and-white photos, mainly of the scientists involved in the many scientific exchanges, accompany the chapters with some "ancient" laboratory equipment also well represented. A very useful 1953 to 2015 U.S./Russian lab-to-lab nuclear cooperation timeline accompanies volume 1. Printed on a glossy heavyweight paper with minimal but handsome page decorations, these books will be formidable occupants of any bookshelf.

There is much to praise here. The effort alone to solicit, collect, translate, edit, and arrange the recollections is enough to make me catch my breath. As mentioned, the entries are first-person accounts and include not only descriptions of the lab-to-lab collaborations but also lighthearted accounts of cross-cultural confusion that inevitably accompanies first-time visits to a foreign land. I imagine the translation and editing effort is responsible for the clarity of these narratives. The reader won't find clunky writing or poor syntax that could distract and take them out of the narrative. That success alone deserves congratulations.

With all that going for it, do not expect a scintillating cover-to-cover read. This is a workmanlike and very competent account of a particular slice of history made interesting by the overall story arc of superpower collaboration. Inevitably, the narrative becomes a bit pedestrian. These are scientists and engineers writing about impressions, their projects, political hurdles, administrative miscues, and other aspects of first-time cooperation in the secret world of nuclear weapons. Writing is not their first calling. How many times can one claim victory for science over politics and make it sound fresh?

One must also remember that the history it spans is a very short period of time: roughly 1988 to 2013. A non-weapons-lab reader such as a historian of science or perhaps a graduate student of nonproliferation studies looking for context, with an interest in this short span of Soviet decline and American concern, will have an easier time making a purchase than a casual reader trying to determine if the book will generate curiosity. In other words, this is first a book for a special audience—and secondly for anyone who seriously wants to join that special group.

Accessing the book's webpages might help potential readers make a purchase decision. Articles that could not be included in the book, plus supplementary material such as photos, videos, and other material, can be found in an electronic archive at https://lab2lab.stanford.edu/electronic-archive-us-russian-nuclear-and-scientific-cooperation. It is a rich trove of information for historians of nuclear science. One hopes that the Los Alamos Historical Society will maintain and add to it.

The "Outreach" link under "The Book" drop-down menu will be of special interest to those considering a purchase. Here, one will find a BBC interview of the editor and articles he wrote about visits to Soviet labs and U.S.–Russian teamwork, along with a presentation of the book at the Center for Strategic and International Studies in Washington, D.C. Under the "About" drop-down, look for "Book origin." Here, you will learn that a Russian version of the book—and not one merely translated from the current two volumes—is expected. Again, before deciding to purchase, check out the table of contents of both volumes under "The Book" to view the nuclear weapons and nonproliferation areas covered.

There is no doubt that constructing *Doomed to Cooperate* was and remains a successful ongoing collaborative effort made possible by the very cooperation it documents. It is a memorial to the heroic efforts of former enemies (who sadly have become more adversarial again), the integrity of the scientists who initiated those efforts and carried them as far as they could, and all the other people who had the foresight to realize that partnership was (and is) a better way for nuclear armed countries to proceed into the murky future of the 21st century.

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