Countering WMD JOURNAL

In This Edition:

- **Thorium: The Threat and the Opportunity**
  Mr. John Leahy
- **Resurrection of a Legacy Nuclear Bomb Effects Code**
  Dr. Behzad Salimi
- **The Nuclear Dimension of Hybrid Warfare**
  Michaela Dodge & Adam Lowther

Issue 25 • Fall/Winter 2022
U.S. Army Nuclear and Countering WMD Agency

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Mission Statement

The *Countering WMD Journal* is published semi-annually by the U.S. Army Nuclear and Countering WMD Agency. It furthers the education and professional development of military leaders and members of government and academia concerned with the nuclear and countering WMD matters.

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About the cover: Airmen fire M-16 rifles during a combat skills training exercise at Joint Base Andrews, Md., Dec. 2, 2022. The exercise involved a chemical gas simulation in which airmen in full mission-oriented protective posture gear.

Table of Contents

Notes from the Director, U.S. Army Nuclear and Countering Weapons of Mass Destruction Agency

COL Pat Nikkila

Welcome all to Issue #25 of the Countering WMD Journal. I am COL Colin P. (Pat) Nikkila, the new Director of the U.S. Army Nuclear and Countering Weapons of Mass Destruction Agency (USANCA). Ongoing world events continue to illustrate the importance of USANCA and our mission. Accordingly, we have established broad overarching themes for the FY23 Issues of this journal. These themes include deterrence, modernization, and relevance. I challenge all members of the CWMD enterprise to consider how your work and efforts are contributing to deterrence, modernization, and relevance. Capture these thoughts and submit them for publication in the CWMD Journal.

Before I share my background and command perspective, I would like to first recognize COL (Ret) Benjamin Miller's outstanding leadership as the outgoing Director of USANCA. COL Miller expanded USANCA's role into many areas that directly contribute to the CWMD mission while always maintaining focus on what is critical for the Army.

I come to USANCA after serving as the Maryland Joint Force Headquarters Command Inspector General. Prior to that I was the Deputy Commanding Officer and Chief of Staff for the 20th CBRNE Command, Aberdeen Proving Ground, MD. I am a graduate of the Senior Service College at the U.S. Army War College, Carlisle Barracks, PA. My prior assignments include command of the 3d Ordnance Battalion (EOD) at Fort Lewis, WA and command of the 759th Ordnance Company (EOD) assigned to Coalition Forces Land Component Command OIF I, II, III, CJTF-J5, Combined Joint Task Force Paladin assigned to ISAF Joint Command, Kabul Afghanistan; and Chief, European Technical Support Group assigned to the Defense Threat Reduction Agency, Stuttgart, Germany.

The Army, the United States, and the entire the world are emerging from the COVID 19 pandemic. Simultaneously, we are experiencing Russia's unjustified invasion of Ukraine and threats of escalating the conflict by using nuclear weapons; North

Korea's renewed ballistic missile testing for its nuclear weapons program and efforts to expand technologies and capabilities; and China's unprecedented military and nuclear expansion. Each of these activities present unique nuclear and countering weapons of mass destruction threats and complicate international relations in the current and future operating environment.

Against this backdrop, USANCA is busy supporting policy development as well as increasing and improving education, doctrine and training related to CWMD for the U.S. Army. As members of the CWMD community we have a unique role and responsibility to assist with combatting threats. Our collective expertise makes us invaluable advisors to decision-makers. In preparing the Army to operate in WMD-compromised battlefields, we demonstrate America's readiness for this challenge. It is at this time that our technical expertise and advice must be at its best. Therefore, this is an opportunity for the CWMD community and USANCA to show our strength to identify challenges and present solutions that will guide our leaders.

I appreciate the hard work, dedication, and resolve of the individuals and organizations who work within and support our community. Your collective excellence as CWMD professionals informs modernization efforts, contributes to deterrence, and stands at the forefront of relevance.

China's Historical Plutonium Production

Dr. John A. Swegle and Dr. Christopher Yeaw
National Strategic Research Institute

Abstract

This paper offers a re-evaluation of China's production of weapons-grade plutonium (WGPu) in order to estimate the maximum number of nuclear weapons that China can build using WGPu.[1] WGPu was produced in the 801 Reactor at the 404 Plant in Gansu Province (or the 404 Plant reactor) and the 821 Plant reactor in Sichuan Province. We review two existing estimates of WGPu production with widely varying methodologies and results: Zhang's 2017 estimate and Esin and Anichkina's 2013 estimate. In addition, we provide our own estimate based largely on the information in Zhang's paper, but with a reconsideration of Zhang's assumptions about the pace of production for 1980 and beyond and on his assumption about the closure date of the 821 Plant reactor.

Our primary findings suggest that Zhang and Esin and Anichkina essentially agree on the WGPu production in the 404 Plant reactor. We also find that Zhang and Esin and Anichkina differ dramatically on WGPu production in the 821 Plant reactor. Finally, we re-evaluated Zhang's estimate, focusing on his assumptions about production reductions after 1979 and the termination date for military production at the 821 Plant. This re-evaluation resulted in a 50 percent increase over Zhang's estimate, from 3,450 kilograms to 5,200 kilograms. Even taking account of losses for tritium production, processing and weapon fabrication, and nuclear testing, this increase could permit China to build, or have built, over 1,000 plutonium-based nuclear devices.

Foundations of Fissile Material Production for China's Nuclear Weapons Program

On January 15, 1955, the Chinese Communist Party (CCP) of the People's Republic of China (PRC) committed to building an atomic bomb.[2] Initially acting with technical and expert assistance from the Soviet Union, China proceeded along two lines in the production of fissile material for nuclear weapons.[3] Highly-enriched uranium (HEU) was to be produced at a gaseous-diffusion enrichment plant to be built at a site near Lanzhou that was originally intended for an aircraft construction factory. Plutonium was to be created and separated at a newly built plant with a light-water-cooled, graphite-moderated production reactor and reprocessing plant located in the Gobi Desert near the city of Yumenzhen in Jiuquan Prefecture.

When Moscow withdrew its experts in August 1960, the building for the enrichment plant was complete and largely equipped for operation. Construction of the plutonium production reactor, on the other hand, was at a much earlier stage. The foundation was complete and the concrete baseplate for the reactor core was in place. Production of HEU was therefore prioritized, slowing the construction of the plutonium infrastructure while China proceeded to its first test of an HEU-based nuclear explosive on November 16, 1964.[4] Notably, the uranium core for the device was machined and prepared at the 404 Plant near Yumenzhen in late April of that year.[5]

With HEU production rounding into shape, work shifted back to plutonium production at the 404 Plant near Yumenzhen.[6] Revisions to the production reactor design were completed in April 1963. The installation of the graphite bricks for the reactor itself began in the spring of 1966. The reactor first achieved criticality on October 20, 1966.

The production reactor at the 404 Plant was the first of two that China operated, with collocated reprocessing plants to support its nuclear-weapon program. A second production reactor was at the 821 Plant near Guangyuan in Sichuan Province. Construction of another underground facility with a plutonium-production reactor and collocated-reprocessing plant was started at the 816 Plant near Fuling in the Chongqing Municipality, but delays associated with building the underground facility led to its cancellation prior to completion.[7]

In the following sections, we examine two estimates of the mass of WGPu produced by China beginning in 1966 until China reportedly halted production in the late 1980s or early 1990s.[8] First, we examine the work of Zhang Hui, who has authored multiple assessments of China's stocks of WGPu.[9] Second, we review Viktor Esin and Tatiana Anichkina's 2013 assessments for the Potomac Foundation.[10] While there is some overlapping information in these assessments, the authors rely on uniquely different sources resulting in dramatically different numbers. Third, we re-examine some of Zhang's assumptions to produce what we believe is an upper limit on China's WGPu production.

The 404 Plant

The 404 Plant is located off the main highway running between the cities of Yumenzhen, Jiayuguan, and Jiuquan. Workers were moved from the original plant site to a new residential area in Jiayuguan in 2006 and now commute by train from the city to work, where the former plutonium production area is located, along with the reprocessing buildings.[11]

According to Chinese bloggers, water was brought to the site beginning in 1959 through a 52-kilometer pipeline.[12] Based on Google Earth imagery, there is one major dam, on the Changma River, southwest of Yumenzhen at roughly the indicated distance from the plant site. About five kilometers downriver from the main dam, in Google Earth we observed what appears to be the beginning of the pipeline to the 404 Plant with features identical to those depicted in a video entitled "China Nuclear City 404."[13]

Zhang and other analysts rely heavily on the 1987 China Today account of China's early nuclear fuel cycle and weapons developments.[14] According to that account, after the reactor first achieved criticality on October 20, 1966, reactor power reached the specified 0.5 percent level for the first time on December 31, 1966. From there, power was increased gradually, and the reactor began stable operations. The report broke the operational history from 1967 to 1985 into three periods.

From 1967 to the first half of 1975, the operators renovated reactor elements, accumulated operating experience, and attained the design rated output. According to a Chinese-language technical publication, the design power was 600 MWt (which was not reported in the 1987 China Today account).[15]

Reactor technical failures were a particular problem until 1970, when operators determined a way to keep the reactor running while technical failures were being cleared, which they began to implement. One such failure, due to core and fuel swelling, resulted in the meltdown of an aluminum channel liner and the fuel elements in it on January 7, 1969.[16] It took 20 hours of work in a high radiation environment to clear the blockage, an event commemorated in a relief displayed in the 404 Plant museum.

On December 30, 1973, the reactor was shut down to repair a leak first discovered in its load-bearing protective water container in October 1972. The reactor was restarted after a delay of over six months. In the first half of 1975, the reactor reached its design power, presumably 600 MWt, for the first time. From the second half of 1975 to 1980 (the last year of China's 5th Five-Year Plan), the pursuit of research and technical innovations became focal areas. Beginning in the second half of 1975, production capacity uniformly exceeded the original design goals. An increased goal was set for production, involving increased fuel burn-up and an increase in operating days from 288 to 324 days per year.[17] As we discuss in the appendix, the new goal for production was 1.2 times the original goal. Since the increase in operating tempo from 288 to 324 days is only a 13 percent increase, we infer that the new goal likely involved a power increase as well. Also, during this period, in June 1968, a tritium production line was built at the site.[18]

Beginning in 1981, the period of the 6th Five-Year Plan, additional uses were found for the reactor, including dual-purpose technologies, especially for production of electrical power from the reactor. The China Today (1987) document provides much less detail about plutonium production during this period, with the account only extending to about 1983. At the fourth meeting of the reactor operators exchange in March 1981, multipurpose uses became a primary 6th Five-Year Plan goal for the reactor, especially conversion of the reactor to a dual-purpose facility producing both plutonium and electricity. To support the new reactor operating parameters, the fuel element producer developed a new fuel casing and the provider of the technical aluminum tubes in the reactor developed a new product, both of which were tested in the 404 Plant reactor.

Enhanced reactor monitoring and additional research indicated that the 15-year lifetime of the reactor, as of 1981, could be extended to 30 years. Based on initial discussions in 1982, the Beijing Academy of Nuclear Engineering Research and Design commenced preliminary work on conceptual and construction designs for the generation of electricity with the reactor in 1983.

We note that there is no available imagery evidence that the reactor ever provided electricity to the site. By 2017, well after the nuclear reactor was shut down, a much larger coal-fired electrical generation capacity was built at the site in another area near the reactor and reprocessing area. Although the China Today account provides no information about the shutdown of the reactor, a blogger recounted a visit with regional dignitaries to the reactor on November 8, 1986, where it was declared that the reactor had completed its mission.[19]

Relying on the efficiency of the PUREX process the Chinese used in the reprocessing of the spent fuel, we assume that virtually all of the WGPu made in the reactor was recovered. Zhang modeled WGPu production in the 404 Plant reactor as follows:[20]

• From 1967 through 1973, the reactor power increased linearly from 0.5 percent of design power to about 85 percent of the design power of 600 MWt.
  - The capacity factor[21] during 1967–69 was assumed to be 40 percent.
  - The capacity factor during 1970–73 was assumed to be 80 percent (288 days per year).

• The reactor was shut down for 103 days, January 1974–April 1974, for repair and maintenance.

• From April 1974 through June 1975, the reactor power increased linearly to the full design power of 600 MWt with a capacity factor of 80 percent.

• From July 1975 through 1979, the reactor linearly increased its plutonium-production rate to 1.2 times the initial design production rate.

• From 1980 until shutdown in November 1986, the plutonium-production rate was about half of that in 1979.

Zhang assumed that WGPu was produced at the rate of 0.9 grams of WGPu per MWt-day of fuel burn-up. Employing continuous piecewise-linear fits to Zhang's model, we calculated the yearly production as shown in Figure 1, which apparently agrees with Zhang's 2017 paper. In Figure 2, we sum up the yearly production to show cumulative WGPu production in the 404 Plant reactor, which totals about 2,000 kg.

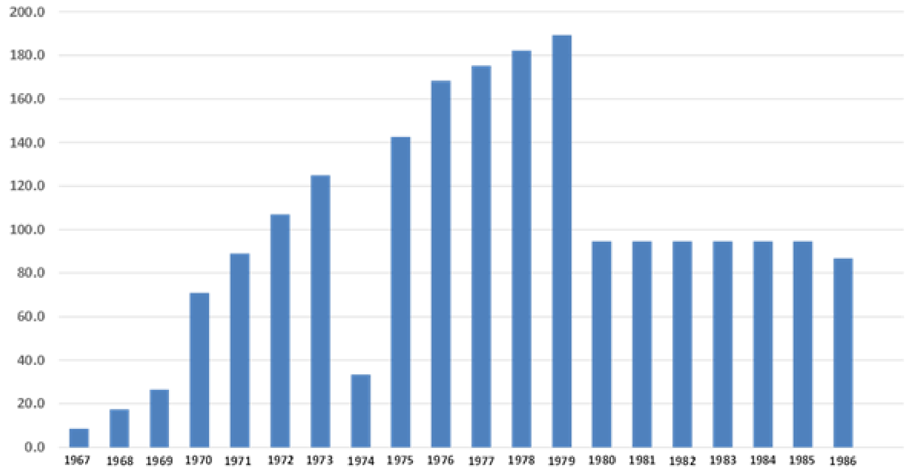

Figure 1. Yearly production of WGPu, in kilograms, in the 404 Plant reactor according to Zhang's model.

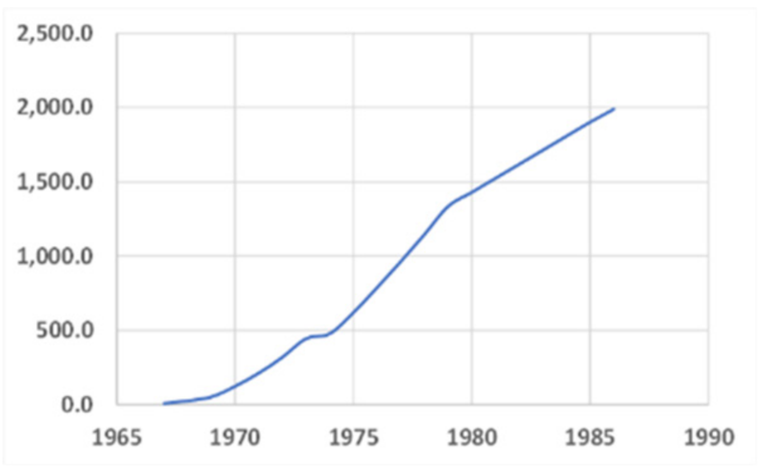

Figure 2. Cumulative WGPu production, in kilograms, in the 404 Plant reactor, from Figure 1.

The 821 Plant

The 821 Plant was built in northern Sichuan Province as part of the overall construction of Third Line facilities, defense-oriented facilities and companies that were built to reduce the threat of foreign attack by siting them farther from China's borders in deep ravines and in underground facilities.[22] Construction of the 821 Plant began in October 1969.

Unlike the 404 Plant, which came first and was more exhaustively discussed in *China Today*, information on the 821 Plant comes almost exclusively from reminiscences and blogs written by former employees. The plant is located on the Bailongjiang River, a small tributary of the Bailong River separating the plant from the residential area in Sanduizhen. The production reactor is downriver and to the east of the reprocessing building. As indicated elsewhere, this Third Line plant was built in an area heavily cut by deep ravines. The reactor is cooled with river water, likely from the Bailongjiang; the larger Bailong is just over two kilometers away. Reportedly, the river water drawn by the reactor was clouded with particulates that presented a problem for the outer cooling loop, especially in the summer when the river was lower.[23] The area adjacent to the reactor building was designated for water treatment according to Zhang.[24]

The production reactor was first started in December 1973, and stable, full-power operation was achieved on October 11, 1974.[25] As mentioned previously, based on a Chinese technical publication, we assess that full power was 600 MWt.[26] From there, the "1.3 reactor" target was reached in 1978, presumably production at a level thirty percent greater than that originally planned. At the same time, reportedly due to the demands posed by a dangerous international situation, the 404 Plant reactor was producing at 1.2 times the original goal, so that the two production reactors were referred to as the "2.5 reactor."[27] The higher production was attributed to "deepening fuel consumption and strengthening power." Presumably, this meant increasing fuel burn-up and the reactor power.

The reprocessing plant commenced production in 1976, and WGPu was apparently produced in May of the same year. In 1977, the reprocessing plant reached the expected production capacity.[28]

The plant continued to produce WGPu until sometime in the 1980s. In the early 1980s, China's nuclear industry began a shift from a military-only posture to a mixed military-commercial model.[29] In June 1982, the 816 Plant project was suspended and terminated two years later. Also in 1982, the 827 Plant project, which was to build a pair of heavy-water reactors and a processing plant at an underground site near Yichang on the Yangtze River, perhaps to produce tritium, was terminated.[30] According to one source, facing a reduced threat in the world, China's State Council decided in August 1987 to "stop production of military products and switch to civilian products" at the 821 Factory.[31] A separate source recorded that military production at the factory was halted in 1988.[32]

In modeling WGPu production at the 821 Plant, Zhang broke production into four time periods:

- December 1973 to October 1974, during which reactor power rose linearly to the design power of 600 MWt with a capacity factor of 40 percent.

• November 1974 to December 1976, during which the reactor operated at 600 MWt with a capacity factor of 80 percent.

• January 1977 to December 1978, over which period the plutonium-production rate increased linearly to 130 percent of the originally designed value—maintained until December 1979.

• From 1980 until shutdown for conversion in August 1984, during which the plutonium-production rate was half that in 1979.

Again, assuming that WGPu was produced at the rate of 0.9 grams of WGPu per MWt-day of fuel burn-up, we calculated the yearly production of the 821 Plant according to Zhang's model as shown in Figure 3. In Figure 4, we sum up the yearly production to show cumulative WGPu production in the 821 Plant reactor according to Zhang's model, which totals up to about 1,450 kg.

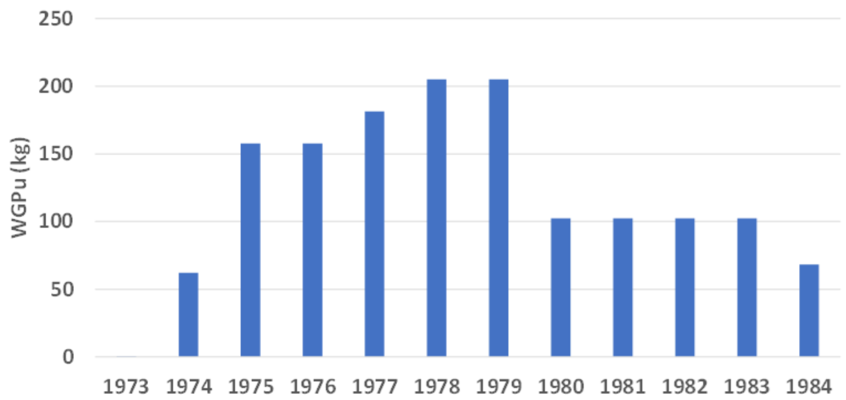

Figure 3. Yearly WGPu production at the 821 Plant reactor according to Zhang's model.

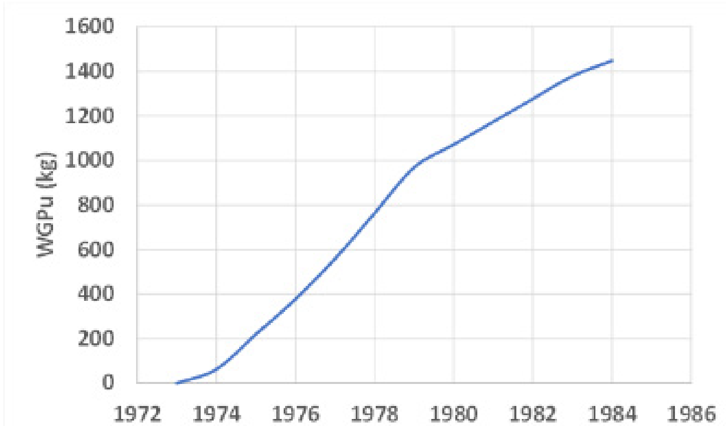

Figure 4. Cumulative WGPu production at the 821 Plant reactor from Figure 3

Review of Esin and Anichkina's Assessment

Esin and Anichkina produced an assessment that they compared to Zhang's 2011 assessment of WGPu production.[33] Zhang's 2011 assessment used a reactor power of 250 MWt for both the 404 Plant and 821 Plant reactors (versus the 600 MWt used in his 2017 assessment and here). Citing informal contacts between Esin and two unnamed scientists who worked for the Dollezhal Scientific Research and Development Institute for Electric Power (NIKIET is the Russian acronym) in the late 1950s and worked with the Chinese on the design of the 404 Plant reactor, Esin and Anichkina employed a reactor power of 500 MWt.[34] Esin and Anichkina also employed the same temporal profile for WGPu production in the 404 Plant reactor as Zhang (in 2011), which differs from Zhang's 2017 assessment discussed here in two respects: (1) the reactor is assumed to have shut down two years earlier, in 1984, and (2) WGPu production is assumed to have held at the peak value until shut down (as opposed to here, using Zhang's model, where production was halved after reaching a peak).

Taking account of some competing factors, Esin and Anichkina assessed that the 404 Plant reactor produced 1,800 kg of WGPu versus the 2,000 kg Zhang assessed in 2017. Given that Esin's unnamed former NIKIET scientists claimed that the 404 Plant reactor had a power of "not less than 500 MWt," Zhang's 2017 assessment and Esin and Anichkina's are essentially the same.

Esin and Anichkina produced a much larger assessment for WGPu production in the 821 Plant reactor. As of the writing of their 2013 report, they stated that the 821 Plant reactor as still running, citing only the website of the Center for Energy and Security Studies in Moscow, with no further information. Further, citing three unnamed scientists from Moscow's Kurchatov Institute who claimed to have personally participated in Russian assistance to the developing Chinese complex, Esin and Anichkina write that they were informed that (1) the 821 Plant reactor had an operating power of 850 MWt, (2) was capable of producing 280 kilograms of WGPu per year, and (3) by 1990, could have produced up to 4.5 tons of WGPu. They also added that the reactor was shifted to tritium production at that time, but that it was capable of producing an additional 2.9 tons of WGPu by 2009 employing intermittent short production campaigns.

Based on these estimates, the total value grew to as much as 7,400 kilograms of WGPu produced in the 821 Project reactor. This is a dramatic increase over the 1,450 kilograms assessed by Zhang. We note the conditional nature of Esin and Anichkina's estimate and assess it possible that the operating power of the reactor could have increased to 850 MWt. However, the discussion in the appendix provides more than one piece of evidence pointing to an original design power of 600 MWt, with an increase in power or WGPu production more generally by an additional 30 percent. We are somewhat skeptical of Esin and Anichkina's estimate for several reasons:

• At a production rate of 0.9 grams of WGPu per MWt-day of fuel burn-up, even accepting an operating power of 850 MWt, yearly production of 280 kilograms of WGPu requires full operation of the reactor, 365 days per year. Practically, this is impossible, given the time required for maintenance and fuel changeout.

• Alternatively, assuming a capacity factor of 90 percent, with the 404 Plant reactor reaching 328 operating days per year, a production rate of about 1.0 grams of WGPu per MWt-day of fuel burn-up is required. This number is higher than the 0.8-0.9 grams per MWt-day from most production reactors.[35] However, the French G1 production reactor approached it, with a reported production rate of 0.95 grams per MWt-day.[36]

• Production of WGPu to 1990 and beyond contradicts two apparently independent sources who claim military production in the 821 Plant reactor ended by 1988.

The production of an additional 2.9 tons of WGPu by 2009 would represent a significant expenditure of effort on what we infer was not the primary focus of reactor operations in that time period. On average, over the 19 years from 1990 to 2009, the reactor would need to produce over 125 kilograms of WGPu per year. Even at 850 MWt, assuming 0.9 grams/MWt-day, the reactor would have to devote an average of 163 days per year to WGPu production.

Reassessing China's WGPu Production in the 404 Plant and 821 Plant Reactors

In our reconsideration of Zhang's assessment, we judge that Zhang's assumption that both reactors halved production in their later years of operation deserves reconsideration. There is no firm confirmation of this assumption, which is based on Zhang's belief that there was a general shift in China's nuclear program in the early 1980s. That shift moved away from the purely military to a greater commercial orientation, which led to a reduction in WGPu production. Additionally, while Zhang assumed that the 821 Plant reactor shut down in August 1984 for conversion, presumably to non-military use, we note that two separate sources (1) claimed that China's State Council decided in August 1987 to "stop production of military products and switch to civilian products" at the 821 Factory,[37] and (2) that military production at the factory was halted in 1988.[38] This acknowledges that neither of these claims is unambiguous about the date of the reactor shutdown, since the reactor may have shut down earlier, while the reprocessing plant may have continued to reprocess spent fuel for WGPu until the latter dates. However, for comparison, we assume that the 821 Plant reactor continued to produce WGPu until the end of 1987. Our results are as follows:

• For the 404 Plant reactor, assuming it continued to produce WGPu at the 1979 peak rate of 190 kilograms per year until November 1986 (prorated to 174 kilograms in that last year) results in about 660 additional kilograms of WGPu and a total of over

2,600 kilograms.

- For the 821 Plant reactor, assuming that it ran continuously to the end of 1987 at the peak 1979 production rate of 205 kilograms per year, results in an additional production of almost 1,200 kilograms and a total of just over 2,600 kilograms.

This results in a total of over 5,200 kilograms for the two reactors.

Conclusion: Implications of the Different Assessments

Table 1 summarizes the three assessments of China's production of WGPu in the 404 Plant and 821 Plant reactors. In summary, the difference between Zhang's 2017 assessment and our reassessment in this paper stems directly from Zhang's undocumented assumption that from 1980 onward WGPu production was halved in both reactors based on a general shift away from a purely military nuclear industry to a mixed military-commercial model. In our reassessment, it is assumed that production proceeded at the 1979 peak value until shut down. The closure date for the 821 Plant reactor from Zhang's inferred, but not confirmed, year of 1984, is extended to 1987, when military production was said to have ended.

Zhang (2017)	Swegle and Yeaw	Esin and Anichkina
	404 Plant	
2,000 kg	2,600 kg	1,800 kg
	821 Plant	
1,450 kg	2,600 kg	4,500 kg (possible, to 1990)
		2,900 kg (possible, 1990-2009)
	Totals	
3,450 kg	5,200 kg	6,300 to 9,200 kg

Table 1. Assesments of China's production of WGPu at the 404 Plants and 821 Plants

The difference between Zhang's assessment and that of Esin and Anichkina results from totally different analyses of the 821 Plant reactor. The two differ in three respects:

1) While Zhang relied on published Chinese sources and personal accounts from Chinese workers at the 821 Plant, Esin and Anichkina appear to draw heavily on personal discussions with three unnamed scientists from Moscow's Kurchatov Institute who claim to have personally participated in Russian assistance to the developing Chinese complex.

2) Esin and Anichkina employed a much higher reactor power of 850 MWt for the 821 reactor versus the 600 MWt offered by Zhang. The lower value was drawn from a 1990 report, described above, which discussed a 600-MWt reactor in terms that implicitly referred to all three reactors at the 404 Plant, 821 Plant, and 816 Plant. Without regard to the actual power level, Zhang, unlike Esin and Anichkina, argues that mentions of 1.2, 1.3, and, in combination, 2.5 reactors imply a common design power level for the reactors.

3) Esin and Anichkina suggest that the 821 Plant produced WGPu well beyond the dates provided by other independent sources.

We judge that the rather conditional nature of Esin and Anichkina's assessment, and the problematic nature of some of their quantitative analysis, makes their assessment less reliable.

In closing, we focus on Zhang's 2017 assessment and our reassessment here and consider the numbers of potential nuclear devices. According to Zhang's methodology for loss of WGPu to tritium production, processing and fabrication, and nuclear testing, his original estimate of 3.4 tonnes of WGPu produced is reduced to a central value of 2.9 tonnes available for nuclear weapons. Applying a similar methodology, our estimate of WGPu available for weapons is reduced to about 4500 kg. We offer two values for the WGPu per weapon. At the upper end, 6 kilograms of WGPu is employed—similar to the Fat Man bomb dropped on Nagasaki.[39] At the lower end, 4 kilograms of WGPu is used—consistent with Zhang.[40] Table 2 shows the numbers of possible nuclear devices.

	Zhang's 2017 assessment (2,450 kg)	Our reassessment (4,500 kg)
6 kg per device	400	750
4 kg per device	600	1,125

Table 2. Numbers of possible nuclear devices

Appendix: Design Power of China's Original Plutonium Production Reactors

The China Today article referenced in the body of this article provides extensive information on timelines and the qualitative operating profile of the 404 Plant reactor; however, it fails to provide the design power of the reactor, which is needed to estimate plutonium production.[41] The thermal design power is given in a 1990 technical publication as 600 MWt.[42] The reactor is also said to have an electrical power of 100 MWe, which implies a thermal-to-electrical conversion that is quite low by comparison with the roughly 30 percent of a dedicated power plant. Although we see no visual evidence of electrical transmission equipment at the 404 Plant reactor building, the low thermal-to-electrical efficiency indicates a lower-temperature core suited to the use of metallic, as opposed to oxide, reactor fuel, as well as targets, if any.

The same article implies that the reactors at the 404 and 821 Plants are basically the same, and the same as that intended for the cancelled 816 Plant. The article mentions one power level, but three reactors "located in a desert area [404 Plant], ravine area [821 Plant], and cave body [816 Plant]." Additional information suggests they have the same power.

Less conclusively, because it does not refer to the reactor directly, a Chinese blogger who worked at the 821 Plant (and referred to the site as "the ravine") wrote that in 1969, the central government shifted equipment planned for installation on the 816 project to build the 821 Plant.[43]

Zhang also took note of the implied math in the commentary of workers from the sites, which also points to both operating reactors having the same design power.[44]

- According to a memoir from Zhou Zhi, former Deputy Minister of the Second Ministry of Machine Building Industry, after reaching design power, the 404 Plant reactor reached a production level to 1.2 times the original design value.[45]

- Two other blogs stated that the 821 Plant reactor increased production to 1.3 times the original design value.[46]

- A blog also indicated that the two reactors were directed by the head of the Second Ministry of Machine Building Industry to produce at a level of 2.5 reactors, i.e., the sum of 1.2 and 1.3 for the pair. Zhang took that straightforward summation to indicate that both reactors had the same original design power.

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American, British Nuclear Experts Conduct Counterproliferation Exercise in United Kingdom

Walter T. Ham IV

Sellafield, England – American Soldiers from Nuclear Disablement Team (NDT) 2 conducted nuclear counterproliferation training with personnel from the U.S. National Nuclear Security Administration (NNSA) and United Kingdom Ministry of Defense during an exercise in May.

The exercise was the first time one of the U.S. Army NDTs have trained in the United Kingdom.

Nuclear Disablement Team 2 is one of three NDTs from the 20th Chemical, Biological, Radiological, Nuclear, Explosives (CBRNE) Command, the U.S. Department of Defense's premier deployable all hazards formation.

As a part of the 2018 Department of Defense Nuclear Posture Review, the NDTs provide advanced forensics and attribution capabilities in support of overseas and domestic missions.

NDTs directly contribute to the nation's strategic deterrence by staying ready to exploit and disable nuclear and radiological Weapons of Mass Destruction infrastructure and components to deny near-term capability to adversaries and facilitate WMD elimination operations.

In addition to the NDT 1 "Manhattan," NDT 2 "Iron Maiden" and NDT 3 "Vandals," the Aberdeen Proving Ground, Maryland-based 20th CBRNE Command is home to 75 percent of the Active Duty Army's Explosive Ordnance Disposal technicians and Chemical, Biological, Radiological, Nuclear (CBRN) specialists, as well as the 1st Area Medical Laboratory, CBRNE Analytical and Remediation Activity and five Weapons of Mass Destruction Coordination Teams.

From 19 bases in 16 states, Soldiers and civilians from the 20th CBRNE Command take on the world's most dangerous hazards in support of joint, interagency and allied operations.

Maj. Neal J. Trump, a nuclear operations officer from NDT 2, said the Nuclear Disablement Team began planning for the exercise in 2020 but COVID-19 postponed it.

In May 2022, the exercise took place at multiple locations in the United Kingdom. NDT 2 participated during the first half of the month at the Sellafield site in northwest England and at the Weeton Barracks about an hour from Manchester, England.

"The exercise as a whole validated the Department of Energy Mobile Packaging Teams in the receipt and processing of material collected from nuclear facilities and also integrated the participation of personnel from the DoE's Plutonium and Uranium Verification Teams," said Trump, an Iraq veteran and former infantry officer from Lancaster, Pennsylvania, who has commanded Soldiers in the 82nd Airborne Division and 3rd U.S. Infantry Regiment (Old Guard).

Sgt. Joshua Kamami, a Chemical, Biological, Radiological, Nuclear (CBRN) specialist for Nuclear Disablement Team 1, watches on as Nuclear Disablement Team 2 CBRN specialist Sgt. Shivam Patel runs a swipe across the surfaces of a glove port to check for the presence of radioactive contamination. Held in the glovebox training facility at Sellafield Site, this training occurred during a training exercise in May 2022 in the United Kingdom. (Courtesy photo)

The exercise offered a unique training opportunity for NDT 2 to characterize an industrial-scale reprocessing facility and to recognize the equipment and materials used there, said Trump.

In addition to seven Soldiers from NDT 2, four Soldiers from the other NDTs were able to participate in the exercise.

"This exercise presented a truly unique training experience for NDT 2 that will pay dividends for a long time to come," said Trump. "Since there are currently no commercial reprocessing facilities for spent nuclear fuel operating in the United States, conducting training at Sellafield exposed team members to a portion of the nuclear fuel cycle that we rarely have the opportunity to work in and at a scale that nobody had witnessed before."

Trump said the NDT Soldiers were able to conduct a reconnaissance and characterization of the Thermal Oxide Reprocessing Plant (THORP), as well as perform sampling operations of highly accurate simulants from large negative pressure gloveboxes.

"The most enduring effect of the exercise, however, will likely be the excellent relationships we developed with Sellafield personnel that we hope to leverage for further training opportunities in the future," said Trump.

During the exercise, NDT Soldiers refined procedures for detecting nuclear material and collecting gamma ray spectra, as well as packaging simulated samples of nuclear material to transfer to the NNSA's Mobile Plutonium Facility.

"Perhaps most importantly, the exercise allowed the team to further develop our relationship with the subject matter experts employed by DoE and NNSA. We hope that our participation in this exercise will open the door to future collaboration between the NDTs and the NNSA," said Trump. "The highlight of the exercise, from my point of view, was the degree of interagency partnership building that was able to occur."

At Sellafield, representatives from the NNSA's Uranium Verification Team and Plutonium Verification Team not only observed the training but also participated in discussions about how both organizations can better support one another in the counterproliferation fight.

NDT 2 Soldiers also used the U.S. Department of Energy's reach-back process while in the United Kingdom to send requests for information to a U.S.-based team of subject matter experts who were able to provide technical guidance in support of the NDT characterization of the Thermal Oxide Reprocessing Plant.

"At the conclusion of our training, NDT 2 prepared and presented an exploitation brief to senior members of the 20th CBRNE Command and leadership of the NNSA's Nuclear Compliance Verification and Mobile Packaging programs," said Trump. "This interaction further served to demonstrate the capabilities of the NDTs to key interagency partners and acted as a relationship-building venue between key DoE professionals and NDT personnel."

Glen L. Jackson, the White Team lead from the U.S. National Nuclear Security Administration, said the NNSA, U.S. Department of Defense, UK Ministry of Defense, Nuclear Decommissioning Authority and countless other mission partners came together to coordinate and deconflict the numerous training activities occurring simultaneously.

The NNSA is responsible for the monitoring, verification, removal and securing of high-risk nuclear and radiological materials and equipment around the world that pose a potential threat to the United States and the international community.

MAJ Ariel Alcaide, a nuclear operations officer on Nuclear Disablement Team 2, performs a glove exchange during a glovebox sampling training event at Sellafield Site, United Kingdom, during a training exercise, May 2022. Courtesy photo. (Courtesy photo)

"Overseas deployment exercises provide the opportunity to practice not just these missions but also the foundational logistics required to execute them through the integrated and collaborative efforts of NNSA and Department of Defense," said Jackson, who has served as a contractor at the Savannah River Site in South Carolina for 31 years.

Jonathan P. Spencer, a manager at the Sellafield site, said joint training exercises give his site invaluable opportunities to share knowledge and learn from the other participants.

"While Sellafield's challenges are different in many ways to the challenges faced by the NDT, there are some similarities," said Spencer. "Seeing how other teams approach tasks like characterization, sampling and radiation and contamination control is very instructive. There are many learning points from the exercise which will help inform our work in the future. Finally, Sellafield recognizes the important role the NDT performs and takes pride in being able to play a small role in the NDT training and exercise program."

Spencer, who has worked at Sellafield Ltd for 12 years, credited the success of the exercise to advanced planning done by NDT 2 Team Chief Lt. Col. Ronald C. Lenker and Maj. Neal Trump with his Sellafield team, including Astelle Batty and Gareth Bawden.

"It was evident that the attention to detail resulted in the successful running of the exercise," said Spencer. "Due to the nature of work on the Sellafield deployments, such as this exercise while on paper may appear simple in reality are not straightforward."

The exercise was the first at the Sellafield site's new Glove Box Training Facility.

"It was a great pleasure and honor for Sellafield Ltd to host this visit within THORP and our Glovebox Training Facility," said Spencer. "It was a particular highlight to see NDT members calmly, methodically and professionally tackle the very challenging scenarios we created for them in this new facility."

Walter T. Ham IV

Walter T. Ham IV is the Deputy Public Affairs Director for the 20th Chemical, Biological, Radiological, Nuclear, Explosives (CBRNE) Command, the U.S. Department of Defense's premier multifunctional and deployable all hazards formation. Soldiers and civilians from 20th CBRNE Command confront and defeat the world's most dangerous hazards in support of joint, interagency and allied operations. A retired U.S. Navy Chief Journalist with a master's degree in nonfiction writing from Johns Hopkins University, he previously served as a Pacific Stars & Stripes reporter and a civilian public affairs officer for the U.S. Navy, U.S. Air Force, U.S. Coast Guard and U.S. Department of Defense.

Leveraging Artificial Intelligence to Detect and Deter Nuclear Proliferation

Angela M. Sheffield

U.S. programs to deter state and nonstate actors from pursuing new programs to develop nuclear weapons have long focused on detecting and controlling special nuclear material, leveraging detection technologies and strategies to deny access to this requisite resource. However, this approach supports strategies to deter an actor only after the program has progressed to the late and high-stakes stages of nuclear material production and nuclear weapons testing. History has shown that deterrence at this point is unlikely to be successful. New techniques leverage big data and artificial intelligence (AI) to detect early warnings of an emerging nuclear weapons program by characterizing the weapons-usable capability of advances in civilian, dual-use, and weapons-related nuclear science and technology and detecting subtle indicators of changes in intent from civilian to military use. This may enable intervention when a program first diverges from peaceful purposes and deterrence is more likely to be successful.

Leveraging white hot advances in artificial intelligence (AI) and related technologies, the United States should broaden the focus of nuclear proliferation deterrence strategies to include early detection and early deterrence. This will increase the likelihood that the United States could successfully encourage an emerging program to restrain from further advances in weapons-usable capability and return to solely peaceful pursuits.

Traditional Nuclear Proliferation Detection

Existing U.S. strategy to deter nuclear weapons development focuses on denying access to nuclear material that can be used to make nuclear weapons.[1] Foundational to U.S. nuclear nonproliferation and arms control is nuclear proliferation detection: the use of technologies and scientific capabilities to detect nuclear material and determine whether nuclear material produced by existing nuclear programs is intended for peaceful or military applications.[2] U.S. national security and international affairs agencies use the information provided by nuclear proliferation detection technologies in combination with other information sources, policies, and programs to support and inform military, security and law enforcement, diplomatic, and economic operations to deny access to nuclear material.[3] These agencies include the Department of Defense, Department of State, Department of Energy, Department of Homeland Security, Department of Commerce, and the Intelligence Community.

For example, within DOE's Nuclear Smuggling Detection and Deterrence program, technical experts and program managers from the National Laboratories work with international partners to integrate radiation detectors at border crossings around the world to detect and disrupt smuggling of illicit material.[4] DOE's Material Management and Minimization (M3) program leverages National Laboratory facilities and experts to minimize the presence, use, and production of weapons-usable nuclear material. M3 works with civilian research reactors and medical isotope production facilities that use highly enriched uranium to convert to low-enriched uranium, which is not usable in weapons development.[5]

Additionally, technologies and technical expertise provided by the DOE National Laboratories enable the International Atomic Energy Agency's programs to monitor for misuse of nuclear facilities and diversion of nuclear material.[6] In addition to denying illicit actors access to nuclear material, nuclear safeguards deter states from nuclear weapons development by increasing the cost of illicit use and rewarding restraint through alignment with international norms and technical cooperation to transfer nuclear technology.[7] Further, they threaten severe punishments, like the economic sanctions levied by the United Nations Security Council following Iran's non-compliance with the Nuclear Nonproliferation Treaty in 2008.[8,9]

Nuclear proliferation detection technologies are also operationalized within Intelligence Community, typically as measurements and signal intelligence (MASINT). MASINT uses sensors and physical collections to detect and characterize unique physics-based signatures of special nuclear material and the process to produce it. Decisionmakers and policymakers depend on MASINT and nuclear proliferation technologies to provide precise information to assess emerging and extant nuclear weapons programs, inform military operations and homeland defense, and confidently monitor treaties and arms control agreements.[10]

Figure 1. NNSA's aerial measuring system is integral to the United States' layered defense against nuclear terrorism and nuclear proliferation. The United States works with international partners to integrate radiation detectors at border crossings around the world to detect and disrupt smuggling of illicit material.

There are two limitations to this nuclear material-focused strategy. First, mastery of the uranium enrichment process, which marks a program's capability to produce nuclear material for peaceful or weapons use, occurs near the mid-point in program development.[11,12] Technologies to detect nuclear material and its production reveal emerging programs only after they possess the capability to produce nuclear material.[13] Second, traditional technologies only detect nuclear proliferation activities related to nuclear material and are blind to other key activities, such as the research, development, or acquisition of special equipment, technologies, and expertise required to build nuclear weapons.[14,15] These activities may be observable far earlier in development of an emerging nuclear program and long before production of nuclear material for nuclear weapons.[16]

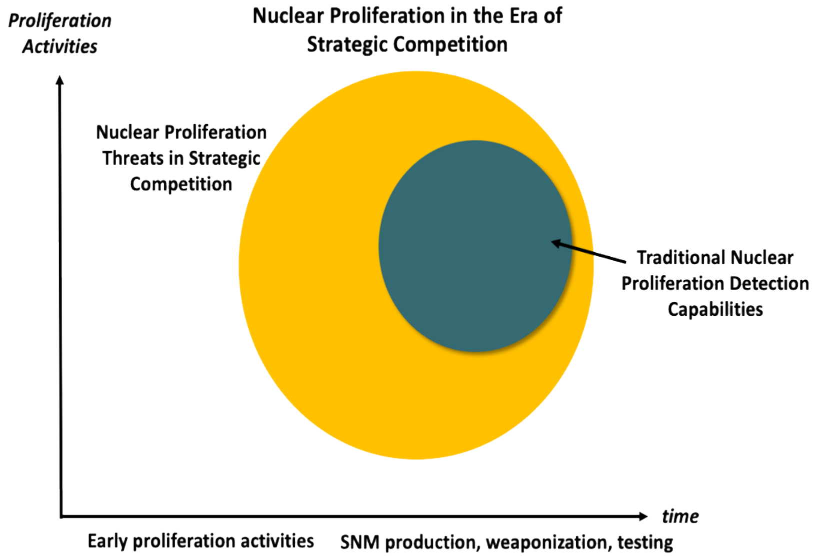

Figure 2. The United States' current strategy to detect and deter nuclear proliferation focuses on denying access to special nuclear material. However, environment for deterrence operations afforded by this narrowly focused strategy is too limited to ensure U.S. vital interests.

Joint Doctrine for Global Deterrence calls for deterrence operations to provide an environment that allows the United States to pursue constructive policy goals.[17] The operating environment afforded by the United States' current, narrowly focused strategy is limited. Recent history shows that it is, in fact, too limited to ensure U.S. vital interests: after nuclear breakout by North Korea, the United States had few policy options for deterrence and intervention. Indeed, for nuclear weapons programs that advance to the stage of nuclear material production and nuclear weapons testing, the level of motivation and perceived benefit from having nuclear weapons – deterrence against U.S. attack while achieving national status equal to the United States[18] – may be so high that deterrence is essentially impossible.[19]

The New Era of Early Proliferation Detection

It is likely that any new nuclear weapons program will leverage dual-use research and nuclear energy science and technology to clandestinely advance weapons-usable capabilities.[20] Leveraging deep expertise and emerging technologies like big data and AI, the National Laboratories have demonstrated new methods to determine the weapons-usable capability of an emerging nuclear program and detect subtle indicators of change in strategic intent from peaceful to military use.[21] For example, National Laboratory scientists in DOE's Advanced Data Analytics for Proliferation Detection (ADAPD) program have developed an AI-powered approach to discover foreign scientists pursuing nuclear weapons-related research and track their progress toward material production.[22,23]

Similarly, the Nuclear Threat Initiative (NTI) recently defined "societal verification" as a possible contributor to monitoring compliance with international agreements. This approach leverages advances in data science and machine learning in combination with greater amounts of publicly available information to enhance capabilities to detect illicit trafficking. In its ongoing work with the Center for Advanced Defense Studies, NTI has demonstrated the use of commercially available satellite imagery, social media content, and other data to reveal subtle clues left by nefarious actors. Such techniques could be used to monitor and verify compliance with future arms control and export control agreements to build transparency and confidence among nuclear and non-nuclear states.[24]

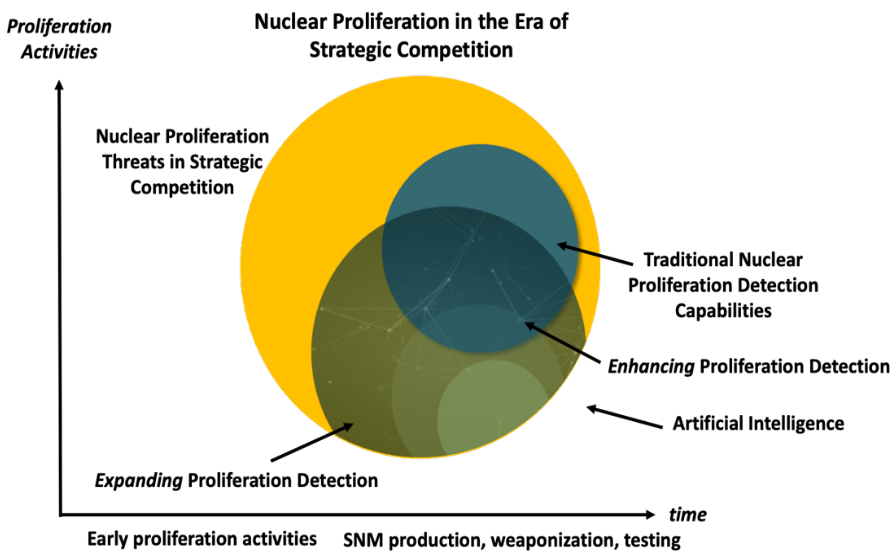

Figure 3. Early proliferation detection will enable the United States to deter programs at early stages of development when stakes are lower because success is still uncertain and there is limited investment in purely weapons-usable capabilities.

The United States has long relied on nuclear proliferation detection technologies to inform operations to deter nuclear proliferation by denying access to nuclear material. While the United States employs a multifaceted approach to prevent, reduce, disrupt, degrade, and defeat nuclear proliferation, deterrence remains at the heart of its strategy. Early proliferation detection methods may provide policy and decisionmakers with essential, timely information to develop deterrence strategies for a wider range of nuclear proliferation activities, like sanctions and export controls to deny key resources beyond nuclear material and impose greater costs to acquiring them. Furthermore, early proliferation detection will enable the United States to deter programs at early stages of development when stakes are lower because success is still uncertain and there is limited investment in purely weapons-usable capabilities. At this point, before public declaration of malintent by withdrawing from the Nonproliferation Treaty and long before the celebration of a successful nuclear weapons test, it may be possible to devise strategies to deter further advances toward military use, encouraging restraint by rewarding the return to solely peaceful pursuit of nuclear science and technology.

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The Importance of Army Leadership in Countering WMD

Albert J. Mauroni

Twenty years ago, world events conspired to push weapons of mass destruction (WMD) into the forefront of defense policy and studies. On October 16, 2001, the Washington Post front page banner blared "Anthrax Scare Comes to Capitol Hill," a story that would remain in the headlines for months following. A week prior, the cover of Newsweek showed a U.S. Marine in a protective mask with overlaid text "Biological and Chemical Terror: How Scared Should You Be?"[1] On February 6, 2003, many newspapers reported on Secretary of State Colin Powell's presentation to the U.N. Security Council, with the picture of him holding a vial of white powder for illustration. In March 23, 2003, the Washington Post breathlessly reported that "Al Qaeda Near Biological, Chemical Arms Production."[2] In May 2003, the headline was "Suspected Bioweapon Mobile Lab Recovered."[3] Like no time before and no time since, the national security community was focused on WMD policy issues.

In particular, the Department of Defense (DoD) instituted several projects between 2001 and 2006 in response to the threat of unconventional weapons. The U.S. government used a newly-released military counterproliferation concept[4] to create a national strategy for combating WMD, following the incidents of anthrax letters being mailed to federal government and commercial media buildings. In 2003, there was a complete reorganization of how the DoD managed its chemical and biological defense acquisition[5], even as it was challenged by increased preparations to face off with Iraq and its alleged WMD program. Following the short Iraq war, DoD hosted several workshops aimed at developing a more biodefense-centric approach[6] and constituting a full-time WMD elimination joint task force. DoD added $1.5 billion to the DoD Chemical and Biological Defense Program (CBDP) to put military chemical and biological defense equipment on U.S. military bases, as an effort to harden these installations against a terrorist WMD attack.[7] In October 2003, the U.S. Army stood up a "Guardian Brigade" to increase the military's ability to respond to WMD incidents.[8] Between 2004 and 2006, DoD officials developed the National Military Strategy to Combat WMD and its eight mission areas. U.S. Strategic Command was appointed as DoD agent to "integrate and synchronize" combating WMD issues in 2005.[9]

That energy has largely since dissipated. The desire for a biodefense-centric concept in 2004-2005 fell apart when no one could quite figure out how to make it work within existing military concepts and organizations. Talks on WMD elimination went on for several years before DoD assigned the task to the Defense Threat Reduction Agency (DTRA) in 2012 without adding more personnel or resources to the mission.[10] Ironically, DTRA's joint task force headquarters for WMD elimination did not lead the Syrian chemical disposal mission in 2013. Efforts to advance CB defense countermeasures bogged down due to unrealistic user requirements[11] and the movement of CBDP funds toward esoteric and duplicative "national" requirements. The DoD installation preparedness effort was run into the ground by an acquisition program that ignored funding constraints and service sustainment challenges. About half the acquisition funds from the installation effort were moved into a "Transformational Medical Technology Initiative" that was supposed to move the department away from "one drug for one bug" and toward broad-spectrum medical countermeasures.[12] After several years burning through two billion dollars, the program failed to produce any viable candidates for acquisition.

Perhaps the most challenging topic is the lack of forward momentum toward moving DoD policies from its 1990s counterproliferation concept to address current adversaries, including sub-state groups seeking WMD capabilities and "great power competitors." After the 2006 Quadrennial Defense Review, direction in national and departmental guidance on required counter-WMD capabilities became increasingly sparse. There was no update to the 2002 National Strategy to Combat WMD. In 2012, the DoD began development of a new military strategy to counter WMD, but it adopted national rather than departmental objectives and did not significantly change from the past "prevent, protect, respond" framework. Of note, the one major change was a push by Office of the Secretary of Defense (OSD) acquisition officials to broaden WMD to include natural infectious diseases and commercially-used fentanyls. The Counterproliferation Program Review Committee was disestablished in 2013. In 2016, U.S. Strategic Command decided that countering WMD was not its priority and pushed its DoD executive responsibilities to U.S. Special Operations Command.

Twenty years later, there has not been much progress from those initial years of the twenty-first century as far as capability development and preparedness for WMD threats. DoD leadership no longer sees WMD as a significant issue, perhaps because Iraq did not have an active WMD program despite the political rhetoric, or perhaps because no country has used chemical or biological weapons against the United States. There have been no domestic terrorist WMD incidents since 2001, and foreign incidents involving chemical or biological hazards have not threatened U.S. national security interests. It is not a defense budget priority or a topic of interest in contemporary international relations studies other than as an arms control topic. Today, the DoD CBDP is lauded more for its contract support to the Department of Health and Human Services than its advancements in military capabilities.

Now one can still find the obligatory quote about adversarial countries and terrorist groups being interested in WMD, and how the United States will not allow itself to be threatened by these threat sources. Congress still holds its obligatory annual review of WMD issues in the Armed Services' committees. But have counter-WMD policy or capabilities advanced since 2006? Given the lack of maturation of policy and relative flat-lining of budgets for defense capabilities to counter WMD, can we believe that the U.S. military, or the U.S. government for that matter, still considers countering WMD as a top national security objective? To understand this, we must review the policy process behind the U.S. government's countering WMD interests.

Defense Policy Process Explained

Defense policy is a subset of public policy, actions that the government takes to address specific issues that the public believes are critical challenges. The policy process creates programs and decisions that are consistent and repetitive on the part of the policymaker and the people that abide it.[13] In the 1990s, the DoD's policy objective was to protect U.S. forces and coalition allies from non-nuclear nations that had chemical and biological weapons programs, believing that these adversaries would not observe arms control treaties or international norms. In the early 2000s, national policy changed to expand the concerns from smaller nation-states with WMD programs to include sub-state groups with WMD ambitions. Countering WMD policy added the objectives of responding to domestic CBRN incidents and interdicting terrorists seeking WMD capabilities to protecting U.S. forces from nation-state threats of WMD use.

There are four significant groups of actors in defense policy: policymakers, the technical agencies, Congress, and non-governmental reformists. Policymakers are expected to develop policy objectives and develop rational agendas to meet them. In the DoD counter-WMD community, these include the National Security Council (NSC) and four assistant secretaries of defense (Space Policy, Homeland Defense, special operations /low intensity conflict (SO/LIC), and Health Affairs). The technical agencies are supposed to execute specific aspects of policy programs. The five Services and defense agencies fall under this group, to include the doctrine centers, acquisition program offices, and intelligence agencies. Congress authorizes programs and appropriates funding, in addition to performing oversight of policy initiatives. In particular, the Armed Services committees and homeland security committees have significant interests here. Finally, the non-governmental reformists seek to improve government policy programs to better address public challenges.

Problems arise when these four actors work against each other or do not execute the roles expected of them. The NSC staff doesn't work interagency counter-WMD policy and instead focuses on arms control and (lately) global health security. Having four different ASDs involved in counter-WMD policy is far from optimal, particularly in crisis management scenarios that cut across portfolios. These positions can be very personality-dependent, with the result of years going by without any real interest in guiding the integration of WMD issues into general policy or defense capabilities. The Services' leadership have never seen WMD as a top priority, believing that other technical specialists will rise to the occasion if any WMD incident emerges. Lacking any crisis, Congress's committees do not dig deep into the policy issues. The Government Accountability Office and Congressional Research Service have not examined WMD issues for years. Without oversight and with no increases in funding, capability gaps continue to grow. Think tanks and advocacy groups have a great capacity for independent research, but often push unrealistic and overly-expensive solutions that are never picked up.

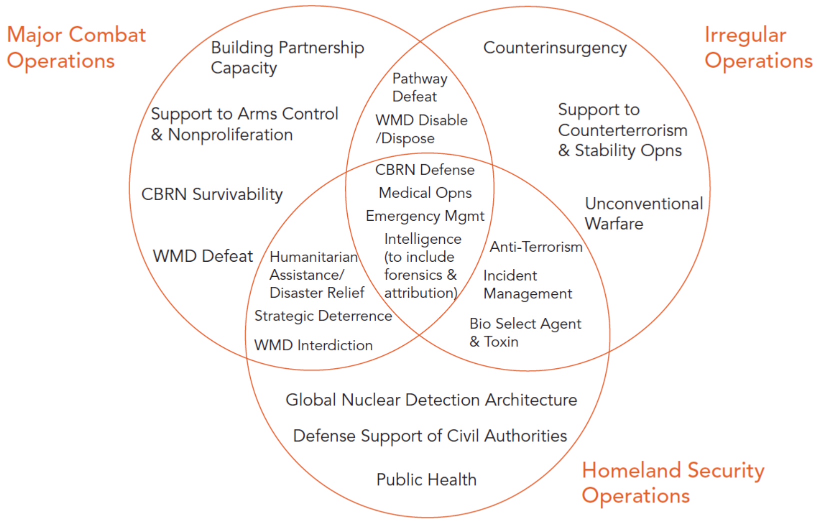
Over the past ten years, OSD policy offices have largely stopped leading WMD policy discussions within the context of larger national security debates. This is particularly disturbing given the change in the threat sources in our field, notably that Russia and China as "great power competitors" that are suspected of not being in compliance with chemical and biological arms control treaties and nonproliferation agreements. With this lack of policy leadership, the CB defense portfolio was pushed to include research and development of countermeasures for natural disease outbreaks. The Service leadership and Congress have not publicly questioned this direction, while business advocates applaud the potential increase in funding that might result. Congress has not increased funding to maintain CB defense budgets to avoid cuts from inflation. There are a few think tanks or activist groups addressing DoD counter-WMD issues today, but certainly the larger, more well-established think tanks do not follow WMD issues at all. There is no demand signal for them to be interested in the topic.

One has to ask the question – is countering WMD still a priority for the White House? Stating that WMD proliferation is still a concern is not enough to define policy direction across the interagency. Given that WMD incidents can occur during military combat operations, homeland security operations, or in operations combating terrorism, there needs to be more specific guidance on exactly what the threats and threat sources are, and how the Services should organize, train, and equip to provide forces that can address defense policy objectives. The 2014 DoD Strategy to Counter WMD does not provide this guidance. In addition, it is far from clear that current counter-WMD operational concepts adequately address the threat posed by WMD developed by Russia and China.[14] With little to no oversight, with limited resources, and with no assessment of how well the U.S. military is prepared for future WMD incidents, we are not in a good place.

It may be that the national security enterprise has other ideas for how to counter WMD. It may be that the Biden administration wants a primary focus on arms control with a healthy side of military power for deterrent effects. And that's okay, if the NSC would clearly articulate this point. Public policy programs, to include defense programs, were meant to be assessed and, if the original challenge has been addressed, terminated. "Termination" is an unpopular word for defense programs, but it remains a valid outcome for people serious in advancing defense capabilities. It may be that a defense program has to be adjusted or expanded following an assessment, but lacking an assessment, one only sees stagnation. If the 1990s counterproliferation concept is no longer valid to address contemporary challenges such as great power competitors and sub-state groups, then it needs to change or be terminated. Perpetuating an old model for the sake of comfort is no way to advance national interests. But leadership has to communicate an agenda that is to be developed, not hidden in rhetorical statements about how "the threat is real."

Why Is This Important

If this topic is important to the national security leadership, then the defense policy needs to accurately reflect what is expected of the Services and combatant commands, provide the funding necessary to develop those capabilities, and assess their readiness to meet clearly stated policy objectives. The acquisition community should not in any way be developing defense policy objectives or operational concepts for the department or the Services. We see this happen anyway, because the acquisition community has a lot of resources and influence, and because OSD policymakers and military offices are not engaged in the process. It may be that how policy and strategy describes counter-WMD objectives is too generic, too broad to provide the specifics of what capabilities are needed. I suggest that there are three operational concepts that address WMD issues: major combat operations, homeland security, and combating terrorism. These three areas have different missions and different required capability sets, but if one were to examine a Venn diagram of their WMD responsibilities, at the center there would be four specific tasks: intelligence operations, CBRN defense, medical operations, and emergency response. While this identifies a commonality between the three areas, each has unique threats that require a focused capability. A CBRN defense capability designed for major combat operations may not be suitable for homeland defense or combating terrorism.



As the nation has been dealing with COVID-19 for the past two years, there has been a lot of reflection as to how the DoD should prepare for future biological threats, including naturally-occurring diseases, deliberate biological attacks, and accidental biological releases. Defense Secretary Lloyd Austin directed a Biodefense Posture Review in November 2021 for the purposes of establishing "the Department's approach to biodefense, to include clarifying biodefense priorities, roles, responsibilities, authorities, capabilities, and posture."[15] Now there are a lot of implications here, first of all that the DoD should in fact have a common strategy for three very different sets of biological hazards encountered in three very different contexts. Using the "prevent, protect, response" model, the DoD does not in fact prevent or protect against naturally occurring diseases the same way as it prevents or protects against deliberate biological attacks. This point should be obvious. Does this new biodefense vision suggest that the military medical community should lose control over how it addresses natural infectious diseases under force health protection? Should the military forces abandon its CBRN defense concepts in exchange for a chemical / nuclear defense concept and a separate biodefense concept? Should the DoD BL-3 and BL-4 laboratories report to an OSD biodefense governance board instead of their respective Services' acquisition commands?

Second, should the DoD CDBP reduce its efforts to develop countermeasures for chemical and biological weapons and instead ramp up efforts for developing pandemic-focused response capabilities for "national priorities?" Using the CBDP as a vehicle for this objective will mean duplicating programs already run by the U.S. Army Medical Research and Development Command and the Department of Health and Human Services. The DoD CBDP has not made significant advances in military biodefense over the past decade (or protective suits, or decontaminants, or collective protection systems) but seems very proud of their support to DHHS programs. There is no free lunch here. If the program increases its focus on providing countermeasures for natural biological diseases, the Services will lose capability to protect U.S. forces against deliberate CBRN threats.

Defense policy requires precise language to ensure that resources are spent toward the objectives identified by national and department leadership. Using terms such as "biological threats" and "chemical threats" allows for acquisition officials to justify spending funds on what they believe are critical priorities but not Service-validated requirements. If the DoD CBDP was initiated to develop military gear for U.S. forces, then it ought to avoid spending funds on capabilities that the Services did not request. This requires clearly identifying what the battlefield threat and threat sources are and recognizing that other government agencies address biological threats for the nation's needs. Duplicating the efforts of other government agencies' efforts is a sure-fire approach of getting Congressional attention in a very negative way.

Another example is the concept of WMD elimination, now called WMD disablement and disposal operations. There was a lot of focus on getting this concept right after the former WMD exploitation task force, formed in 2003, failed to find any evidence of an active WMD program in Iraq. While the initial concept was to develop a full-time joint task force, it settled on a standing joint force headquarters that would be the basis for a larger response effort. It was planned to be both a multi-service and intra-agency organization, however, when the Syrian chemical disposal effort kicked off, this concept failed. DTRA no longer has a standing joint force headquarters for elimination, despite the relative success of the ad-hoc group that completed the Syrian chemical disposal effort. Is WMD disablement and disposal supposed to be a multi-national, interagency effort like Syria's chemical destruction mission or is it just a specialized Army CBRN technical mission, being practiced occasionally with the South Korean army?[16] Current strategy and policy guidance does not inform us here. Lacking appropriate priorities and resources, Army efforts to develop capabilities for this national mission may be in peril.

In these days, it is largely the CBRN defense technical specialists and arms control advocates who work in counter-WMD policy, but one should not forget the offensive options (special operations, counterforce operations) and theater air and missile defense capabilities. At one time, people used to talk about developing specialized capabilities through these means to defeat WMD delivery systems. That hasn't happened in a very long time. The topic of incident response has likewise been relegated to supporting civil authorities, but are military installation commanders prepared to direct recovery operations following a chemical or biological attack on their base? It's unclear. During the Obama administration, there was a great deal of interest in "left-of-boom" actions that the DoD could take. Today, military support to nonproliferation and security cooperation exists but is uncoordinated and sporadic. Lacking any platform to openly discuss these important aspects of counter-WMD operations, we are left to crisis management as the only available option to WMD incidents.

Who Will Lead?

In an ideal world, one would expect to see OSD policy offices generating counter-WMD policy and budget priorities, rather than OSD acquisition offices. One would expect the Services' leaders to develop and exercise their capability to operate against a near peer competitor with a WMD program. The Services' action officers should understand the important differences in operating against military warfare agents, industrial hazards, and natural diseases. The major think tanks (e.g., CNAS, CSIS, AEI, Hudson Institute) should engage in academic debates over military readiness to counter adversaries with WMD programs, given the significance of this threat. In this ideal world, it would be great to have a community that understands the difference between CBRN defense tactics and countering WMD policy. This ideal world does not exist today.

There is a DoD "Unity of Effort" council for counter-WMD that aims to be "a collaborative and cross-cutting venue for raising awareness of issues, identifying shortfalls and opportunities, and driving toward solutions."[17] This is a forum through which OSD offices, the Services and National Guard Bureau, and combatant commands can work these issues. It became active in 2019. U.S. Special Operations Command is hosting a counter-WMD senior leader forum to advance understanding of the threat and inform the development of capabilities required to deter, defend against, and respond to WMD use.[18] Is this enough, however, to address the current lethargy within the U.S. government? Many of these efforts are behind closed doors and within the counter-WMD community of interest. If this topic is not fully shared in open forums and engaged by the larger national security enterprise, will anything truly change for the better?

The Services and combatant commands do appreciate the need for CBRN defense capabilities, at least enough to fund the bare minimum to outfit active-duty forces to survive and sustain combat operations in a contaminated environment. That's a start, but usually not enough to bring three- and four-star general/flag officers to the table, lacking an actual military contingency that demands their attention to this detail. The Joint Staff and U.S. Special Operations Command have stepped up their efforts to assess military capabilities and update combatant command plans, but their focus is largely aimed at operational capabilities and not policy discussions. The Army and Air Force both have senior-leader counter-WMD forums, but these are often used for internal coordination and not external engagement. Lacking any substantive progress at the strategic level, how do we advance defense policy and strategy?

Given that the majority of interest is from the CBRN defense community, it makes sense that the Army take on this mission. The Secretary of Defense appointed the Army as the Executive Agent for chemical and biological defense in 1976,[19] and has renewed that appointment numerous times. It remains part of public law (50 USC 1522), although this responsibility is largely limited to coordinating the four Services' and National Guard Bureau's positions on the annual CBDP budget. But shouldn't the Army do more than this one function? Could the Army develop thought leaders for countering WMD, given its interests?

One can find Army lieutenant colonels and colonels in nearly every office that has any DoD counter-WMD functions. There are Army chemical officers working in every OSD policy and acquisition office, in every Joint Staff and geographic combatant command, in DTRA and U.S. Special Operations Command. The Army has the largest and only full-time specialist force addressing WMD in major combat operations, homeland defense operations, and countering WMD terrorism. The Army procures the overwhelming majority of CB defense equipment and owns the most research and development infrastructure for this mission. The networking opportunity, if managed effectively, would be limitless, and only requires a general officer or senior executive service civilian to guide these actions toward a joint counter-WMD concept. Lacking a single OSD policy office to drive counter-WMD strategy, lacking any think tank or NSC function that deliberates about this function, this option represents a very pragmatic approach to update and improve the department's strategy and capabilities.

When the Joint Staff created 'joint operating concepts' 15 years ago, it decided that countering WMD should be an integrating concept rather than an operating concept. The immediate problem was that, while there was WMD language inserted into the joint operating concepts, it didn't result in active collaboration with military operators outside of the CBRN defense community. This resulted in more of a vertical silo, focusing on building specialized technologies, than horizontal integration into capabilities that addressed the capability gaps of other communities. As a result, countering WMD remains very much focused on major combat operations, but has not advanced to address the contemporary challenges of the national security community, in particular with regards to great power competition.

The Army Chemical Corps needs to network and gain partners from the other Services to advance this venture, but it also needs to ensure that its general officers and senior executive service civilians, on the Army staff and Army Futures Command, are engaging the CBDP process as well. If these senior leaders do not directly engage the OSD policy offices and other Services' general/flag officers, then the issue of improving CB defense capabilities will continue to drop below the level of interest of defense policy makers. This is just a fact of Beltway politics. The price of not integrating counter-WMD issues into contemporary defense policy discussions is irrelevance.

Recommendations

The only way that our profession will continue to grow is through reinvigoration of critical reviews and discussions of how the defense policy should address WMD threats. To be clear, this does not mean hosting meetings of CBRN defense acquisition leaders talking about business opportunities of the future. While defense acquisition is always important, this isn't an area that needs embellishment. We need to break out of the cycle of hosting conferences that support the status quo rather than asking the hard questions about countering WMD. Given the Army's stake in this area, the opportunity to lead these critical reviews and question poorly-developed defense policies must be maximized.

Creating Army thought leaders in CBRN defense and counter-WMD is a feasible task but will take dedication and resources to develop. Fundamentally, it requires that the Army counter-WMD community learns to navigate Beltway politics, lead policy discussions that focus rather than disperse counter-WMD capabilities, and sponsor research on the policy aspects of WMD issues rather than just the technical nature of

WMD attacks. This approach is not natural to Army professional culture, unfortunately, but it is eminently possible to develop over time. This would include:

- **Learn how to play the defense policy game.** Many Army field grades will come to the Pentagon with reluctance, doing good staff work but not engaging in policy discussions. A few will openly back political appointee agendas without questioning the negative impact to the Service. Take the time to learn who is sitting in the ASD/DASD positions and who their staffs are, what meetings are taking place, how the military Services get a vote in the process (often through the Joint Staff). In time, one can anticipate and counter poorly-developed policy initiatives with good staff work.

- **Network with your peers and support a single agenda.** The tyranny of distance can cause the Army CB defense community to fracture along internal agendas, with Army organizations at Edgewood, Leonard Wood, Belvoir, and the Pentagon being at odds rather than in synch. No other Service has the depth that the Army does. This asset should be exploited, not wasted on short-sighted turf battles.

- **Maintain long-term, stable leadership at the three- and four-star level.** Beltway politics are won based on seniority and personalities, not on merits. If the Army does not have a consistently strong leader working with the Air Force and Navy and challenging OSD on its bad calls, then poor policy will be the result. The CBDP's Program Analysis and Integration Office should be constantly working for Army leadership to provide critical analysis on CBRN defense.

- **Lead the counter-WMD policy as well as the CBRN defense acquisition communities.** Supporting the development of CBRN defense materiel is the easy part of our business. The hard part is convincing OSD and other Service leaders that CWMD is worth investing and that there are talented Army leaders who know how to advance DoD policy objectives.

- **Energize the think tanks to work on these issues.** The National Defense University does host an annual CWMD conference. However, this event only preaches to the choir. We need to get CNAS, CSIS, AEI, Hudson Institute, as well as the traditional arms control centers back into the business of talking about this important topic. DC think tanks are the weather vanes for contemporary defense priorities, and their resources need to be applied to WMD issues.

- **Develop future leaders and education opportunities.** Developing a long-term CWMD leader development and education program has been plagued with problems since it was started more than 15 years ago. A joint CWMD education program is never going to happen, but if the Army War College and Command and General Staff College had dedicated faculty and courses on the topic, one might see a significant advance in developing future thought leaders in this area.

It used to be a thing for the older generation of WMD analysts to say, "back during the Cold War..." to identify when the U.S. military used to treat this topic with a little more emphasis. There really aren't any Cold Warriors still active in the WMD business, and now we say "in the post-9/11 period..." in our story-telling. Even this reference is becoming dated and less of value to contemporary security discussions. But it is important to recognize historical trends, and more importantly, recognize stagnation and even retardation of capabilities still required by the U.S. military. The Army is the only organization that can save the DoD counter-WMD community from itself. The other Services do not see this as a priority, and even DTRA and U.S. Special Operations Command have limited abilities to move the needle at the strategic level of policy discussions. This is an opportunity for the Army Chemical Corps community to engage at the top levels of defense policy, if the desire and commitment is there. If the DoD does not change and integrate counter-WMD into the mainstream of defense interests, then counter-WMD policy and strategy should be terminated. Continuing on as an insignificant and bypassed defense topic is truly a fate worse than death.

The views expressed in this article are those of the author and do not necessarily reflect the official policy or position of the Air Force, the Department of Defense, or the U.S. Government.

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Thorium: The Threat and the Opportunity

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Abstract

The breeding of fertile Thorium-232 (Th-232) to fissile Uranium-233 (U-233) is both a weapons proliferation risk and an opportunity to greatly and economically expand non-military uses of nuclear technology. Although some have claimed that U-233 is not a weapons proliferation risk, it may be a greater risk than Plutonium-239 (Pu-239). Abundant Thorium based reactor fuel also represents a potential tool in the effort to oppose climate change. Thorium based fuel gives developing countries which run on coal and have little or no Uranium a more abundant nuclear energy fuel option. Thorium also represents an opportunity for greatly advancing nuclear medicine and increasing drinking water availability. Initiatives outside of the US to pursue the Thorium-Uranium (Th-U) nuclear fuel cycle are increasing. The US CWMD and intelligence communities must increase their awareness of the Thorium-Uranium (Th-U) nuclear fuel cycle to avoid being surprised. The US nuclear power community and its regulators must reconsider its proven past success from the 1960s in order to best determine our nation's future course.

Introduction

Since the 1945 Trinity Test, the dominant nuclear weapons' fissile materials have been Uranium-235 (U-235) and/or Plutonium-239 (Pu-239). However, U-235 and Pu-239 are not the only fissile materials and the conversion of Uranium-238 (U-238) to Pu-239 is not the only option for breeding fissile fuel. The CWMD and intelligence communities must increase their awareness of the reality that fertile Thorium-232 (Th-232) may in a similar manner be converted to fissile Uranium-233 (U-233). Public information proliferation on the attractiveness of the Th-U cycle has motivated global competitors and others to publicly and perhaps secretly accelerate their Th-U nuclear cycle pursuits. Its attractiveness has significant implications for both advancing weapons proliferation pursuits and also advancing many peaceful technological pursuits including clean energy generation, nuclear medicine and seawater desalination. The CWMD and intelligence communities must be able to recognize, report and respond to all such interrelated possibilities with special focus on those that are weapons related. (Tickell, 2012)

Definitions

• Fissile Materials: Those capable of generating sufficient neutrons with their internal reactions to sustain a supercritical fission chain reaction.

• Fertile Materials: Those that may be converted to become fissile materials. Some fertile materials may fission when sufficient additional neutrons are provided from another source.

• Breeding: The process of converting a fertile material to a fissile material.

• Breeder Reactor: Breeds more fissile fuel than it consumes. The conversion ratio of fissile fuel output to fissile fuel input is greater than 1.0.

• Actinides: The heaviest elements. Those listed on the bottom row of the periodic table beginning with Actinium. All are radioactive metals. Most do not occur naturally.

• Denature: To make something unfit for its intended purpose.

Risks

Weapons Proliferation Risk: The Department of Energy National Nuclear Security Administration (DOE NNSA) scientific community concluded that U-233 and Pu-239 were equally viable, suitable and feasible for weapons purposes (Tickell, 2012). In an internal 1966 DOE memo which was declassified in 1994, DOE officials described U-233 as a “highly satisfactory” weapons material. They indicated further that if today’s pits were made with U-233, then there would be no interest in switching to Pu-239 (Woods, 1966).

Foreign U-233 Detonations: The conversion of Th-232 to U-233 is a weapons proliferation risk which has been demonstrated on a proof-of-concept basis at least twice. The Soviet Union and India have each successfully demonstrated weapons containing fissile U-233. In 1955, the Soviet Union dropped its first two stage thermonuclear weapon on the Semipalatinsk Test Site in Kazakhstan. See Figure 1 below. It was known in the Soviet Union as the “RDS-37” and in the West as “Joe 19”. Its core included both U-235 and U-233 and yielded 1.6 Mt (Holloway, 1980, pp. 195, 197). In 1998 as part of India’s Operation Pokhran-II, the Shakti V test shot employed a low-yield (0.2 kt) U-233 pit (Weaver, 2013).

Figure 1: USSR detonates the 1955 RDS-37 also known as "Joe 19" containing U-233. (Public Domain)

U-233 Proliferation Risk: Uranium-233 has several advantages when compared with either Pu-239 or U-235 which makes U-233 a proliferation risk. As indicated in Table 1, the preceding U-233 fertile isotope is Th-232 which has a much larger thermal (slow) neutron absorption cross section than the fertile isotope U-238 which precedes Pu-239. The nearly three times larger Th-232 cross section makes the conversion of Th-232 to U-233 more efficient than the conversion of U-238 to Pu-239 in the thermal spectrum (IAEA Nuclear Fuel Cycle and Materials Section, 2005, p. 8). Also as indicated in Table 1, the U-233 neutron release rate per absorption is greater than that of U-235. Neither Uranium isotope generates significant spontaneous fissions. Accordingly, neither Uranium isotope will detonate prematurely using a simplified gun-type detonating process whereas Pu-239 must undergo a complex implosion process to detonate. Given its relatively small non-fissioning neutron capture cross-section, U-233 is more likely to fission than either U-235 or Pu-239 whenever its nucleus contacts a neutron (Holloway, 1980).

Bare Metal Sphere Critical Mass Comparison: (Paxton & Pruvost, 1987, pp. 97-104)			
Material	U-233	U-235	Pu-239
Purity (weight)	98%	93%	95%
Density	18.4 (g/cc)	18.7 (g/cc)	15.6 (g/cc)
Critical Mass	16.2 kg	49.1 kg	16.8 kg
Reference	(Table 33)	(Table 29)	(Table 32)
Other Properties Comparison			
Property	U-233	U-235	Pu-239
Half Life	160,000 yrs	700,000,000 yrs	24,000 yrs
Preceding Fertile Isotope	Th-232	None	U-238
Preceding Fertile Isotope Abundance in Earth's Crust	9.6 ppm	N/A	2.7 ppm
Preceding Fertile Isotope Thermal Neutron (0.025 eV) Absorption Cross-section	7.4 barns	N/A	2.7 barns
Neutrons Released per Thermal (0.025 eV) Neutron Absorbed	2.3	2.1	2.1
Neutrons Released per Fast (1 MeV) Neutron Absorbed	2.5	2.3	2.9
Spontaneous Fission Rate	0.5/(sec-kg)	0.6/(sec-kg)	25,000/(sec-kg)
Other Properties Comparison: (IAEA Nuclear Fuel Cycle and Materials Section, 2005, p. 8)			
Property	U-233	U-235	Pu-239
Non-fissioning Neutron Capture Cross-Section	46 Barns	101 Barns	271 Barns
Thermal Fission Cross-Section	525 Barns	577 Barns	742 Barns
Other Properties Comparison: (Brookhaven National Laboratory, 2022)			
Property	U-233	U-235	Pu-239
Fast Fission (1.0 MeV) Cross Section	1.8 Barns	1.2 Barns	1.7 Barns

Table 1: Fissile Materials Comparison

Facts and Details

Th-232 Conversion to U-233: The most significant way in which fissile U-233 differs from fissile U-235 is that U-233 is not naturally occurring. Therefore, it is not isotopically separated from natural Uranium using a cascade of centrifuges or in any other manner as is normally required for isolating U-235. Instead, U-233 is converted or bred from fertile Th-232 in a nuclear reactor. To convert or breed any fissile material from any fertile material, a nuclear reactor is normally employed. The reactor must be started with fissile fuel that will supply sufficient neutrons with each fission for the fertile isotopes to capture. The only sufficiently abundant fissile isotopes which may be used to start a reactor are U-233, U-235 and Pu-239. The only sufficiently abundant fertile isotopes which have ever been promoted for conversion are Th-232 and U-238. To some small extent, all Uranium fueled Light Water Reactors (LWR) convert some

U-238 to create Pu-239 along with other actinides and then burn some fraction of that created. However, only those which create a greater quantity of fissile material than the initial fissile material input are known as breeder reactors. In other words, the breeding conversion ratio is greater than 1.0. Breeding requires neither centrifuge cascades nor any other type of energy inefficient enrichment (Thorium, 2020).

Denaturing: Denaturing (or dilution) of purified U-233 with U-238 for use in reactors is possible, but it is not a completely effective safeguard against proliferation. There are at least two reasons to believe that a small but determined nation which acquires isotopic enrichment capabilities for peaceful purposes may also be able to weaponize denatured U-233. First, in comparison to U-235, a much smaller mass of the more reactive U-233 material is needed to configure a critical mass. Secondly, the atomic mass difference between U-233 and U-238 is much greater than the mass difference between U-235 and U-238. The greater atomic mass difference makes the isotope separation process easier.

Smaller U-233 Mass Requirement: To illustrate the smaller U-233 mass requirement in greater detail, consider a critical bare sphere of denatured Uranium which remains enriched to 60% in the U-235 isotope. It has a mass of 66 kg. If, however, the fissile isotope is switched from U-235 to U-233, the critical mass is reduced by 2/3 to only 22 kg. With optimal reflection, the enriched material mass requirement is further reduced by at least 50% to no more than 33 kg for the U-235 and 11 kg for the U-233. With all else being equal, the predicted yields will be approximately proportional to the masses so the U-233 yield will be only 1/3 of the U-235 yield. Even so, at 10% efficiency, the prompt energy release from 11 kg of denatured U-233 is calculated in Equation 1 below (Paxton & Pruvost, 1987, pp. 42-101).

$$11{,}000\ grams \times \frac{1\ mole}{233\ grams} \times \frac{6.02 \times 10^{23}\ atoms}{1\ mole} \times \frac{180.7\ MeV}{1\ atom} \times \frac{1\ kiloton\ TNT}{2.61 \times 10^{25}\ MeV} \times 10\%$$

$$= 19.7\ kilotons\ TNT$$

Equation 1

Fertile becomes Fissile: Just as the fissile Pu-239 isotope is converted in a reactor from the fertile Uranium-238 (U-238) isotope so also the fissile U-233 isotope is converted in a reactor from the fertile Th-232 isotope. Both conversion processes include one neutron capture and two beta decays. In the U-Pu cycle, the Uranium first becomes Neptunium (Np). In the Th-U cycle, the Thorium first becomes Protactinium (Pa).

$$^{238}_{92}U + n \rightarrow {}^{239}_{92}U \rightarrow \frac{\beta^-}{23.5\ min} \rightarrow {}^{239}_{93}Np \rightarrow \frac{\beta^-}{2.4\ days} \rightarrow {}^{239}_{94}Pu$$

Equation 2

$$^{232}_{90}Th + n \rightarrow {}^{233}_{90}Th \rightarrow \frac{\beta^-}{21.8\ min} \rightarrow {}^{233}_{91}Pa \rightarrow \frac{\beta^-}{27\ days} \rightarrow {}^{233}_{92}U$$

Equation 3

Undesirable Isotopes: For use in weapons, the undesirable and more radioactive Pu-240 isotope production must be minimized incidental to the production of Pu-239. The Pu-240 is undesirable because of it's high spontaneous fission rate, which can lead to an unexpected pre-detonation (Plutonium, 2021). Similarly, the undesirable and more radioactive U-232 isotope (70 years half-life) production must be minimized incidental to the production of U-233. There are multiple reaction paths that lead to U-232 production. The most typical path is in the presences of 6 MeV or higher energy neutrons. The fast neutrons convert a fraction of the U-233 to U-232 in an (n,2n) reaction as per Equation 4. This is undesirable because the Thallium-208 (Tl-208) daughter product at the end of the U-232 decay chain shown in Equation 5 generates a 2.6 MeV gamma which is hazardous to workers (Tickell, 2012) (Knief, 2008, pp. 168-169).

$$^{233}_{92}U + n_{\,E\geq 6MeV} \rightarrow {}^{232}_{92}U + 2n$$

Equation 4

$$\text{Decay Chain: } {}^{232}_{92}U \rightarrow \frac{\alpha}{70\text{ y}} \rightarrow {}^{238}_{90}Th \rightarrow \frac{\alpha}{1.9\text{ y}} \rightarrow {}^{224}_{88}Ra \rightarrow \frac{\alpha}{3.7\text{ d}} \rightarrow$$
$${}^{220}_{86}Rn \rightarrow \frac{\alpha}{56\text{ s}} \rightarrow {}^{216}_{84}Po \rightarrow \frac{\alpha}{0.15\text{ s}} \rightarrow {}^{212}_{82}Pb \rightarrow \frac{\beta^-}{10.6\text{ h}} \rightarrow {}^{212}_{83}Bi \rightarrow \frac{\alpha}{1\text{ h}} \rightarrow$$
$${}^{208}_{81}Tl \rightarrow \frac{\gamma(2.6\ MeV)+\beta^-}{3\text{ m}} \rightarrow {}^{208}_{82}Pb\ (stable)$$

Equation 5

US Experience

US Abandoned the Th-U Cycle: Just as current weapons grade Pu-239 stocks are bred in such a way as to minimize the Pu-240 pre-detonation hazard so also must the less traditional U-233 weapons material be optimally bred to protect workers from the U-232 decay chain gamma radiation hazard. The contaminating U-232 content is co-produced with U-233 and must be either minimized or mitigated such as by remote handling inside of shielded cells (Tickell, 2012). The early difficulties associated with the U-232 decay chain gamma radiation which complicated 1950s weapons production is the main reason for the US abandoning the Th-U cycle (Alvarez, Managing the Uranium-233 Stockpile of the United States, 2013).

US Plutonium Weapons: US DOE Policy for Plutonium weapons requires that the Pu-240 isotope be less than 7%. Normally, the Pu-239 content is 93% of all Plutonium atoms but the policy limitation applies to the Pu-240 maximum (US Department of Energy, 2009, p. 5). To optimize U-238 conversion to Pu-239 such that the other isotopes of Pu are minimized, the irradiation duration is limited to no more than 3 months. This is also known as short cycling the reactor. A commercial power LWR irradiation cycle duration is normally on the order of 1.5 to 3 years. Such a long duration raises the proportion of the undesirable Pu-240 isotope which disqualifies it for use in weapons (Plutonium, 2021).

US DOE U-233 Purification Research: Some have claimed that the Th-U cycle is not a proliferation risk due to the high U-232 content which is co-produced with U-233. A weapon with a high U-232 content is not only a radiological hazard but is also easy to detect. However, US DOE researchers at Hanford in the 1960s developed improved procedures which protect workers by minimizing U-232 co-production. First the Th-232 isotope input was maintained free of contamination. Secondly, the bombarding neutron energy was kept below 6 MeV. Thirdly, the reactor fuel was emptied when the fertile Pa-233 was maximized. Lastly, the Pa-233 was immediately chemically isolated and allowed to spontaneously beta decay on its own. The improved procedures were not sufficient to un-seat the entrenched and dominant U-Pu cycle in a low demand environment. In fact, the DOE has produced no U-233 since 1970. For weapons, the U-Pu cycle remains uncontested. The small DOE U-233 stockpile remains under guard and is decaying at ORNL and INL.

Molten Salt Reactor (MSR): The first experimentally successful breeding model was the Molten Salt Reactor developed at Oak Ridge National Laboratory (ORNL) in the 1960s and then put aside. The MSR bred Th-232 to create U-233. The success accomplished under lab director Alvin Weinberg was initially in response to a USAF request to develop a bomber which would be able to remain aloft indefinitely without tanker support (Thorium, 2020) (Gawne, 2016).

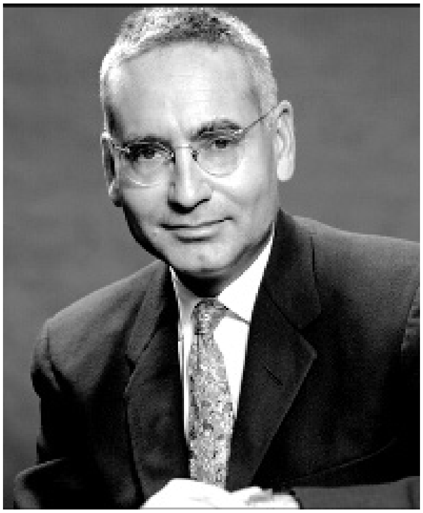

Fig 2. Alvin Weinberg, 1960, Oak Ridge National Laboratory, Public Domain

Forgotten Improvements are Future Possibilities:

Traditionally Dominant Fast Breeding Pursuits: Apart from the forgotten successful ORNL experiment, the dominant breeding pursuit world-wide has traditionally involved solid fuel of the U-Pu cycle in a sodium cooled, fast neutron environment. From 1984 to 1994, scientists at Argonne National Laboratory (ANL) in Illinois brilliantly developed the Integral Fast Reactor (IFR) capable of delivering limitless safe nuclear power while burning natural Uranium or recycled LWR waste. It also sharply reduced waste both in terms of its radioactive lifetime and quantity. The IFR program was cancelled suddenly in 1994 before the wider scientific community had an opportunity to offer opinions and long before the technology could be commercially deployed. President Clinton stated in his 1994 State of the Union speech that "We will terminate unnecessary programs in advanced reactor development" (Charles E. Till, 2011). Breeding has continued to be the source of many disappointments world-wide for many reasons over many decades. Today, there are only two currently commercially successful fast breeder reactors (FBR) in the world and they both employ the more traditional type of technology similar to that of the ANL IFR. They both produce commercial power in Zarechny, Russia (Fast Neutron Reactors, 2021).

MSR Improvements: The MSR experiment of the 1960s introduced several radical improvements beyond those of the IFR which have not been commercially exploited. The experiment employed Th-232 dissolved in liquid-fluoride salt rather than solid U-238/Uranium dioxide (UO2) as the fertile material. Although not required, the fertile Th-232 material change was an improvement in that it greatly reduced actinide production and as previously mentioned, absorbed neutrons more readily than U-238. The liquid fuel eliminated the fabrication requirement which accounted for 90% of the fuel expense. A solid fuel melt down could not happen because the fuel was always in a liquid state and drained to a non-critical configuration during any out of tolerance event. The fertile material circulated in and out of the reactor with the molten salt until it was converted to U-233 and then either fissioned or was separated for later use. The circulating liquid fuel not only enables the removal of fission fragment neutron absorbers but also enables the complete burnup of the fissile material which is far superior to the 4% burnup typical of open-cycle solid fuel LWRs (Fuel Burnup, 2022). These improvements greatly reduced shutdown frequency. However, safety and maintenance shutdowns were still easily accomplished on command or passively for undetected out of tolerance events. As opposed to LWR relatively higher pressures and relatively lower temperatures, the molten salt reactor operated at near atmospheric pressure for improved safety and at a much higher temperature on the order of 700° C for improved efficiency (IAEA, 2020).

Th-U Cycle Advantages: The Th-U cycle offers many additional advantages over the U-Pu cycle. The short-lived U-233 daughter radionuclides associated with a domestic Th-U cycle will also greatly facilitate the development of life-saving diagnostic and therapeutic medical solutions to include treatments which must be experimentally tailored for individual patients. For example, the U-233 decay chain includes short lived Actinium-225 (Ac-225) (10-day half-life) and Bismuth-213 (Bi-213) (46 minute half-life) which oncologist use as alpha emitters for treating acute myeloid leukemia (Jurcic, 2018). As of 2008, the only viable method for securing Ac-225 and Bi-213 in the US was through U-233 decay which is stored only at Oak Ridge and Idaho National Laboratories. Additional domestic sources of medical isotopes are in demand for research, clinical trials and improved treatments for bone marrow transplants and diseases including Non-Hodgkin Lymphoma, AIDS, lung cancer, pancreatic cancer, and kidney cancer. The quality, availability and reliability of foreign medical radionuclide sources is generally not satisfactory (Friedman, 2008).

Comparing Solid Fertile Oxide Breeding Materials: In the Th-U breeding process, a conversion ratio greater than 1 is theoretically possible across the spectrum of neutron energies. In the U-Pu breeding process, a conversion ratio greater than 1 is theoretically possible only in a fast neutron environment. Thorium dioxide (ThO2) is more chemically stable and is a better thermal conductor than UO2 which means heat diffuses more rapidly, more widely and more evenly. Solid ThO2 has a lower co-efficient of thermal expansion than UO2 which means that the ThO2 and its cladding are more resistant to radiation damage (Dekoussar, et al., 2005, p. 2).

Radioactive Waste: The Th-U cycle radioactive actinide net waste is an order of magnitude less than that of U-Pu cycle. Among those reduced is Pu-239 which is a widely known proliferation risk. Others reduced include Neptunium, Np; Americium, Am; and Curium, Cm.

Thorium Resources and Processing: As indicated in Table 1, Thorium is 3 to 4 times more abundant in the earth's crust than uranium (Dekoussar, et al., 2005, p. 01). Its relative abundance is similar to that of lead, Pb. Nearly all naturally occurring Thorium is the Th-232 isotope. The four countries with the greatest estimated resources in order from most to least are India, Brazil, Australia, and the USA (Thorium, 2020). It is most commonly found in a rare earth phosphate mineral known as Monazite which is all over the world in rock and placer deposits found in beach or river sands along with heavy minerals. Monazite is typically 6-7% Thorium. Thorium recovery usually involves leaching with sodium hydroxide at 140°C followed by precipitation to isolate pure Thorium dioxide (ThO2). Presently, world-wide Thorium production is as a by–product of rare earth extraction from monazite taken from open pits. World-wide resources are estimated to be about 16 million tonnes. The total radioactive waste production rate in monazite mining operations is about 2 orders of magnitude less than that of uranium mining operations (Dekoussar, et al., 2005, p. 7).

Thorium Disadvantages

Th-U Cycle Conversion Duration Disadvantage: The Th-U cycle also has some disadvantages when compared to the U-Pu cycle. The Th-U cycle produces Protactinium-233 (Pa-233) as an intermediate product with a half-life of ~27 days. The U-Pu cycle produces Neptunium-239, Np-239, with a half-life of ~2.4 days. The Pa-233 radiation cooling duration to achieve 100% conversion to U-233 will be 12 months. Conversely, the Np-239 radiation cooling duration to similarly achieve 100% conversion of Np-239 to Pu-239 will be only one month (Dekoussar, et al., 2005, p. 65).

Th-U Cycle Solid Fuels Disadvantage: In regard to the possibility of producing fabricated solid fuels, the melting point of ThO2 is 3350°C which is much greater than that of UO2 which is 2800°C. Therefore, a much higher sintering temperature is required to produce high density ThO2–based mixed oxide fuels. Admixing of sintering aids such as CaO, MgO and Nb2O5 are needed to achieve desired solid fuel densities at more easily achievable lower temperatures. Additionally, in regard to fabricated solid fuels, ThO2–based mixed oxide fuels are relatively inert unlike UO2 and do not dissolve easily in concentrated nitric acid, HNO3. Therefore, longer dissolution periods supported by the addition of small quantities of hydrofluoric acid, HF, to the HNO3 are necessary. The HF is highly corrosive to steel pipes and equipment and its effects must be mitigated. Thorium is effectively more difficult and more expensive to extract than uranium (Dekoussar, et al., 2005, p. 2).

Thorium Radioactivity Disadvantage: Solid Thorium is also more radioactive than Solid Uranium which demands additional safeguards. The surface dose rate from a 55-gallon drum of ThO2 is approximately 60 mR/hr or about 13 times higher than a similarly sized drum of UO2. A worker spending time inside a thorium storage facility could expect to encounter dose rates of 60–100 mR/hr, reaching the U.S. occupational annual exposure limit of 5 rem in just over 6 days. Lastly, the database and experience record of the Th-U cycle is much less than that of the U-Pu cycle (Dekoussar, et al., 2005, p. 3).

Current Efforts

US Enterprise Moves Forward in Indonesia: Renewed interest in the Oak Ridge molten salt power reactor (MSR) concept of the 1960s has recently re-surfaced. Unfortunately, however, regulating authorities have not updated the regulations necessary to enable commercial MSRs initiatives to go forward in the US. Updating is necessary since the US regulations were written for the current LWRs which are significantly different from MSRs. Indonesia may be about to benefit from this US regulatory paralysis. None of the US based nuclear energy firms have been able to move any of their commercial MSR initiatives forward in the US. However, the ThorCon firm of Stevenson, WA is on the threshold of moving a commercial MSR proposal forward in Indonesia. If implemented, the ThorCon MSR proposal will be Indonesia's first commercial nuclear reactor of any kind. It is also on track to becoming the world's first commercial MSR (Luo & Gaspar, 2017) (IAEA, 2021).

Floating Power Plant: ThorCon's Indonesia plan calls for a factory built 500 MWe MSR prototype to be modularly assembled aboard a floating hull. Once operable, the hull will be towed to a protected shallow water site and ballasted to the seabed. The plant will be accessible to ships for fuel exchanges. An underwater electrical transmission cable will be connected. A staff of 200 employees will operate the plant. Once the concept is proven, many more units are anticipated. ThorCon's analysis indicates that the proposed modularity and the floating hull concept will significantly decrease future costs. Regular 30 day maintenance and refueling shutdowns will occur on a four year cycle (IAEA, 2020).

Others in Planning: Several other countries are also known to be in various MSR planning stages. These include China, Japan, Canada, France and Denmark. Other entities within the USA that are also involved in MSR initiatives include ORNL, Flibe Energy, UC Berkeley (IAEA, 2021).

MSR Design Features: The Thorcon plan calls for an improved, scaled-up version of the original experimental 8 MWt Oak Ridge MSR of the 1960s. The original experimental unit was first fueled with U-235 and then later with U-233. The same will be possible for the proposed unit. ThorCon's initial Pre-fission testing is projected to begin possibly as soon as 2025. The testing will enable improvements intended to accommodate varying molten salt flows, temperatures, pressures, and simulated perturbations and failures. The prototype will have a fuel salt operating temperature of 700°C which will be sufficient to also enable the unit to economically desalinate sea water suitable for drinking but will remain well below fuel salt boiling temperature of 1430°C. Any event that raises the fuel salt temperature to 750°C or higher will passively and safely shutdown the unit. Gravity will passively insert three gadolinium control rods into the core, but a single rod will be sufficient to stop the chain reaction. In any sort of unexpected shutdown, the molten salt to include the fuel and the fission products is designed to gravity flow to a drain tank where it will assume a non-critical configuration. Out of tolerance shutdowns will depend only on passive physical principles which may not be disabled or subverted and will not require an energy source. Typical radiation exposure limits of 20 mSv/year for workers and 1 mSv/year for the general public will not be exceeded (IAEA, 2020).

Containment Breach Prevention: In the event of a containment breach, there will be no radioactive fission product release into the environment. Unlike the high pressure of a LWR containment vessel, the MSR containment vessel pressure will be only one atmosphere. Unlike a LWR, an MSR containment vessel breach will not cause a molten salt phase change and the most troublesome fission products, including I-133, Sr-90 and Cs-137, are chemically bound to the molten salt. The proposed exterior containment structure includes a triple layered vapor barrier. The outer most vapor barrier is structurally designed to stop the perpendicular impact of a Boeing 777 aircraft at 400 knots (IAEA, 2020).

MSR Fuel: The proposed Thorcon unit is designed to convert fertile Th-232 to burnable U-233 fuel in a thermal neutron environment. The continuous removal of fission products together with the conversion reduces the U-235 requirement by half but since the combined conversion ratio is expected to initially be only around 0.5, it will not qualify as a breeder. Since its fuel salt is molten, no effort to detect failed solid fuel is necessary (IAEA, 2020).

MSR Attractions: The proposed Thorcon unit is attractive also for other reasons. Except for scheduled shutdowns on four-year intervals and potentially un-scheduled emergencies it will operate continuously for at least 80 years prior to decommissioning. Customers are expected to pay only US$0.03/kWh without subsidies which will be less expensive than electricity generated with carbon-based fuels. Like all nuclear power plants, it is environmentally friendly in that it will not emit CO2. The proposed water desalination capability is an attractive and important feature for Indonesia and for many other countries. Unlike other clean energy sources including wind and solar, the MSR performance will not depend on weather (IAEA, 2020).

Chinese Experimental MSR: China also is preparing to test and commercialize a very small experimental thorium fueled reactor which is also modeled on the same Oak Ridge design. The situation in China, however, is different from that of Indonesia. China is the fastest expanding nuclear power producer in the world. As of June 30, 2020, China has 47 operational commercial nuclear power units with 11 more under construction. Between 2000 and 2019, China has grown its nuclear fueled electricity generation by 17.3% per year and in 2019, nuclear powered electricity accounted for 4.9% of its total electricity mix (IAEA, 2020, p. China).

Chinese Experimental MSR Schedule: The Shanghai Institute of Applied Physics (SINAP) launched China's molten-salt reactor program in 2011 with a $500 million investment. The experimental thorium MSR construction at the Wuwei site in Gansu province was scheduled to be complete in Aug 2021. Testing was scheduled to be complete in Sep 2021. At this time, reliable English language open sources do not indicate whether the construction and testing schedule was met. The reactor is designed to produce 2 MWt for 1,000 homes. If the project is successful, China plans to build a 373 MWt MSR by 2030.

Chinese Thorium Reserves: In China, domestic Thorium is an attractive alternative to imported Uranium. It is an inexpensive and plentiful waste product of the growing Chinese rare-earth mining industry. Chinese research leaders see the Thorium MSR as part of the growing Chinese nuclear power landscape which will lead to zero carbon emissions by 2050.

Conclusion

Threat Conclusion: The proliferation of US Government information pertaining to the Th-U fuel cycle has made it theoretically possible for even very small nation-states to develop U-233 fission weapons from the abundant and fertile Th-232 isotope. The entire CWMD and intelligence communities both within the military and beyond to include entities such as the International Atomic Energy Agency (IAEA) and the Nuclear Suppliers Group must increase awareness, be actively vigilant and prepare to take action. US interests may have been better served if US Government findings on Th-U cycle had never been de-classified.

Opportunity Conclusion: On a planet dealing simultaneously with climate change, a rising energy demand and a diminishing supply of carbon-based energy options; a nuclear technology renaissance is inevitable. The same Th-U fuel cycle and MSR information proliferation also has the potential to improve human conditions through non-military nuclear technology applications. Most significantly, this includes inexpensive clean energy production expansion potential. Secondly, this includes potential medical advances to oppose many serious threats to human life. Thirdly, this potentially includes increased water purification capabilities where they are most needed. Rather than sharing technology to benefit our competitors, the US DOE and NRC must work with US industry to create conditions that will proliferate the next generation of efficient commercial reactors in the US.

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The Nuclear Dimension of Hybrid Warfare

Michaela Dodge and Adam Lowther

It is often said that generals prepare to fight the next war as they fought the last war. The same is often said about the United States' nuclear deterrence strategy and policy, with the military often accused of failing to shed its Cold War mindset. Today's environment, however, is much different than it was three decades ago when the Cold War came to an end. With a nuclear peer in Russia and a rapidly expanding and modernizing China? The United States is finding itself in a world where it must face two nuclear peers. When a nuclear North Korea and a near-nuclear Iran are added to the milieu, the challenge facing the United States becomes even more difficult.

Today, the United States risks failing to adapt to its adversaries' understanding of warfare and failing to grasp the corresponding implications for nuclear deterrence. In 2016, former Chairman of the Joint Chiefs of Staff, General Joseph Dunford, declared, "We're already behind in adapting to the changing character of war today, in so many ways."[1] In February 2022 there was a reticence from some to believe Russian President Vladimir Putin would launch a full-scale invasion of Ukraine, despite the obvious Russian troop build-up and US warnings.[2] Now, more than 200 days into the war, Ukraine, expected to suffer defeat within a week, is driving Russian forces from Ukraine through the innovative use of new technologies and hybrid warfare.[3]

Early in the war, with Russian forces performing poorly, Putin threatened to use nuclear weapons against the North Atlantic Treaty Organization (NATO)—perhaps in expectation that the threat would cause NATO member states to end their material support of Ukraine.[4] The threat did not have the desired effect. In the shadow of Putin's nuclear threat, Ukraine is waging a successful hybrid war that includes conventional conflict, asymmetric conflict, and a large-scale effort to maintain Western support. Russia's dis/misinformation campaign failed relatively early in the war, but the threat of nuclear use remains.

Events in Ukraine are, of course, all playing out at the same time as China is ratcheting up military pressure on Taiwan as the People's Liberation Army (PLA) challenges Taiwanese sovereignty. According to Hsiao Bi-khim, Taiwan's unofficial ambassador to the United States, Taiwan is facing unprecedented "gray zone," "cyber," and "economic" challenges.[5] For the United States, the "Arsenal of Democracy" is facing growing pressure from two peer authoritarian regimes that desperately want to change the global status quo.[6] Although neither Russia nor China are conventional military peers of the United States, Russia is a nuclear peer and expert in hybrid warfare. The People's Republic of China (PRC) is an economic peer and rapidly moving to nuclear parity. The PRC's prowess in hybrid warfare is also significant.[7] For both Russia and

China, avoiding a conventional conflict with the United States is paramount, which makes nuclear weapons attractive for their capacity to deter American conventional military power. Hybrid warfare is similarly attractive in its ability to skirt that same conventional power, but at the other end of the conflict spectrum.[8]

The extended conflict in Ukraine, pre- and post-invasion, offers an opportunity to reflect on the nuclear dimensions of hybrid conflict. There are a number of questions deserving assessment. First, what roles will nuclear weapons play in hybrid warfare? Second, what types of change can we expect to see as the international system moves to tripolarity? Third, how can the United States minimize the risk of nuclear escalation, or manage it should adversaries opt to employ nuclear weapons in support of strategic objectives? The following pages will seek to address these questions.

Hybrid Warfare: Definitions and Intersection with Nuclear Deterrence

The Department of Defense does not precisely define the term "hybrid warfare."[9] The 2016 *Joint Operating Environment 2035* mentions a trend of competitor states likely employing "hybrid stratagems using a confusing combination of direct and indirect approaches to contest U.S. global interests."[10] According to the document, these approaches "will be designed to avoid overt commitment to major foreign operations, minimize the risk of escalation, provide plausible deniability, and avoid the costs of direct involvement."[11] They "will feature regional nuclear deterrence in support of conventional military operations and a desire to build 'off ramps' to avoid escalation with the United States."[12]

The 2018 *National Defense Strategy* mentions capabilities "designed to help us compete more effectively below the level of armed conflict."[13] The 2017 *National Security Strategy* states that "adversaries and competitors became adept at operating below the threshold of open military conflict and at the edges of international law."[14] The specific advantage that these actors possess is the faster ability to integrate "economic, military, and especially informational means to achieve their goals."[15] The *National Security Strategy* emphasizes the unique role of the law enforcement and intelligence communities in countering actors using these tactics, as well as the need for the United States to develop operational concepts and capabilities "to win without assured dominance in air, maritime, land, space, and cyberspace domains."[16] The 2021 *Interim National Security Strategic Guidance* does not refer to these concepts at all.[17]

Bipolarity

Russia and China benefitted from American failure of imagination in the early 1990s, namely the assumption that American primacy will remain uncontested for decades.

They also benefited from the United States' focus on counterinsurgency operations and wars in Iraq and Afghanistan—post-September 11, 2001. The post-9/11 period was particularly important for Russia and China because both closely observe the American way of war, and were able to develop asymmetric capabilities designed to target American weaknesses.[18] They also modernized their nuclear arsenals, because, as Matthew Kroenig points out in *The Logic of American Nuclear Strategy*, strategic superiority matters in a crisis between nuclear-armed adversaries.[19] In essence, the American focus on violent islamic jihadism, preventing terrorism, and other US policies at the time, gave Russia and China time and space to reach a level of strategic (Russia) and economic (China) parity with the United States. Thus, America's unipolar moment was short-lived and quickly followed by the current tripolar period.[20]

While a detailed discussion of Russia's and China's strategy and force posture is beyond the scope of this article, we will highlight aspects that are most relevant for American nuclear deterrence and force posture and most different from the Cold War bipolar strategic environment. We argue that the United States must improve its understanding of Russian and Chinese strategic thinking and develop detailed profiles of their respective senior leaders, values, and decision-making structures. Identifying influential players—avoiding the mirror imaging that plagued nuclear deterrence efforts vis-à-vis the Soviet Union—is also a critical need for the US government. American decision-makers can no longer assume that Russian or Chinese leaders have similar values to their own. This means no presidential administration can assume nuclear weapons are distinct. They must instead view them as enablers across all domains and levels of conflict.

The United States' strategic problems are magnified by the fact that after the end of the Cold War it largely stopped thinking about the role of nuclear weapons in national security strategy and focused on their reduction and elimination. Four consecutive presidential administrations, Democrat and Republican, let the nuclear enterprise atrophy and withdrew from competition in nuclear weapon systems.[21] American withdrawal from competition emboldened adversaries to exploit the opportunity. Over time, it induced American adversaries to develop a variety of nuclear weapons for use on lower levels of the escalatory ladder, giving them escalation options unavailable to the United States. Where, for example, over the past decade, Russia developed more than a dozen short-, medium-, and intermediate-range delivery vehicles for ultra-low and low-yield nuclear weapons, the United States developed the W76-2 low-yield warhead for the Trident D-5 submarine-launched ballistic missile.[22] The W76-2 is hardly an effective counter for Russia's diverse options. The same can be said for China's variety of warheads and delivery vehicles.

Distinguishing between strategic and non-strategic nuclear weapons makes sense, depending on the circumstances. As Jacek Durkalec points out in the context of Russia's 2014 invasion of Ukraine, "The credibility and effectiveness of this hybrid warfare campaign was backed up by Russia's potential to use its full spectrum of military capabilities, including conventional and nuclear forces."[23] Durkalec goes on to detail an increase in Russia's signaling activities across the spectrum of its nuclear weapon capabilities following Russia's 2014 invasion of Ukraine, which started out as hybrid warfare to buy Russia time to accomplish its objectives before the West could politically and militarily mobilize to help Ukraine meaningfully counter it.[24] The remark is reminiscent of Paul Nitze's comment that the "atomic queens may never be brought into play; they may never actually take an opponent's pieces, but the position of the atomic queens may still have a decisive bearing on which side can safely advance a limited war bishop or even a Cold War pawn."[25]

The use of a nuclear weapon in conflict would signal warfare's transition to a new phase and out of a purely hybrid war. In this context, it is important to note that the United States judges for itself what constitutes "gray zone" conflict and hybrid warfare.[26] While the judgment of what constitutes "below the threshold" activities might be straightforward in some cases, in others those judgments are subject to domestic politics, the evolution in threat perceptions, and the willingness to risk escalation to counter an adversary. Because American decision-makers perceive hybrid warfare as less malign than a direct military conflict, adversaries seek to rely on ambiguity as a screen for operations that undermine American interests. The United States must be careful that its perception of adversary action is informed by the view of allies, particularly allies under assault from Russian and/or Chinese hybrid operations.[27]

Russia does not use the term hybrid warfare. In its understanding the "non-military non-linear hybrid segment is embedded within Russia's more broadly conceived and fully integrated conflict spectrum and relies on the leveraging or actual employment of conventional, unconventional and nuclear forces."[28] This is an important point because Russian doctrine does not have a phasing construct as is so prevalent in American thinking.[29] Where *Joint Publication 5-0: Joint Planning* has long discussed distinct phases in conflict and a clear distinction between peace and war, neither the Russians nor the Chinese see such distinctions and phases.[30] Should Russia or China use a nuclear weapon, there is reason to believe that, much like efforts to counter the United States with hybrid warfare, they will use nuclear weapons in such a way that an American nuclear response is difficult. The use of a single low-yield weapon in a remote location, for example, may not readily see an American nuclear response.[31] The desire to create ambiguity, even in nuclear weapon use, remains.[32]

Tripolarity

The following section discusses the main distinctions between hybrid warfare's nuclear dimension in a bipolar and a tripolar environment. These distinctions are, in part, speculative because the tripolar strategic environment is still young and has no real predecessor.

American nuclear forces are not sized to deter two peer strategic nuclear competitors with a counterforce strategy. This disparity can lead to adversaries employing hybrid tactics more aggressively, believing that the United States fears escalation to nuclear use. Both adversaries see the United States as susceptible to hybrid tactics.[33]

During the Cold War, the United States sized its nuclear forces to maintain nuclear parity with the Soviet Union. The Department of Defense's Fiscal Year 1975 Annual Report discussed the importance of "essential equivalence" with the Soviet Union not just for American deterrence goals, but also for "third audiences," including allies.[34] It assumed that solving the deterrence problem with the Soviet Union translated into being able to solve the deterrence problem with China, which deployed a comparatively smaller number of nuclear weapons. Such a simple calculation is no longer possible.

The nuclear equation is changing, with the United States only slowly waking to the new and unfavorable reality. Not only is China's rapidly expanding nuclear arsenal concerning, but Russia's large arsenal of non-strategic weapons makes both a regional and strategic nuclear conflict more difficult to deter for the very reasons explained by Kroenig—strategic superiority carries the day in a nuclear crisis.[35] With both Russia and China sustaining a capable nuclear weapons production complex that United States may not be able to match, the nation is at risk of leaving gaps in its nuclear forces. Scenarios involving Ukraine and Taiwan are most prescient.

With the recent discovery of China building 300 new silos for its intercontinental ballistic missile (ICBM) force, it is plausible that China reaches nuclear parity with the United States by the end of the decade, emboldening Chinese President Xi Xinping to act more assertively in challenging the United States.[36] This is exactly what occurred when the Soviet Union reached parity with the United States in the second half of the 1970s. Georgy Shakhnazarov, a member of the International Department of the Central Committee of the Communist Party of the Soviet Union, remarked, "How was it [the situation in 1977-1979] different from the previous years? It was different because the Soviet Union entered that period at the peak of its military might. Never before did we have such a powerful military force. And it had to fire, it was seeking to find a use for itself."[37] In what ways might China's force contemplate asserting itself?

The magnitude of China's rapid nuclear expansion calls into question whether the American nuclear force is sufficient to address China and Russia's use of nuclear coercion. Under the New Strategic Arms Reduction Treaty (New START), the latest strategic arms control agreement between Russia and the United States, each party is limited to 1,550 operationally deployed strategic nuclear weapons on 700 delivery vehicles.[38] Each party can retain up to 800 accountable deployed and non-deployed strategic launchers and heavy bombers.[39] While the United States can alter its strategy from one of counter-force to one of counter-value and seek to achieve deterrence against both China and Russia, a strategically inferior United States could fail to achieve its objects in a crisis.[40] Given Russia's proximity to both Europe and China, President Putin can rely on non-strategic nuclear weapons to achieve deterrence, leaving his strategic arsenal focused on the United States, where the United States cannot do the same because of distances to targets. Likewise, China can use its non-strategic nuclear weapons to deter Russia, while deploying its strategic arsenal to deter the United States.

Although the United States can rapidly retarget its strategic nuclear arsenal to face the pressing threat, it will soon find it impossible to maintain numbers parity with both adversaries. Given Russia's long history of cheating on treaties it has signed, the United States may suddenly find itself in a weaker position than anticipated.[41] When the Obama Administration stated that large-scale cheating would not have an effect on an American second-strike, there were no indications China would launch a large-scale build-up of its nuclear forces.[42] It is not clear whether New START considered Russia's violations of the Intermediate-Range Nuclear Forces Treaty and its subsequent deployment of these forces. Similarly, American nuclear force posture may be challenged soon by Russia's development of its so-called exotic nuclear systems.[43]

The reality is America's adversaries are blending and blurring the difference between conventional and nuclear weapons. They are developing dual-capable systems that make it more difficult for the United States and allies to discern whether they are facing nuclear-armed or conventional systems. China co-locates its non-strategic nuclear and conventional forces. In both the Russian and Chinese cases, the hybrid warfare-like tactic is designed to increase ambiguity and deter American action.

There should be little doubt within the United States that it is the nation's conventional military superiority that is driving adversaries to rely on both hybrid warfare and nuclear weapons to alter the global status quo while deterring an American military response. The turn to nuclear weapons was only natural because the United States ceded superiority to any competitor willing to devote the resources to a large and advanced arsenal. This does not mean that Russia and/or China will reach for a "nuclear hammer" first, nor that they prefer a nuclear solution to a conventional one. (After all, they continue to invest in conventional military capabilities.) But America's adversaries, even those relatively weaker than the United States, namely Russia, might conclude that a relative asymmetry of stakes makes risks associated with nuclear weapon use a risk worth taking. They might exploit nuclear weapons in ways that are not available to the United States and signal a willingness to escalate further.[44]

Russia may take from its experience in Ukraine that its use of hybrid warfare in Crimea and Eastern Ukraine was much more successful than its use of large-scale conventional force backed by nuclear threats.[45] While America's adversaries cannot be certain they will win a protracted war against the United States, there is potential for protracted hybrid conflicts backed by strong nuclear arsenals.[46] Should either a hybrid or conventional strategy fail, the ever-present internal instability of autocracy might increase the pressure on Russia and/or China to use nuclear weapons. An adversary may assume given limited American non-strategic nuclear weapons capability, a limited strike with ultra- or low-yield weapons is a safe bet.

Another challenge for the United States is China's anti-access/area-denial strategy aimed at denying American forces the ability to deploy conventional forces rapidly to the Indo-Pacific. Although Russia would like to employ a similar strategy, European geography presents a challenge. Thus, Russia, and, to some extent, China, are exploiting reflexive control (perception management) and influence operations against the United States and its allies.[47] These operations are both part of a hybrid strategy and have a nuclear dimension.

Russia and China are exploiting modern technologies to undermine the American-led alliance system. Russia has a long history of doing so and expended great effort to vilify Ukraine's government early in the war and drive wedges between NATO member states.[48] Russia's efforts on this front utilize the concept of reflexive control, which involves manipulation of a target nation's view of itself and an adversary—making it hard to discern fact from fiction. In doing so, Russia tries to incentivize the target's decision-making in Russia's favor without the decision-maker knowledge of the manipulation. Russia perfected the concept in the 1960s and 1970s when the Soviet Union realized it could not win a competition with the United States on equal footing.[49]

It is prudent to assume that Russia and China are thinking about information operations strategies that accompany attacks against American or allied forces. As Keith Payne appropriately writes, "The conditions of the Cold War facilitated the expectation that the United States would recognize if an attack had occurred, by whom, and with what. Armed with such knowledge, the United States could identify the likely opponent in advance and bring to bear its specified retaliatory deterrence threat."[50] Influence operations may be tailored to make such straightforward identification more difficult and challenge tacit assumptions that the United States and allies are able to recognize they are under attack and from whom. Attribution becomes particularly important in this context.

There are a myriad of ways in which influence operations can complicate a response in a regional hybrid conflict. For example, Russia might obscure its role at the beginning of conflict, just long enough to gain a first-mover advantage and put the United States and its allies on the defensive. Influence operations were an integral part of Russia's invasion of Ukraine in 2014 and remain an important aspect of its foreign policy. President Putin communicated he "was ready for nuclear alert" during the 2014 invasion.[51]

It is not just during a conflict that the United States must worry about influence operations. Russia and China are conducting campaigns aimed at undermining the United States' trustworthiness as an ally—questioning American commitment.[52] Russia and China are also using influence operations to counter American deployments to allied countries that threaten their influence. A concrete example of this phenomenon is Russia's influence operations in the Czech Republic when the Czech Republic was invited to host an element of a US missile defense system from 2007-2009.[53] Another example is when China applied a host of coercive measures, primarily economic, to dissuade the Republic of Korea from deploying a Terminal High Altitude Area Defense (THAAD) system.[54] The United States has not been effective in countering these efforts.

It is worth keeping in mind that influence operations are not a regional phenomenon. Both Russia and China are actively engaged in influence operations in the United States.[55] These hybrid efforts seek to undermine American society by inflaming existing social tensions. In a more targeted fashion, they also seek to slow or stop nuclear modernization by attempting to control the narrative on the effects and dangers of modernization. In seeking to shape a domestic narrative, Russia and China counter the defense of American interests in regional scenarios where they seek to undermine American nuclear and conventional postures in a region. In short, Russian and Chinese influence operations at home can affect American freedom of action abroad.

Aside from the question of Russian and Chinese nuclear capabilities and willingness to threaten their use—to preserve freedom of action at lower levels of conflict—the United States struggles to distinguish between military operations and grey zone provocations (what some strategic documents call "below the threshold" of armed conflict).[56] It is worth keeping in mind that it is in Russia's and China's interest to rely on grey zone tactics to convince the United States and its allies that they are engaging only in something less than armed conflict. Both Russia and China understand the American reluctance to recognize that they are broaching a "gray zone" threshold to engage in acts of war that require a response. In the case of both Russia and China it is for economic interests (Russian oil and gas for Europe and Chinese manufactured goods) that these conflicts are allowed to continue.

There is some evidence that Russia and China are justified in thinking that the United States lacks the willingness to take retaliatory action in these "grey-zone" conflicts. For example, China steals an estimated $200-600 billion of intellectual property each year.[57] Yet the US has taken no significant public action in retaliation. Establishing credibility in the grey zone—demonstrating a willingness to respond to relatively limited actions—has direct consequences for credibility further up the escalation ladder. The United States needs a credible plan for dealing with (at a minimum) two parallel hybrid contingencies perpetuated by distinct actors in different geographical regions.[58]

The challenge might be compounded by adversaries' nuclear superiority on lower levels of escalation because the United States may be self-deterred from responding with a nuclear weapon given its lack of symmetrical nuclear capabilities. For example, the United States lacks short-, medium-, and intermediate-range ballistic missiles with ultra- and low-yield warheads. Russia has these options and sees them as a tool for using nuclear weapons in a theater conflict without escalating to strategic nuclear conflict. Thus, they appear, at least to the Russians, to provide a potential *fiat accompli* option.[59]

This problem is made worse because the United States now faces Russia and China simultaneously—while maintaining important alliances. Politics in NATO, for example, increase the complexity because the United States and NATO member states might have different thresholds for action in hybrid scenarios, particularly when nuclear threats or use is involved. What would constitute a mild provocation not particularly worth responding to for the United States might generate grave concerns and a need to respond on the part of an ally. Solidarity with allies is an important element of deterring hybrid threats.[60]

The problem of reliably communicating is magnified by modern technologies, their low costs and accessibility. Russia, for example, is actively waging information campaigns across Europe for the purpose of finding and exploiting cracks in the NATO alliance. As mentioned previously, fracturing NATO has long been a top priority for Vladimir Putin. Thus, using modern forms of communication to undermine solidarity (hybrid tactics at work), particularly as they relate to the nuclear issue, is important for Russia. There is a parallel development in advancing technologies that make some aspects of hybrid warfare cheaper and more potent than they were during the Cold War—the utilization of social media for information operations. These developments provide opportunities to adversaries and allies alike, but given Russia's long history of propaganda operations, it has a level of experience missing in most Western nations.[61]

A separate problem is obtaining reliable information in the middle of conflict and protecting the integrity of American and allied command, control, and communications (C3) networks. In the nuclear context, the need for selective employment might impose additional requirements on nuclear command, control, and communications (NC3) networks as well as on operational planning. It is certainly the plan of Russia and China to disrupt these networks and confuse the image of the battlefield, making it harder to have accurate situational awareness and, thus, decide.[62]

A key challenge for the United States is fighting a limited war while preventing nuclear escalation, including on the strategic level. Maintaining reliable communications with adversaries is a requirement for preserving the ability to offer off-ramps.

Conclusion

Early in the War in Iraq, Secretary of Defense Donald Rumsfeld was questioned by Soldiers about their lack of armored vehicles. He famously responded, "As you know, you go to war with the Army you have, not the Army you might want or wish to have at a later time."[63] The United States is at a similar point in the new tripolar era. The United States is clearly behind Russia in both hybrid warfare tactics and nuclear modernization. China is rapidly catching the United States in the latter. Any significant force posture change in the American arsenal takes time. This generates another asymmetry. Even if the United States has strategic parity with both Russia and China simultaneously on all levels of conflict, its delaying of nuclear modernization implies its nuclear weapons and warhead infrastructure is less capable than Russia's and China's infrastructure that has been actively modernizing for two decades and, at least in the case of Russia, has modernized eighty-nine percent of its nuclear systems.[64]

The nuclear modernization deficit is driven by both choice and politics. Even limited efforts to train the upcoming generation of nuclear warhead designers under the aegis of the Stockpile Stewardship Program face congressional opposition due to concerns over developing new nuclear weapons.[65] The United States has not deployed a new warhead design since the late 1980s leaving it with warheads tailored to a strategic competition with the Soviet Union. Are there nuclear warhead designs that the United States could explore to counter adversaries' hybrid approaches? American politics is not ready to debate this question.

Countering Russia and China across a full spectrum of conflict requires the United States to ask some rather uncomfortable questions. Are Cold War warhead designs best suited to the current competition? Do they accommodate developments in new materials and defensive capabilities? Are self-imposed restraints, in areas like yield-producing experiments, worth the costs? Answering these questions and many others like them are beyond the scope of this article, but the need to fundamentally rethink the size, composition, and capability of the American nuclear arsenal is clear. The new strategic environment facing the United States should leave no doubt that simply building newer versions of remnant Cold War systems is sufficient. With Russia and China looking to wage hybrid warfare to avoid large scale conventional war—all backed by nuclear threats—it is time to consider afresh the nation's nuclear arsenal requirements.

Brad Roberts, Director of Global Security Research at Lawrence Livermore National Laboratory, recommends a sensible three-step process to counter adversaries' respective theories of victory, "'Go to school' on Red the way Red has gone to school on Blue; develop a generic counter to the generic Red theory of victory; and tailor that model to specific regional contexts."[66] This is a good intellectual start, but worthless unless followed up by specific program and policy changes. These changes must be implemented in time to make a difference in the Russian and Chinese calculus. Both states are actively employing hybrid tactics and engaged in attacks on American interests.

Competition with Russia and China is intensifying. On September 21, 2022, President Putin, in advance of illegitimate plebiscites in Eastern Ukrainian provinces declared, "In the event of a threat to the territorial integrity of our country and to defend Russia and our people, we will certainly use all means available to us."[67] The clear implication is that Russia will defend the newly annexed provinces with nuclear weapons should Ukraine—aided by the West—seek to restore them to Ukraine. Putin's threats make it clear, nuclear weapons are returning to prominence. Effective deterrence during hybrid conflicts will require the United States match Russian and Chinese capabilities at both the high and low end. Ignoring both Russian and Chinese threats endangers the effectiveness of deterrence.

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Notes

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9. United States Department of Defense, *DoD Dictionary of Military and Associated Terms* (Arlington, VA: Department of Defense, 2021), https://www.jcs.mil/Portals/36/Documents/Doctrine/pubs/dictionary.pdf.

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13. United States Department of Defense, *Summary of the 2018 National Defense Strategy of the United States of America* (Arlington, VA: Department of Defense, 2018), 7.

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15. Ibid, 26-27.

16. Ibid, 29 and 32.

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18. Sebastian Roblin, "The Russian New Warfare Doctrine Has the Army Worried Enough to Make a Manual About It," *The National Interest*, February 11, 2018, https://nationalinterest.org/blog/the-buzz/the-russian-militarys-new-warfare-doctrine-has-the-army-24439.

19. See Matthew Kroenig, *The Logic of American Nuclear Strategy* (Oxford: Oxford University Press, 2018).

20. For a full view of the challenge facing the United States, see Anthony Cordesman, *The Biden Transition and U.S. Competition with China and Russia: The Crisis-Driven Need to Change U.S. Strategy* (Washington, DC: Center for Strategic and International Studies, 2021).

21. Reasonable people disagree on the degree to which these steps were prudent given what the United States knew at the time and discussing so is beyond the scope of the paper.

22. United States Department of Defense, "Statement on the Fielding of the W76-2 Low-Yield Submarine Launched Ballistic Missile Warhead," Press Release, February 2, 2020.

23. Jacek Durkalec, *Nuclear-Backed 'Little Green Men': Nuclear Messaging in the Ukraine Crisis* (Warsaw: The Polish Institute of International Affairs, 2015), 5.

24. Ibid, 15.

25. Center for Technical Studies on Security, Energy, and Arms Control, *The Role of Nuclear Weapons in the Year 2000* (Washington, DC: 1990), 100.

26. There may be disagreement within the military. For example, "U.S. Special Operations Command and Army officials characterized the Russia-Georgia conflict as conventional warfare, while Air Force officials considered it a hybrid conflict." Government Accountability Office, Hybrid Warfare, Briefing to the Subcommittee on Terrorism, Unconventional Threats and Capabilities, Committee on Armed Services, House of Representatives (September 10, 2010), 14 and 17, https://www.gao.gov/assets/gao-10-1036r.pdf.

27. For example, while the United States tended to consider the conflict in Eastern Ukraine,

prior to the Russian invasion, a "grey zone" conflict, it was hardly "grey zone" for the Ukrainian government. In a potential conflict, the United States should be aware of the disparity and communicate with allies to ensure perceptions of conflict align.

28. Dave Johnson, *Russia's Approach to Conflict — Implications for NATO's Deterrence and Defense* (Rome: NATO Defense College, 2015), 9-10.

29. Andrew Bowen, *Russian Armed Forces: Military Doctrine and Strategy* (Washington, DC: Congressional Research Service, 2020), 1.

30. Kevin Scott, *Joint Publication 5-0: Joint Planning* (Arlington, VA: Department of Defense, 2017).

31. James Ragland and Adam Lowther, "America Isn't Ready For Russia's Battlefield Nuclear Weapons," *1945*, February 1, 2022, https://www.19fortyfive.com/2022/02/america-isnt-ready-for-russias-battlefield-nuclear-weapons/.

32. For example, a non-state actor uses a dirty bomb out of material provided by a state actor. The target could be in the United States, in an allied country, or even in an aggressor's country as a part of a deception operation intended to increase ambiguity and buy time to conduct a large-scale operation.

33. See Jeffrey Bristol, "Hybrid War and What to Do About It," *The Strategy Bridge*, April 21, 2021, https://thestrategybridge.org/the-bridge/2021/4/21/hybrid-war-and-what-to-do-about-it; and Luke O'Brien, "Let's Get Something Straight about Nuclear Weapons," *The Modern War Institute*, March 26, 2019, https://mwi.usma.edu/lets-get-things-straight-nuclear-weapons/.

34. United States Department of Defense, *Annual Defense Department Report FY1975* (Arlington, VA: Department of Defense 1974), 6.

35. Matthew Kroenig, *The Logic of American Nuclear Strategy*, 198-203.

36. Matthew Loh, "Researchers Say China Is Constructing 300 Possible Missile Silos, Which Could Make Its Nuclear Arsenal Bigger than Russia's or America's," *Insider*, November 3, 2021, https://www.insider.com/china-300-nuclear-missile-silos-beyond-russia-us-fas-2021-11.

37. Svetlana Savranskaya and David A. Welch, eds., *Global Competition and the Deterioration of U.S.-Soviet Relations, 1977-1980* (Washington, DC: National Security Archive, 1995), 38.

38. United States Department of State, *New START Entry Into Force*, February 5, 2011, https://2009- 2017.state.gov/r/pa/prs/ps/2011/02/156037.htm.

39. Ibid.

40. We again highlight the findings of Kroenig as he demonstrates that strategic inferiority leads to failure in crisis between two nuclear-armed adversaries.

41. Hearing, *The New Strategic Arms Reduction Treaty (START) Treaty* (Treaty Doc. 111-5): Views from the Pentagon, Committee on Foreign Relations, U.S. Senate, 111th Cong., 2nd Sess., June 16, 2010, http://www.foreign.senate.gov/hearings/the-new- start-treaty-treaty-doc-111-5-views-from-the-pentagon.

42. Hearing, *New Strategic Arms Reduction Treaty (START) Implementation*, Committee on Armed Services, US Senate, 111th Cong., 2nd Sess., July 20, 2010, http://www.armed- services.senate.gov/hearings/2010/07/20/oversight-new-start.

43. See Matthew Kroenig, Mark J. Massa, and Christian Trotti, *Russia's Exotic Nuclear Weapons and Implications for the United States and NATO* (Washington, DC: Atlantic Council, 2020).

44. Michael Rühle raises an example of Argentina attacking the United Kingdom over the Falklands in Michael Rühle, "The (Incomplete) Return of Deterrence," in Amelia Morgan and Anna Péczeli, eds., Europe's *Evolving Deterrence Discourse* (Livermore, CA: Center for Global Security Research, 2021), 18.

45. Kateryna Zarembo and Sergiy Solodkyy, *The Evolution of Russian Hybrid Warfare: Ukraine* (Washington, DC: Center for European Policy Analysis, 2021), https://cepa.org/the-evolution-of-russian-hybrid-warfare-ukraine/.

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47. Timothy Thomas, "Russia's Reflexive Control Theory and the Military," *Journal of Slavic Military Studies*, 17, (2004), 237-256.

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50. Keith Payne, *How Much Is Enough? A Goal-Driven Approach to Defining Key Principles for Measuring the Adequacy of U.S. Strategic Forces* (Fairfax, VA: National Institute for Public Policy, 2010), 3.

51. "Ukraine conflict: Putin 'was ready for nuclear alert'," *BBC News*, March 15, 2015, https://www.bbc.com/news/world-europe-31899680.

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53. Michaela Dodge, "Russia's influence operations in the Czech Republic during the radar debate," *Comparative Strategy*, 39, no. 2 (March 2020), 162-170.

54. Ethan Meick and Nargiza Salidjanova, *China's Response to U.S.-South Korean Missile Defense System Deployment and its Implications* (Washington, DC: U.S.-China Economic and Security Review Commission, 2017), 8-9.

55. Gabrielo Consentino, *Social Media and the Post-Truth World Order* (New York: Springer, 2020), 37-54.

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57. Dan Blumenthal and Linda Zhang, "China Is Stealing Our Technology and Intellectual Property. Congress Must Stop It," *National Review*, June 2, 2021, https://www.nationalreview.com/2021/06/china-is-stealing-our-technology-and-intellectual-property-congress-must-stop-it/.

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59. Sebastian Roblin, "Russia Has A Massive Stockpile Of 'Tactical' Nuclear Weapons," *1945*, February 26, 2022, https://www.19fortyfive.com/2022/02/russia-has-a-massive-stockpile-of-tactical-nuclear-weapons/.

60. Vytautas Keršanskas, *Deterrence: Proposing a More Strategic Approach to Countering Hybrid Threats* (Helsinki: The European Centre of Excellence for Countering Hybrid Threats, 2020), 18-21.

61. See Thomas Rid, *Active Measures* (New York: Farrar, Straus, and Giroux, 2020). Rid offers one of the most complete and concise histories of what the Russians call Dezinformatsiya.

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63. Ray Suarez, "Troops Question Secretary of Defense Donald Rumsfeld About Armor," *Public Broadcasting Corporation*, December 9, 2004, https://www.pbs.org/newshour/show/troops-question-secretary-of-defense-donald-rumsfeld-about-armor.

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65. Hugh Gusterson, “Understanding the Reliable Replacement Warhead,” *Bulletin of the Atomic Scientist* (March 7, 2007), https://thebulletin.org/2007/03/understanding-the-reliable-replacement-warhead/.

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Modeling and Simulation of a Nuclear Weapons Test: Operation Teapot MET

Julius McBride, Claudio Barros, Maj Jeremy Best, USMC, (Ret),
Jasper Thrussell, Dr. Nathan Woods and Dr. James Cooley

Introduction

The era of American nuclear weapons tests was a unique period for the United States Department of Defense, Atomic Energy Commission, and the general public. However, the decades of atmospheric nuclear tests had little overlap with the rise of high-performance computing. As a result, there is still much to be learned from hydrodynamic simulations of atmospheric nuclear explosions. From February to May of 1955, the Department of Defense carried out one such test on the sands of the Nevada Proving Ground: Operation Teapot. Shot number 12, also known as the Military Effects Test (MET). This is of interest because of extensive instrumentation and peculiar shock speed results.

The motivation for this project was to attempt to replicate the results of the test with the multi-physics hydrodynamic code xRage, and evaluate the trustworthiness of the simulation along with the experimental data. This report outlines a computer simulation of Teapot MET, with respect to the surface material. Observed trends in experimental data were compared to ideal calculations and used to form expectations for the simulations. To create the simulations, Los Alamos National Laboratory's hydrodynamic code xRage was employed. Included in this report is data from multiple simulations over granite, water, and Nevada alluvium surfaces, with a focus on the pressure front and shock speed parameters.

Glasstone & Dolan's Nuclear Weapons Effects and Northrop's Effects Manual 1 (EM-1) —both standard DoD references for nuclear weapons effects — served as the primary sources for mathematical formulation and theoretical tools.

Theory of the Shock Front

Shortly after the detonation of a nuclear weapon, the fission within the bomb casing ionizes the surrounding air, resulting in a fireball whose growth can be divided into three phases. The first of these is known as the burnout phase, where the shock front is driven by the energy of the explosion. During this phase, the fireball may be as hot as half a million degrees Fahrenheit. After tens of nanoseconds, the fireball enters its diffusion phase, during which it will continue to expand while simultaneously cooling down. Hundredths of seconds after detonation, the expanding front cools down and eventually reaches the local speed of sound.

The end of the diffusion phase marks the moment of hydrodynamic separation or "breakaway" — when the propagating shock is no longer being driven by the energy from the explosion. This is the part of the evolution when hydrodynamic factors dominate, with which the simulation is principally concerned. Fig. 1 depicts this phase of the spherical shock front evolution. At t_3, the ground reflects the shock back towards the source. The air within the shock front is much hotter than ambient, and since the speed of sound in air rises with temperature, the reflected wave travels faster and is more energetic than its incident counterpart. When the reflected shock reaches the slower incident shock from behind, they partially merge, creating a new, doubly strong shockwave called the Mach stem or Mach front, an important feature that is unique to air bursts. Since the Mach stem is nearly vertical, and the pressure is significantly greater, it is more destructive to tall structures such as buildings than the incident wave, which travels with about half the pressure. The point where all three shocks meet (incident, reflected, and Mach stem) is called the triple point. Fig. 1 depicts the formation of the Mach stem and triple point as well as a snapshot from simulation data.

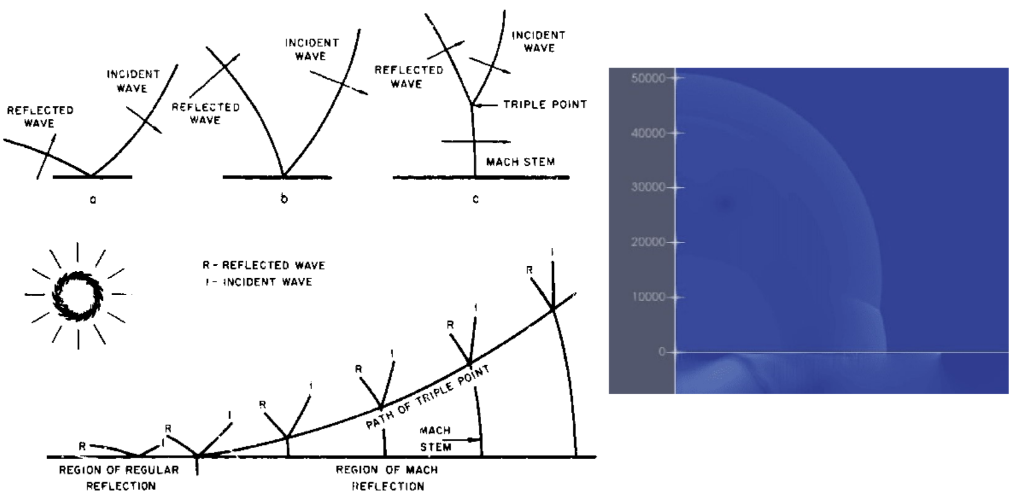

Fig. 1. Left: The path of the triple point as a function of the distance from explosion, from Sachs et al., p. 89. Right: Paraview simulation clearly showing the Mach stem formed from wave interference (Author created).

A-scaling

The results of any weapons test are sensitive to the environment, including altitude, weather, ground composition, humidity, etc. Sachs' scaling equations are used to reliably compare two nuclear blasts of different yields detonated at different altitudes. With them, it is possible to "normalize" an air burst, adjusting for variations in altitude and temperature in a consistent and predictable manner. In the discussion that follows, the subscript "1" denotes the reference burst, and the subscript "2" denotes the burst at hand, which in this case is MET. The scaled pressure and scaled time of arrival equations are given by the equations below.

$$p_1 = \left(\frac{d_2}{d_1}\right)^3 \frac{W_1}{W_2} p_2$$

$$t_1 = \left(\frac{W_1 p_{o1}}{W_2 p_{o2}}\right)^{\frac{1}{3}} \left(\frac{T_{o1}}{T_{o2}}\right)^{\frac{1}{2}} t_2$$

Here, WX is the yield (in kilotons of TNT equivalent, or "kT"), dX is the distance in feet and ToX and poX are the temperature and ambient pressure for blast X (1 or 2) in Kelvin (K) and pounds per square inch (PSI). The atmospheric conditions during the 22 kt MET blast were recorded as po2 = 12.98 PSI, po1 = 13.17 PSI, To2 = 292 K, and To1 = 292.65 K." With all these conditions and taking a 1 kT burst at sea level, these equations can be simplified:

$$p_1 = 0.045 \left(\frac{d_2}{d_1}\right)^3 p_2$$

$$t_1 = 0.355 t_2$$

These are the two equations that were used to scale all overpressures and arrival time data measured in the simulations.

WT-1109 Report Overview

Teapot MET Instrumentation and Data

Teapot MET boasted more measurements than any other nuclear weapons tests of the time, with radial lines of instrumentation extending outwards to test the effects of different surfaces on wave propagation. The MET weapon was detonated on a 400 ft tower and as previously stated yielded a 22 kT burst[10]. Three blast lines, water (North), natural desert (West), and asphalt (South), were outfitted with pitot tubes and baffle-mounted gages in a symmetrical manner, and at different heights at the same distance for comparison of data across the three lines (See Fig. 2).

On the asphalt and water lines, the furthest gages sat at a range of 3000 feet, while on the desert line it extended to 4500 feet. In general, gages were placed along each line at ground level in regular intervals, with additional gages sometimes added at varying heights above the ground on those same intervals, most commonly at 3 ft up, occasionally at 10 ft, and once each at 25 ft and 40 ft along each blast line.[11]

The report claims that the baffle gage pressure measurements have an uncertainty of 5% in ideal conditions, which can be worsened by pressures lower than the gage rating, extreme heat, and "excessive acceleration." The timing signals used were "highly accurate," with a reported uncertainty of less than 10 parts per million.

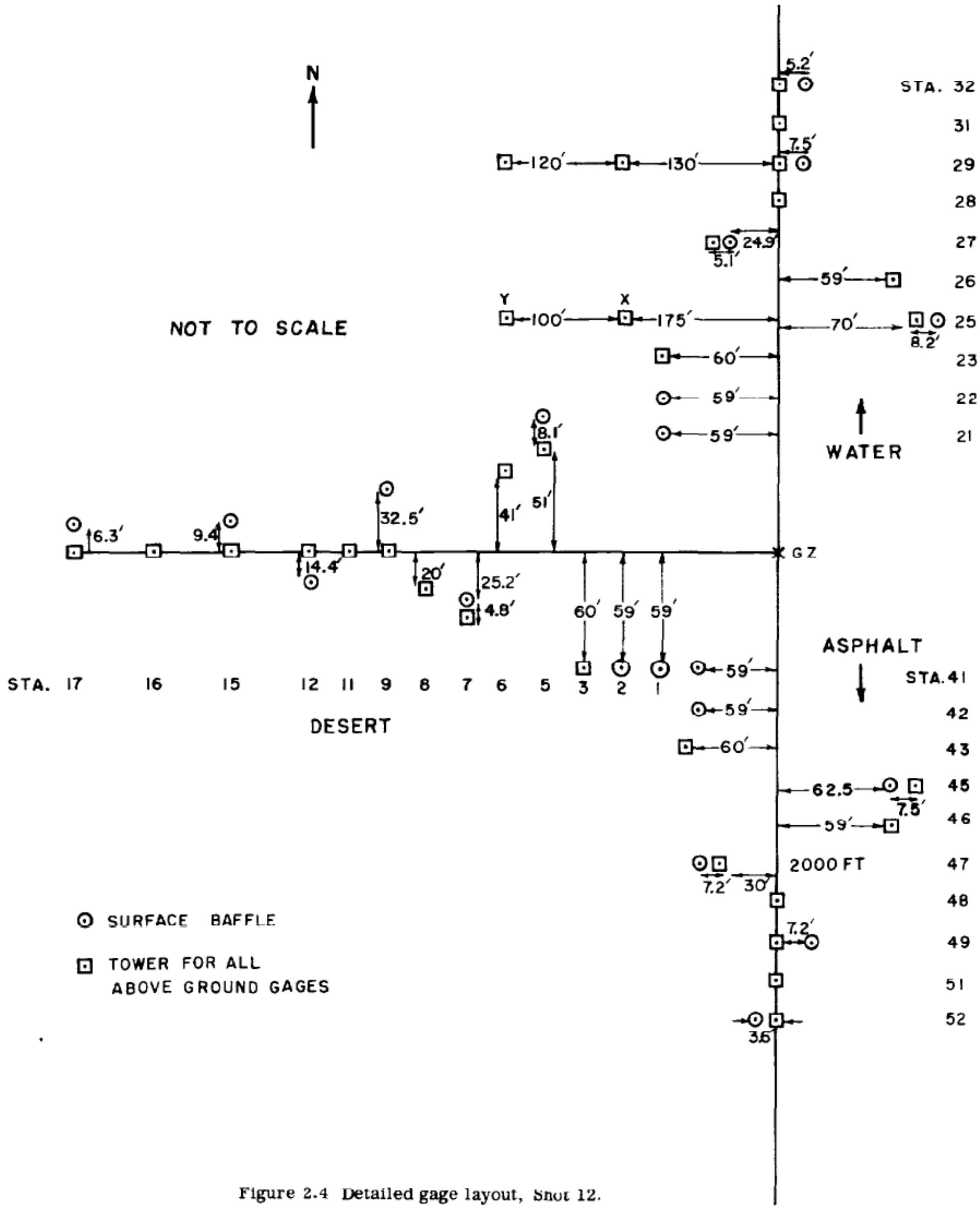

Figure 2. Detailed gage layout taken from WT-1109.

WT-1109 Data Trends

Data was taken from the WT-1109 report results. The data show that the shock front behavior over each material was distinct, especiallythe speed of the Mach front (Fig. 3, top). The front was fastest over asphalt, slightly slower over desert, and much slower over water. In addition, the speed of the front was higher than theoretical. The arrival times of the frontover water mostly agree with WT-1109's ideal curve, but not entirely. Teapot scientists noticed this:

> "Considering the horizontal-trace velocity of the shock front as determined from gage arrival times over the various surfaces instrumented on Shots 6 and 12, the velocities over the asphalt and desert surfaces are well above ideal, particularly at close-in (less than 1500 feet) ground ranges. Even over the water surface, shock velocities determined near 1000 foot ground range are well above ideal values."

The fact that this pattern was observed in two separate test shots hints at an underlying physical phenomenon. A reproduction of this phenomenon was the primary goal for the simulations.

WT-1109 gage overpressure data suggests the same sort of divergent behavior as Mach front arrival time, but to a lesser extent (Fig. 3, bottom). In general, the data for the overpressure are lower than ideal but rank in a similar way to arrival time data. Water agrees most closely with the ideal curve but suggests slightly lower pressures at a large distance. Desert comes next and isfollowed by asphalt with the worst theoretical agreement. At distances along a particular blast line with multiple gages, the variance inthe data can be chalked up to differences in gage heights. Even with this in mind, it is still clear that that the surface material has effects on the shock that extend beyond ground level.

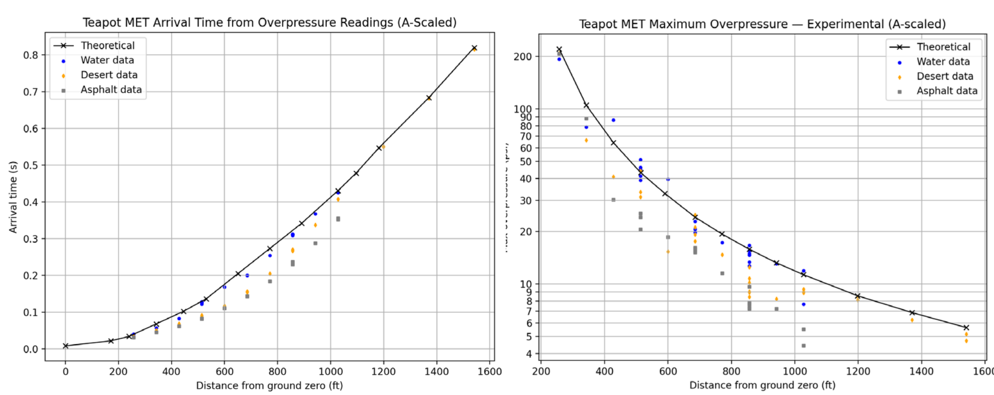

Figure 3. Shock arrival time/maximum overpressure vs. ground range (respectively) using data from WT-1109 and theoretical model from Northrop's EM-1 (Author produced pictures).

Simulation Procedure

The tool of choice for simulation was xRage, an Eulerian hydrodynamics (hydro) code with adaptive mesh refinement (AMR), developed by Los Alamos National Laboratory (LANL).

The code can be run in one, two, or three dimensions, but due to the cylindrical symmetry of the problem a two-dimensional vertical cross-section was used. Over a timescale of just 1.5 seconds, the team felt gravitational effects would be negligible, and so excluded gravity from the simulation altogether. Furthermore, the fission of such a weapon was not simulated. Instead, the simulation was initialized with a 50 cm (about 1.64 ft) ball of "source air" containing the yield energy at the burst height. Parameters such as temperature were not analyzed in depth and simulated only for reference.

Material properties such as molecular makeup and strength parameters were sourced from a LANL database, and the relevant data was generated with Sesame: a code developed by the laboratory for this purpose. To simulate desert, alluvium — the specific sand composition found at the Nevada proving ground — was chosen as the surface material. Because the specific composition and age of the asphalt used are not noted in WT-1109, replicating its material parameters would have been little more than guesswork. Like asphalt, granite is much harder, more durable, and heavier than water or alluvium, and its specific material parameters were available. So, the team felt a granite simulation would suffice as a loose comparison to asphalt.

The final three input decks (water, alluvium, and granite) used a maximum cell size of 100 by 100 cm. The water and alluvium were simulated over a one square kilometer area, with the ground extending 300 m below the surface. The granite deck's dimensions were smaller: 0.9 km across and 0.75 km wide, the ground extending 150 m below. xRage output was parsed in Paraview v. 5.8.1. Since most of the detectors in WT-1109 were situated on 3 or 5 ft posts , the simulation data were taken over a horizontal line 150 cm off the groundboth to better replicate the test data and to avoid boundary effects from the surface.

Results and Discussion

The principal results from the simulation runs are depicted in Fig. 4, while the entirety of a single simulation run is qualitatively shown in Fig. 5 for increasing time intervals. All plots are A-scaled and color coded according to material.

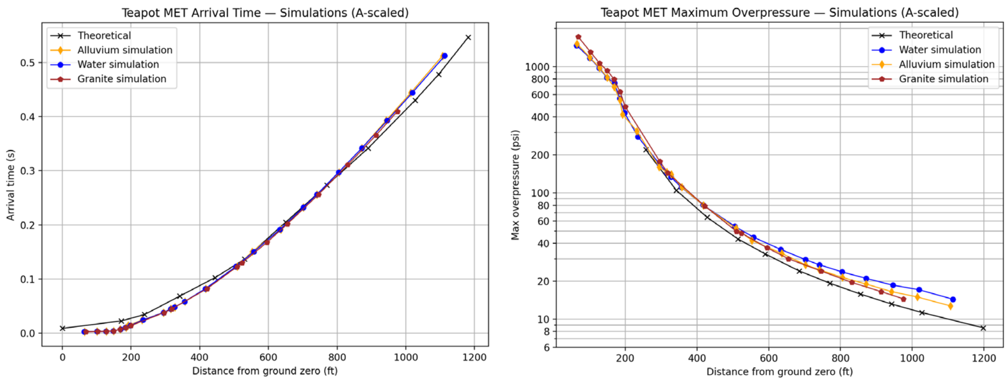

Figure 4. Left: Simulation shock arrival times over different surfaces. Right: Simulation overpressures. Theoretical data taken from Northrop's EM-1[15] (Author produced pictures).

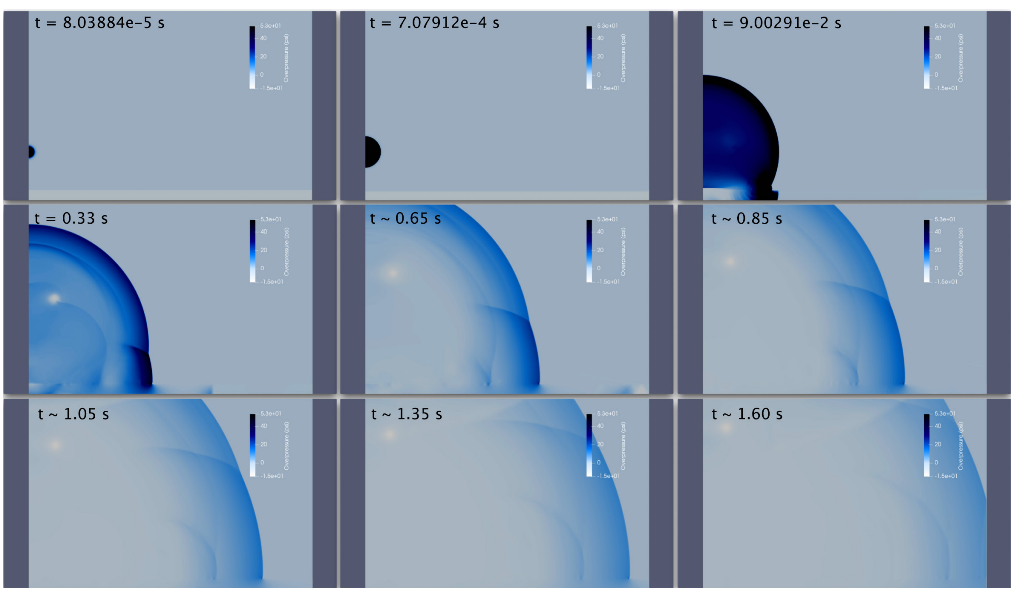

Figure 5. Selected frames from the water simulation in Paraview, with a color scale to emphasize different pressure values at increasing time intervals and labeled at the top left with the time in seconds. Each frame is approximately 1 km wide and 0.7 km high (Author produced pictures).

Figure 6. Close-up capture of one of the first granite simulations in Paraview at about t = 0.06 sec, showing the resolution near the ground-air interface and premature Mach stem. The pressure scale is in units of dyn/cm2 (Author produced pictures).

Simulation Features

One of the first and simplest comparison tests was a loose measurement of the triple point height as a function of the ground range, as it provides an intuitive picture of how close the simulation is to expected results. Fig. 8 shows the outcome, where the blue line on the left represents the measured height of the triple point for the 22 kT blast at 400 ft. The resulting A-scaled 143 ft HOB curve falls between the theoretical 100 ft and 200 ft HOB curves.

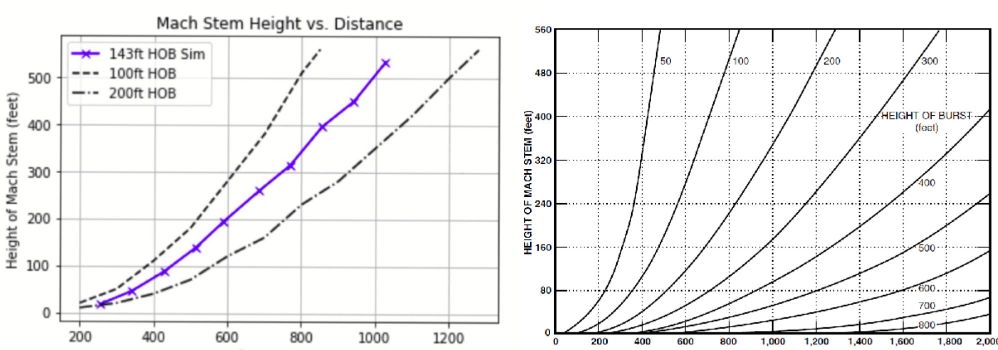

Figure 7. Comparison of the measured triple point height (blue) to theoretical curves (Author produced picture). Right: Various theoretical curves showing a vanishing triple point with increasing HOB (Fig. 2.26 from Northrop's EM-1).

One of the most noticeable features of the simulations is a persistent pale spot, likely due to a Rayleigh-Taylor instability. It makes an appearance inside the high-pressure shock front at around t = 0.1 sec (see Figs. 7 and 9). Around the spot swirls a mass of high-pressure air in a manner resembling a vortex. Furthermore, the region is stable and rises with time, bearing a striking resemblance to the rotating billow of the famous mushroom cloud phenomenon.

A mushroom cloud comes from a central column of rising hot air curling over the top and towards the outside in what is called *toroidal circulation* (Figure 8). Therefore, if this pale spot is the center of the ring of the forming mushroom cloud, the air should flow clockwise around it. Curiously, the pressure contours curl counterclockwise around the pale spot in the simulation (Figure. 9 — this effect is obvious on video but does not translate well to still images).

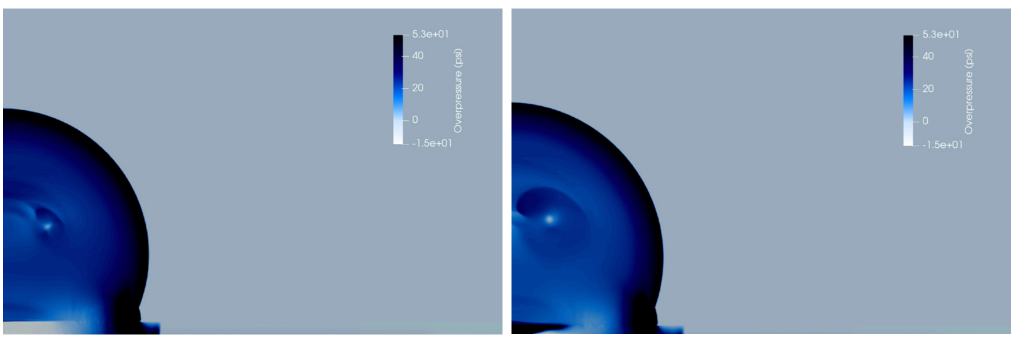

Figure 8. Captures of the final granite simulation at around t = 0.1 sec (left slightly earlier than right). The low-pressure spot (pale) inside the shock front is enclosed by a mass of higher-pressure air (dark) that revolves around it. It may be the rising torus that forms the iconic mushroom cloud. (Author produced pictures).

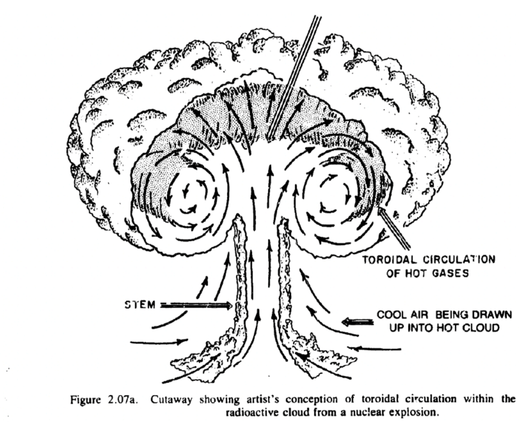

Figure 9. Depiction of toroidal circulation in a mushroom cloud from Glasstone & Dolan, p. 29.

Comparison of Simulation Data Samples

Substantial data samples from each simulation were collected over the relevant time window and ground range. Overall, the simulations lack the diversity exhibited by the real tests, as is most evident with the arrival time curves. These simulation arrival time curves are indistinguishable from each other and the ideal curve (Fig. 4, left). The four overpressure curves are virtually identical from 200 ft to 600 ft, and they only begin to barely diverge at the tail end of the simulation (Fig. 4, right). It is worth noting that the arrival time and overpressure simulation data were typically higher than theoretical and the experimental lower.

The largest discrepancy between the simulation and experimental data is the lack of difference in speed between materials. By comparing Figs. 3 and 4, this is easy to see. Since these simulations did not account for gravity on account of the short duration, nor did they account for surface irregularities or roughness on account of the limitations of xRage. Therefore, it is suspected that this discrepancy is due to unimplemented physics or the fidelity of xRage itself.

If the granite simulation is taken as a reasonable approximation for a blast over an asphalt surface, then the overpressure data from the three simulations have the same "ranking" as the report data over the relevant ranges (Compare Figs. 3 and 4), but just barely. While conceding that this is not by a significant margin and not true in the early phase of the simulation, it may suggest that some physics may not be missing but simply under-resolved.

Comparison of Data by Material

The best agreement between experimental, theoretical, and simulation data sprang from the water simulation (Fig. 10). Just as in the Teapot data, the water simulation arrival time matches most closely with the theoretical curve. In fact, many of the experimental points fall on the simulation curve. Likewise, several simulation points fall within the rudimentary overpressure confidence band and/or sit remarkably close to an experimental data point, though there is significant divergence in overpressure data at larger distances.

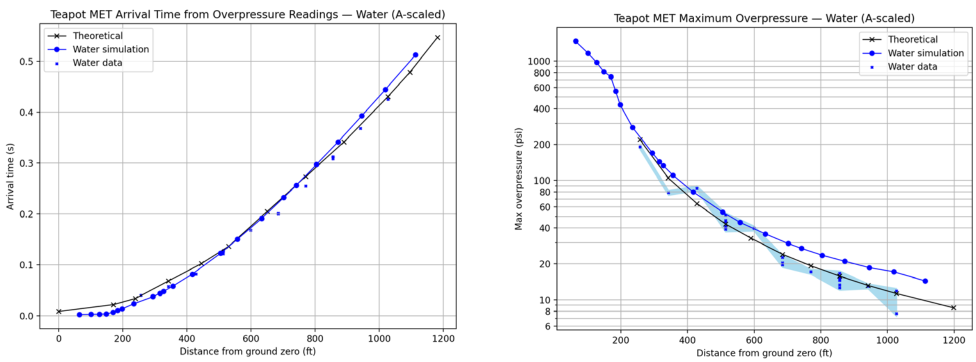

Figure 10. Left: Arrival Time for the water simulation. Right: overpressures above the simulated water surface. Theoretical data taken from Northrop's EM-1.[15] (Author produced pictures)

There is less agreement between the desert/alluvium data, but the expected trends are present (Fig. 11). The simulation shock failed to travel as fast as the actual shock beginning at around 400 ft, clinging closely to the theoretical curve. However, the arrival time data does appear to converge as the distance is increased. The overpressure data does not agree as well as the water overpressure data, with no simulation data points and notably less of the theoretical curve falling within or near the confidence band.

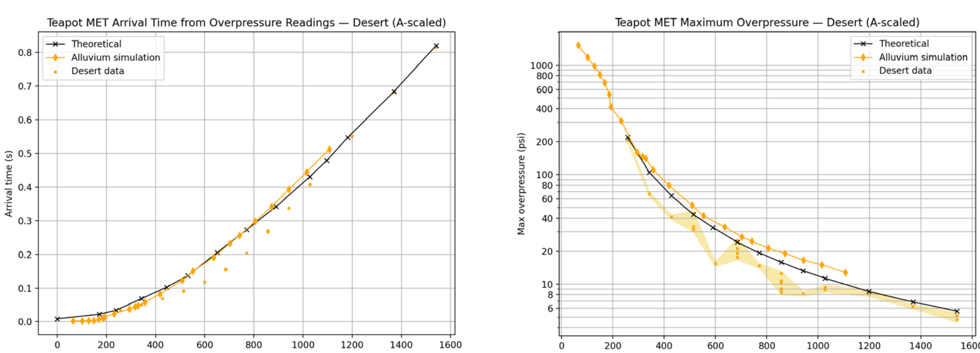

Figure 11. Left: Arrival Time for the alluvium simulation. Right: overpressures above the simulated alluvium surface. Theoretical data taken from Northrop's EM-1.[15] (Author produced pictures)

Upon brief inspection, the same thing can be said about asphalt/granite as about desert/alluvium, albeit to a greater degree. The simulation has much later arrival times and overpressures than both theoretical and asphalt report data, diverging further with increased distance. Because this comparison must be taken with more skepticism, the two data sets are not shown together here, though they can be seen in Figs. 3 and 4.

Limitations of WT-1109

The final simulations assumed a smooth, flat, and uniformly dense surface regardless of which material is used for the ground, which may not be an honest approach for simulation and theory. Teapot scientists suspected this:

> "It may be more than mere coincidence that most of the BRL gages which recorded the higher peak overpressures were those located near or on a stabilized pad. The obvious conclusion is that abrupt localized changes in the characteristics of the surface over which the blast wave is traveling may have significant effects upon the peak overpressure and time history of a measurement taken in the near vicinity of the altered surface."

Additionally, the simulation data suggest that the alleged 5% error of the pressure gages presumed in the test was an underestimate. Even in areas with moderate pressures and temperatures, there is still variation in the data that suggests an error of greater magnitude. Conversely, it is not known whether it is possible to evaluate the accuracy of the timer used in the Teapot MET test with the data available.

Conclusions

Overall, the EM-1 theoretical, experimental, and xRage simulation data agree well with one another, and the Teapot MET report data was successfully reproduced with just one major discrepancy: In the simulations, the material surfaces did not cause a difference in the shock speeds. Though the experimental water speeds data were ideal to begin with, the alluvium and granite simulations also produced speeds indistinguishable from ideal. In general, the simulation data matches the theoretical model more so than the experimental, and the homogeneity of the simulation arrival time curves is a strong example of this.

It is suspected that one source of this discrepancy is the simplicity of the input deck used, which did not have an extremely high fidelity. It is also possible that small variations in elevation were responsible for deviations in parameters such as speed and pressure in the MET report data, which were not a part of the simulations.

A simulation of an air bursts over surfaces with arbitrary roughness and natural height variations, or the use of a hydro code with a higher fidelity, would be the next logical direction to explore for this test. Perhaps this would help in replicating the distinct differences between wave speeds that Teapot scientists observed 70 years ago.

Appendix

TABLE 4.5 OVERPRESSURE, SHOT 12 WATER LINE

Gage	Ground Range	Gage Height	Arrival Time	Maximum Pressure	Time of Maximum Pressure	Positive Phase Duration	Positive Phase Impulse	Wave Form Type	Corr. for γ
	ft	ft	sec	psi	sec	sec	psi-sec		
				As-Read					
21BA	750	0	0.1185	170	0.125	0.56	11.0	1+	—
22B	1,000	0	0.1695	69.8	0.200	0.83	7.9	1	—
23P3A	1,250	3	0.242	76.3	0.300	0.42	5.10	1	Yes
25B	1,500	0	0.3665	34.5	0.400	0.44	4.39	2	
25P3	1,500	3	0.373	41.0	0.380	0.42	4.44	3	Yes
25B10	1,500		0.376	37.3	0.380	0.05			
25P10	1,500	10	0.376	39.8	0.410	0.43	4.21	2	Yes
26P10A	1,750	10	0.493	35.1	0.500	0.39	3.06	7	Yes
27B	2,000	0	0.589	17.4	0.695	0.54	3.34	1	—
27P3	2,000	3	0.5865	20.1	0.695	0.56	3.92	1	Yes
27B10A	2,000		0.587	15.8	0.600	0.06			
27P10	2,000	10	0.5865	18.1	0.700	0.54	3.42	1	Yes
28P10	2,250	10	0.7455	15.2	0.775	0.57	3.17	6	No
29B	2,500	0	0.914	11.8	0.960	0.63	2.66	7	—
29P3	2,500	3	0.913	13.2	0.940	0.44	1.83	7	No
29B10	2,500		0.914	12.9	0.915	0.70			
29P10	2,500	10	0.913	12.9	0.960	0.65	3.08	7	Yes
29P25	2,500	25	0.913	13.7	0.915	0.62	3.11	7	No
29P40A	2,500	40	0.913	11.2	0.960	0.61	2.61	7	No
31P3	2,750	3	1.077	11.5	1.100	0.67	2.85	7	No
32BA	3,000	0	1.246	8.76	1.255	0.73	2.39	8	—
32P3	3,000	3	1.245	10.5	1.250	0.64	2.43	8	No
25P3X*	1,500	3	0.3715	45.3	0.380	0.45	4.44		No
25P3Y*	1,500	3	0.3575	36.5	0.425	0.33	3.06		No
29P3X*	2,500	3	0.903	14.7	0.965	0.27	1.66		No
29P3Y*	2,500	3	0.914	13.0	0.945	0.58	3.04		No
				A-Scaled to 1 KT Radiochemical Release at Sea Level					
21BA	257	0	0.0405		0.0427	0.191	4.20	0+	—
22B	342	0	0.0579		0.0684	0.284	3.02	1	—
23P3A	428	1.0	0.0827		0.1025	0.144	1.95	1	Yes
25B	514	0	0.1253		0.1367	0.150	1.68	2	—
25P3	514	1.0	0.1275		0.1299	0.144	1.69	3	Yes
25B10	514	3.4	0.1285	42.2	0.1299	0.017			
25P10	514	3.4	0.1285		0.1401	0.147	1.61	2	Yes
26P10A	599	3.4	0.1685		0.1709	0.133	1.17	7	Yes
27B	685	0	0.2013		0.2376	0.185	1.27	1	—
27P3	685	1.0	0.2005		0.2376	0.191	1.50	1	Yes
27B10A	685	3.4	0.2006	17.9	0.2051	0.021			
27P10	685	3.4	0.2005		0.2393	0.185	1.31	1	Yes
28P10	770	3.4	0.2548		0.2649	0.195	1.21	6	No
29B	856	0	0.3124		0.3281	0.215	1.02	7	—
29P3	856	1.0	0.3121		0.3213	0.150	0.70	7	No
29B10	856	3.4	0.3124	14.6	0.3127	0.239			
29P10	856	3.4	0.3121		0.3281	0.222	1.17	7	Yes
29P25	856	8.6	0.3121		0.3127	0.212	1.19	7	No
29P40A	856	13.7	0.3121		0.3281	0.208	1.00	7	No
31P3	942	1.0	0.3681		0.3760	0.229	1.09	7	No
32BA	1,027	0	0.4259		0.4290	0.250	0.91	7	—
32P3	1,027	1.0	0.4255		0.4273	0.219	0.93	7	No
25P3X*	514	1.0	0.1270		0.1299	0.154	1.69		No
25P3Y*	514	1.0	0.1222		0.1453	0.113	1.17		No
29P3X*	856	1.0	0.3086		0.3298	0.092	0.63		No
29P3Y*	856	1.0	0.3124		0.3230	0.198	1.16		No

*Gages offset from blast line; see Figure 2.4.

Table 1. Complete WT-1109 asphalt line data, both as-read and A-scaled.

TABLE 4.7 OVERPRESSURE, SHOT 12 DESERT LINE

Gage	Ground Range	Gage Height	Arrival Time	Maximum Pressure	Time of Maximum Pressure	Positive Phase Duration	Positive Phase Impulse	Wave Form Type	Corr. for γ
	ft	ft	sec	psi	sec	sec	psi-sec		
				As-Read					
1BA	750	0	0.104	164	0.133	>0.64	>14.2	1	—
2BA	1,000	0	0.149	68.6	0.224	0.361	5.26	1	—
3P3	1,250	3	0.202	36.2	0.365	0.288	3.06	1	Yes
5B	1,500	0	0.265	29.6	0.520	0.553	4.80	1	—
5P3	1,500	3	0.265	39.1	0.517	0.61	4.74	1	No
5B10	1,500	10	0.269			0.04			
5P10	1,500	10	0.268	27.8	0.520	0.58	4.30	1	Yes
6P10A	1,750	10	0.3465	13.5	0.730	0.641	3.90	1+	No
7B	2,000	0	0.4525	16.9	0.520	0.78	4.94	3	—
7P3	2,000	3	0.4525	18.6	0.530	0.78	5.51	3	Yes
7B10	2,000	10	0.458	21.9	0.560	0.11			
7P10	2,000	10	0.4565	15.5	0.530	0.67	4.36	3	Yes
8P10A	2,250	10	0.599	13.0	0.680	0.83	3.96	3	Yes
9B	2,500	0	0.781	7.44	0.885	0.77	2.74	4	—
9P3	2,500	3	0.780	9.0	0.955	0.8	3.39	4	Yes
9B10	2,500	10	0.786	8.0	0.920	0.44			
9P10	2,500	10	0.782	11.0	0.945	0.77	3.60	5	Yes
9P25	2,500	25	0.7885	9.5	0.955	0.76	3.51	5	Yes
9P40A	2,500	40	0.7915	7.9	1.020	0.71	2.74	5	Yes
11P3	2,750	3	0.987	7.25	1.150	0.72	2.76	5	No
12B	3,000	0	1.192	8.0	1.295	0.86	2.39	6	—
12P3	3,000	3	1.192	8.25	1.297	0.84	2.47	6	No
12P10	3,000	10	1.194	7.86	1.296	0.82	2.36	6	No
15B	3,500	0	1.6115	7.17	1.635	0.86	2.20	6	—
15P10	3,500	10	1.610	7.45	1.630	0.83	2.13	6	No
16P10	4,000	10	1.995	5.50	2.010	0.95	1.94	7	No
17B	4,500	0	2.3875	4.57	2.400	0.89	1.67	7	—
17P3	4,500	3	2.386	4.19	2.395	0.98	1.66	7	No
				A-Scaled to 1 KT Radiochemical Release at Sea Level					
1BA	257	0	0.0355	186	0.0455	>0.219	>5.42	2	—
2BA	342	0	0.0509	77.7	0.0766	0.1234	2.01	2	—
3P3	428	1.0	0.0690	41.0	0.1248	0.0984	1.17	2	Yes
5B	514	0	0.0906	33.5	0.1777	0.1890	1.83	2	—
5P3	514	1.0	0.0906	44.3	0.1767	0.208	1.81	2	No
5B10	514	3.4	0.0919			0.014			
5P10	514	3.4	0.0916	31.5	0.1777	0.198	1.64	2	Yes
6P10A	599	3.4	0.1184	15.3	0.2495	0.2191	1.49	2	No
7B	685	0	0.1547	19.1	0.1777	0.267	1.69	3	—
7P3	685	1.0	0.1547	21.1	0.1812	0.267	2.10	3	Yes
7B10	685	3.4	0.1565	24.8	0.1914	0.038			
7P10	685	3.4	0.1560	17.5	0.1812	0.229	1.66	3	Yes
8P10A	770	3.4	0.2047	14.7	0.2324	0.284	1.51	5	Yes
9B	856	0	0.2669	8.4	0.3025	0.263	1.05	4	—
9P3	856	1.0	0.2666	10.2	0.3264	0.27	1.29	4	Yes
9B10	856	3.4	0.2687	9.1	0.3145	0.150			
9P10	856	3.4	0.2673	12.5	0.3230	0.263	1.37	5	Yes
9P25	856	8.6	0.2695	10.8	0.3264	0.260	1.34	5	Yes
9P40A	856	13.7	0.2705	8.9	0.3486	0.243	1.05	5	Yes
11P3	942	1.0	0.3374	8.2	0.3931	0.246	1.05	6	No
12B	1,027	0	0.4074	9.1	0.4426	0.294	0.91	6	—
12P3	1,027	1.0	0.4074	9.3	0.4433	0.287	0.94	6	No
12P10	1,027	3.4	0.4081	8.9	0.4430	0.280	0.90	6	No
15B	1,198	0	0.5508	8.1	0.5588	0.294	0.84	6	—
15P10	1,198	3.4	0.5503	8.4	0.5571	0.284	0.81	6	No
16P10	1,370	3.4	0.6819	6.23	0.6870	0.325	0.74	7	No
17B	1,541	0	0.8160	5.17	0.8203	0.304	0.64	7	—
17P3	1,541	1.0	0.8155	4.74	0.8186	0.335	0.63	7	No

Table 2. Complete WT-1109 asphalt line data, both as-read and A-scaled.

TABLE 4.9 OVERPRESSURE, SHOT 12 ASPHALT LINE

Gage	Ground Range	Gage Height	Arrival Time	Maximum Pressure	Time of Maximum Pressure	Positive Phase Duration	Positive Phase Impulse	Wave Form Type	Corr. for γ
	ft	ft	sec	psi	sec	sec	psi-sec		
				As-Read					
41BA	750	0	0.093	183	0.135	0.57	10.8	1	—
42BA	1,000	0	0.1335	78.1	0.230	>0.70	~8.2	1	—
43P3	1,250	3	0.183	26.8	0.370	0.48	5.08	1	Yes
45B	1,500	0	0.241	18.1	0.270	0.76 *	4.1 *	2	—
45P3	1,500	3	0.241	21.3	0.275	0.65 *	4.8 *	2⁻	No
45B10	1,500		0.244	21.2	0.270	0.07			
45P10	1,500	10	0.2445	22.4	0.260	0.56	4.09	2	Yes
46P10	1,750	10	0.324	16.4	0.360	0.8 *	4.5 *	2	Yes
47B	2,000	0	0.418	13.9	0.440	1.6 *	6.0 *	4	—
47P3	2,000	3	0.418	14.2	0.455	—†	—†	4	Yes
47B10	2,000		0.421			0.27			
47P10	2,000	10	0.421	13.4	0.460	—†	—†	4	Yes
48P10	2,250	10	0.5395	10.2	0.595	1.2 *	3.9 *	4	No
49B	2,500	0	0.674	6.60	0.730	0.75	2.34	4	—
49P3	2,500	3	0.674	8.5	0.720	1.3 *	4.2 *	4	Yes
49B10	2,500	10	0.679	6.38	0.705	—†	—†	4	—
49P25	2,500	25	0.688	6.9	0.785	0.68	3.58	7	Yes
49P40	2,500	40	0.695	6.80	0.725	1.3 *	3.6 *	7	Yes
51P3A	2,750	3	0.843	6.38	0.885	0.9 *	2.20 *	4	No
52B	3,000	0	1.034	3.92	1.065	0.7	1.45	5	—
52P3	3,000	3	1.032	4.87	1.300	1.1 *	2.5 *	5	No
				A-Scaled to 1 KT Radiochemical Release at Sea Level					
41BA	257	0	0.0318	207	0.0461	0.195	4.12	1	—
42BA	342	0	0.0456	88.4	0.0786	>0.239	~3.1	1	—
43P3	428	1.0	0.0625	30.3	0.1265	0.164	1.94	1	Yes
45B	514	0	0.0824	20.5	0.0923	0.260 *	1.6 *	2	—
45P3	514	1.0	0.0824	24.1	0.0940	0.222 *	1.8 *	2	No
45B10	514	3.4	0.0834	24.0	0.0923	0.024			
45P10	514	3.4	0.0836	25.4	0.0889	0.191	1.56	2	Yes
46P10	590	3.4	0.1107	18.6	0.1230	0.27 *	1.7 *	2	Yes
47B	685	0	0.1429	15.7	0.1504	0.55 *	2.3 *	4	—
47P3	685	1.0	0.1429	16.1	0.1555	—†	—†	4	Yes
47B10	685	3.4	0.1439			0.092			
47P10	685	3.4	0.1439	15.2	0.1572	—†	—†	4	Yes
48P10	770	3.4	0.1844	11.5	0.2034	0.41 *	1.5	4	No
49B	856	0	0.2304	7.5	0.2495	0.256	0.89	4	—
49P3	856	1.0	0.2304	9.6	0.2461	0.44 *	1.6 *	4	Yes
49B10	856	3.4	0.2321	7.2	0.2410	—†	—†	4	—
49P25	856	8.60	0.2352	7.8	0.2683	0.232	1.37	7	Yes
49P40	856	13.7	0.2376	7.7	0.2478	0.44 *	1.4 *	7	Yes
51P3A	942	1.0	0.2881	7.2	0.3025	0.31 *	0.84 *	4	No
52B	1,027	0	0.3534	4.44	0.3640	0.24	0.55	5	—
52P3	1,027	1.0	0.3527	5.51	0.4443	0.38 *	0.95 *	5	No

* Data uncertain due to apparent instrumentation difficulties.

† Gage record does not return to zero.

Table 3. Complete WT-1109 asphalt line data, both as-read and A-scaled.

Ground range (ft)	Max. Overpressure (psi)
257	220.10
342	105.10
428	64.10
514	43.20
590	32.90
685	24.10
770	19.30
856	15.80
942	13.20
1027	11.30
1198	8.56
1370	6.86
1541	5.63

Table 4. Theoretical overpressure data for a 22kt blast with 400 ft HOB, A-scaled (taken from an equation In Northrop's EM-117).

Ground range (ft)	Arrival Time (s)
0.0000	0.008545
171.2146	0.022216
239.7004	0.034179
342.4292	0.068357
445.1579	0.102536
530.7652	0.136715
650.6154	0.205072
770.4656	0.273429
890.3158	0.341787
1027.2875	0.430651
1095.7733	0.478501
1181.3806	0.546859
1369.7167	0.683574
1540.9313	0.820288

Table 5. Theoretical arrival time data for a 22kt blast with 400 ft HOB, A-scaled (taken from WT-1109 theoretical data. The equation is not explicitly published in the report.).

Ground range (ft)	Arrival Time (s)	Max. Overpressure (psi)
64.3207	0.002396	1470.93
101.3948	0.002736	1169.96
127.2347	0.003081	974.98
148.5803	0.003419	817.95
169.6417	0.006840	740.62
184.2467	0.010259	561.49
197.7281	0.013672	431.32
234.8022	0.023927	279.31
294.3453	0.037601	170.56
315.6909	0.044434	144.38
326.9255	0.047858	133.62
356.1353	0.058104	110.89
416.8019	0.082032	80.21
505.5549	0.123044	54.36
557.5181	0.150387	44.56
633.6288	0.191401	35.67
702.1595	0.232431	29.63
741.4805	0.256372	27.00
804.3940	0.297354	23.66
871.8013	0.341804	21.04
945.9493	0.393079	18.61
1018.9739	0.444350	17.13
1113.3442	0.512697	14.41

Table 6. A-scaled water simulation data sample (Author created).

Ground range (ft)	Arrival Time (s)	Max. Overpressure (psi)
65.1604	0.002396	1516.06
101.1110	0.002736	1181.91
128.0739	0.003081	981.05
149.4196	0.003419	819.68
168.5183	0.006840	688.87
185.3701	0.010258	540.76
192.1109	0.013681	418.49
232.5552	0.023931	308.68
294.3453	0.037602	160.46
315.6909	0.044444	146.10
328.0489	0.047854	140.40
357.2588	0.058112	111.07
417.9254	0.082042	79.82
508.9252	0.123049	52.31
552.7400	0.150387	42.05
635.8757	0.191408	33.20
702.1595	0.232426	27.01
741.4805	0.256355	24.64
805.5174	0.297370	21.38
871.8013	0.341804	18.98
942.5790	0.393058	16.54
1014.4801	0.444330	15.00
1106.6035	0.512684	12.74

Table 7. A-scaled desert simulation data sample (Author created).

Ground range (ft)	Arrival Time (s)	Max. Overpressure (psi)
66.7332	0.002393	1546.3
101.111	0.002736	1194.3
128.411	0.003078	1044.5
149.644	0.003419	829.87
167.844	0.006837	710.78
185.033	0.01026	603.92
200.200	0.01367	493.55
296.255	0.03760	169.35
318.500	0.04444	142.97
421.633	0.08203	77.338
511.622	0.1230	50.680
524.766	0.1299	47.974
595.544	0.1675	36.813
656.210	0.2017	30.439
745.188	0.2563	23.602
830.121	0.3110	19.425
912.021	0.3657	16.550
975.721	0.4102	14.795

Table 8. A-scaled granite simulation data sample (Author created).

Notes

1. Bridgman p. 239
2. Bridgman p.240-243
3. Bridgman p.243-247
4. Bridgman p.247-248
5. Glasstone & Dolan p.39 (2.36)
6. Glasstone & Dolan p.89
7. WT-1109 p.44
8. Adapted from eqs. 3.65.1 - 3.66.4, Glasstone & Dolan p.101-104
9. DOE/NV--209-REV 16 p.7, Table "U.S Nuclear Tests — by Date"
10. WT-1109 p. 16, Table 2.1
11. WT-1109 p. 15-16, noting Figures 2.2 - 2.4
12. WT-1109 p. 28
13. WT-1109 p. 21
14. WT-1109 p.153-154
15. Northrop ch. 2 p. 13
16. Glasstone and Dolan, p. 29
17. WT-1109 p. 100

References

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Resurrection of a Legacy Nuclear Bomb Effects Code

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Introduction

The goal of this paper is to demonstrate that 1- legacy software, in this case over a half century old, can often be ported to modern computer platforms without too much effort using common Linux software tools; 2- legacy codes provide information and data that is not easily, or not at all, possible using existing modern codes; 3- legacy codes can be highly useful modeling and simulation tools because of the minimal learning effort for the large amount of computed data they provide. (In common software developer's jargon, the term "code" is synonymous with "software.") At the United States Army Nuclear and Countering Weapons of Mass Destruction Agency (USANCA) we continually explore new, and sometimes old legacy, codes to apply the best available tools and analysis to support WMD survivability of our combat forces.

There are many software tools that end up on the shelves of oblivion because of lack or cessation of support, unavailability of the authors (developers), or obsolete hardware and compiler technology. There are cases where the software was distributed without the source code, the developers move on or retire, their files are lost or destroyed, and their codes simply vanish because without the source code it is almost impossible to port a code to other or newer platforms. Sponsoring agencies rarely catalog or actively maintain an archive of their software, so researchers do not even know what to look for or what to ask from the agencies. One government entity, Radiation Safety and Information Computational Center (RSICC) at Oak Ridge National Laboratory maintains a substantial archive of many legacy and current software. Most of the RSICC archival codes are related to nuclear radiation safety, radiation transport, or nuclear criticality safety. This author has discovered and ported codes from this archive that prove to be useful in CWMD modeling and simulation analysis. In this article, we describe the legacy code SMAUG-13, what we changed to compile and run on a typical commercial off-the-shelf (COTS) computer, and present brief results of a sample calculation. This software is unclassified and may be obtained by a single-user license agreement with RSICC.

The Description and Purpose of SMAUG-13

The best way to concisely describe this code may be direct quotes (with minor edits) from the code abstract page and source code comment blocks, as follows.

Name and Title

SMAUG-13: Calculation of Neutron and Prompt Gamma-Ray Doses Resulting from an Atmospheric Nuclear Detonation. The name SMAUG is not an acronym; it is a fictional name from literature. This is version 013, 1 February 1974. This program was written by Harry M. Murphy, Air Force Weapons Laboratory(AFWL), Kirtland Air Force Base, New Mexico, January–October 1970.

Nature of Problem Solved

Using mass integral scaling of infinite, homogeneous air data sets made through the use of the discrete ordinates code CCC-254/ANISN-ORNL, SMAUG calculates the neutron and the prompt gamma-ray (including neutron-induced secondary gamma-ray) fluences, spectra, and doses at user-selected receiver points. Requiring minimal input preparation effort on the user's part, SMAUG provides very rapid dose solutions in a readable format. The computed neutron results include: fluence, spectrum in 22 energy bands, energy fluence (MeV/cm^2), mean energy, tissue dose, midline dose in a 30-cm diameter tissue-equivalent phantom, and silicon dose. The computed gamma-ray results include: fluence, spectrum in 18 energy bands, energy fluence, mean energy, tissue dose, midline phantom dose, air dose (Roentgens) and silicon dose. The discrete ordinates data is taken from ORNL-4464.

Method of Solution

The information in the ANISN- and SORS-computed SMAUG data bases has been reduced to a series of 419 six-constant empiric transmission functions of the areal density between the source and the receiver. SMAUG performs 12-point Gauss-Legendre quadrature of the air density between the source and the receiver using the exponential air model in the "U.S. Standard Atmosphere, 1962" to compute areal density. The transmission functions are evaluated to scale the infinite, homogeneous air results to the problem at hand. SMAUG uses a 9-band neutron source spectrum and prints the neutron receiver spectrum in 22 bands. The gamma-ray source spectrum consists of 10 bands; the receiver spectrum consists of 18 bands. For depths beyond the range spanned by the data bases, SMAUG performs simple exponential extrapolation for each source-receiver band. SMAUG allows the option of user-input source spectrum. It also includes a default fission and thermonuclear source spectrum.

Restrictions, Limitations, Requirements

SMAUG was written in ANSI FORTRAN to be as machine-independent as possible. It was developed and run on the AFWL CDC 6600 computer and should be capable of running on any scientific computer with adequate core size. When compiled on the AFWL CDC 6600, SMAUG required 18,650 words of central memory (44,200 octal) [miniscule requirements for today's personal computers]. It uses one tape unit to dump or load the labeled COMMON blocks. A FORTRAN compiler is required to compile and build the executable code.

Modifications to Port & Update Software

We had to apply only a few relatively simple modifications to port this code to a current Linux operating system (OS) openSUSE 15.4 on a COTS laptop computer. We used the popular open-source FORTRAN compiler in the gnu compiler collection (gcc), which can be downloaded and installed from gcc web site (https://gcc.gnu.org/). Most modern versions of Linux OS have precompiled gcc compilers in their main software repository. The version we used and currently included in our Linux OS repository is gfortran-7. We expect our revised, updated version of SMAUG to compile and run requiring no further modifications using any newer versions of gcc FORTRAN. Let us highlight our major modifications.

The entire original source code, as obtained from RSICC, was contained in a single source file. The first action was to separate each function and subprogram (subroutine) into a separate file with the same file name as the subprogram name. The files are then organized, as common practice for software maintenance, into four sub-directories where:

bin/ (contains the executable)
inc/ (contains the include files)
obj/ (contains the individual compiled source binaries)
src/ (contains the individual source code files)

We wrote a **`makefile`** script for using the **`Make`** utility to manage and simplify the compilation and update procedures in a semi-automatic fashion. To compile source files and build the executable, in a Command Console (Terminal) apply only two required simple steps:

1- **`make clean`** (optional)
2- **`make`** (to compile source files)
3- **`make link`** (to assemble the executable **`smaug.x`** in the bin/ subdirectory)

This architecture was not necessary in this case, but it is the most efficient method to maintain and update software projects with a large number of individual source files. We separated the source code into 29 separate files, 6 common block files in subdirectory inc/ and 23 source code files in subdirectory src/.

In the main program, **`smaug.f,`** we changed the first active line, the program statement, from:

```
program smaug(input,output,tape7= . . .)
```

to:

```
program smaug
```

because with the new compiler, the program statement must not have any arguments. The modern gcc FORTRAN compiler performs input/output and “tape” read/write specifications by explicit declaration statements following the program statement. For example,

```
open(unit=7,file="filename.out",status="new",err=n1)
```

At the end of the program execution, all open files may be optionally closed by, for example:

```
close(unit=7,err=n2)
```

where n1 and n2 are statement labels to execute if the execution encountered errors upon opening or closing a file, respectively.

We created three separate output descriptors:

1- The Console Terminal, to print brief information on execution progress.
2- The output file **`smaug.out`** where all of the calculation details are written.
3- The new file **`dose.dat`** where only the dose vs. range is printed.

In most programming languages, lines can be split by a continuation tag to help with readability of long lines. This is common and preferred practice. However, splitting variable names across two lines is very undesirable as it makes the code very hard to diagnose by those other than the original author. We fixed the split-variables in the common blocks to help with search, diagnostics, and debugging of the code.

We added a new (short) subroutine **`stopend.f`** to streamline the terminal execution state from different subprograms in the code.

We fixed the occurrence of a negative index to an array in subroutine **`value.f`** which caused a runtime error. In our judgement, the author or users of that time should have caught this error. So, we suspect the archived version in RSICC was not the latest version of the original author.

The new updated version of SMAUG has, in rounded numbers, a total of 3800 lines of code including 1260 comment (non-executable) lines and 2540 lines of active statements.

Program Execution

This program reads the input file **`smaug.in`** where several different problem types can be specified, as described in the user manual. We ran a typical scenario to calculate neutron and gamma dose to tissue and silicon versus horizontal range (on the ground level) from a nuclear explosion. The input file has the following structure:

1- line 1: problem title, will be printed verbatim in the output file
2- line 2: *key words (special keywords to define problem setup)

3- line 3: *key words (additional problem setup specifications)
4- . . .
5- range receiver-height (numeric input)
6- range receiver-height (repeated as desired)

Our sample problem runs extremely fast, less than one elapsed clock-time second from start to end of execution on our laptop computer, which is now two years old.

The new file **`dose.dat`** includes a few lines of header text to identify the problem, followed by a table of seven columns of data that includes range, neutron dose in tissue, gamma dose in tissue, total neutron + gamma dose in tissue, neutron dose in silicon, gamma dose in silicon, and total neutron + gamma dose in silicon. We are not aware of any other modern simulation code that can produce all of this data in a super-easy, super fast way. This tabular dose vs. range data could be conveniently used as input to other simulation codes for nuclear effects analysis in personnel and specific electronic equipment.

Post Processing Plot of Calculated Data

In our sample calculation, we used a generic 20 kiloton surface explosion source. The user can select any post processor of choice to readily extract or graphically display dose versus range printed in **`dose.dat`** file. We used the popular open-source scientific data plotting program **`gnuplot`** (http://www.gnuplot.info/) to display the calculated data printed in the **`dose.dat`** file. Figure 1 shows the calculated dose in centiGray (cGy) in tissue versus horizontal range.

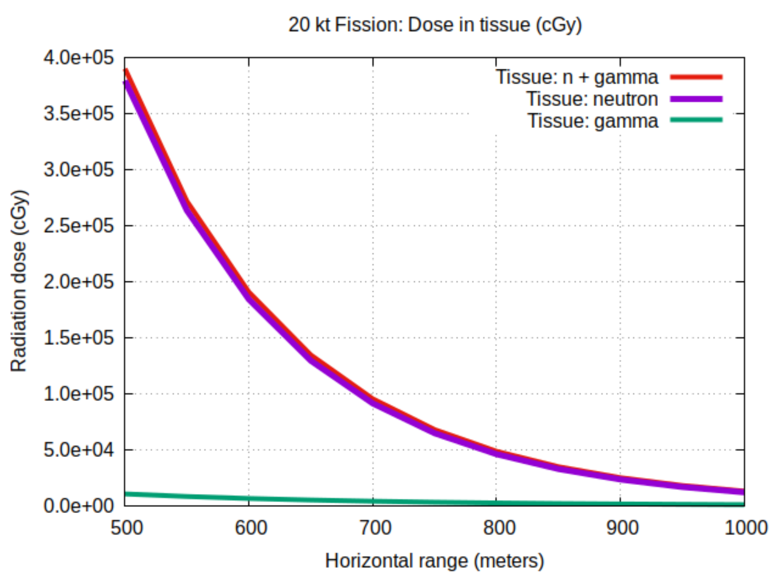

Figure 1. Dose vs. range in tissue.

Figure 2 shows the calculated dose in cGy in silicon versus horizontal range.

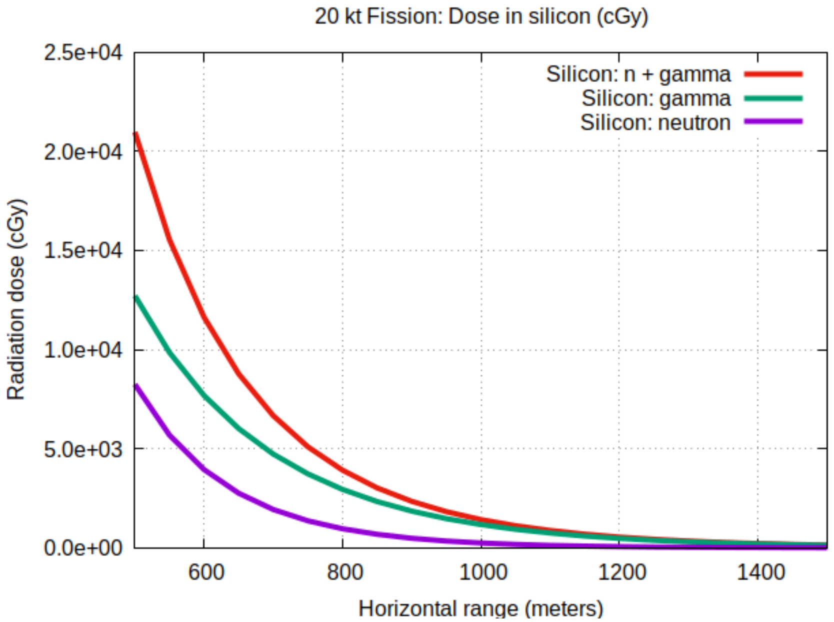

Figure 2. Dose vs. range in silicon.

Figure 3 shows the calculated total dose in cGy in both silicon and tissue.

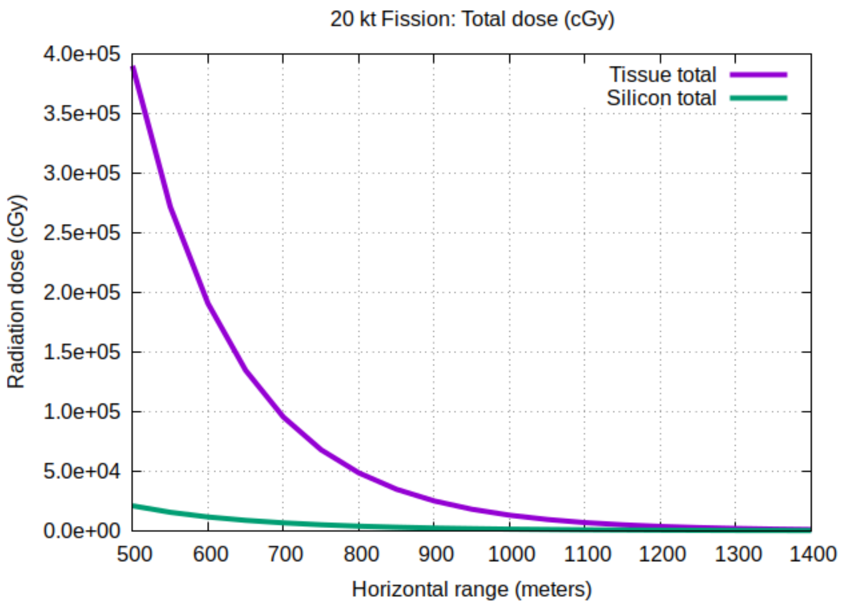

Figure 3. Total dose vs. range in tissue and silicon.

Figure 4 shows the same calculated dose as in Figure 3, in a close-up zoom view.

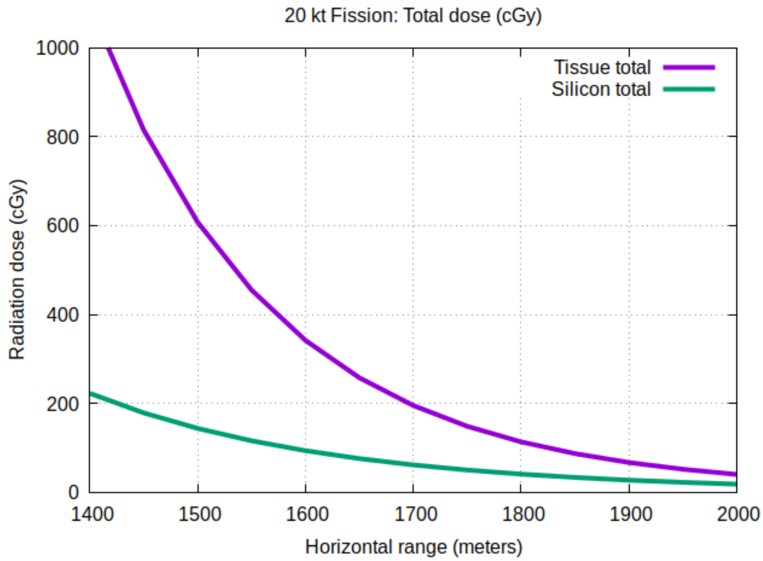

Figure 4. Total dose vs. range in tissue and silicon.

Conclusion

We modified, compiled, and executed the legacy code SMAUG, written more than half a century ago, with only five to ten days of uninterrupted effort. We made improvements in the output stream. We also added the ability to print a new summary table of calculated dose versus horizontal range from a nuclear explosion. The user can create a problem setup for large number of calculations very easily and quickly. The generation of the convenient tabular listing of dose versus range data is very difficult, if possible, with any of the existing modern codes. We can now efficiently use such calculated dose data to perform nuclear survivability analysis for radiation exposure to personnel and electronic equipment. We regard the SMAUG calculations, based mostly on first-principle physics, to be reasonably accurate under the given approximate source energy spectrum and well-established models for radiation transport in nominal free air. This new version will be submitted to RSICC for permanent archive retention.

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