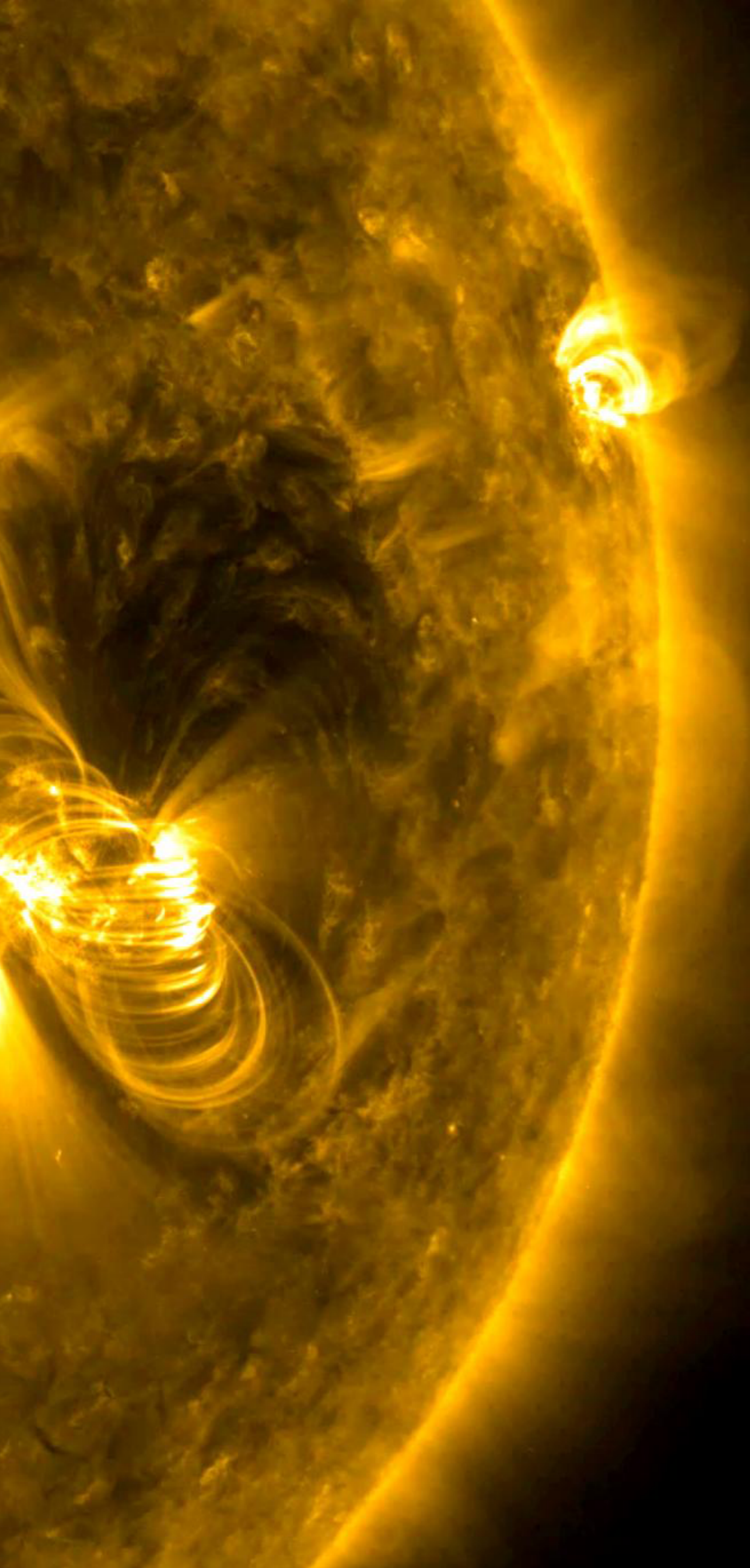

PIR

SUMMER-FALL 2017
VOL. 69, NO. 5

THE TRILLION-DOLLAR (SOLAR) STORM

FRENCH NAVAL NUCLEAR WASTE

HEAVY-ELEMENT WEAPONIZABILITY

ACTUARIAL APPROACH TO RADIOLOGICAL COUNTERTERRORISM

FAS Survey

IMPROVING RELATIONS BETWEEN THE FBI AND SCIENTIFIC COMMUNITY

and ***more inside.***

July 14 image of a medium-sized (M2) solar flare and coronal mass ejection (CME) eruption on the sun.

Photo/NASA/GSFC/Solar Dynamics Observatory

Published by the Federation of American Scientists.

PUBLIC INTEREST REPORT

Volume 69, Number 5

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LETTER TO THE EDITOR

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To submit a letter, email it to **fas@fas.org.**

CONTRIBUTORS

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President's Message

People are Primary: Cultural Life of FAS

Charles D. Ferguson
President, Federation of American Scientists (2010-2017)

It has become a cliché in the business world that organizations succeed or fail because of the people in an organization, and whether they are mission- and team-oriented. While the public perception of a scientist is often a lone genius more interested in things than people, this is almost always off the mark. Indeed, two years ago in *Nature*, two researchers showed definitively that, by analyzing Albert Einstein's network, Dr. Einstein "received a great deal of help from friends and colleagues" in developing his landmark theories.[1] Einstein was also engaged in societal issues. Notably for FAS and the scientists' movement of the mid-1940s, he served on the Emergency Committee of Atomic Scientists, which aimed to warn the public about nuclear weapons, promote the use of peaceful nuclear energy, and work toward world peace. The committee also sought to raise funding to support the nascent scientists' movement. We who have worked at and have supported FAS owe Albert Einstein, the committee's members, and the FAS founders a debt of gratitude for their dedication.

I dedicate this last president's message of mine to them as well as the numerous friends, colleagues, and coworkers I have been privileged to work and interact with for about 10 years (two-and-a-half years from February 1998 to August 2000 as a senior research analyst and seven-and-a-half years from January 2010 to August 2017 as president). Unfortunately, there is not enough space in this brief message to list and discuss the hundreds of people who have been involved with and supported FAS during the time periods I have worked at FAS. (Some of their work I have described in previous president's messages.) I will highlight several people to illustrate how FAS has attracted many incredibly talented people to devote their time and efforts to FAS and to the greater public good.

Long before I first started working at FAS, I was influenced by two amazing scientists who were affiliated with FAS (though I did not know their affiliation at that time). In 1984, when I was writing a term paper on missile defense issues for a class at the U.S. Naval Academy, I discovered a popular, but still technically written, article in Scientific American co-written by Hans Bethe (a founder of FAS) and Richard L. Garwin (who had served on the FAS Board of Directors for many years), along with Kurt Gottfried and Henry Kendall.[2] I was struck by several aspects of the article: clear writing, technically detailed (and accessible) analysis, illustrations that supplemented the writing, and an assessment of the strategic dimension of the issues, especially the authors' informed view that the proposed Reagan administration's missile defense system would likely be destabilizing by stimulating further arms-racing unless appropriate arms control agreements could be negotiated. This combination of technically sound analysis and evidence-based policy advice is a hallmark of FAS-affiliated scientists when advising the government and informing the public.

About 13 years later, soon after I was hired by then FAS president Dr. Jeremy J. Stone to work at FAS, I was privileged to meet for the first time Dr. Garwin, who for more than 60 years has performed tremendous service for national and international security. (When I was FAS president, FAS and I benefited from Dr. Garwin's sage advice when he served on the Board of Directors.) Dr. Stone and Dr. Frank von Hippel, then the Chairman of the FAS Board, were not just supervisors but were mentors to me as

1 Michael Janssen and Jürgen Renn, "History: Einstein was no lone genius," *Nature*, November 17, 2015.

2 Hans A. Bethe, Richard L. Garwin, Kurt Gottfried, and Henry Kendall, "Space-based Ballistic-Missile Defense," *Scientific American*, October 1984.

I was climbing a steep learning curve from academic physics to arms control analysis. For decades, Dr. Stone and Dr. von Hippel mentored numerous young people, many of whom started their careers at FAS. FAS has thus served as an incubator for younger technical and policy analysts and new projects.

During the past four years, FAS has branched out its network to attract a diverse group of younger to senior experts spanning the fields of law, policy, political science, physics, naval nuclear propulsion, and nuclear engineering. FAS Chairman Gilman Louie helped lead the FAS strategic review several years ago that resulted in the plan to form a network of experts mostly focused on nuclear issues and organized in study groups and task forces. I am thankful for Mr. Louie and the FAS Board of Directors in June 2013 for approving this plan. The plan worked because of FAS' hard-working team, including Chris Bidwell, who has been directing some of the task force studies, Pia Ulrich, who has provided excellent research and project assistance, and Frankie Guarini (along with his predecessors Allison Feldman and Katie Colten) who have edited and helped create professional-looking publications from these projects.

While developing this network, FAS has continued to have Steve Aftergood, Director of the Project on Government Secrecy, and Hans Kristensen, Director of the Nuclear Information Project, direct individual projects that have garnered widespread acclaim and international recognition. I continue to be impressed by their commitment to their fields and their passion for public service. FAS is also fortunate to have other extraordinary people affiliated with the organization as adjunct senior fellows, including Martin Hellman, Bruce MacDonald, Jenifer Mackby, Robert S. Norris, Thomas Shea, Paul Sullivan, and Ward Wilson.

As FAS transitions to new leadership, I invite you to continue to read FAS' publications, and I thank you for your continued interest in and support of FAS.

The Trillion-Dollar (Solar) Storm

Robert Coker
Aerospace Engineer, NASA Marshall Space Flight Center (Former)

INTRODUCTION

Space weather events such as solar flares, the ejection of energetic particles from the sun, and geomagnetic disturbances can have measurable detrimental impacts on satellite operations, the ubiquitous Global Positioning System (GPS), high-frequency (HF) airplane communications, navigation, aviation, and the electrical power grid. These disruptions can have ripple effects, so that even economic sectors that are not ostensibly dependent on space assets (e.g., financial services) can suffer losses.

Even with satellite observations, the advanced notification of space weather events as provided by the Space Weather Prediction Center (SWPC), run by the National Oceanic and Atmospheric Administration (NOAA), can range from days to mere minutes. Although major disruptions are predicted to occur only once a century, significant impacts, with extended local outages and disruptions, occur once a decade. Minor events, resulting in aircraft rerouting and short-term GPS disruptions, for example, occur almost yearly.

As the United States' economic and national security becomes more dependent on spaceborne assets, and its aging power-grid becomes more susceptible to cascading failures, the impact of space weather events will continue to grow. Furthermore, unlike individual component failures, space weather events induce failures in entire groups of assets, so that shifting demand, such as rerouting communication traffic from one satellite to another or power from one transformer to another, will be of limited use. While meetings, such as NOAA's annual Space Weather Workshop (SWW), discuss the issue, limited national resources have been allocated to prepare for a major space weather event. This report enumerates the current activities of different agencies that are exploring how the United States can become more resilient to space weather events in the future.

SPACE WEATHER EVENTS

The sun regularly produces storms of enormous magnitudes that flood the solar system with energetic debris. The Solar and Heliospheric Observatory (SOHO), a joint ESA and NASA mission, is one of a number of satellites that monitor the sun in real time.[1] Sometimes, the energetic detritus from these storms intercepts the orbit of the Earth. High-energy photons, such as X-rays from a solar flare, can ionize the Earth's upper atmosphere, severely interfering with radio communication and GPS satellites. Unprotected astronauts in space could be exposed to dangerous radiation exposure. Slower-moving particles from a solar storm can form a coronal mass ejection (CME) that can reach the Earth in several days or even hours. These particles can impact the Earth's magnetic field, producing strong electromagnetic fluctuations on the ground, too. These fluctuations, in turn, can produce powerful electric currents through natural rock,

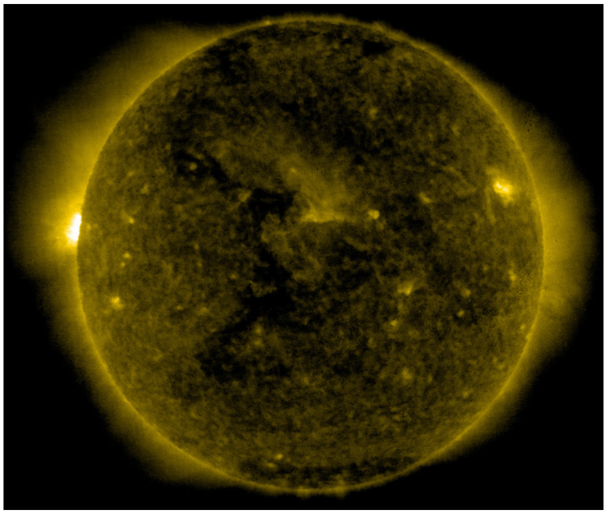

Figure 1: SOHO 284 Angstrom image of the sun, probing the upper atmosphere at 2 million degrees.

1 "The Very Latest SOHO Images," https://sohowww.nascom.nasa.gov/data/realtime-images.html.

power lines, and pipelines. These currents can be strong enough to blow out large power transformers, resulting in widespread blackouts and phone and internet communication failures. Replacing a large power transformer can take months or even years, so these outages could last for a significant time.

The first known modern occurrence of such a solar storm impacting the Earth was the Carrington Event in 1859.[2] Richard Carrington observed a large flare on the sun. Then, the next day, auroras could be seen in tropical latitudes and telegraph systems all over the world, starting to shock telegraph operators, operating while unplugged, and igniting the telegraph paper.[3] In March 1989, a solar storm significantly smaller than the Carrington Event resulted in a nine-hour power outage for 6 million people in Canada.[4] Other Carrington-level events have been observed in approximately the last 150 years, such as the super-flare observed on November 4, 2003,[5] so there is no expectation that the Carrington Event was a unique event.

Most events have not resulted in CMEs impacting the Earth. However, in May 1921, a storm approximately as strong as the Carrington Event hit the Earth, causing similar damage to telegraph facilities. If the Carrington Event or the 1921 storm happened again today, the damage is estimated to be well over $1 trillion,[6] as many millions of people would be without power or communications for months or even years. In July 2012, a large CME, estimated to be even more severe than the CME from the Carrington Event,[7] barely missed impacting the Earth. If it had hit the Earth, the damage would have been so severe that, according to experts, the world "would still be picking up the pieces."[8] This storm was important in that it missed Earth but impacted STEREO-A, a probe designed to measure such events. By being outside the Earth's magnetosphere, the probe survived the storm and provided, for the first time, detailed data on the shockwaves and energetic particles produced by a major solar storm.

In October 2003, a moderate-size CME forced astronauts on the International Space Station (ISS) to take shelter from the increased radiation, caused diversions in polar region airline flights, degraded GPS performance, caused a Japanese satellite failure, and induced power outages in Europe[9] and Africa.[10] In January 2005, a relatively minor space weather event caused the degradation of the HF radio communications of transpolar airline travel, resulting in the rerouting of dozens of flights and subsequent reduction in cargo capacity.[11] In November 2015, a similar solar event affected radar stations in Sweden, putting air traffic

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2 R.-C. Carrington, "Description of a Singular Appearance seen in the Sun on September 1, 1859," *Monthly Notices of the Royal Astronomical Society* 20 (1859), 13-15.

3 M.A. Shea & D.F. Smart, "Compendium of the eight articles on the 'Carrington Event' attributed to or written by Elias Loomis in the American Journal of Science, 1859–1861," *Adv. Space Res.*, 38 (2006) 313–385.

4 "March 13, 1989 Geomagnetic Disturbance," http://www.nerc.com/files/1989-Quebec-Disturbance.pdf.

5 "Biggest ever solar flare was even bigger than thought," American Geophysical Union, March 15, 2004, http://www.spaceref.com/news/viewpr.html?pid=13844.

6 Severe Space Weather Events: Understanding Societal and Economic Impacts: A workshop Report (2008).

7 Baker, et al., "A major solar eruptive event in July 2012", *Space Weather* 11 (2013), 585-591, https://science.nasa.gov/science-news/science-at-nasa/2014/23jul_superstorm.

8 https://science.nasa.gov/science-news/science-at-nasa/2014/23jul_superstorm.

9 R. J. Pirjola & D. H. Boteler, "Geomagnetically Induced Currents in European High-Voltage Power Systems," CCECE. 1263-1266, May 2006

10 Makhosi, T., G. Coetzee, "GENERATOR TRANSFORMER DAMAGE IN ESKOM NETWORK," EPRI Workshop on Transformers and Geomagnetic Currents, Washington DC, Sept 23, 2004.

11 http://www.lloyds.com/~/media/lloyds/reports/360/360 space weather/7311_lloyds_360_spaceweather_03.pdf, July 8, 2011.

control offline for about an hour.[12]

NATIONAL IMPACT

At the peak of solar cycle 23, in March 2002, during Operation Anaconda in Afghanistan, ionospheric variability hampered UHF communications. The miscommunications resulted in an intense firefight that left 7 Americans dead.[13] In May 1967, a solar storm brought the world to the brink of nuclear war[14] due to disruption of high-frequency communication across the polar cap; this was at the height of the Cold War when the United States interpreted the radio disruption as jamming by the Soviet Union. Only the fledgling U.S. Air Force space weather forecasting group was able to connect the disruption with an energetic solar event and prevent escalation. Although this storm did not result in large geomagnetically induced currents, today's cell phone and GPS systems would have been significantly impacted by such a storm today.

It is important to note that, unlike atmospheric storms such as hurricanes, the theoretical intensity limits of space weather events are unknown. That is, events much stronger than the 1859 Carrington Event, or even the July 2012 "near-miss," may be possible. Thus, the United States is in a race against time to beef up its power and communication infrastructure before the next "trillion-dollar storm" hits. For example, GPS can be made more resilient to geomagnetic storm effects with improved codes and frequencies. Improved forecasting of events could permit the off-lining of sensitive hardware, resulting in short-term power outages rather than month-long outages. Present spacecraft, such as SOHO, STEREO, ACE, DSCOVR, and Wind, are intended to study the underlying physics of flares, CMEs, and geomagnetic storms in order to improve NOAA's SWPC forecasts. However, spacecraft located closer to the sun than the L1 point could significantly improve warning times for some events.

Beginning with a National Academies of Science (NAS) committee report in 1979,[15] the importance and relevance of space weather has been discussed at the national level. The 1989 space weather event induced a Quebec power outage that resulted in impacts as far-reaching as the failure of a large power transformer in New Jersey, showing there could be large regional cascading impacts. Therefore, by the early 1990s, NOAA and the U.S. Air Force started providing space weather support services. In 1994, the National Space Weather Program (NSWP) was formed at the federal level to form a strategic plan to study space weather.[16] Due to the breadth of the topic, the NSWP evolved to include a large number of agencies, such as NASA, NOAA, DOD, USAF, USGS, NSF, FAA, DOE, DHS, and FEMA. Coordinating the efforts of these agencies, the NSWP was instrumental in establishing NOAA's Space Environment Center (SEC), which provides space weather forecasts to this day under the SWPC label.

Through NOAA's annual SWW, the NSWP continued to raise the visibility of space weather issues at the national level. For example, the North American Electric Reliability Corporation (NERC) hosted a Geomagnetic Disturbance (GMD) Workshop in 2011,[17] establishing an alert system to prepare and mitigate the GMD impacts to the planning and operations of power companies. Further NSWP studies helped provide the foundation for agreements that have resulted in critical space weather

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12 https://phys.org/news/2015-11-sweden-solar-flare-flight.html#nRlv.

13 M.A. Kelly, et al., "Progress toward forecasting of space weather effects on UHF SATCOM after Operation Anaconda," *Space Weather* 12 (2014), 601-611.

14 D.J. Knipp, et. al, "The May 1967 great storm and radio disruption event: Extreme space weather and extraordinary responses," *Space Weather* 14 (2016), 614-533.

15 http://sites.nationalacademies.org/cs/ groups/ssbsite/documents/webpage/ssb_088218.pdf.

16 M. Bonadonna et al, "The National Space Weather Program: Two decades of interagency partnership and accomplishments," *Space Weather* 15 (2017), 4-25.

17 http://www.nerc.com/files/GMD_Draft_Proceedingst_Nov_10_2011_v3.pdf.

monitoring missions, such as COSMIC-2 and DSCOVR. The NSWP studies also made it clear that a Carrington-level event will happen again — it is only a question of when. By analyzing solar storm records dating back over 50 years, a 2014 report concluded that there is a 12% chance of Earth being hit by a Carrington-class storm within a decade.[18] This statistic helped lead to the "Fixing America's Surface Transportation Act" that established a strategic reserve of spare large power transformers.[19] By 2010, even the insurance industry was taking note of space weather issues, with a report by the Lloyds Company agreeing with the severity of the issue and estimating a return period of 50 years for a Quebec-level event.[20] Most at risk are regions such as the U.S. East Coast, where cascading failures of transformers serving highly populated areas could create a prolonged power outage. In 2011, relevant industry leaders, after meetings at the SWW, formed the American Commercial Space Weather Association (ACSWA) to identify technology gaps that could be filled by private action. In 2014, the establishment of the Space Weather Operations, Research, and Mitigation (SWORM) task force provided the National Science and Technology Council (NSTC) oversight over the NSWP. The NSWP, before being deactivated in 2015, provided SWORM with vital input in developing a National Space Weather Strategy[21] (NSWS) and Space Weather Action Plan[22] (SWAP) that was released in October 2015.[23] These activities have resulted in cooperation between academia, industry, international partners, and over 20 diverse government agencies to amass data and models on how to deal with a Carrington-level event.

The goals of the NSWS are to establish benchmarks for space weather events; enhance response and recovery capabilities; improve protection and mitigation efforts, improve assessment, modeling, and prediction of impacts on critical infrastructure; improve space weather services through advancing understanding and forecasting; and increase international cooperation. The SWAP identifies approximately 100 activities with associated deliverables and timelines to achieve the goals identified in the NSWS. Additionally, the SWAP assigns each activity to at least one federal agency and emphasizes the need for collaboration with industry, academia, and other nations. SWORM was given an unfunded mandate to carry out these activities and thus achieve the goals of NSWS. As of June 2017, 80% of these activities have been completed.

RECENT ATTENTION

In addition to the SWW, a variety of meetings in recent years have been held in order to bring the space weather community together. The American Meteorological Society occasionally holds Space Weather Conferences, with the latest in 2016. The international Committee on Space Research (COSPAR) hosted a SW Roadmap meeting in India in 2016. This enhanced visibility of space weather issues, combined with the "near-miss" of 2012, got the attention of the White House, resulting in the signing of an October 2016 executive order intended to begin officially coordinating national efforts to prepare for a major space weather event. Furthermore, on May 2, 2017, the Senate passed the "Space Weather Research and Forecasting Act,"[24] the first bill specifically focusing on space weather issues; a nearly identical bill,

18 P. Riley, "On the probability of occurrence of extreme space weather events," *Space Weather* 10 (2012), SO2012.

19 https://www.congress.gov/114/bills/hr22/BILLS-114hr22enr.pdf.

20 https://www.lloyds.com/~/media/lloyds/reports/emerging-risk-reports/solar-storm-risk-to-the-north-american-electric-grid.pdf.

21 http://www.ofcm.gov/meetings/SWEF/2015/Presentations/2-1 SWORM SWEF 20 October 2015-1.pdf.

22 https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/final_nationalspaceweatheractionplan_20151028.pdf.

23 S. Jonas & E.D. McCarron, "White House Releases National Space Weather Strategy and Action Plan", *Space Weather* 14 (2016), 54-55

24 https://www.govtrack.us/congress/bills/115/s141.

H.R. 3086, was introduced in the House on June 27, 2017, where it is expected to pass as well. The bills essentially codify much of the NSWS and SWAP, giving those activities the weight of a congressional mandate. For example, it directs the National Science and Technology Council (NSTC) to establish a Space Weather Interagency Working Group (SWIWG), coordinated by the Office of Science Technology and Policy (OSTP), with the primary goal of establishing cross-agency benchmarks defining space weather events. However, it is an authorization bill, not an appropriations bill, so funds are not allocated to achieve the stated goals of improving the nation's ability to "prepare, avoid, mitigate, respond to, and recover from potentially devastating impacts of space weather events."19

Building upon the work of the NSWP and SWORM, the SWIWG should be able to publish final benchmarks within 18 months as required by the bill, but it is up to the new administration to follow up on this by providing funding to implement the activities called out in the SWAP. However, the proposed FY2018 budget calls for the elimination of the USGS geomagnetism program that monitors changes in Earth's magnetic field, providing data that help NOAA and the USAF track magnetic storms.[25] So far, space weather has been an ideal example of how the federal government should approach complex, far-reaching issues — it is now up to the new administration to follow through with the next steps before the "near-miss" event of 2012 becomes a reality.

25 https://www.sciencenews.org/blog/science-public/trump-proposed-budget-science-research-funding.

How Is Nuclear Waste from Naval Propulsion Activities Currently Managed in France?

Elsa Lemaître-Xavier
Head Project Engineer, Andra

This article is linked to the French-American naval nuclear assessment project managed by FAS, generously funded by the Richard M. Lounsbery Foundation. It follows and complements the FAS Special Report France's choice for naval nuclear propulsion by Alain Tournyol du Clos, published at the end of 2016, by looking specifically at the "back end" (including irradiated nuclear material and radioactive waste) of the nuclear fuel cycle. The author thanks the various participants of FAS' project as well as M. Daniel Delort and Damien Dubois for their thoughtful input during the group meeting in Paris in October 2016.

This article aims at presenting an overview of France's nuclear waste disposal strategy and how that is connected to the management of spent fuel and associated waste from nuclear-powered ships.

Before going deeper into the subject, one should be aware that France's Nuclear Waste Management strategy is based on:

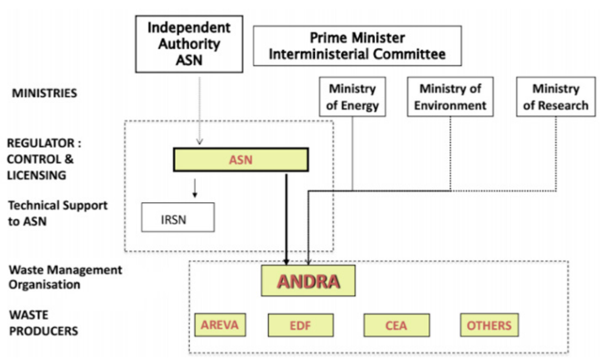

Figure 1: Actors in the back end of the nuclear fuel cycle in France (via Andra, http://www.andra.fr/).

- The establishment of the December 1991 Waste Act of Andra, an independent public body appointed in charge of the long-term management of all radioactive waste under the supervision of the government and the Nuclear Safety Authority, the ASN.
- The polluter paying principle, meaning that operators need to have sufficient financial resources to ensure proper management of their waste and decommissioning of their nuclear installations. Moreover, producers of waste are considered responsible for those substances without prejudice to the responsibility their holders have as nuclear activity operators.
- The non-adoption by French regulators of the notion of "clearance threshold" (generic levels of radioactivity below which the effluents and waste from nuclear activity can be disposed of as conventional waste). This means that any waste produced in a nuclear zone will have to be managed as nuclear waste.

FRENCH NAVAL NUCLEAR WASTE

Nuclear waste from the French National Defence represent 9% of the total volume of ra-

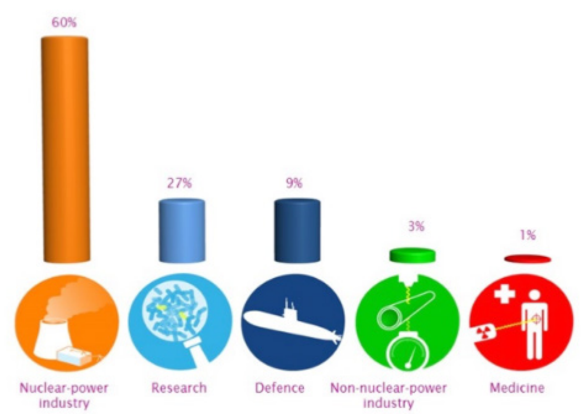

Figure 2: Distribution of the total volume of radioactive waste by economic sector (via National Inventory, http://www.inventaire.andra.fr).

dioactive waste inventoried in France;[1] It encompass waste from its armed activities, from the nuclear deterrent force, from nuclear propulsion for submarines, and the aircraft carrier and from the associated research activities.

The French Navy is currently operating:

- 4 ballistic missile submarines (SSBN) — *Triomphant*-class;
- 6 attack submarines (SSN) — *Rubis*-class;
- 1 aircraft carrier (CVN), the *Charles de Gaulle*.

With one reactor per submarine and two reactors in the aircraft carrier, that totals 12 reactors, compared to the 58 civilian reactors operated by the French utility EDF.

HOW IS INFORMATION SHARED?

As defined in the Environment Code, not only Andra is responsible for designing, installing, and managing storage facilities or disposal facilities for radioactive waste and to carry out all the studies necessary for this purpose, it also has to produce and publish the national inventory of radioactive materials and waste in France. This mission aims to provide the public with detailed information about the management of radioactive waste and supply policymakers with an overall and realistic inventory of nuclear waste; thus, it is financed exclusively through government subsidies.

Anybody can view and download files listing waste quantities and associated locations in France.[2]

It requires waste producers and holders to declare existing stockpiles of nuclear waste and material annually, and projected quantities every three years — this approach complements their own effort in terms of transparency. In terms of procedure, they have to complete a remote declaration and, after meticulous verification from Andra, are included in the database. The verification is based on data cross-checking by experts but not onsite inventory accounting.

Waste producers and holders have to declare quantity, physical characteristics, main radionuclides, and the packaging per waste categories. Nuclear waste produced in France is varied in terms of content, activity level, and half-life; these categories were created so as to define specific management systems to adapt the final disposal solution. Dubbed "proportional management," the more radioactive the waste is, the stronger the safety barriers have to be, e.g., the deeper it will be disposed of (surface versus near-surface versus deep geological disposal). The classification that was developed is presented in Figure 3, and each waste type requires the financing and conception of at least one disposal facility depending on the volume of waste estimated versus the facility capability.

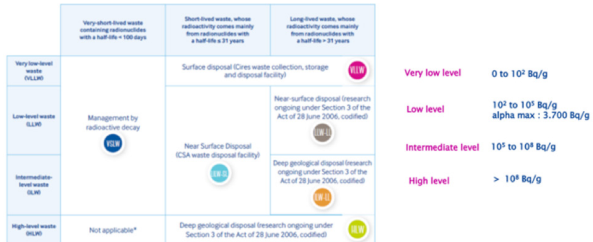

Figure 3: Classification of radioactive waste (via National Inventory, http://www.inventaire.andra.fr).

Volume (m^3) at the end of 2013	Nuclear power	Research	Defence	Industry other than nuclear power	Medical
HLW	2,700	190	230	-	-
ILW-LL	26,000	10,000	6,200	170	-
LLW-LL	42,000	20,000	17,000	12,000	2
LILW-SL	580,000	200,000	61,000	22,000	8,500
VLLW	220,000	160,000	42,000	11,000	3
DSF	2,400	740	650	4	1
Grand total	**880,000**	**390,000**	**130,000**	**45,000**	**8,500**

Figure 4: Breakdown of the total volume of waste by economic sector and management method. (via National Inventory, http://www.inventaire.andra.fr).

For defense-related nuclear facilities, the inventory only contains a description of the radioactive waste concerning those facilities.

1 All the data presented in the article are taken from the national inventory published by Andra in 2015. It is based on declarations from the end of 2013. As it is revised every three years, the next national inventory will be published in 2018.

2 National Inventory, http://www.inventaire.andra.fr.

But in reality, the French Navy and the military branch of CEA — responsible for the spent fuel from naval cores — are prone to give more information. They are subject to the same classification and regulations; the figures given in Figure 4[3] correspond to stockpile quantities at the end of 2013. Waste from the French Navy represent a fraction of the French National Defence stockpiles.

CONCEPTION/FINANCING OF A FRENCH NUCLEAR WASTE DISPOSAL FACILITY

The conception and design process of the surface and near-surface disposal facilities are similar. It stems from iterative studies between science, engineering, and safety leading to a site-specific concept and related waste acceptance criteria. Usually these criteria are expressed in different ways: some are applied either to the waste package unit or to a set of packages, and others to the whole disposal facility.

But to start off, the iterative studies need a waste inventory hypothesis. Financed through a bilateral convention with these waste producers and Andra, these studies are briefly detailed through the following:

- The engineering studies aim at finding technical solutions to site and safety constraints.
- The sciences studies mainly through R&D programs permit a thorough understanding of nuclear waste, disposal component, and site evolution with time.
- The safety studies demonstrate the respect of the safety standards through natural evolution and in case of altered evolution of the whole disposal system, e.g., inadvertent human intrusion or a disposal component that is not functional. These demonstrations are grounded on what is known from the scientific studies and conservative hypotheses to cover the remaining uncertainties.

Currently two facilities in the East of France are in operation (Cires and CSA), and the operating costs depend on the delivered volumes of waste. Andra's first disposal facility — for low and intermediate short-lived radioactive waste — is located near La Hague in the North of France and was closed in the early '90s. Monitoring operations are still being billed to owners of waste. The conception of a near-surface disposal in the Aube district is currently being studied for the management of low-level long lived radioactive waste.

The deep geological disposal facility called Cigéo cannot be designed and thought in the same way as it is supposed to accept all end-waste that cannot be safely disposed at a lower depth. Moreover, to render its industrial service, the facility must be able to adapt to significant new hypothesis in terms of inventory, e.g., due to an evolution of the national energy policy or even of the waste management policy. This adaptation capability is incorporated early on into the conception process, as defined as an aspect of the project conducting tool.

Andra has chosen an appropriate clay formation, demonstrated the feasibility of having such repository in that formation, and built in the early 2000s, a laboratory at around 500m depth to further study the rock behavior and construction technics. The next important milestone is the submission of the repository license application to the National Safety Authority in 2019.

This project is currently financed by two funds:[4]

- A research fund fed by an additional tax to the nuclear facilities tax. The latter is due from the year of the authorization of creation to its decommissioning. These facilities correspond to reactors — for research

3 DSF : Déchets Sans-filière designates that have not yet being attributed to a specific category of the classification.

4 http://www.andra.fr.

or electricity production, nuclear materials storage, nuclear waste disposal facilities, nuclear facilities from the overall fuel cycle — e.g., conversion or reprocessing. The former concerns only nuclear facilities which produces intermediate and high level long-lived radioactive waste (reactors and the reprocessing facility) and are calculated using a specific multiplying factor for each facility determined by the government.

- A conception fund started in 2014 fed by a special contribution from producers of waste. This fund should be dedicated to industrial conception studies of the project and preliminary earthworks.

Moreover, it is planned that the construction, the operation, the closing and surveillance of Cigéo will be financed through a multilateral convention with the producers of waste and Andra. In order to be prepared for the effective disbursement, it was decided by ministerial order that operators of nuclear installations shall establish reserves to cover the costs and earmark the necessary assets for the exclusive coverage of these costs.[5] These assets shall present a sufficient degree of security and liquidity to meet the needs for the different phases of the deep geological project. The process starts when the fuel is being irradiated in the reactor meaning the management of all the nuclear waste (HLW and ILW-LL) that will be generated from that fuel have to be taken into account in the reserves, presented annually in a report to the government.

The reserves are currently calculated on the basis of a reference price, fixed by the government in the January, 15 2016 ministerial order to be 25 billion euros with the economic conditions of 2011, the start year of the studies on the estimation of the price of the underground installation Cigéo.[6]

NUCLEAR PROPULSION ACTIVITIES AND ASSOCIATED NUCLEAR WASTE

The military ports of Cherbourg, Ile Longue in Brest and Toulon generate waste associated with all the maintenance and refueling operations required for the upkeep of the nuclear naval fleet.[7] When during a major overhaul, the fuel on board needs to be replaced as it won't be able to provide enough energy for the submarine until the next overhaul, it is stored in cooling pools. These land-based support facilities also produce nuclear waste.

The very low-level waste produced corresponds to rubble, concrete, scraps metal, and filters. In addition, the low- and intermediate-level waste encompasses all clothing, gloves, tools, chemistry glassware, and ion-exchange resins used to decontaminate water. To be accepted in the corresponding disposal facility, this waste has to be conditioned in big bags or drums and in concrete or metal containers. Because these maintenance activities have been operating on submarines, these types of waste have been disposed of in Andra's facilities in respect of all the acceptance criteria.

After several years in cooling ponds, naval spent fuels are sent to the CEA facility in South of France to be placed in the dry storage CASCAD[8] where natural convection cools down the facility. Today, naval cores represent to end of 2013 around 156 metric tons and are estimated to be at 271 tons in 2030.[9] They currently use one-third of the total wells available in the facility; the remaining wells are mostly

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5 Securing the funding of nuclear waste management, https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000000823278.

6 The estimation of the price of the underground installation Cigéo, https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000031845115&dateTexte=&categorieLien=id.

7 National Inventory, http://www.inventaire.andra.fr/.

8 Analysis of the possibility of long-term storage of nuclear spent fuels: http://www.assemblee-nationale.fr/11/rap-oecst/r3101-1.asp#P1726_267584.

9 National Inventory.

filled with cores from experimental reactors. As France has made the choice of a closed fuel cycle for its electricity-generating reactors, naval cores will also be reprocessed in the future.[10] Thus, in the meantime these are considered valuable materials thanks to their depleted uranium and plutonium content and are not accounted for in the nuclear waste stockpile given in Figure 4.

Nevertheless, the last report from IRSN — the technical support to the French Nuclear Regulator analyzes the safety options presented by Andra for Cigéo and indicates in the appendix the list of the different nuclear waste families taken into account for the design and dimensioning of Cigéo.[11] The final waste generated from nuclear propulsion spent fuels are specifically identified: the vitrified waste naval activities in the responsibility of the CEA represents 14 cubic m of 10,072 cubic m total and the associated compacted hulls represents 72 cubic m of 73,609 cubic m total. Considering these low volumes, one can induce that the military branch of the CEA won't be a major contributor to the financing of the deep geological disposal facility. According to the ministerial order it still has to establish reserves for all of the irradiated fuels.

Moreover, six ballistic missile submarines — *Le Redoutable*-class — are currently being decommissioned in Cherbourg. This operation can be detailed as being divided into two independent processes: the dismantling which contains all the operations under nuclear safety supervision, and deconstruction of the reactor-free ship. The timeline of these operations can be detailed as follows:[12]

- **The final shutdown:** discharge the core of the nuclear reactor.
- **Dismantling level I:** materials of the reactor are disembarked.
- **Dismantling level II:** a thorough decontamination is operated, all fluids are drained and the primary circuit is dried out. The walls are soldered with metallic tapes and the waterproofing of the compartment is verified. This phase ends with the separation of the reactor, which is perfectly confined.
- **Long-term storage:** the reactor is stored under control for tens of years to decrease the radioactivity of the reactor's activated or contaminated metallic materials.
- **Dismantling level III:** all nuclear materials are conditioned into waste barrels for Andra.
- **Deconstruction of the hull:** after approval from the safety authorities the hull is recycled out of nuclear domain.

The six ballistic missile submarines aforementioned have achieved Dismantling level II. The national inventory details that each of these ships contain: (i) 645 tons of very low level metallic waste — mainly structure of primary circuit which should represent around 92 m3 of conditioned waste and (ii) 55 tons corresponding to 8 m3 of low and intermediate level conditioned metallic waste.[13]

In order to seek to minimize doses received by workers and optimize operational costs, the possibility of transporting a reactor vessel or a steam generator directly as a whole to the disposal facility is currently being studied by Andra and the CEA. As this type of waste doesn't respect the waste acceptance criteria applied either to the waste package unit or to

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10 Alain Tournyol du Clos, "France's Choice for Naval Nuclear Propulsion," https://fas.org/wp-content/uploads/2016/12/Frances-Choice-for-Naval-Nuclear-Propulsion.pdf.

11 Analysis of the safety options presented by Andra for Cigéo: http://www.irsn.fr/FR/expertise/theme/Pages/Avis-rapports-Projet-Cigeo.aspx#.WarXFMgjE2w.

12 French armament procurement agency website: http://www.defense.gouv.fr/dga/equipement/dissuasion/le-demantelement-des-batiments-a-propulsion-nucleaire.

13 National Inventory.

a set of packages, a specific safety study must be carried out.

This section demonstrated that the French Navy is using the infrastructures developed to fulfill the French utility needs for safe disposal.

TAKING A STEP FURTHER: HEU VERSUS LEU FUELS

The French nuclear waste management strategy gives the opportunity to know that solutions to LEU spent fuels exist and are currently being studied. The waste classification used by Andra shows that all reprocessed spent fuels (either LEU or HEU) create HLW and ILW-LL which are planned to be disposed of in the same underground facility, Cigéo.
Then comparing the two options:

- Fueled by LEU, the Navy is using three times as many nuclear cores than would be necessary if they were fueled by HEU.

- Heat generation and the content of mobile radioactive elem[14]ents are the two key parameters looking at the back end of the fuel cycle. Heat generation is directly linked to the space used within the disposal facility and cooling time required before being disposed of in the repository. Transuranic content are usually heavy atoms and contribute far less to the environmental impact of the repository than the mobile atoms like iodine or chlorine.

- There shouldn't be any proliferation issues comparing the two options as the plutonium in the spent fuels is not weapons-grade due to the content of plutonium 240 and especially in the case of an open fuel cycle like in the US where this fissile material is pretty inaccessible.

14 "France's Choice for Naval Nuclear Propulsion."

Fifteen Dysfunctional Decisions of Chernobyl

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The explosions that destroyed reactor number four at Chernobyl, Ukraine on April 26, 1986 still reverberate today as the possibilities of using nuclear power to meet the related challenges of growing world populations and global warming are assessed. The triad of nuclear accidents, whose consequences cannot be escaped, are Three Mile Island, Chernobyl and Fukushima. Of the three, Chernobyl had, by far, the greatest impact of human beings and their associated terrain. Yet, 30 years later, society is still grappling with efforts to unravel the causes of Chernobyl's demise. If those causes were inextricably interwoven with fundamental design features of nuclear power plants, then that technology might be forever eschewed. However, if Chernobyl is revealed to be an idiosyncratic event, then, while there may be lessons to be learned, one need not anticipate the inevitable demise of nuclear energy.

The history of the decision to build this reactor, the events surrounding its construction, the details regarding events preceding and subsequent to the tragic explosion, the manner in which this calamitous event was presented to the people of the Soviet Union and then to the world are clouded by multiple instances of obfuscation, misrepresentation and cover up. In an attempt to unravel this muddled history, this essay picks apart individual events of consequence and tries to isolate them. While not a definitive portrayal of the history of the Chernobyl disaster, the sheer number of questionable actions and the outright lies that are identified call for taking a fresh look at the possible lessons that might be drawn from this catastrophe.

1. WRONG DESIGN

Decisions in the Soviet Union about the development of nuclear power were made by senior bureaucrats in the late 1970s largely in secret and not subject to full vetting by scientists. Warnings by scientists that the design of the Chernobyl reactor was dangerously flawed, dating from1965, were ignored. The first dysfunctional decision is that this reactor should not have been built. This type of reactor was designed by the military to optimize the production of plutonium for nuclear weapons. It was decided early on by Soviet bureaucrats to use this military reactor for civilian use. It was a light-water cooled, graphite moderated reactor with 2% enriched uranium with boron-carbide control rods. There were 1600 fuel elements that could be extracted individually using a crane on top of the reactor. That arrangement allowed the extraction of fuel elements at the most desirable moment for the harvesting of weapons grade plutonium. The plutonium production reactors developed by the military did not take into consideration the safety features required of civilian power reactors being developed in the United States, Canada and elsewhere.[1]

2. DESIGN FLAW #1

The reactor, known in the Soviet Union as the RBMK, had several major design flaws. The initials RBMK, in Russian, stand for "Reactor high-power boiling channel type." A significant design flaws was that it had no containment enclosure.[2] Containment enclosures were used routinely, elsewhere in the world, to prevent material from a possible steam or hydrogen gas explosion contaminating the environment. Because this reactor design had been used in the Soviet Union in the 1970s without serious problems, a false sense of confidence prevailed at the time of its introduction for civilian power in 1983. While many RBMK reactors were built in the Soviet Union and in Soviet satellite countries, no other country in the world emulated the RBMK design.

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1 *The Legacy of Chernobyl*, Zhores Medvedev, W.W. Norton, 1990, p.259.

2 Ibid.

3. DESIGN FLAW #2

The second major design flaw was a reaction to overheating that caused more overheating; this defect proved fatal to the reactor. Bureaucrats, as early as the mid '60s, knew about this problem. The issue arose because water flowing through the fuel rods, as a coolant, also absorbed neutrons thus limiting the amount of heat arising from nuclear fission. Scientists[3] had pointed out that when this water flowing through the fuel assemblies became overheated, steam bubbles would form creating voids that allowed additional neutron flow, thereby generating more fission, thus producing more heat and even more steam bubbles. This sequence of events is known as a positive feedback loop, which can get easily out of control — and it did. That critique from the '60s was ignored as well as suppressed. The reactor went online December 20, 1983 two days before employees of the Soviet nuclear industry received awards and bonuses for their good work in completing construction early.

4. OPENED WITHOUT BACKUP POWER SYSTEM

By going online before the end of December, 1983, the construction team completed the work ahead of schedule, but in doing so they skipped doing a very important safety test of backup electrical power for emergency cooling. The reactor was vulnerable in the following way: if there were a power failure in the region, the electricity for the pumps that cooled the fuel rods would go down. Within a minute, emergency generators would provide the electricity for the cooling, leaving one minute where there would be no electricity. Intervention by an emergency electrical system was required to maintain operations during that critical one minute time period. Hence, when the Chernobyl four reactor was placed into operation there was no emergency electrical system in place to meet this critical need. This defect was kept secret within the operational staff of the reactor and was a source of constant anxiety. The disaster occurred when a long-delayed effort, on April 26, 1986, was made to test an electrical system that was designed to cover that one minute.[4]

5. HISTORY OF KYSHTYM KEPT SECRET

Before going to the accident itself, it should be noted that there was a lack of safety culture in the Soviet Union regarding nuclear development. There are several examples of this lack of safety culture. While Chernobyl and Fukushima are the largest nuclear power accidents in history, there was an event of similar magnitude, in 1957, that was kept secret. While not a reactor accident per se, it was an event intimately connected to nuclear reactor development that should have been known to all nuclear engineers in the Soviet Union. This happened in the Urals, in a place called Kyshtym, where the Soviets had been developing nuclear weapons and had large waste disposal areas. One of those waste storage areas blew up. It was probably a chemical explosion in the waste containment area, rather than a nuclear explosion. It's force was estimated to have been equivalent to that of about 85 tons of TNT.[5] More than 10,000 people were evacuated and an area larger than New York City was seriously contaminated.[6] While we do not know how many deaths there were, claims that there were 300 immediate deaths among villagers nearby are plausible.[7] Since the area was remote and world monitoring of radioactive fallout was limited, the Soviets were able to keep the event secret for 32 years until 1981. As a result, nuclear engineers and other people working in the nuclear industry in

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3 Ibid, "as early as 1965 Dr. Ivan Zhezherun, a senior scientist at the Kurchatov institute had been warning about a defect known as the "positive steam void coefficient," p.258.

4 Ibid, p.11.

5 Kyshtym Disaster (via Wikipedia).

6 *Nuclear Disaster in the Urals*, Zhores A. Medvedev, translated by Georges Saunders, W.W. Norton & Company, 1979.

7 Kyshtym Disaster.

the Soviet Union did not have the opportunity to learn about radiation, its effects and all the related issues associated with a major nuclear accident.

6. HISTORY OF CHERNOBYL-LIKE REACTORS IN USSR KEPT SECRET

In the 1970s, there were a number of Chernobyl-like RBMK reactors in the USSR with graphite moderating structures and separate fuel assemblies. These reactors experienced accidents of various types: small explosions, fires, shut downs, and other problems. However, they were not reported or discussed in the USSR or with international agencies.[8] As a result of this secrecy, professionals in the industry, especially the operators and manager of RBMK nuclear fuel plants, did not learn anything from those experiences.

7. EMERGENCY SYSTEM TESTING NOT OPENLY PLANNED

After the reactor opened without full testing in 1983, there was an urgent need to implement the missed test of an the emergency electrical system. In 1984, such a test failed and in 1985, another trial emergency mechanism also failed. The cognizant managers at the reactor were nervous and secretive. However, many higher level bureaucrats in the nuclear management and government hierarchy did not know that there was a problem at this Chernobyl reactor.[9] The Chernobyl IV reactor was the fourth of its type at that location. There were already three operating and at least two more planned. Not only was the integrity of Chernobyl IV itself consequential, but the viability of the RBMK design was of critical importance for national energy planning. This location in the Ukraine was envisioned by central planners in the Soviet Union to become the site of the largest concentration of nuclear power plants in the world. Unfortunately, at the time of the disastrous test on April 26, 1986, the reactor had been in operation for quite a while. As fuel is utilized it undergoes fission thereby creating radioactive byproducts. At the time of the test, the fuel containers had produced large concentrations of dangerous radioactive material; it was the worst possible time for such a test.

8. REGIONAL COORDINATION DID NOT EXIST

The test was scheduled for daytime on April 25, 1986. Because of issues with the regional power agency, operations were postponed until nearly midnight, at which time the team of operators who had been trained for this test went off duty. The night time team was not as well prepared; they didn't really know what they were getting into, and they didn't understand many of the factors involved. The test was started after midnight the next day on April 26, but during the delay, there was a need to lower the power level of the reactor. However, it was lowered too much. There were nuclear reactions that kicked in at this low power level known as Xenon poisoning,[10] which impeded further operation of the reactor, that should have stopped the test at that time, but that did not happen. The delay imposed by regional managers, who did not know what was happening at Chernobyl IV, ultimately led to the test being implemented by an untrained crew and the triggering of Xenon poisoning.

9. FAULTY OPERATIONAL DECISIONS

The operators on duty, who did not understand the nature of Xenon poisoning tried to raise the power level. Because the reactor did not respond, they removed many control rods and shut off emergency systems.[11] Eventually, the boiling process that precipitates positive feedback kicked in. The voids in the boiling water led to more neutrons initiating additional heat producing fission with an exponential increase in temperature of the fuel rods. As this started to happen, the operators realized that it was essential to shut down the reactor.

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8 *The Legacy of Chernobyl*, 261.

9 Ibid, p.19.

10 Ibid, p.27.

11 Ibid, p.31.

10. DESIGN FLAW #3

The operators tried to insert all of the available control rods, not realizing that the control rod designs were also defective. When the first tip of the control rod went in, it actually increased power levels.[12] While the body of the control rods was made of boron-carbide, the tip was graphite. While boron-carbide absorbs neutrons and slows reactions in a reactor, graphite on the control rod tips in the RPMK reactor displaced water which had been absorbing neutrons. The net result was therefore an increase in neutrons participating in fission. This increase in the fission process resulted in rapid heating that precipitated a steam explosion followed by a hydrogen explosion. The hydrogen was produced when the fuel rods melted, accompanied by oxidation of the titanium containers. As the oxygen was being taken from the water in the fuel rods, it freed hydrogen gas which is extremely explosive. It needs to be said that these explosions were caused by steam and hydrogen gas, they were not nuclear explosions.

The explosion took place at 1:23 a.m. on April 26, 1986. There was a 2,000-ton cover over the reactor, but no containment structure; this vast cover became vertical and broke apart. The large graphite matrix of the reactor is a form of carbon that is a common fuel for fires. Thus, the exposed graphite body of the reactor ignited. A great deal of radioactive material and some uranium and plutonium flew out of the reactor. The fire went on for some time before it could be stopped. Extensive amounts of radioactive material were dispersed over regions more than two thousand miles distant. During that two weeks or so afterwards, the weather patterns sent plumes of radioactive material in all directions.

11. CHERNOBYL ACCIDENT INITIALLY KEPT SECRET

At first, the Soviets tried to keep the explosion a secret. However, it was not easy to keep that secret and on April 28, 1986, workers at a power plant in Sweden thought that they had a problem at their facility because they were measuring serious levels of radioactivity. They realized it was coming from someplace else.[13] They analyzed some of the airborne particles that were coming through to Sweden and found isotopes that could only have originated in a nuclear reactor with melted fuel rods. The clear conclusion was that a reactor had failed in the Ukraine. They then confronted the Soviets. After initial denials, the Soviets finally admitted that there had been an accident. At 9 p.m. on April 28, there was a report on Moscow television. It was a succinct report which stated that, “An accident has occurred at the Chernobyl Atomic Power Plant. One of the reactors has been damaged. Measures are being taken to eliminate the consequences of the accident. Aid is being given to those affected. A government commission has been set up.”

12. FIRST RESPONDERS IGNORANT OF AND ILL-PREPARED FOR DANGERS OF RADIOACTIVITY

After the explosion, other defects in decision making became apparent. Most tragically, the firefighters and other initial responders didn’t know what they were getting into.[14] They didn’t understand radioactivity and they didn’t have instruments to measure the radioactivity. Also, they didn’t have protective clothing and didn’t know what precautions they should take. Consequently, the death rate among firefighters was high.

13. EVACUATIONS AND PROTECTION OF CIVILIAN POPULATIONS NEGLECTED

Nearby to the Chernobyl IV reactor, the nuclear workers town of Pripyat, with a population of 50,000 people, were not immediately told that there had been a serious reactor explosion with high levels of radioactivity in the region.[15] On the day of April 26, the people of Pripyat,

12 Ibid, p.28.

13 Ibid, p.56.

14 Ibid, p.42.

15 Ibid, p.46.

who were unaware of the dangers, went about their activities as usual. Normal events were held, children played outside, people strolled in the streets; this behavior should not have been allowed. Since news of the accident was not disclosed to the Soviet nation until 9 p.m. on the night of April 28, this secrecy prevented proper action being taken in Pripyat. The secrecy also seriously delayed planning of actions that were needed to protect citizens who were being exposed to high levels of radiation. These delays resulted in the people of Pripyat not being evacuated until 2 p.m. on April 28. More than 1,000 busses succeeded in evacuating the population that afternoon.

While in the region near to the damaged reactor, protective action was delayed, during the ensuing days, in more distant regions, needed action was ignored. Kiev, which is just 63 miles from Chernobyl, was then the eighth largest city in Europe with a population of 2.5 million people. The residents of Kiev were not alerted to the problem and went about business as usual for weeks. In Kiev and other cities in the Ukraine and Russia, May Day was celebrated as usual despite the fact that there were serious levels of radiation and fallout. Children of Kiev were not evacuated until mid-May. The full health consequences of this irresponsible behavior by the Soviet authorities will probably never be known.

14. INTERNATIONAL COMMUNITY DECEIVED

The world was quite agitated about the explosions and the aftermath at Chernobyl IV. There was intense concern throughout Europe and elsewhere. The International Atomic Energy Agency (IAEA) was under pressure to provide answers and information. The IAEA held an international conference in August of 1986[16] and the presentation from the Soviet Union was made by Academician Valery Legasov, who had been instrumental in helping ameliorate post-accident impact at the accident site and nearby. Legasov presented a report in conformity with the instructions that he had received from the Politburo to lay the blame for the entire event on operator failure. He asserted to the international community that managers and operators at the reactor had failed in their duties.

In keeping with the idea that everything that went wrong was due to the actions of the people managing and working at the plant itself, a show trial was held in July 1987, and six individuals, managers and operators were tried. They were charged with negligence, irresponsibility and mistakes in behavior. Those convicted were sentenced to between two and 10 years in corrective labor camps. This was the last show trial in the Soviet Union.

Not long after the 1986 IAEA conference, Legasov regretted what he had done. He became depressed and after about a year, started writing his memoirs with a more accurate account of events leading up to the disaster. On the second anniversary of Chernobyl, he was found hanging in the hallway of his apartment house. While officially judged to be a suicide, there is speculation about other causes.[17] His memoirs were never completed.

New information about Chernobyl started to emerge in 1992 that exposed the misrepresentation of events at the August 1986 IAEA conference. The second IAEA Chernobyl conference report[18] asserted that the USSR lacked a culture of safety.

After the disaster, the three other reactors at that location were closed down, but it took a while to do that. It wasn't until 1991, 1996, and 2000 that the other three reactors were dismantled.

The unique RBMK design was also implemented in Soviet Union satellite countries and elsewhere in the Soviet Union. The Soviets built two Chernobyl type reactors in Lithuania with the result that Lithuania was not allowed to

16 IAEA International Nuclear Safety Advisory Group (INSAG) - 1, 1986.

17 *The Legacy of Chernobyl*, 259.

18 IAEA International Nuclear Safety Advisory Group (INSAG) - 7, 1992.

have accession to the European Union unless they were closed. That was done with significant outside assistance in 2000 and 2009.

15. CONTINUED OPERATION OF CHERNOBYL-TYPE RBMK REACTORS

There are 11 RBMK Chernobyl-type reactors that are operating today in the Russian Federation. Russia says that these have been modified and enhanced[19] and that they are safer than they were, but observations by experienced nuclear engineers makes it clear that this type of reactor would not be allowed today in Western Europe or in the United States. Closing them would be economically difficult for the Russian Federation because they provide one-third of all their current nuclear electric power. Although the IAEA should ask for visits and analysis of the safety of these 11 nuclear reactors today, there is little likelihood of that happening.

NOTE REGARDING REFERENCES

The references noted for this analysis rely heavily on "The Legacy of Chernobyl" by Zhores Medvedev (W. W. Norton and Company, 1990). While there are a large number of published accounts regarding the origins and consequences of the Chernobyl disaster, it is the opinion of the author of this essay that the observations of Zhores Medvedev provide the most reliable account. Because there was both secrecy and cover-up regarding the origins and events leading up to and following the explosions on April 26, 1986, construction of an accurate narrative is challenging. This author's opinion about Zhores Medvedev is based largely upon a review of his impeccable credentials. Dr. Medvedev is an accomplished biologist who had the rank of Senior Research Scientist and was head of a prominent molecular radiobiology laboratory in the Soviet Union. In 1962, he wrote an expose of the fallacies of Soviet Genetics, "The Rise and Fall of T.D. Lysenko," which was published in the United States in 1969 by Columbia University Press. Publication of this book in the United States resulted in his being dismissed from his academic positions. In 1970, Soviet authorities began an attempt to have Dr. Medvedev isolated in an asylum for the insane. With the help of his brother, also a distinguished scientist, and support from human rights advocates inside the Soviet Union as well as from the international community, the effort to have him committed failed. He and his brother then wrote an expose of that effort entitled "A Question of Madness," which was published in the United States in 1971, by Alfred A. Knopf. In 1972, during a stay at as a visiting scholar in England, he was stripped of his Soviet citizenship. Dr. Medvedev continued to speak out for truth in science by publishing the first analysis of the 1957 Kyshtym explosion, in his book, "Nuclear Disaster in the Urals," published in the United States in 1979. His Soviet citizenship was restored in 1990 by Mikhail Gorbachev. It is noteworthy that in 2007 he published a series of articles linking the Polonium-210 poisoning of Alexander Litvinenko in London to leadership in Russia. It is surprising that some scholars of the history of Chernobyl overlook the writings of Zhores Medvedev.

19 *The Bulletin of Atomic Scientists*, 1993 (September) p.40.

A Graphical View of Heavy-Element Weaponizability Factors

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The accompanying articles in this edition of the *PIR* serve as excellent reminders of the complexity of the nuclear policy landscape. For scholars and policymakers in the national security arena, nuclear issues involve weapons and their deployments, modernization programs, international arms control and mutual-security treaties, and the political influence of government bureaucracies, national laboratories, and contractors that employ large numbers of constituents. In the civilian world, the issues include reactor safety, waste disposal, and ensuring that dual-use technologies are utilized in beneficial commercial applications while minimizing proliferation risks. Students of both nuclear engineering and policy have a lot to keep in mind.

For several years now, I have taught a general education course at Alma College on the Manhattan Project and its legacies.[1] Many students who take this class are history, political science, or pre-law majors who not only need to acquire a physical science credit as part of their graduation requirements, but also aspire to enter governmental or nongovernmental policy-development service. My goal is to cover not only the Manhattan Project *per se*, but also how present nuclear issues came to be.

As might be imagined, the challenge in teaching such a course is to find a comfortable balance between quantitative and qualitative content; most of the students are not science majors. In particular, I want to give them a sufficiently strong understanding of the technical background that they would be able to accurately brief a listener on an issue such as why possession of tons of uranium-238 would not be of particular concern in nonproliferation negotiations, but that possession of only tens of kilograms of U-235 would be a matter of grave concern. They are often very surprised to learn that, of some three thousand known isotopes of all of the elements, only uranium-235 (U-235) and plutonium-239 (Pu-239) are practicable for powering fission weapons. Effective policies hinge on understanding the backgrounds of these details.

This issue of why some isotopes are of more concern than others is always the technically trickiest unit of the class. Without becoming submerged in the nuances of nuclear physics, I have to find a way to describe how fundamental physics restricts the number of possible candidate "weaponizability" isotopes to just a handful, and then explore how a complementing set of issues regarding real-world materials acquisition and engineering practicalities reduces the list of possibilities to just two or three, none of which are easy to obtain. Over the years, I have converged on a system of summarizing this information in graphical form; this is useful in today's classrooms in which many students are primarily visual learners. This article, which is based on a more technical paper which appeared in *American Journal of Physics*,[2] describes and presents these graphs; my hope is that they will be of use to students of both science and policy. Specifically, I have in mind the issue of what isotopes would be of interest to a state or group aspiring to build a "simple" World War II-era Hiroshima- or Nagasaki-type "first generation" fission bomb.

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1 Reed, B. C. "Reflections on Teaching the Manhattan Project." Federation of American Scientists, *Public Interest Report* 64(3), 45-48 (Fall 2011).

2 Reed, B. C. "An examination of the potential fission-bomb weaponizability of nuclides other than 235U and 239Pu." *American Journal of Physics* 85(1) 38-44 (2017).

FACTORS AFFECTING WEAPONIZABILITY

The weaponizability of any given isotope is dictated by a number of factors. While these factors interact to some extent, for presentation to my students I find it convenient to introduce them as four essentially independent issues which can ultimately be summarized in two graphs (Figures 1 and 2 in the Appendix). These factors are:

1. The fission barrier,
2. The effective number of neutrons emitted per fission,
3. Risk of weapon pre-detonation caused by natural decay mechanisms (specifically alpha-decay and spontaneous fission), and
4. Critical mass.

These issues are discussed in the following paragraphs. Some of the technical background is summarized in the Appendix.

THE FISSION BARRIER

When a nuclide (synonymous with nucleus or isotope) captures a neutron, it becomes a heavier isotope of itself, a so-called "compound" nucleus. If the nuclide so created has a mass which is less than the sum of the masses of the neutron and the original nucleus — which is the case for all instances considered here — the "lost mass" appears as energy thanks to Einstein's famous equation $E = mc^2$. This "neutron-binding energy" appears in the form of agitation of the compound nucleus. In the physics community, the preferred unit for binding energy is the MeV, an abbreviation for "millions of electron-volts." Binding energies are typically of the order of 4-6 MeV. These energies are not to be confused with the even more remarkable ≈200 MeV liberated when a compound nucleus subsequently undergoes fission. In contrast, chemical reactions typically liberate only a few electron-volts per reaction. It is the immense energy release inherent in nuclear reactions that makes nuclear weapons so compelling.

Every isotope possesses a so-called "fission barrier energy," which is the amount of energy that must be put into nuclei of the isotope concerned in order to induce them to fission. In neutron-mediated nuclear reactions — like those that happen in a nuclear reactor or explosion — this energy can be supplied in either or both of two ways: (i) The binding energy liberated upon neutron capture, and/or (ii) kinetic energy carried in by the bombarding neutron. If the binding energy liberated exceeds the barrier energy, then the nuclide is said to be "fissile," which means that capture of a neutron of any kinetic energy will induce fission. A nuclide for which the binding energy is less than the barrier energy is said to be "fissionable," meaning that it can be fissioned only if the neutron brings in enough kinetic energy to supply the shortfall between the binding and barrier energies. In such cases, the shortfall is known as the "threshold" energy.

For the vast majority of elements, fission barriers are very great, peaking at about 55 MeV for nuclei of elements in the middle part of the periodic table. Barrier values decline from this maximum as one moves to heavier elements, but even for bismuth (atomic number 83) still amount to ≈20 MeV. Because the two or three neutrons that are released in fissions that are necessary to keep a chain reaction going are emitted with kinetic energies that average ≈2 MeV, it is clearly impossible to achieve a self-sustaining chain reaction with any element lighter than bismuth. Between bismuth and radium (atomic number 88), there are no isotopes of any elements with decay half-lives long enough to warrant consideration for use in nuclear weapons (see below). Thus, as a "first cut" for considering weaponizability, we can restrict attention to radium and heavier elements.

EFFECTIVE NUMBER OF NEUTRONS PER FISSION

Even if a nuclide is not fissile, it can still be potentially weaponizable. This is because the neutrons emitted in fissions emerge with a spectrum of kinetic energies. As cited above, the average energy is about 2 MeV, but many are emitted with higher energies. If enough of these neutrons are more energetic that the gap between the binding and barrier energies, they might be numerous enough by themselves to keep a chain reaction going.

This possibility — or lack thereof — is well-illustrated by the case of uranium-238, for which the binding energy liberated falls about 1.6 MeV short of the barrier energy. (In contrast, for U-235 the binding energy exceeds the barrier energy by nearly 1 MeV; U-235 is inherently fissile.) About half of fission-emitted neutrons have kinetic energies greater than ≈1.6 MeV. Because 2-3 neutrons are emitted per fission, it thus looks as if U-238 could serve as a bomb fuel. The catch, however, is that when such neutrons strike U-238 nuclei, they are about eight times as likely to suffer an energy-robbing inelastic collision than they are to induce a fission. In an inelastic collision, a bombarding neutron effectively bounces off the nucleus that it strikes, but loses speed in the process. The result is that the vast majority of fast neutrons that strike U-238 nuclei are promptly slowed to kinetic energies less than the critical 1.6 MeV threshold. U-238 is rendered useless as a fission-bomb fuel because of this combination of its binding/barrier energetics and scattering properties.

To formulate a measure of the effective number of neutrons liberated per fission, I follow the recipe used by Robert Serber in his historic *Los Alamos Primer*:[3]

$$\begin{pmatrix}\textit{effective neutrons}\\ \textit{per fission}\end{pmatrix}=\begin{pmatrix}\textit{fraction of neutrons}\\ \textit{above threshold energy}\end{pmatrix}\begin{pmatrix}\textit{probability of}\\ \textit{causing fisison}\end{pmatrix}\begin{pmatrix}\textit{number of neutrons}\\ \textit{liberated per fission}\end{pmatrix}.$$

If the nuclide is fissile, the probability of causing a fission is taken to be unity. Otherwise, this probability is taken to be the fission cross-section divided by the sum of the cross-sections for fission and inelastic scattering. The computation of the fraction of neutrons above the threshold energy is described in the Appendix. Overall, the effective number of neutrons per fission must be greater than one to keep a chain reaction propagating.

DECAY MECHANISMS

All isotopes of all elements heavier than bismuth are radioactive; they decay to isotopes of other elements by various mechanisms, though some do possess very great half-lives. Beyond the dangers inherent in processing highly-radioactive materials, it is obviously not feasible to fuel a nuclear weapon with short-lived material if the weapon is to be kept in a stockpile for years or perhaps decades.

For the purposes of this article, the decay mechanisms of interest are alpha decay and spontaneous fission. For reasons described below, I adopt, with one exception, 1,000 years as an acceptable lower limit of practicable half-life for considering weaponizability. The exception is americium-241 (Am-241), an alpha-emitter of half-life 433 years. This isotope is included here as it has an everyday use as an ionization source in household smoke detectors. A 1,000-year half-life cutoff may seem restrictive, but is in fact quite generous in view of an effect known as the "alpha-*n*" problem, which involves alpha decay and how a fission bomb is triggered.

For heavy elements like uranium or plutonium, a 1,000-year half-life corresponds to emission of some 5 x 10^{14} alpha particles per second for a bomb core of mass 10 kg. Now, in a Hiroshima-type uranium "gun bomb," two subcritical pieces of fissile material are combined to make a supercritical mass by firing a "projectile" piece initially located in the tail of the bomb toward a mating "target" piece located in the nose, usually by setting off a conventional chemical charge to propel the projectile piece. For pieces on the order of 10 cm in size and the maximum propulsion speed that could be achieved by a World War II-era cannon, about 1,000 meters per second, approximately 100 microseconds, will be required for the pieces to fully seat together after the leading edge of the projectile piece encounters the target piece. This is a brief interval, but for the decay rate cited above corresponds to emission of some 5 x 10^{10} alpha particles.

If the nuclear chain reaction should begin before the target and projectile pieces are fully seated, the result will be an explosion of less efficiency than what the bomb was designed to achieve. This is because the chain reaction,

3 R. Serber, *The Los Alamos Primer: The First Lectures on How To Build An Atomic Bomb*, University of California Press (1992).

once initiated, requires only about a single microsecond to cause the bomb core to heat up and expand to a density low enough that a chain reaction can no longer be sustained. This is much less than the seating time. The 10^{10} alpha-particles are not by themselves the problem here; they are not energetic enough to closely approach the nuclei of the fissile material against the repulsive force that the dozens of protons contained within the latter will exert on them. Rather, the issue is that if the fissile material contains any light-element impurities, the chain reaction could be initiated prematurely; this is because nuclei of light elements such as aluminum emit neutrons when struck by alpha-particles. Some impurities will inevitably be present due to chemical processing of the fissile material; if the level of impurities is too great, a "pre-detonation" during the seating time would be virtually guaranteed due to alphas emitted by the fissile material interacting with impurity nuclei. Since a single stray neutron will have some probability of initiating the chain reaction, keeping the alpha-emission background as low as possible is a serious consideration for bomb designers. The terminology "alpha-*n* problem" is entirely apt.

Fortunately for bomb engineers, the alpha-*n* danger is mitigated by two factors. First, atoms are largely empty space; most of the alphas will not strike the nucleus of a contaminant element. Second, good chemical processing techniques should be able to reduce the level of impurities to on the order of parts per tens of thousands. As explained in reference 2, these factors conspire to result in a rate of neutron emission about one billionth that of the alpha emission. But even with this, our $\approx 5 \times 10^{10}$ alpha particles emitted during the seating time could be expected to yield perhaps ≈50 neutrons, far too many for comfort. Setting a lower-limit half-life cutoff of 1,000 years will by no means exclude any alpha-emitter from practical consideration; indeed, one could argue that 1,000 years is not great enough.

During the Manhattan Project the alpha-*n* issue was not an overwhelming problem. The Hiroshima bomb used about 60 kg of U-235, but the half-life for this isotope is about 700 million years, so alpha-*n* pre-detonation was not at all a serious concern for this weapon. In the case of the Nagasaki bomb, Pu-239 has a half-life of only 24,100 years, so the purity of the fissile material was a much greater concern for that device, although not impossible to achieve. But as described in the following paragraphs, plutonium suffered from a much more serious complication.

In addition to alpha decay, many heavy isotopes suffer spontaneous fission (SF), a process that has its own characteristic half-life for each isotope. Secondary neutrons are emitted in SFs, so this presents a pre-detonation hazard like the alpha-*n* problem. For most heavy-element isotopes, SF half-lives are very great. Because the rate of neutron emission is inversely proportional to the half-life, neutron emission will be correspondingly low. However, here there are no factors which help suppress the resulting pre-detonation probability: SF neutrons are emitted directly by the fissile material, quite independently of the presence of any impurities. Given the arguments above, this means that an isotope whose SF half-life is one billion years will be as effective at generating background neutrons as one whose alpha-decay half-life is but a single year. To avoid getting into the details of particular impurities while having a way to compare alpha and SF half-lives in an equivalent way, I reduce SF half-lives by a factor of one billion to effect a fair comparison between the two and adopt the shorter one as an "effective" half-life for deciding which process presents the greater danger of pre-detonation.

Plutonium-239 has a SF half-life of 8×10^{15} years, or, on accounting for the factor of one billion argued above, an effective half-life of eight million years — far greater than its alpha half-life. Pure Pu-239 is thus fairly immune to pre-detonation. However, when Pu-239 is created in a reactor, it is inevitable that a small amount of Pu-240 is also created by neutron capture by already-formed Pu-239 nuclei. The problem with this is that the SF half-life of Pu-240 is only 10^{11} years, or effectively about 100 years. It can be calculated that if a 10-kg Pu-239 core is contaminated with only 1% Pu-240, one can expect on average about 5 SFs over 100 microseconds, which would again practically guarantee a pre-detonation. During the

Manhattan Project, it was (and probably still is) essentially impossible to remove the Pu-240, so engineers were forced to develop the high-speed implosion technique for crushing a plutonium core to critical density over a timescale on the order of a microsecond when triggering the bomb in order to beat the Pu-240 contamination problem. Pu-239 is an example of an isotope that by itself looks very promising as a nuclear explosive but can be compromised by production factors largely beyond human control.

CRITICAL MASS

Even if an isotope looks weaponizable on the basis of its energetics, reactivity, and stability, it faces two daunting real-world practical constraints. First, it will have to be acquired by either some enrichment or synthesis technique. How difficult will it be for a state or group to master the necessary technology? Second, is its critical mass sufficiently small — say on the order of tens of kilograms — that enough material to make a bomb can be acquired in a reasonable amount of time? Small critical masses are preferable not only from the point of view of acquisition, but also because a weapon will have to be compact and light enough to mount on an aircraft, missile, or other delivery vehicle. Heavy elements typically have densities of 15-20 grams per cubic centimeter; a sphere of radius 10 cm (about that of a melon) at this density will have a mass of ≈60-85 kg. But an element whose critical radius is 50 cm would have a mass of thousands of kilograms, which is utterly impractical.

As described in the Appendix, a simple formula is available for estimating the critical radius for a non-imploded (i.e., Hiroshima-type) bomb core of a given isotope. The numbers predicted by this formula are approximate but are accurate to within a factor of two or so, which will suffice for the purposes of this article.

POTENTIALLY WEAPONIZABLE ISOTOPES

A survey of the Chart of the Nuclides published by the Knolls Atomic Power Laboratory reveals two dozen isotopes of nine elements from radium through berkelium with decay half-lives > 1,000 years; this tally includes Am-241.[4] No isotopes of any heavier elements have half-lives for any decay process in excess of this length of time. From this list of two dozen I deleted four: radium-226 (critical radius > 20 meters), and curium-246, -248, and -250, all of which have SF half-lives which correspond to much less than a year upon normalization by the factor of one billion described above. In addition, I deleted Pu-244 from further consideration as I could locate no cross-section data for it; the effective half-life for this isotope is < 100 years.

Figures 1 and 2 summarize the weaponizability factors discussed above for the 19 remaining isotopes. For readers viewing this article online, isotopes of a given element appear in the same color. Sources of data are described in the Appendix; please refer to a spreadsheet with all input and computed data.[5] Not all isotopes appear on both plots as some lack corresponding published data. Bear in mind that what these graphs do not convey is the possible issue of "mixed" isotopes such as Pu-239/Pu-240.

Figure 1 plots the effective number of neutrons per fission (vertical axis) versus the binding energy release in excess of the fission barrier (horizontal axis). Figure 2 plots the effective half-life as defined above versus the approximate critical radius in centimeters, irrespective of the data of Figure 1. Th-232 is not included in this plot as its critical radius is on the order of 80 centimeters. The vertical axis of this plot is logarithmic.

Figure 1 shows that the list of practicable weaponization candidates reduces at once

4 Baum, E. M., Ernesti, M. C., Knox, H. D., Miller, T. R., Watson, A. M., and Travis, S. D., "Chart of the Nuclides," 17th ed. (Schenectady, NY: Knolls Atomic Power Laboratory, 2010), http://www.knollslab.com/nuclides.html.

5 https://almacollege-my.sharepoint.com/personal/reed_alma_edu/_layouts/15/guestaccess.aspx?docid=03cc7959696174ab2ba2b5f0741a7058b&authkey=AWh1SJmzsXeEgVF9_80BvXQ. The spreadsheet is large; be sure to scroll down and pan across.

to seven: Am-241, U-233, U-235, Np-236, Pu-239, Cm-245, and Cm-247. However, Figure 2 shows that Am-241 and Cm-245 are likely too short-lived to be practical. Cm-247 can also be eliminated: curium is quite scarce, with perhaps only a few grams being produced each year. This brings us down to four possibilities, including U-235 and Pu-239.

U-233 is an example of an isotope with excellent energetics and stability, but which proves not readily weaponizable for reasons akin to the Pu-239/Pu-240 situation. U-233 is bred in reactors by neutron capture by thorium-232 and two subsequent beta-decays:

$$n + {}^{232}_{90}Th \rightarrow {}^{233}_{90}Th \xrightarrow[22\,\text{min}]{\beta^-} {}^{233}_{91}Pa \xrightarrow[27\,\text{days}]{\beta^-} {}^{233}_{92}U \;.$$

The difficulty here is that this process inevitably creates some U-232 by neutron capture and subsequent emission of two neutrons by the U-233 so created. However, U-232 is a copious alpha-emitter (70-year half-life), and is also a gamma-ray emitter. Even a small contamination of U-232 will render a U-233 core susceptible to severe alpha-n pre-detonation, be dangerous to work with, and would be easily detectable.

Neptunium-236 is an interesting case. Like Pu-239, its situation is confounded by a non-fissile sister isotope, in this case Np-237. This comparison is not entirely fair, however, as Np-237 is much more stable than Pu-240 while having an effective number of neutrons per fission close to unity. Np-237 is formed in reactors by infrequent successive neutron captures by U-235 and then U-236 when fission does not occur; the U-237 so created decays to Np-237 after a half-life of 6.7 days. Np-236 is fissile, but is even rarer than Np-237 as it is formed by an already-formed Np-237 nucleus itself capturing a neutron and then emitting two neutrons. As with Pu-239 and 240, Np-236 and 237 are virtually impossible to separate from each other. A 2004 Los Alamos National Laboratory report described how researchers there achieved a critical assembly comprising a 6-kg sphere of Np-237 surrounded by an assembly of nested shells of enriched uranium of mass approximately 60 kg.[6] Thus, while perhaps not readily weaponizable, neptunium production needs to be carefully monitored.

In summary, the only viable weaponizable isotopes appear to be U-235, Pu-239, and perhaps U-233 and Np-236, but with the latter two suffering serious disadvantages. All other possibilities are either insufficiently fissile, short-lived, or scarce. In the end, any group aspiring to acquire nuclear weapons will for practical purposes be restricted to using U-235 or Pu-239.

CLOSING THOUGHTS

For all of their cost, complexity, and military, political, and social impacts, the production, testing, and deployment systems of the world's nuclear powers depend on a combination of physical and acquisition factors, which narrow the choices of nuclear explosives to a very few isotopes. A sense of the sheer improbability of this confluence of factors is elegantly captured in a quote from Nobel laureate Emilio Segrè: "In an enterprise such as the building of the atomic bomb the difference between ideas, hopes, suggestions and theoretical calculations, and solid numbers based on measurement, is paramount. All the committees, the politicking and the plans would have come to naught if a few unpredictable nuclear cross-sections had been different from what they are by a factor of two."[7] It seems that in some sense Nature is on our side: It is very difficult but not impossible to liberate nuclear energy on a large scale. What use is made of this apparently lucky break is a matter of human nature.

This article is dedicated to the memory of Stella and Cassie Reed.

APPENDIX

FIGURE 1

Binding energy releases were calculated from

6 http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-04-0216.

7 Rhodes, R.: The Making of the Atomic Bomb. Simon and Schuster, New York (1986).

nuclear mass excesses tabulated in the Nuclear Wallet Cards published by the National Nuclear Data Center.[8]

The calculation of the fraction of neutrons above a threshold energy E is predicated on modeling the spectrum of fission-neutron kinetic energies as a Maxwell-type distribution.[9] In this formulation, the fraction of fission-spectrum neutrons whose kinetic energies exceed E is given by

$$f = \frac{2}{\sqrt{\pi}} \int_{E/\alpha}^{\infty} \sqrt{x} e^{-x}\, dx ,$$

where α is an empirically-fitted constant, which for U-235 has the value ≈1.29 MeV. I assume that this value applies to all of the isotopes considered in Figures 1 and 2. This integral can be expressed in a form suited to spreadsheet computation by a transformation which renders it in terms of the "error function" *erf* of statistics:

$$f = 1 + \frac{2}{\sqrt{\pi}} z e^{-z^2} - erf(z) ,$$

where $z = \sqrt{E/\alpha}$.

Average numbers of neutrons per fission were adopted for U-233, U-235, U-238, Pu-239, Pu-240, Pu-242, Am-241, and Cm-245 from an International Atomic Energy Agency document;[10] for other isotopes the number of neutrons per fission was assumed to be 2.5. Fission and scattering cross-sections were adopted from the Table of Nuclides maintained by the Korea Atomic Energy Research Institute (KAERI).[11]

FIGURE 2

Alpha-decay half-lives were adopted from the Nuclear Wallet Cards cited for Figure 1. Spontaneous fission half-lives were adopted from N. E. Holden and D. C. Hoffman, "Spontaneous Fission Half-Lives for Ground-State Nuclides," Pure. Appl. Chem. 78(2) 1525-1562 (2000). Fission barriers were adopted from an International Atomic Energy Agency document.[12]

The approximate expression for critical radius is

$$R_{crit} = \pi \sqrt{\frac{\lambda_{fiss} \lambda_{trans}}{3(\nu - 1)}} .$$

In this expression, λ_{fiss} is the "fission mean free path," the average distance a neutron will travel before it causes a fission; for U-235 this is about 17 cm. λ_{trans} is the "transport mean free path," the average distance a neutron travels before it is scattered or causes a fission (≈3.5 cm), and ν is the number of neutrons liberated per fission. The mean free paths can be computed from the fission and scattering reaction cross-sections and density of the fissile material (see Chapter 2).[13] Strictly, this formula overestimates critical radii. In the case of U-235 the overestimate amounts to about 30%, but this will not drastically affect the distribution of points in Figure 2.

8 http://www.nndc.bnl.gov/wallet/wccurrent.html.

9 B. C. Reed, *The Physics of the Manhattan Project* (Berlin: Springer, 2015).

10 www-nds.iaea.org/sgnucdat/a6.htm#ref.

11 http://atom.kaeri.re.kr:8080/ton/index.html.

12 https://www-nds.iaea.org/RIPL-2/fission.html.

13 *The Physics of the Manhattan Project.*

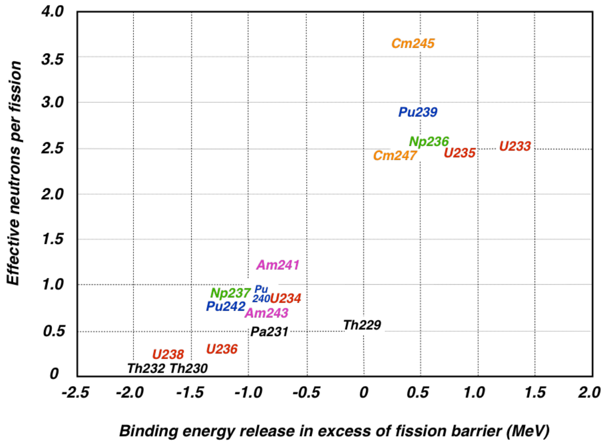

Figure 1: Effective number of neutrons per fission vs. binding energy release in excess of the fission barrier in millions of electron-volts for heavy-element isotopes of half-lives exceeding 1,000 years. This graph should not be used for technically-detailed analyses.

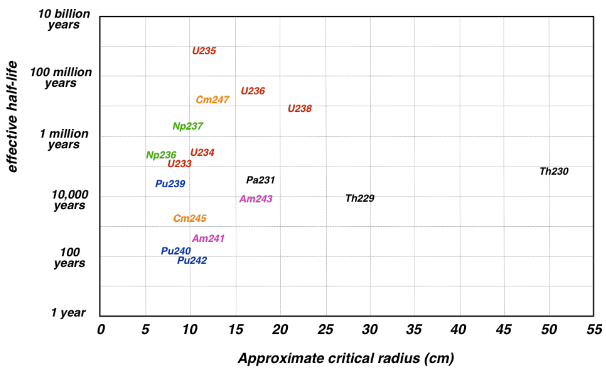

Figure 2: Effective half-life vs. approximate critical radius in centimeters for heavy-element isotopes of half-lives exceeding 1,000 years. This graph should not be used for technically-detailed analyses.

Considering an Actuarial Approach to Prioritizing Radiological Counterterrorism Expenditures

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ABSTRACT

State and non-state actors have demonstrated throughout history their intent to use weapons of mass destruction (WMD), but it is only recently that they have also attained the potential capability to develop and deploy these weapons. This type of terrorism will have huge implications on the United States' national security and its decision-makers; at the same time, resources are not infinite. Thus, it seems reasonable that nations and policymakers consider taking what may be referred to as an "actuarial" approach to prioritizing WMD counterterrorism efforts as described in this paper.

The decision-making process a nation must undergo in order to reasonably protect itself and its citizens from an attack by a state or non-state actor using a WMD is similar to the decision-making a homeowner must undergo in order to reasonably protect their home and their family from the impact of various incidents that harm their homes. Some of the factors that must be considered by policymakers when considering WMD preparations are the magnitude, likelihood, and economic costs of the attack, as well as the mass chaos and social disorder resulting from such attacks. The government must draw parallels when considering these factors between the decision-making at the individual level, with attaining insurance policies to insure their assets, and WMD counterterrorism efforts at the national or even international level, especially as it relates to radiological and nuclear counterterrorism expenditures.

INTRODUCTION

While counterterrorism is important, no nation has unlimited resources. No country can afford to cast so fine a net as to guarantee that no attack will take place, which forces governments at all levels to prioritize their spending in this area. In addition, some interdiction strategies, while likely to be successful, would require the abrogation of civil liberties to an extent that might be unacceptable to a nation's citizens. Such strategies might include intrusive searches of persons, vehicles, storage areas, and/or homes; requiring security and financial checks to accompany any purchase of radioactive materials; performing frequent site visits to verify radioactive materials inventory; reducing the threshold for which added security is required; and so forth.

It is recognized that many types of terrorist attacks — particularly those involving CBRNE agents — frighten both the public and policymakers more than others. For this reason, there is a tendency to spend inordinate amounts of money to guard against these, even if their effects are likely to be minor or their probability of occurrence very low. However, the fact that a particular type of weapon might be more frightening does not necessarily mean that it warrants extraordinary prevention efforts; one must balance the expenses (in terms of cost and social impact) of preventative measures against the expected impact (in terms of economic cost and impact on society) of a particular attack.

An analogous dilemma faces those who purchase insurance policies for their homes, vehicles, businesses, and so forth. A homeowner cannot afford to purchase insurance against every possible eventuality — some are so uncommon as to be virtually impossible, while others are so minor in nature, common, and difficult to prevent that prevention is simply not practical. In another paper,[1] this team has developed this concept in some detail, describing how this methodology might be implemented in the specific case of radiological

1 Almemar, ZF and Karam, PA. *Measure for Measure*, CBRNE World, June 2017 (pp 50-53). https://content.yudu.

counterterrorism.

FACTORS AFFECTING THE COST OF A RADIOLOGICAL ATTACK

A radiological dispersal device (RDD) is a device designed to disperse radioactive material in order to cause disruption, deny access to the area contaminated, and impose a cost on society. This cost can be economic (the cost of remediation, lost jobs, lost tax revenue, loss of tourism, etc.) as well as socioeconomic (societal disruption, loss of life, increased fear, loss of trust and confidence in government, etc.). Against the socioeconomic costs must be balanced the cost of preventative measures. In the case of radiological weapons, preventative costs include the cost of radiation detectors and the number of detectors needed to interdict a radioactive source of a given strength, as well as the cost of the personnel needed to operate and monitor the detectors (including the cost of training personnel).

Dispersing radioactivity will contaminate an area; regulations limit the amount of contamination that can be present in areas that are accessible to the public for unrestricted use. The amount of area that can be contaminated is proportional to the amount of radioactivity present in a radioactive source — sources with higher levels of radioactivity can contaminate a larger area. During the time that an area is contaminated, the public (including workers and residents) will not be permitted to access the contaminated area. The government, in turn, will be unable to collect tax revenues from the businesses that are not operating or from the people who are not working. In addition, the contamination must be removed before access can be restored; the cost of remediation is proportional to the area to be decontaminated and to the amount of contamination that must be removed. Not only that, but it is not always possible to fully decontaminate a particular radionuclide from a given surface; Cs-137, for example, clings tenaciously to bricks and concrete, and often cannot be removed without removing the surface to which it is adhering.

Surprisingly, the radioactivity from the explosion of an RDD is unlikely to cause widespread health effects in either the short or the long terms.[2,3] The primary health effects — and quite possibly the only fatalities — are likely to stem from the explosion itself. However, it is possible that the health effects can also include stress and anxiety among those living in the city that was attacked. In addition, in the aftermath of an attack, the city might order an evacuation, and citizens might choose to self-evacuate even if not ordered. Evacuations following the Fukushima reactor accident resulted in about 1,600 fatalities, even though the radiation itself almost certainly would have caused no health effects.[4]

The societal effects of a radiological attack are more difficult to determine and complex at best. For example (and almost trivially), traffic will be rerouted around contaminated areas, people living in those areas will have to find other places to live, workers at businesses in the affected area will either be temporarily unemployed or will have to travel to a different place to work, and so forth. More significantly, there will almost undoubtedly be social stigmatization of those living in the affected city; this was seen following the 1987 radiological accident in Goiania Brazil, following the 1986 reactor accident in Chernobyl Soviet Union, and most recently following the 2011 reactor accident in Fukushima, Japan. This social stigmatization imposed a financial cost (e.g., the loss of agricultural sales) as well as a social cost (depression, anxiety, substance abuse, etc.).[5] These costs are more difficult to quantify and quantification will not be attempted here; however, it is possible to

com/libraryHtml/A42y5m/CBRNeWorldJune2017/reader.html?page=52.

2 Nuclear Regulatory Commission. Fact Sheet: Dirty Bombs. Published online at https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/fs-dirty-bombs.html (last accessed 9/6/2017).

3 World Health Organization. *Health risk assessment from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami*. World Health Organization, 2013

4 Johnson, G. "When Radiation Isn't the Real Risk." *New York Times*, page D3. Sept 22, 2015.

5 World Health Organization Expert Group. *Health Effects of the Chernobyl Accident and Special Health Care Programmes: Report of the UN Chernobyl Forum Health Expert Group*, Editors Burton Bennett, Michael

analyze the cost of preventative measures as discussed below.

Radioactive materials can be interdicted using radiation detectors. The performance of these detectors is well understood, as is their cost; the cost of developing an interdiction network capable of averting a given amount of radioactivity and the concomitant cost can be calculated as discussed below. Detecting gamma radiation is both easier and less expensive compared to other forms of radiation (e.g., alpha, beta, or neutron radiation). These costs are described in the following section.

COST OF PREVENTATIVE OR MITIGATION EFFORTS

The most common radioactive sources are the ones with the least amount of radioactivity; these sources are the easiest to obtain but will cause the least damage and are the most difficult to detect and to interdict (hence, the most expensive). It is possible to calculate the cost of establishing an interdiction network for radioactive sources of various activity levels and to calculate the cost of a successful attack using one of these sources. Therefore, it makes no sense to spend far more on interdiction than it would cost for response and remediation.

Factors affecting the cost of implementing a protective action include the difficulty involved in taking the action, the equipment needed for implementation, and the extent of the "net" that must be cast. Consider an example in which it is decided to outfit every officer in a major police department (e.g., NYPD) with relatively inexpensive radiation detectors ($1,000 each). The overall cost to issue a radiation detector to every officer in New York City (about 35,000) would be $35 million, with additional annual recurring costs (for calibration, instrument replacement, and training) of about 10-20% of this total (depending on the average lifespan of the instruments used). Extending the network outside of New York City extends the cost substantially. The same concept applies to conducting background checks on every person buying any amount of any chemical that could be used as an explosive precursor, given that many of these chemicals are used routinely in high school and college chemistry laboratories, and a large variety of industries. Exercising this level of control would require a substantial infrastructure and a large number of personnel, increasing the impact on business, teaching, farming, research, and so forth.

As a rule of thumb, actions that have little cost, are limited in scope, and/or easy to implement should obviously be taken. Actions that have a high probability of averting a high-cost attack are also likely worth taking, providing the attack has a reasonable probability of occurring. On the other hand, it might not make sense to take expensive actions that have a low probability of averting improbable events, and it might not make sense to attempt to protect at all against difficult-to-detect events that will have only a limited economic impact. The difficulty lies in trying to determine whether or not to take actions that lie between these endpoints. The following section attempts to address this decision-making process in a semi-quantitative fashion using the example of radiological terrorism.

QUANTIFYING THE COST OF PREVENTION

The most probable attacks are those that will pose the least risk, will have the lowest impact, and will require the greatest number of detectors (and expenses) to interdict. This is because the most common radioactive sources (and those that are easiest to acquire) are relatively low activity and their malicious use would have relatively low consequences. It should also be noted that there are recurring costs associated with any sensor network to calibrate instruments, replace broken or aging detectors, provide ongoing training, and so forth. For a variety of reasons, 100% of instruments should undergo annual calibration and experience shows that about 5-10% of detectors require replacement annually, so annual recurring costs of about 10-20% of the initial equipment cost should be planned to accommodate instrument maintenance, replacement, training, and the other factors noted.

Zimmerman and Loeb (2004) estimate that a ra-

Repacholi and Zhanat Carr, World Health Organization, Geneva, 2006.

diological attack in a major city can result in direct and indirect costs on the order of tens of billions of dollars for sources containing hundreds of curies of activity (sources with this level of radioactivity are less common than lower-activity sources). This is used as a baseline for comparison in the analysis below. In addition, the number of Personal Radiation Detector (PRD)-style instruments has been calculated (costing about $1,000 each) that are needed to have a high probability of interdicting various activity levels of a number of potential threat radionuclides (Cs-137, Co-60, Ir-192, and Am-241). The assumptions and findings are summarized below:

- Assumption: An attack using a 1 Ci radioactive source is about 10 times as likely to occur as an attack using a 10 Ci radioactive source.

- Assumption: An attack using a 1 Ci radioactive source will incur about 10% the economic and societal cost as an attack using a 10 Ci radioactive source.

- Thus, an attack using a:
    - 100 Ci radioactive source will inflict approximately $10 billion in damages,
    - the cost of an attack using a 10 Ci source will inflict about $1 billion in damages, and
    - an attack using a 1 Ci source will inflict a cost of about $100 million.

Using detector performance characteristics provided by instrument manufacturers and the personal experience of one author (Karam) in performing radiation detection, it is possible to calculate the number of instruments required to detect a given source of radiation:

- Establishing a network of PRD-style instruments to cover an area of 10-kilometers-by-10-kilometers (about 6 miles on a side) that will detect the gamma emissions from a 1 Ci source of Am-241 (used in smoke detectors and some types of instruments used for well logging, and the most difficult of these nuclides to detect) will require approximately:
    - 6,000 detectors (at a cost of about $6 million) to detect an Am-241 source with an apparent activity[6] of 1 Ci, or
    - 600 detectors (at a cost of about $600,000) to detect an Am-241 source with an apparent activity of 10 Ci, or
    - 60 detectors (at a cost of about $60,000) to detect an Am-241 source with an apparent activity of 100 Ci.

- The surface area of the United States is about 10 million square km; the cost of instrumenting the entire nation will be about 100,000 times the cost of instrumenting 100 square km.

- Thus, establishing an effective network to interdict a 1 Ci radioactive source will cost approximately 100 times as much as a network to interdict a 100 Ci radioactive source, while an attack using a 1 Ci source will cost only 1% as much as an attack using the higher-activity source.

Using this information, for example, it can be estimated that instrumenting the entire United States sufficiently to interdict a 1 Ci source of Am-241 will cost over $500 billion with recurring annual costs of at least $50 billion and an extended (10-year) cost of over $1 trillion.

Given that an attack using a 1 Ci source might inflict a cost about $100 million, it does not make sense to spend $1 trillion per decade for interdiction efforts unless multiple attacks of this magnitude are expected to occur annually. Thus, it cannot be reasonably expected to instrument the entire United States sufficiently to prevent an attack using a 1 Ci radioactive source. In fact, it makes sense to instrument no more than about 0.1% of the United States (about 10,000 square km) sufficiently to stop an attack using a 1 Ci source; and no more than about 1% of the nation

6 The apparent activity refers to the radiation exposure at the surface of the package or shield containing the source. An unshielded 1 Ci source of Cs-137 produces a dose rate of about 0.3 R/hr at a distance of 1 meter. This same dose rate will be produced at the same distance by a 10 Ci source of Cs-137 encased within a 1"-thick lead shield. Thus, an unshielded 1 Ci source and a shielded 10 Ci source will have the same apparent activity.

(10,000 square km) sufficiently to interdict a 10 Ci source. This might involve, for example, installing instrumentation networks in the approaches to major cities, the approaches to likely targets (e.g., iconic locations, tourist attractions, high-value economic targets, etc.), and possibly city centers — as well as major transportation corridors, and even marinas and portions of the coastline where radioactive contraband might be landed and off-loaded. Similar analyses can be performed for other radionuclides or combinations of radionuclides.

CONCLUSIONS AND RECOMMENDATIONS

The discussion in this paper was intended to analyze the cost of interdiction compared to the economic impact and likelihood of a WMD attack launched by a terrorist organization, which was done by analyzing the "costs" associated with a radiological incident. An estimated relationship between the probability of an attack and its severity can be developed, for which an attack of various magnitudes could be prevented. The problem of course goes beyond the property damage, and other factors, such as long-term impact, societal disruption, and possible panic and unreasoned response, which could extend into other states, are not factored into the cost estimates. Providing such assessments and cost estimates could provide the U.S. government with consistent and fact-based information upon which decision-makers and policymakers can base their expenditures.

In a sense, WMD interdiction efforts are analogous to a societal insurance policy in that they are aimed at helping to protect society from the socioeconomic costs of suffering through an attack with one of these agents. Thus, the policy recommendations made here focus on evaluating the level of preparedness for a WMD attack by comparing it to an insurance policy. In a way, this comes down to a sort of Pascal's Wager argument: If the consequences of an attack are sufficiently dire, then it makes sense to accept almost any cost to try to avoid it. But if the consequences are more constrained, then so must be what is spent for prevention (or "insurance").

Analogous reasoning can be used to evaluate the utility of the expenses incurred by the government's biological counterterrorism measures. Estimates can be calculated for the cost of a biological attack with respect to property and infrastructure damage using an understanding of the weapons' effects and real estate costs.[7] The same concept applies to quantifying the cost of prevention of a chemical attack. A sarin attack on a critical infrastructure, such as on Washington, D.C.'s subway system, which hosts thousands of commuters a day, would probably halt government operations in the city for months — not to mention the costs for cleanup and continuing costs for long-term interdiction efforts, ongoing medical treatment for the injured, the cost in human lives, and so forth. This was illustrated by the brutal example of the cost in human lives when the Assad regime used sarin gas on the civilians in Syria, which resulted in over 100 Syrian citizens killed. While governments have accumulated a great deal of tacit knowledge regarding maximizing the efficacy of various WMD agents, this level of tacit knowledge is not required to carry out an attack similar to the 1995 Aum Shinrikyo chemical attack against the Tokyo subway system.

The bottom line is that, just as no insurance policy holder can pay an unlimited amount for insurance, no insurance company can accept unlimited potential liability. Both sides must accept limitations on their coverage based on their economic means. Thus, this same logic must apply to government efforts to avert a WMD attack.

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7 For example, Schmitt and Zacchia (2012) estimated that the 2001 American anthrax attacks cost over $300 million in cleanup costs alone.

Improvements in the Relationship between the FBI and Scientific Community

Federation of American Scientists

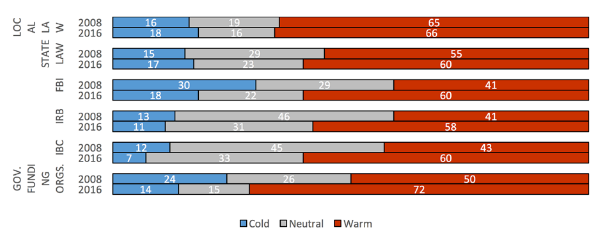
In 2008 a survey conducted by the Federation of American Scientists (FAS), in collaboration with the Federal Bureau of Investigation (FBI), the American Association for the Advancement of Science (AAAS), and Greenberg Quinlan Rosner Research (GQRR) found that a majority of the scientific community had notably unfavorable feelings and displayed a greater level of mistrust towards the FBI compared to regulatory agencies and other levels of law enforcement.

In an effort to bridge the gap between the scientific and law enforcement communities, and to encourage collaboration, the FBI Weapons of Mass Destruction Directorate (WMDD) launched a dynamic biosecurity outreach initiative. Results from a more recent survey in 2016 suggests that such efforts may be paying off. At a minimum the results clearly show substantial improvement in the relationship since 2008.

In order to reevaluate the relationship between the scientific and law enforcement communities, identify perceived or real challenges for establishing new partnerships, and determine areas to reinforce existing relationships, FAS again partnered with the FBI, AAAS, and GQRR. A modified version of the original survey, including a combination of multiple choice, open-ended, and rating scale questions, was sent to 48,342 AAAS members who had indicated their primary field of study as agriculture, biological science, medical science, chemistry, physics, astronomy, engineering, or earth science. A total of 1,352 AAAS members completed the survey via a secure link between May 5 and May 27, 2016, and data were statistically weighted to be representative of the selected AAAS scientific disciplines. Appendix A contains a complete version of the survey questions.

The responses revealed a noticeable shift among the scientific community in terms of overall favorability toward various people and organizations since 2008 (Figure 1). The biggest increase of scientists indicating warm, favorable feelings of at least 51 on a 100-point scale, was toward government funding organizations, which observed a 22-point increase, followed by the FBI with a significant 19-point increase. Feelings about state level law enforcement (+5 points) and local law enforcement (+1 point) remained relatively stable over the past eight years. Scientists still maintain more favorable feelings overall toward local law enforcement (66%) and equally favorable feelings toward state level as they do the FBI (both 60%), despite the FBI's drastic 19-point increase.

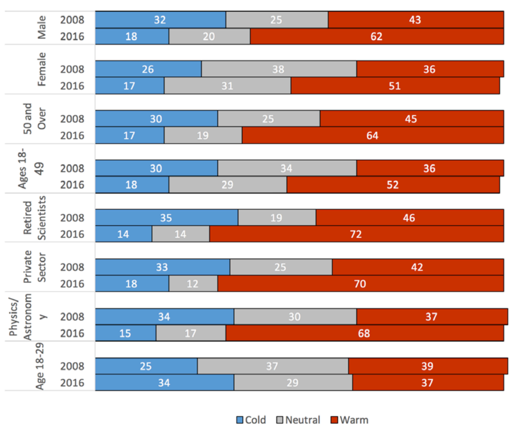
Figure 1. Percent of scientists indicating cold, unfavorable feelings (0-49), neutral feelings (50), and warm, favorable feelings (51-100) on a 100 point scale toward select organizations in 2008 and 2016.



Source: Greenberg Quinlan Rosner Research (June 2016).

As discovered in 2008, numerous factors may influence scientists' perception of law enforcement and the FBI, including demographic characteristics, scientific discipline, and work environment. Several trends still hold true including male scientists (62%) and those over 50 years of age (64%) expressing greater favorability toward the FBI than their counterparts (Figure 2). The highest levels of favorability were noted among retired scientists (72%) and those working in the private sector (70%), both of which experienced substantial improvement (+26 points and +28 points, respectively). Interestingly, while physicists and astronomers indicated the highest percentage of favorable feelings toward the FBI among the scientific disciplines (68%, +31 points), they also revealed the lowest favorability rates for state and local law enforcement (52% and 61%, respectively). Scientists aged 18-29 years were the only cohort that failed to show an improvement in their regard toward the FBI; feelings toward local law enforcement and state level law enforcement exposed a combination of positive and negative trends among the various cohorts.

Figure 2. Percent of scientists from select cohorts indicating cold, unfavorable feelings (0-49), neutral feelings (50), and warm, favorable feelings (51-100) on a 100 point scale toward the FBI in 2008 and 2016..

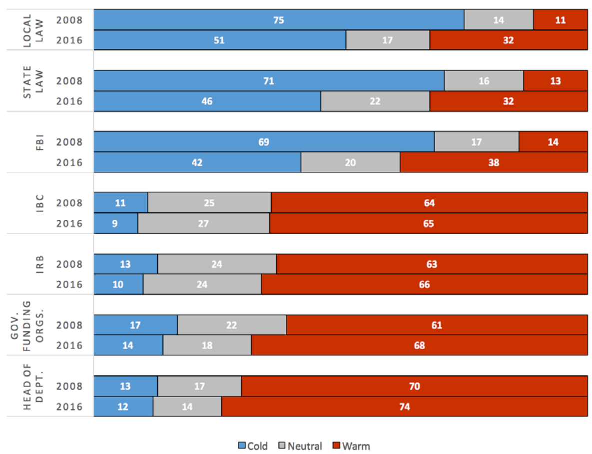


Source: Greenberg Quinlan Rosner Research (June 2016).

Scientists continue to indicate hesitancy when it comes to the relationship between their research and law enforcement. The percentage of scientists willing to share details of their research with academic and non-profit scientists (93%) and public sector scientists (90%) remains unchanged compared to 2008, while 3% less reported being as receptive to sharing with private citizens (84%). In comparison, only 52% of scientists are receptive to sharing details of their work with the FBI, ranking higher than both state (47%) and local level law enforcement (46%), both of which improved by 13 points.

It is not surprising that a smaller percentage of scientists are in favor of an individual or agency monitoring scientific research as opposed to simply sharing details, regardless of who is providing the oversight. Respondents were most receptive toward the head of the department (74%), government funding organizations (68%), IRB (66%), and IBC (65%) monitoring scientific research; however, the greatest improvements were seen among the FBI (+24 points), local law enforcement (+21 points) and state law enforcement (+19 points) (Figure 3). While still low, the FBI maintains higher favorability ratings (38%) for monitoring research than state and local level law enforcement (both 32%).

Figure 3. Percent of scientists indicating cold, unfavorable feelings (0-49), neutral feelings (50), and warm, favorable feelings (51-100) on a 100 point scale, toward select organizations playing a role in monitoring scientific research under certain cir



Source: Greenberg Quinlan Rosner Research (June 2016).

When asked whom they would feel comfortable reporting to in the event that they saw suspicious activity in the workplace that could pose a potential threat to public safety, scientists again favored the head of department (82%), followed by a public safety or security officer (69%) (Figure 4). These were distantly followed by local law enforcement (39%), the FBI (38%), and state level law enforcement (32%). However, when asked who had the ability to resolve potential safety issues that arise from research, scientists revealed they have more confidence in the FBI than in campus police or private security; 19% rated the FBI an 8 or higher on a scale of 1 to 10 (mean= 4.4) compared to only 11% for campus police or private security (mean=3.9).

Scientists were also given a number of scenarios and asked to evaluate whether it was appropriate for authorities to speak with them in their role as a scientist. An 82% majority said that it was an excellent or good reason for an Institutional Biosafety Committee (IBC) to

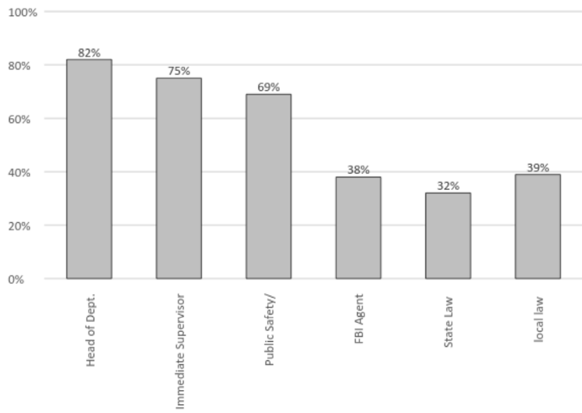


Figure 4. Percent of scientists who feel comfortable reporting a suspicious happening in their workplace that may pose a potential threat to public safety to select individuals.

Source: Greenberg Quinlan Rosner Research (June 2016).

evaluate research for public safety risks. Only 50%, however, believed it was an excellent or good reason for a law enforcement officer to do so. A slightly higher percentage (55%) were supportive of law enforcement involvement if the research was considered a potential target of foreign intelligence agencies, but the number remains significantly lower than the support shown for IBCs.

When assessing situations specific to an FBI agent, 90% agreed that approaching a scientist to aid in an ongoing criminal investigation was appropriate, while only 84% responded similarly for an ongoing terrorism investigation; a margin between the two that has lessened considerably since 2008 (then 80% and 65%, respectively). When respondents were asked directly about their willingness to aid in ongoing criminal investigations over terrorism investigations, 113 people provided answers; more than forty people stated that terrorism is a vague term, while 37 shared a lack of trust in terror investigations.

While scientists seem to be open to aiding the FBI in various situations, a majority hold several concerns that may arise from potential interactions with the FBI including interference with their ability to conduct research (52%) and an invasion of privacy by asking to read related correspondence (62%). Interestingly, a greater rate of scientists (65%) indicated concern for the FBI misinterpreting their peer's research as a potential public safety risk compared to their own (61%).

Despite these concerns, 77% of scientists believe the FBI is on their side and 71% believe that working closely with the FBI is good for the scientific community; however, only 59% admit to trusting the FBI and just 50% believe the FBI currently works well with the scientific community. The view that the FBI does not understand scientists' work remains one of the biggest beliefs among polled scientists (62%), second to the opinion that the FBI is more interested in restricting research for security purposes than they are in the scientific value of work (64%). Though it may appear the line between security and research is a leading point of contention, a 14-point increase in scientists' reporting that science needs to be kept under tight security and withheld from the public for safety or security reasons (59%) could suggest an evolving mindset.

Overall, this survey revealed that the relationship between the scientific and law enforcement communities has demonstrated notable progress since 2008. The data indicates improved favorability toward the FBI, confidence in the FBI over local and state level law enforcement, and the scientific community's recognition of the benefits of working together. The outreach is working, however, there is still work to be done to gain the full trust and respect of scientists, especially the younger generation. Efforts targeting accessibility may address the discrepancy among scientists who feel confident in the FBI's ability to resolve a situation, but lack the same level of comfort to report. As in 2008, scientists continue to suggest ensuring scientific literacy among agents as key to promoting more trusting and transparent collaborations.

Based on the responses from the current study, Greenberg Quinlan Rosner gleaned the following steps that the FBI can take to further their significant progress in establishing better relationships with the scientific community:

1. **Respect Protocols and Chains of Command:** Address a scientist's department head or superior first before contacting them directly. Following their institution's

protocol and conduct inquiries with respect to the rules of the workplace.

2. **Focus on a Conversational Versus Interrogation Style:** When FBI or law enforcement officials communicate with scientists requesting information try to be respectful tonally and do not, as one scientist said, behave "in an authoritarian manner."

3. **Demonstrate Scientific Literacy:** Though FBI and law enforcement officials are not all scientists, they must at least have a working knowledge of the topic they are inquiring about. If that is not possible, then FBI or law enforcement officials should be accompanied by an expert, or someone with better knowledge of the subject matter in question.

4. **Maintain Transparency in Communications:** To combat suspicion from scientists about the motives of FBI or law enforcement officials, strive to establish and maintain open communications about all possible details pertaining to any inquiry.

APPENDIX: A COMPLETE LIST OF SURVEY QUESTIONS

Question 1. Please indicate your feelings toward the following people and organizations with 100 meaning a VERY WARM, FAVORABLE feeling; 0 meaning a VERY COLD, UNFAVORABLE feeling; and 50 meaning not particularly warm or cold. You can use any number from 0 to 100, where the higher the number the more favorable your feelings are toward that person or organization.	
Local law enforcement organizations	Private funding
State level law enforcement funding organizations	Government
Federal Bureau of Investigation **(FBI)** regulatory authority	State
Institutional Biosafety Committee **(IBC)** regulatory agency(ies)	Federal
Immigration officials and technology policymakers	Federal science
Campus police Safety Officer	Biological
Institutional Review Board **(IRB)** Officer	Research Integrity
Head of your department Animal Care and Use Committee **(IACUC)**	Institution
Private security, such as those found at private research centers	
Question 2. The following people and organizations might have some role in monitoring scientific research under certain circumstances. Please indicate your feelings about each one having a role in monitoring scientific research, with 100 meaning a VERY WARM, FAVORABLE feeling; 0 meaning a VERY COLD, UNFAVORABLE feeling; and 50 meaning not particularly warm or cold. You can use any number from 0 to 100, where the higher the number the more favorable your feelings are toward that person or organization having a role in monitoring scientific research under certain circumstances.	
Local law enforcement organizations	Private funding
State level law enforcement funding organizations	Government
Federal Bureau of Investigation **(FBI)** regulatory authority	State
Institutional Biosafety Committee **(IBC)** regulatory agency(ies)	Federal
Private security, such as those found at private research centers	Biological Safety Officer
Institutional Review Board **(IRB)** Officer	Research Integrity
Institution Animal Care and Use Committee **(IACUC)** department	Head of your
Question 3. From time to time, individuals other than your immediate colleagues might be interested in the work you do. Please indicate how receptive you would be to sharing details of your work with each of the following: 1 = Very receptive, 2 = Somewhat receptive, 3 = Neither receptive nor unreceptive, 4 = Somewhat unreceptive, 5 = Very unreceptive	
A federal law enforcement officer scientist	A private sector
A state level law enforcement officer scientist	A public sector
A local law enforcement officer academic/non-profit scientist	An
An official from a regulatory agency	A journalist
An agent from an intelligence agency	An FBI agent
A corporate executive in a related industry committee	A legislative
A private citizen with an interest in science from another country	An academic
Question 4. There are many reasons that an outside authority might want to talk to you about your role as a scientist. For each of the following, please indicate whether you believe it is an excellent, good, fair, or poor reason for an outside authority to want to talk to you. 1 = Excellent, 2 = Good, 3 = Fair, 4 = Poor	
Intellectual curiosity about your area of research	
To evaluate a research grant you have applied for	
To assess issues surrounding an intellectual property case	
To be evaluated by an Institutional Review Board **(IRB)** for ethical concerns	
To be evaluated by an Institution Animal Care and Use Committee **(IACUC)** for humane use concerns	
To have law enforcement evaluate the research as a potential public safety risk	
To be evaluated by an Institutional Biosafety Committee **(IBC)** for potential public safety risks	
To have law enforcement evaluate if the research is a potential target of foreign intelligence agencies	
To be evaluated for dual-use potential regardless of whether select agent(s) is(are) used in research	
Question 5. Now you are going to see some pairs of statements about (SPLIT A - law enforcement officers, SPLIT B - FBI agents) who sometimes need to work with scientists in the course of their duties. After reading each pair of statements, please indicate whether the FIRST statement or the SECOND statement comes closer to your own view, even if neither is exactly right. 1 = FIRST statement STRONGLY, 2 = FIRST statement NOT SO STRONGLY, 3 = SECOND statement NOT SO STRONGLY, 4 = SECOND statement STRONGLY	
I trust them **OR** I am suspicious of them	
I believe that they are on my side **OR** I believe they are working against me	
They understand my work **OR** They don't understand my work	
They work well with the science community **OR** They do not work well with the science community	
They are primarily interested in the scientific value of my work **OR** They are primarily interested in restricting my work for security purposes	
Scientists working closely with (SPLIT A: law enforcement officers; SPLIT B: FBI agents) is good for the scientific community **OR** Scientists working closely with (SPLIT A: law enforcement officers; SPLIT B: FBI agents) is bad for the scientific community	
Some science needs to be kept under tight security and not released to the public for safety or security reasons **OR** All science should be made open to the public once it is ready for publication	
More security equals more censorship **OR** More security does not equal more censorship	
Question 6. There are many reasons that (SPLIT A - law enforcement officers, SPLIT B - FBI agents) might want to talk with a scientist. For each of the following, please indicate whether you believe it is an excellent, good, fair, or poor reason for (SPLIT A - a law enforcement officer, SPLIT B- an FBI agent) to approach a scientist. 1 = Excellent, 2 = Good, 3 = Fair, 4 = Poor	
To clarify the nature of the scientist's research	
For the evaluation of the scientist's research as a potential public safety risk	
To assess intellectual property rights issues related to the scientist's research	
To aid in an ongoing criminal investigation	
To aid in an ongoing terrorism investigation	
To request technical expertise in a particular area of science or technology	
To interview the scientist because they are listed as a reference for a foreign student or researcher	
To evaluate if a scientist's work has possible alternate applications that might constitute a security risk, sometimes called "dual-use" research (legitimate work being subverted for nefarious use)	
To help safeguard high-risk research from theft	
To inquire about the activities of one of the scientist's colleagues who is an American citizen	
To inquire about the activities of one of the scientist's colleagues who is not an American citizen	
For the evaluation of the scientist's research as a potential national security risk, including economic espionage potential	
To interview the scientist because they are listed as a reference for a student or researcher who is a US citizen	
To discuss faculty/staff/student who has been identified as a risk to themselves or to others	
Question 7. (For respondents indicating excellent/good for criminal investigation and fair/poor for terrorism investigation in Question 6) Why do you believe it would be appropriate for (SPLIT A - law enforcement officers, SPLIT B - FBI agents) to talk to scientists to aid in an ongoing criminal investigation, but not appropriate to talk to scientist to aid in an ongoing terrorism investigation?	
Question 8. If you saw something suspicious happening in your workplace that made you concerned about a potential threat to public safety, who would you feel comfortable reporting to?	
Your immediate supervisor Review Board **(IRB)**	An Institutional
Federal Bureau of Investigation **(FBI)** Agent department	Head of your
An Institutional Biosafety Committee **(IBC)** enforcement officer	A local law
Institution Animal Care and Use Committee **(IACUC)** law enforcement officer	A state level
A public safety/security officer associated with your institution	Other **(SPECIFY)**

Question 9. Assess the ability of the following organizations or individuals to resolve potential safety issues that arise from your research with 10 meaning it is very capable of resolving your safety issue(s); and zero meaning it is not able to help resolve your safety issue(s). You can use any whole number from 0 to 10, with the higher the number the more capable the organization or individuals are at resolving potential safety issues that arise as a result of your research.

Local law enforcement Institutional Review Board **(IRB)**

State level law enforcement Head of your department

Federal Bureau of Investigation **(FBI)** Federal regulatory agency(ies)

Institution Animal Care and Use Committee **(IACUC)** Biological Safety Officer

Threat Assessment/Management Team State regulatory authority

Federal science and technology policy makers Institutional Biosafety Committee **(IBC)**

Campus police/private security, such as those found at private research centers Funding organization

Question 10. Please assess the following potential national security threats as they relate to research on a scale of zero to ten with 10 would meaning it is a very serious threat; 0 meaning it is not a serious threat at all. You can use any whole number from zero to ten, where the higher the number the more serious the national security threat as it relates to research.

A terrorist group obtaining the knowledge to produce a chemical, nuclear or biological weapon.

A terrorist group obtaining the material to produce a chemical, nuclear or biological weapon.

Intellectual property/proprietary information theft

Exploitation of products/applications/technologies for criminal enterprise

Dual-Use Research of Concern **(DURC)**

Other **(SPECIFY)**

Question 11. In light of the recent dual-use research of concern/gain-of-function debates, use a scale from zero to ten to determine the following communities' ability to protect the safety and security of the public from intentional misuse. You can use any whole number with a 10 meaning the community is highly capable; and a zero meaning the community is not able to protect the safety and security of the public from intentional misuse. If not sure please type 11.

Your institution Local law enforcement

The research community, at large State level law enforcement

Policy makers Federal Bureau of Investigation **(FBI)**

Regulatory agency(ies)

Question 12. Have you or any of your colleagues ever been approached by (SPLIT A - a law enforcement officer, SPLIT B - an FBI agent) to discuss something related to your work as a scientist?

Question 13. What is the best method for (SPLIT A - law enforcement officers, SPLIT B - FBI agents) to initially contact a scientist?

Question 14. What could (SPLIT A - law enforcement officers, SPLIT B - FBI agents) do to improve relations with the scientific community?

Question 15. Suppose you received a message that (SPLIT A- a law enforcement officer, SPLIT B- an FBI agent) wanted to speak with you in your capacity as a scientist. Please indicate how concerned you would be that the (SPLIT A- law enforcement officer, SPLIT B- FBI agent) might... 1 = Very concerned, 2 = Somewhat concerned, 3 = Not too concerned, 4 = Not at all concerned

Ask permission to read your correspondence (e.g. mail, emails)

Ask you to assess the activities of one of your peers

Investigate immigration issues related to you or one of your peers

Interfere with you conducting your research

Misinterpret your research as a potential public safety risk

Misinterpret your international travel as a security problem or vulnerability

Stop you from publishing your research

Interfere with your research funding

Embarrass you in the eyes of your peers

Ask you to assess the activities of one of your students

Ask you to assess your peer's research

Misinterpret your peer's research as a potential public safety risk

Interfere with your peers conducting their research

Question 16. What is your sex?

Male Female

Question 17. In what year were you born?

Question 18. Which of the following best describes the current stage of your career?

Undergraduate Laboratory technician

Graduate student Academic staff scientist

Post doctorate Lab manager

Primary investigator Retired

Industry scientist Other **(SPECIFY)**

Question 19. Please indicate how often you work with foreign nationals in your capacity as a scientist.

Often (at least once a week) Never

Sometimes (at least once every 3 months) I am a foreign national.

Rarely

Question 20. Please indicate the highest biosafety level **(BSL)** work environment you have worked in.

BSL 1 BSL 4

BSL 2 I have never worked in a facility with biosafety levels.

BSL 3 I don't know what the biosafety level was in the facility.

Question 21. Please indicate which of the following you work with in your capacity as a scientist.

Animals Radioactive isotopes

Human subjects Select agents

Viruses Nuclear material

Bacteria Sensitive data (e.g. human subject data)

Fungi None of the above **(EXCLUSIVE RESPONSE)**

Explosive, corrosive, or otherwise toxic chemicals

Question 22. Please mark the category that best describes the sector you are employed in as a scientist.

Academic Private sector

Government, but not military Other **(SPECIFY)**

Military

Question 23. Please indicate the level of security in your current workplace.

High (Military level security)

Medium (Secure facility, picture ID required for access, armed guards)

Low (Restricted access to facility, some security personnel present)

Minimal (Basic locks on doors, no restricted access to facility)

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