Weapons of Mass Destruction-- 2018

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(Errors corrected on pages 10, 14, 15, and 19)

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Rather than providing an entirely new document, I use my 2016 lecture https://fas.org/rlg/wmd-2016.pdf, correcting errors as indicated on the title page of this document.

To update and expand the 2016 lecture, I incorporate by reference a lecture of May 1, 2017, "Strategic Security Challenges for 2017 and Beyond," to be found in the Garwin Archive at https://fas.org/rlg/nas-challenges.pdf.

Beyond that, I need to say a few words about the November 29, 2017 North Korean test of the Hwasong-15 missile, with range, as tested, that could reach any point in the continental United States, but with uncertain payload and thus-far untested reentry vehicle that would have to survive the "dynamic pressure" and heating of the atmosphere on reentry, https://allthingsnuclear.org/dwright/reentry-of-hwasong-15 . As indicated in my May 2017 lecture, "This threat is nothing new, in view of the long-standing vulnerability of U.S. coastal cities to attack by North Korean short-range missiles launched from ships near U.S. shores."

The 2018 lecture will proceed by my showing extracts of the text and illustrations, as appropriate, leaving time for 30 minutes of discussion.

Abstract:

Millions of deaths and the end of civilizations can be inflicted by knife, machete, or fire, or even by the pen or the spoken word, but a *weapon of mass destruction* – WMD-- implies such a result more centrally imposed. Specifically, I class nuclear, , biological, and cyber weapons as WMD, relegating chemical, high-explosive, and incendiary weapons to a lesser category. Along another dimension, there are near-universal bans on states' use of biological weapons--BW, chemical weapons--CW, antipersonnel land mines, exploding anti-personnel bullets, and even on possession of BW; not all these treaties or agreements are honored by all. This talk will focus on nuclear weapons, their effects, development, deployment, delivery, control, and on efforts to limit or eliminate them—e.g., the Nonproliferation Treaty—NPT, Limited Test Ban Treaty—LTBT, Comprehensive Test Ban Treaty—CTBT, ABM Treaty limiting systems for intercepting ballistic missiles carrying nuclear weapons, Strategic Arms Limitation or Reduction Treaties—SALT or START, etc. But mostly on the technical aspects of nuclear weapons. A key tool to learning is simple search of my web site:

site:fas.org/RLG/   biological weapons Nixon

that yields 18 results, including http://www.fas.org/rlg/020821-terrorism.htm

First, a brief overview of my personal involvement and views on WMD as a prelude to questions in the last half of the session.

I have worked since the 1950s on chemical and biological weapons, nuclear weapons, and to some extent on cyber weapons—CW, BW, NW, and CyW. Of course, millions or hundreds of millions of people can be killed and have been killed by relatively crude techniques such as knives, bullets, and fire, but a WMD implies a single agent that can kill a lot of people, variously and arbitrarily given as 50,000 or 0.5 million.

Chemical Weapons—CW.

Among CW, one can begin with industrial chemicals such as chlorine, used in warfare in WW I and up the line to more sophisticated nerve agents prepared for use in WW II and used since then, for instance, in the Iraq-Iran conflict. As military weapons, these are not very effective in killing troops prepared to fight, but even the threat of CW can reduce the effectiveness of a fighting force by a factor 10 or more, because of the protective garb and tactics. Much is known about the LD50 of various CW, but less about long-term debilitating effects of sub-lethal doses. In general, CW are an anti-population weapon. The United States and the UK had big CW programs, as did the Soviet Union and most other countries, with sophisticated means of delivering CW against areas and relatively small point targets. These ranged from ground-carried nebulizers or aerosol generators to cluster munitions that would strike the ground and explode, dispersing CW. I won't discuss CW any further and do not regard it as a WMD in the same class as BW or NW. Exposure levels for CW are typically expressed as mg-minutes of agent per cubic meter of air. A lethal dose of sarin corresponds to an hour exposure at about 2 mg/m^3 of air—about 100 $mg\text{-}min/m^3$.

Biological Weapons—BW.

BW has a long history going back to the siege tool of spreading infection by catapulting corpses into a fortified enclosure. In the early days of the colonies or the United States, blankets infected with smallpox were given to the Native Americans, and many died as a result.

Many pathogens (living agents capable of causing disease) were weaponized by the great powers and tested. For military use, the ideal BW is one that is nonlethal but debilitating. And many of these have been identified. At the beginning of the modern age of molecular biology, the President's Science Advisory Committee considered BW and a special panel of the Committee was convened in response to a request from President Nixon, conveyed through his National Security Advisor, Henry A.Kissinger, to study the pros and cons of BW. I was a member of that panel, which reported to Kissinger and Nixon the results of its analysis. Even less than CW, BW is not a military weapon, since it can readily be defended against. Unbroken skin is a pretty good barrier, so a reasonable defense against BW can be deployed with relatively simple masks to protect eyes, mouth, nose, and the respiratory system, combined with discipline in donning, removing, and disinfecting the protective gear. Laundry bleach diluted 100:1 is an excellent disinfectant.

But BW is a potent anti-population tool, as exemplified by the Black Death of the middle ages, the Spanish Flu of 1918-1919, and the potential impact of smallpox in a population with no immunity to smallpox since vaccination in the United States was terminated in 1972—a decision reviewed by the President's Science Advisory Committee (Nixon Administration) at that time, of which I was a member and from which I heartily dissented.

Diseases can be separated pretty well into those that are simply infectious from the pathogen initially distributed and those that have a high degree of contagion, spreading from one human host to another as in the case of influenza, smallpox, and, especially measles and the common cold. Some diseases are largely nonlethal, but even among influenzas, the mortality (deaths per person infected) can vary from well below one per cent to 50%.

Against both BW and CW, one can have personal protective measures (PPM) or collective protection—CP—in which a small overpressure is maintained in an enclosure by a blower bringing in air through a filter or of a device adequate to screen-out or destroy the poison or pathogen.

President Nixon astonished the world by issuing a statement 11/25/1969 banning U.S. use, possession, or research on offensive BW. Many were critical of this saying that Nixon had thereby abandoned any possibility of obtaining the agreement of the Soviet Union to a treaty to the same ends, but they were proved wrong when the Soviet Union promptly signed up. Unfortunately, the USSR apparently believed that the United States was not sincere in its actions, and although the U.S. promptly terminated all of its BW programs known to the government, the Soviet Union (and later Russia) did not, until much later. A major loose end was the lack of proscription of "toxins"—chemicals of biological origin, of which one example is botulinum toxin. On 02/14/1970, President Nixon renounced also toxins, bringing them under the same control as living BW agents[1].

That is the last I will say here about BW, although I have written about it.

Nuclear Weapons—NW.

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[1] http://ndupress.ndu.edu/Portals/68/Documents/casestudies/CSWMD_CaseStudy-1.pdf

There is an enormous history of technical aspects of nuclear weapons, including the basic phenomena involved in their operation, their effects, stockpiles, delivery systems, and means of commanding and controlling nuclear weaponry, including agreements and treaties. Many of these topics are treated in papers and speeches on my website, www.fas.org/RLG/, and especially in my books with Georges Charpak and Venance Journé, most recently in English Megawatts and Megatons, 2001/2002. In French there is an expanded version of Megawatts and Megatons[2], but untranslated into English.

Technical history of nuclear weapons. The scientific concept of nuclear weaponry really got its start with Leo Szilard who read an account of a speech by Lord Rutherford in September, 1933 that "anyone who looked for a source of power in the transformation of the atoms was talking moonshine." Szilard, living in London, was well aware of Chadwick's discovery of the neutron in 1932 and had carried out some experiments himself, with others, especially chemists. Goaded by Rutherford's dismissive comment[3], Szilard filed a patent application in London for a system that employed an element that gave more than one neutron out per neutron in, on average, so that there could be an exponentially growing "chain reaction" with a sufficiently

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[2] *De Tchernobyl en tchernobyls*, by G. Charpak, R.L. Garwin, and V. Journé, Odile Jacob, September 2005

[3] http://www.fas.org/rlg/04_07_2014LeoSzilardinPhysicsandInformation.pdf

large amount of this material to minimize neutron escape probability. Szilard's experiments began at the light end of the periodic table and ended without showing a hopeful candidate.

In the meantime, Enrico Fermi's group at Rome ran with the neutron activation of all of the elements of the periodic table, and in December 1938 Fermi received the Nobel Prize in Stockholm for his discovery of transuranic elements and for the efficacy of slow neutrons in causing nuclear reactions.

Artificial nuclear reactions were first observed by the use of alpha-particle bombardment of target nuclei, but Fermi's group showed that neutrons produced by alpha particles incident on beryllium could be much more widely effective, because a neutron is not repelled by the Coulomb barrier—that is by the positive charge on a nucleus, as are other elementary particles that can be accelerated in cyclotrons or electrostatic accelerators. The Fermi group early on made a crucial discovery that immersing the neutron source or the target in water, or surrounding them with paraffin wax or other material containing large amounts of hydrogen, increased the effectiveness of the neutron by as much as a factor 100, essentially because repeated "elastic" collisions of the neutron with the hydrogen (billiard-ball collisions) slowed the neutron from the initial energy of millions of electrons volts (MeV) to "thermal energies" of 1/40 eV, and the slow neutrons spent much more time in the vicinity of the nucleus than did the fast neutrons and thus were correspondingly more effective in causing transmutation.

In fact, although Fermi had produced transuranics, the radioactive evidence of their existence did not come from transuranics in large part, but from the breakup of the rare isotope of uranium (U-235, 0.7% of natural uranium) by "fission" into two nuclei of mass adding up almost to that of the U-235 atomic mass (250 amu). The fission products are normally intensely radioactive because they have far more neutrons per proton than is stable for a nucleus of intermediate mass. Zirconium (Zr) and barium (Ba) are representative of the light and heavy fission fragments.

The act of fission is accompanied by the emission of more than two neutrons on average (about 2.5 from thermal-neutron fission of U-235), which are typically boiled off the fission fragments during a fraction of a picosecond, although about 0.65% of the neutrons are emitted in the course of the radioactive decay of the fission fragments long after they have come to rest—over an interval of 1-100 s. "Delayed neutrons" essential to the design and control of nuclear reactors, and almost irrelevant in nuclear weapons.

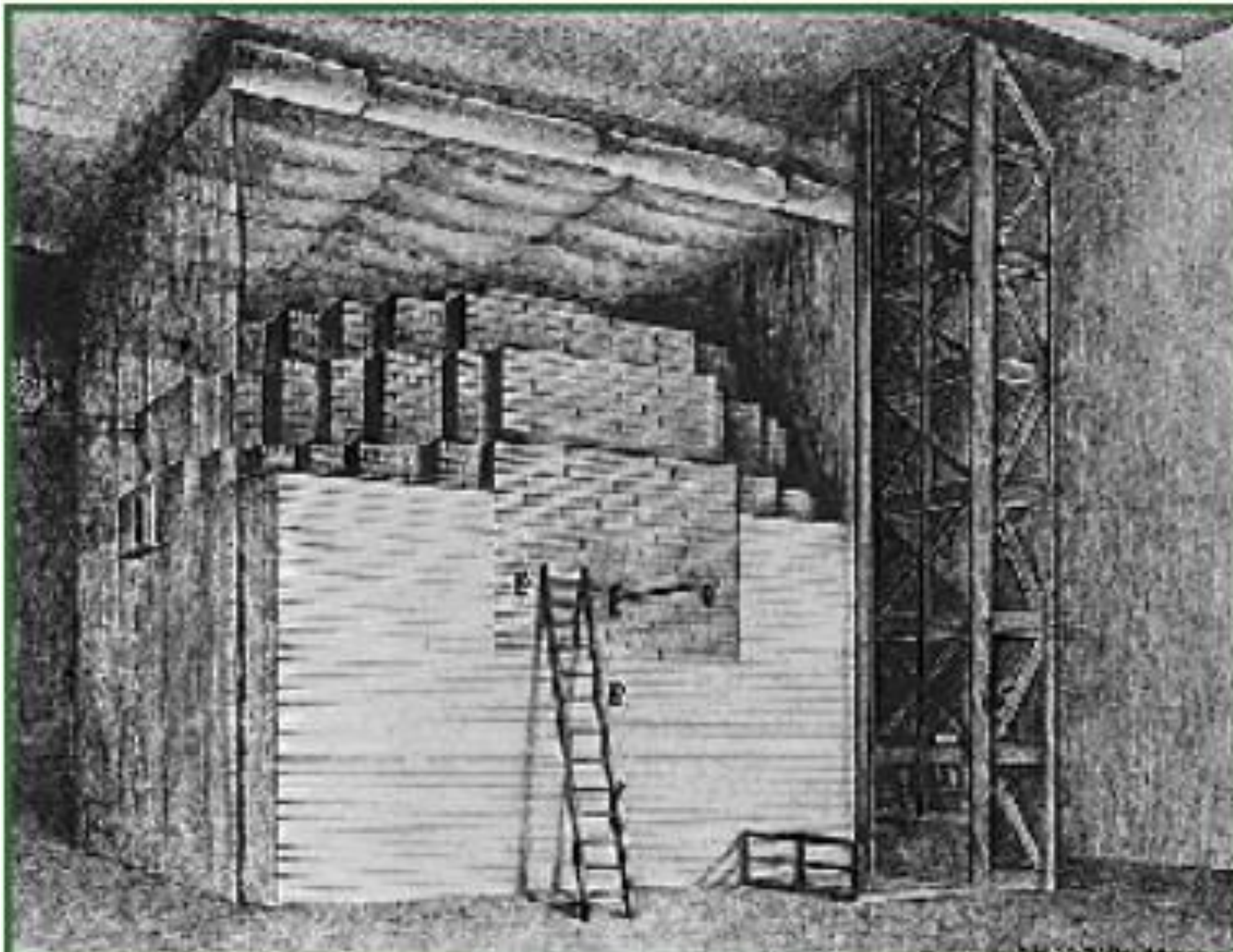
The Fermi group had been causing fission, reproduced all over the world for four years or more, without any recognition of the fact, until shortly after the Nobel Prize a group of German radiochemists determined that some of the radioactivity produced by neutron capture in uranium was chemically identical to barium, and Lise Meitner and Otto Frisch attributed it to the breakup of the nucleus, which could be understood by the “liquid drop” model of nuclei.

The LDM estimates the “surface tension” of the nuclear material, the oscillation frequencies of the drop, and the probability of fission when even a slow neutron is absorbed and contributes on the order of 8 MeV in excitation to the nuclear matter.

In early December 1938 Fermi had traveled with his wife, Laura, and children, Nella and Giulio, to Stockholm to receive the Nobel Prize, secretly having accepted a job as Professor of Physics at Columbia University in order to escape fascist Italy, which had just passed the “race laws” under which the Fermi children would not have access to universities because Laura’s family was Jewish. Laura’s father, Italian Admiral Augusto Capon felt secure remaining Rome because he had served with great distinction in WW I. Nevertheless, when the Nazis entered Rome on October 16, 1943, Admiral Capon, with 1000 other Jews, was shipped to Auschwitz where he died on October 23.

Szilard was already a hanger-on at the Columbia University Physics Department and when news of fission reached New York in early January, 1939. Szilard pressed Fermi to explore fission not in detail as a physical phenomenon, but to explore the possibility of the neutron chain reaction and, especially, of using the chain reaction to create nuclear weapons.

You are probably familiar with the “Einstein letter” to President Franklin D. Roosevelt of August 2, 1939, actually written by Leo Szilard, who recognized that Einstein’s name would provide authority that Szilard’s would not. A small team at Columbia University continued to work with Fermi on the “exponential pile”, which was moved in mid-1942 to the University of Chicago, where a full-size proof of principle, CP-1, was built containing 400 tons of graphite as moderator, with 6 tons of uranium metal and 34 tons of uranium oxide in lumps or cans to allow the fast neutrons to slow down in the moderator without being captured by the 99.3% U-238 in the natural uranium with which the pile was loaded. The 3-D arrangement was probably due to Szilard; Fermi had originally proposed a 2-D arrangement of alternating layers of uranium and graphite. Criticality was achieved on December 2, 1942, and work began immediately on the design of the plutonium production reactors in Hanford, Washington.



Drawing of CP-1

Although the capture of neutrons on U-238 was an impediment to achieving a self-sustaining neutron chain reaction with natural uranium, the result of that capture was U-239 which decayed into neptunium (Np-239) and then into plutonium (Pu-239) within a couple of days, to the extent that a gram of Pu-239 was produced in a day in a pile that had a "thermal power output" of 1 MW. It was realized first by Louis Turner, a Princeton physics professor, that Pu-239 should be as good a material as U-235 for the "fast-neutron chain reaction" involved in a nuclear explosive, and it was clear that "only" chemical separation would be required to obtain the plutonium from fuel irradiated in a production reactor. Scale-up from CP-1 to the first production at Hanford was enormous—a factor 100 million, from 2 W to 200 MW thermal power output. The Hanford reactor thus produced about 0.2 kg of plutonium per day, and it turned out that the bare-sphere critical mass of Pu-239 is 10 kg for alpha-phase metal of density 19.6. Using a neutron reflector of natural uranium or beryllium (Be) can reduce the critical mass by a factor two, and in fact, the plutonium bomb tested at Alamogordo, NM, 07/16/45 and used to destroy Nagasaki on 08/09/45 used about 6 kg.

Before the chain reaction with natural uranium was established as feasible and the plutonium route opened to nuclear weapons, the initial concept in Germany, the UK, and the United States was a U-235 weapon, which would require "isotopic separation" or enrichment from the U-235 content of 0.71% in natural uranium (NU) to something of the order of 90% U-235 in the weapon-grade highly enriched uranium—HEU. In the 1930s, physicists and chemists had done isotope enrichment of chlorine, mercury, and, especially hydrogen by various chemical or physical means, all relying (except for the separation of deuterium from hydrogen) on the relatively small mass difference between the isotopes, which in the case of uranium amounts to about 1%, or 3 amu. Almost all the approaches utilize the gas UF6, solid at room temperature but a vapor slightly above room temperature, which has the additional virtue that natural fluorine is monoisotopic, with a mass of 19 amu.

The massive uranium enrichment facilities built at Oak Ridge, TN, during WW II employed two processes—gaseous diffusion and electromagnetic (Calutron) enrichment. The thermal velocity of a UF6 bearing U-235 is about ½% (the square root of the mass ratio) larger than that of a U-238, so a nickel-bearing porous barrier served to provide an enrichment per stage of about 0.5%. Two hundred stages would thus provide a factor 2 or e (2.71828…) enrichment, so that on the order of 2000 stages would be required. Many large low-pressure compressors were used between stages to bring the gas back up to pressure, and the output from a stage was routed into the "cascade" which had a feed point, a "tails" delivery point, and a "product" delivery point.

The electromagnetic separation approach used a beam of ions not unlike that in an old-fashioned TV tube (electrons) for which the magnetic rigidity of U-235 and U-238 in a beam accelerated to a given energy differs, again by 0.5%. But because many "spots" can be resolved on the (one-dimensional) TV tube, a "pocket" or collector for the product U-235 can be placed at one point and one for the tails (U-238) at another, so that only a single stage of separation would be necessary, in principle. However, to obtain an atom of U-235, 140 atoms of NU would need to be ionized and accelerated, so that the system would be very inefficient. For example, if all ions are accelerated to 100 kV there would be an investment in acceleration alone of about 14 MeV per U-235 separated.

Although thermodynamically the energy to separate U-235 almost entirely from U-238 in NU should take less than 1 eV per atom of U (about 100 eV per product atom of U-235), the overall power required for the gaseous diffusion plant amounted to about 5 MeV per atom of U-235 in the product HEU—one of the least efficient processes known to me.

Other approaches to enrichment were also a matter of research, including chemical rate differences and centrifuge enrichment, but the Manhattan Project (as the overall secret effort was called after September 1942) really had the wrong concept of the centrifuge, as conceived by Jesse W. Beams.

The real invention of the gas centrifuge for uranium separation was due to G. Zippe, an Austrian swept up by the Soviet Union after WW II and put to work on uranium enrichment. Zippe's genius resulted in the centrifuge used almost universally today for enrichment of uranium for use in power reactors or nuclear weapons worldwide, at a commodity cost of about $100 per kilogram separative work unit-- $100/kg-SWU[4].

[4] https://www.fas.org/rlg/SWU_Calculations_version_3_1.xls for an active Excel spreadsheet.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	**SWU per kg for various enrichment parameters.**						SWU_Calculations (version 3).xls				R.L. Garwin, 12/19/2007			
2	Row													
3	3	Xp	Xw	Xf	P	W/P	F/P	Vp	Vw	Vf	ΔSWU/	ΔSWU/	ΔSWU/	
4	4	(product)	(waste)	(feed)	kg	kg W/kg P	kg F/kg P	--------------value function--------			kg product	kg U-235	P kg of	
5	5	% U-235	% U-235	% U-235	kg of product			----------- (2x-1) ln [x/(1-x)] ------				in product	product.	
6	6													
7	7	95.000	0.250	0.711	1.00	204.53	205.53	2.65	5.96	4.87	220.75	232.37	232.37	
8	8	90.000	0.250	0.711	1.00	193.69	194.69	1.76	5.96	4.87	208.03	231.15	231.15	
9	9	80.000	0.250	0.711	1.00	171.99	172.99	0.83	5.96	4.87	183.46	229.32	229.32	
10	10	19.900	0.250	0.711	1.00	41.62	42.62	0.84	5.96	4.87	41.35	207.77	207.77	
11	11	90.000	0.400	0.711	1.00	287.10	288.10	1.76	5.47	4.87	170.42	189.36	189.36	
12	12	3.500	0.400	0.711	1.00	8.97	9.97	3.08	5.47	4.87	3.64	103.89	103.89	
13	13	90.000	0.400	3.500	1.00	27.90	28.90	1.76	5.47	3.08	65.33	72.58	72.58	
14	14	3.500	0.360	0.710	1.00	7.97	8.97	3.08	5.58	4.87	3.89	111.22	111.22	
15	15	4.400	0.250	0.711	1.00	8.00	9.00	2.81	5.96	4.87	6.66	151.41	151.41	
16	16	3.500	0.400	0.710	1.00	9.00	10.00	3.08	5.47	4.87	3.64	104.02	104.02	
17	17	95.000	0.500	0.711	1.00	446.87	447.87	2.65	5.24	4.87	163.79	172.41	172.41	
18	18	95.000	0.500	19.900	1.00	3.87	4.87	2.65	5.24	0.84	18.85	19.84	19.84	
19	19	19.900	0.711	4.400	1.00	4.20	5.20	0.84	4.87	2.81	6.69	33.62	33.62	
20	20	90.000	0.400	3.500	1.00	27.90	28.90	1.76	5.47	3.08	65.33	72.58	72.58	
21														
22	**Enter your desired set** of enrichment parameters in Columns B-D for Xp, Xw, and Xf-- the U-235 conentrations in %, and in Col. E the kg of product.													

In order to define the task of making actual nuclear explosives out of the U-235 scheduled to arrive from Oak Ridge and the Pu that would be produced if the reactor at Chicago proved a success, scientists convened a summer study in June 1942 at the University of California at Berkeley, chaired by J. Robert Oppenheimer, a Professor of Physics at Berkeley and also at Caltech (Pasadena, CA). The group of about a dozen theoretical physicists at Berkeley spent perhaps a day on defining solutions to the problem of maintaining the fissile material subcritical in transport but then quickly bringing it to a (neutron-chain-reaction) supercritical state. If the degree of criticality is defined by the number of fissions in the successive generation, divided by the number of fissions in the previous generation, its value must be maintained below 1.0 (and in fact below 0.9935) because the system in transit must be subcritical when delayed neutrons are taken into account, even though only prompt neutrons contribute to useful yield in a nuclear explosive.

The considerations involved are well recorded in a monograph by Robert Serber, a participant at the Berkeley summer study and one of the first denizens at Los Alamos when the Laboratory was established there in March 1943 as “Site Y” of the Manhattan Project. Serber had the responsibility of briefing the Laboratory personnel as they arrived from all over the country (and from England) on what the program was about. Edward Condon at Los Alamos took notes which were to become the famous “Los Alamos Primer (LA-1)”, the first official document of the Manhattan Project at Los Alamos. This was classified for a long time, then declassified, then reclassified, but is now available in a version later annotated by Bob Serber, from the University of California Press. As you may know, Bob Serber was a professor here at Columbia for many years after leaving Berkeley in 1950 over the “loyalty oath”, but that is another story.

The baseline approach from the 1942 Berkeley summer study was to use “gun assembly” of about 60 kg of HEU or correspondingly less (perhaps about 10 kg) of Pu-239 in order to move quickly from the subcritical configuration to one of maximum supercriticality. The system was to be provided with a neutron generator so that when the two portions of fissile material were fully assembled, a copious stream of neutrons would initiate the chain reaction before mechanical disassembly could occur. Of course, after many e-foldings of neutron population, the internal energy would be so high that the system would blow itself apart before all of the fissile material was consumed in the chain reaction. In fact, the Hiroshima bomb, gun-assembled 60-kg of U-235, which at 100% fission would have a full yield of about 1000 kT (kilotons of TNT equivalent), actually had a yield of about 11-15 kT, so about 1% efficiency. This was predicted, although with some uncertainty, by the Bethe-Feynman formula, worked out at Los Alamos.

Los Alamos was the designated site for making nuclear explosives from the fissile material arriving from Oak Ridge or Hanford—U-235 and Pu-239 respectively. But when the plutonium began to arrive in tiny amounts from Hanford, early in 1944 it needed to be investigated for its “spontaneous” neutron generation rate. Because the Pu-239 half-life is 27,000 years, compared with the 730 My half-life of U-235, a tiny amount of beryllium or oxygen in the Pu could cause unacceptable neutron generation rate from the (alpha,n) reaction, and lead to premature initiation of the neutron chain and thus to a "fizzle." Much effort was expended at Chicago to purify Pu metal of these light elements, but when the Hanford Pu was investigated at Los Alamos by Emilio Segre, it turned out to have unacceptably high neutron generation rate that was quickly attributed to Pu-240 content, formed by neutron capture on the Pu-239 itself. This was minimized by short exposure of the natural uranium fuel slugs in the reactor, but still the Hanford Pu could not be used for gun assembly in the "Thin Man" Pu gun. The U-235 gun assembly was dubbed "Little Boy."

In the Los Alamos Primer another assembly mechanism is sketched, using a surrounding shell of high explosive to more rapidly assemble pieces of Pu, but when at Los Alamos the gun assembly means for plutonium proved to be impossible, there were major concerns about the symmetry of the explosive assembly approach. The UK contingent had brought with them the design of high-explosive "lenses" to convert a number of detonation points on the high explosive (32 in the Nagasaki bomb) from spherically expanding detonation waves to a single spherical contracting detonation wave, but there were still imperfections in the use of this "implosion" technique to assemble surrogate materials such as steel, lead, or the like—stand-ins for plutonium in tests. The problem was resolved by an observation perhaps due to John von Neumann and Edward Teller that the explosive assembly of plutonium metal would lead to significant compression of the metal, so that even a solid sphere could be driven under explosive influence from subcritical to substantially supercritical.

At the Metallurgical Laboratory at Chicago, the scientists from the beginning decided that everyone within the program should have full access to all of the ideas and progress, and that was carried over to Los Alamos under the leadership of Robert Oppenheimer, despite initial objections by the overall head of the Manhattan Project, Brigadier General (BGen) Leslie R. Groves. Robert Christie proposed the solid sphere plutonium core, which then took the name of "Christie Gadget," and was the approach used in the Alamogordo test and the identical Nagasaki bomb, Fat Man.

The two bombs, Little Boy and Fat Man, were delivered August 6 and 9 against Hiroshima and Nagasaki from the North field at Tinian Island. They were assembled at Tinian by a contingent from Los Alamos headed by Norman Ramsey, Professor of Physics at Harvard University for a long time after the war. Luis Alvarez, Professor of Physics at Berkeley and part of the Los Alamos assembly team on Tinian had the idea, for the Nagasaki drop, to attach to some parachute-borne "yield gauges" a letter to R. Sagane, known to three of the scientists on Tinian, explaining that these were the first two of many nuclear weapons that would be used against Japan, and that Sagane should bring this to the attention of the Emperor. Apparently this was done, and perhaps was instrumental in obtaining the prompt and unconditional surrender of Japan.

Both the HEU gun-assembled weapon and the Pu implosion weapon had switchable neutron generators in the form of hundreds of curies of Po-210 (137-day half-life) adjacent to beryllium metal, but with a thin layer of nickel coating the Po alpha source so that the alpha particles from the radioactive decay (37 billion per second per Ci) could not provide neutrons by the (alpha,*n*) reaction until the Ni film was disrupted by the passage of a shock wave.

After the surrender of Japan, there was little urgency for additional nuclear weapons until the Cold War developed with the Soviet Union, which picked up the pace of weapon development at Los Alamos. One problem with the early nuclear weapons was that they were not "one-point safe" in the sense that accidental detonation of the explosive by lightning or a bullet would have given a nuclear yield. Initially a portion of the nuclear weapon was kept separate and armed by a person carrying it to the rest of the assembly once the aircraft neared the target, but this was clearly not practical for a widely dispersed nuclear weapons delivery capability.

The story of one-point safety, insensitive high explosive, and the like, is too long to tell here.

External initiators.

The continuous resupply of 137-day Po-210 for internal initiators and the requirement for access to the very core of the nuclear weapon caused major design, maintenance, and logistical problems. Accordingly, Norris Bradbury, the Director of the Los Alamos Laboratory following Robert Oppenheimer in 1945, in 1951, as I recall, convened a small meeting in his office (at which I was present) at which Edward McMillan of the Berkeley Radiation Laboratory took the responsibility to provide external initiators in the form of betatrons that would be packaged with the implosion weapon, that would at the appropriate time of maximum criticality fire an intense burst of high-voltage x-rays into the core of the nuclear weapon, thus producing photofission neutrons that would initiate the chain reaction.

Another approach committed at that time proved to be better in the long run, and that was to use electrostatic acceleration of tritons or deuterons, in the d-t reaction producing 14.7-Mev neutrons that would penetrate to the weapon core and initiate the chain reaction. This is the approach used today in essentially all U.S. nuclear weapons.

Boosting and two-stage fission-fusion weapons.

Edward Teller from the 1942 Berkeley summer study joined the Los Alamos program, but with the intent of working on thermonuclear weapons, in which the energy release came not from the initially room-temperature exponential growth of neutrons and fission in a supercritical mass of U-235 or Pu-239, but from an initially intensely hot mixture of mass of deuterium (or deuterium-tritium mixture). Rather than about 150 MeV of prompt energy release from a fission, the *d*-*t* reaction gives 17.6 MeV as the product He-4 and n fly apart. Teller never had more than a couple of people working with him at Los Alamos on this because it was clear that the only way to get sufficient temperature was with a successful fission bomb, and sensible people realized that would be enough to end the war. But after 1945 Teller continued to push on fusion weapons, and a major experiment in the GREENHOUSE series in the Pacific was committed for 1951—GREENHOUSE GEORGE, an experiment on burning thermonuclear fuel. Unfortunately, nothing more can be said about GEORGE except that it was highly successful. In the same series, GREENHOUSE ITEM was a test of an implosion weapon containing *d*-*t* mixture at the center of the fissile core—not to produce a significant amount of energy but to "boost" the number of neutrons present in the core at that time, and with each of those neutrons provoking a fission in the highly supercritical assembly, to increase the fission yield. This was a major step forward and is used in essentially all U.S. nuclear weapons to this day.

But Teller's dream of a weapon fueled with the unlimited energy supply of deuterium from water was unrealized and probably unrealizable until in February 1951 the Los Alamos mathematician Stan Ulam came to Teller with a proposal that nuclear weapons could be built with an auxiliary external nuclear explosion to compress a main charge. Edward Teller was dismissive of the prospect, because he had long formulated an unwritten "theorem" that if you couldn't get deuterium to burn at normal liquid density (about 0.17 g/cc) compressing it 100-fold or 1000-fold would do no good, because the rate of energy gain from fusion reactions would go up as the square of the density (per unit volume) but the rate of energy loss from the hot ions by collision with electrons and electrons with collision with photons would go up similarly. So an unfavorable balance would be preserved.

But when he decided actually to put some numbers on paper, Teller discovered that he had made a logical error and that the ultimate loss to photons of the radiation field was limited by the equilibrium energy density of such photons. The energy content at a given temperature per unit volume of photons was independent of the compression, but the available fusion energy would go linearly as compression (per unit volume) and the rate of generation as the square of the compression. So there was much to be gained by compression.

Two-stage thermonuclear weapons by radiation implosion.

When I arrived at Los Alamos for the second summer in May 1951, Teller asked me to design an experiment that would incontrovertibly demonstrate the effectiveness of this "radiation implosion" approach to burning thermonuclear fuel. I decided that the best and quickest way to demonstrate was at full size and provided the initial design of the IVY MIKE experiment. From the date of my paper at Los Alamos, July 25, 1951, to the actual detonation at Eniwetok on November 1, 1952 was 15 months.

So here I make the transition to mention my presentation ten years ago[5] at the American Philosophical Society in Philadelphia, on the same platform with a (recorded) speech by Robert Oppenheimer that had been made to the same group 60 years earlier. And then we will go to questions.

But first a caution. Although the principles of nuclear weapons have not changed since the early 1950s, the evolution of technology and the spread of knowledge has made the acquisition of nuclear weapons much easier. "Two nuclear weapons for $2 billion" (the cost of the Manhattan project by 1945) has nothing to do with the investment required now, if HEU or plutonium compound from the nuclear power industry is available. Hence the major concern with preventing the proliferation of nuclear weapons.

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5 *Living with Nuclear Weapons: Sixty years and Counting*, fas.org/rlg/050430-aps.pdf, and (slides), *Living with nuclear weapons: 60 years going on 100 (if we are wise, vigilant, and lucky)*, fas.org/rlg/050430-apsslides.pdf

A stark threat of such proliferation was Iran, the subject of a second lecture[6] I gave last spring in this course, anticipating the successful conclusion[7] of the "Iran Deal"

between that state, the EU, and the five permanent members of the UN Security Council. I must close here, but invite attention to the documents I have cited.

Finally, a reminder of the urgency of preventing the proliferation of nuclear weapons and their use by those already possessing them:

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[6] "*Technical Aspects of the Proposed Iran Deal Barring the Acquisition of HEU or Pu for a Nuclear Weapon*," by R.L. Garwin. Presented in Columbia University Physics Course W3018, April 21, 2015 (at http://fas.org/rlg/irandeal.pdf).

[7] "*The 14 July 2015 Iran Agreement: Joint Comprehensive Plan of Action-- JCPoA*," by R.L. Garwin. International Seminar on Nuclear War and Planetary Emergencies, Plenary Presentation of 20 August 2015, Erice, Sicily. (at http://fas.org/rlg/jcpoa-erice.pdf)

Hiroshima, October 1945

Strategic Security Challenges for 2017 and Beyond

by

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For presentation to the NAS Membership at the Annual Meeting,
May 1, 2017 at 07:30 AM

(Note added post-delivery: In the interest of efficiency, I did not use slides, so none of the Figures was shown or discussed. Cogent questions followed the 30-minute presentation, but I think it inappropriate to respond to them here.)

Thank you for your interest in my views on some of the most important challenges facing the United States. By a "strategic security challenge," I mean a threat that can imperil the United States or the larger world within the next decade or so.

I'll describe the nature of each threat, how we got there, and some of the possible solutions.

None of these is an easy problem; if they were, they would not have persisted so long. Almost all involve constraints of domestic or international law, the interests of other parties, and, of course, problems in reaching agreement on a course of action. From the landscape of existing threats I choose four for detailed attention, as follows:

1. The greatest threat, based on expected value of damage, is cyberattack. Modern society's near-universal dependence on information systems, coupled with the connectivity of these systems via the Internet, makes this threat the top priority now and in the foreseeable future.
2. The second strategic security challenge is North Korea. Throughout its existence it has pursued the development and acquisition of nuclear

weapons, and of missiles to deliver them (and other munitions) to distances ranging from South Korea to intercontinental range. North Korea has had a record of non-compliance with U.N. Security Council resolutions and of not fulfilling its commitments under international agreements. It has long had the financial and political support of China, a global superpower, and aside from the direct security threat it can pose, is also a potential disruptor of international security if its force of nuclear weapons were to lead to their acquisition by South Korea and Japan. North Korea might also add nuclear weapons or the means to produce them to the list of items it sells to other states or to non-state actors.

3. The third threat of significance is Iran, which has substantial competence in technology in general, and in the development and acquisition of missile systems in particular. The response to the potential nuclear threat in Iran is much better developed than is the case with North Korea, perhaps because the nuclear threat of Iran was more urgent and the potential for destabilization in the Middle East even greater than that in Northeast Asia. In addition, because its

citizenry are better informed and Iran is much more in contact with the world than is North Korea, it was more amenable to a negotiated solution. The Joint Comprehensive Plan of Action (JCPoA) is an international agreement that was implemented in 2016 between Iran and six counterparties to address the Iranian nuclear threat, and I discuss it in some detail in this talk.

4. The existing U.S. nuclear weapon arsenal and its evolution is the fourth strategic security challenge I address here. I rank it so highly because of the great expenditures involved, and one particularly destabilizing aspect in regard to the other nuclear superpower, Russia. This is the potential for accidental or unintended nuclear war on a vast scale because the U.S. silo-based intercontinental missiles (Minuteman) are ready to launch within a minute of being commanded to do so, and such a launch might be provoked by false warning or interpretation.

I will address these threats in order of estimated ease of making progress to reduce the threat: the Iranian nuclear program; North Korea; the U.S. nuclear weapon capability and its evolution; and, finally, most importantly and probably most difficult of solution, the cyber threat to the United States.

Iran and nuclear weapons

In 1974 the Shah of Iran stated that Iran would have nuclear weapons "without a doubt and sooner than one would think." At the time, Iran also stated a need for a large civilian nuclear power program, looking forward to the day when oil would be gone, or reserved for transformation into chemicals. Iran's nuclear ambitions were legitimized by the Eisenhower Atoms for Peace program—a veritable proliferation initiative.

The International Atomic Energy Agency (IAEA) has long stated that a critical mass of U-235 metal is 52 kg, but efficient nuclear weapons could be made with substantially less U-235. If one takes a nominal 20 kg of U-235 per nuclear weapon, the plant that would supply fuel for Iran's sole power reactor at Bushehr could instead provide 32 nuclear weapons per year. That is the rub: the necessity to ensure that not even a tiny fraction of civil enrichment capacity is diverted to the production of highly enriched uranium.

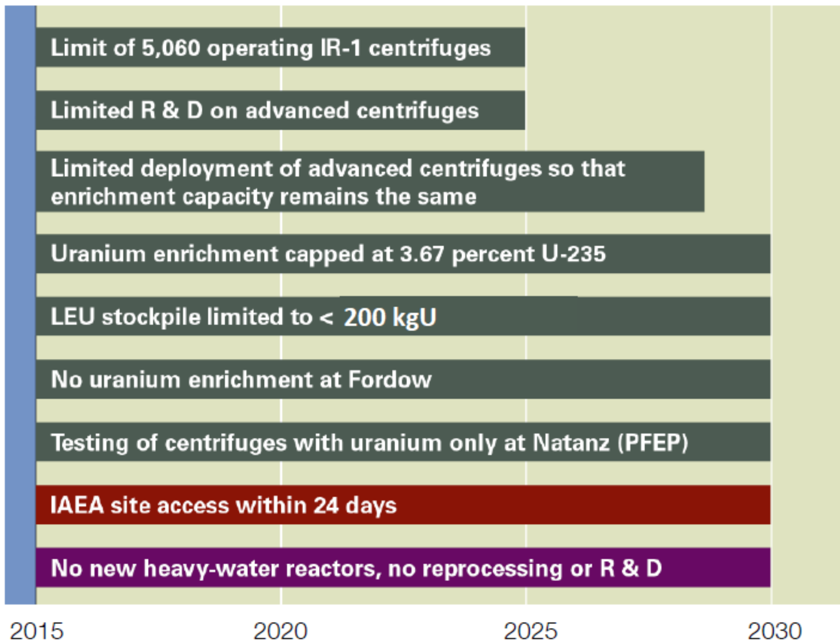
In the few years after 2000, and particularly after 9/11/2001, the United States and most of its allies introduced sanctions against Iran, and maintained that the sanctions would not be lifted until Iran gave up its work that it maintained was strictly peaceful and allowable under the IAEA. The criterion was “not a centrifuge will turn,” which was anathema to Iran, for which enrichment had become a “sacred value”. That enrichment is not necessary for fueling civil nuclear power is shown by South Korea, for instance, which has a vibrant nuclear power sector, with extensive development and construction of nuclear reactors there and abroad, but has no enrichment capacity of its own.

Javad Zarif, Iran’s Foreign Minister, who had been their ambassador to the United Nations in New York, stated in 2014, “If at the time of the imposition of sanctions we had less than a couple of hundred centrifuges, now we have about 20,000. So that’s the net outcome.”

Although there was no doubt that Iran possessed and was operating gas centrifuges and had accumulated many tons of enriched UF_6—some of it 20% U-235, as documented by IAEA inspections—there was no such international evidence of a nuclear weapon program in Iran, and Iran vehemently denied having such a program.

By giving up the absolutist requirement of no centrifuges operating in Iran, six like-minded powers were able to undertake extensive negotiations with Iran, resulting in the 2015 Agreement, which entered into force January 16, 2016. These two slides show some of the limitations agreed to by Iran in exchange for immediate relief from sanctions related to its nuclear activities.

Constraints are Very Long Lasting



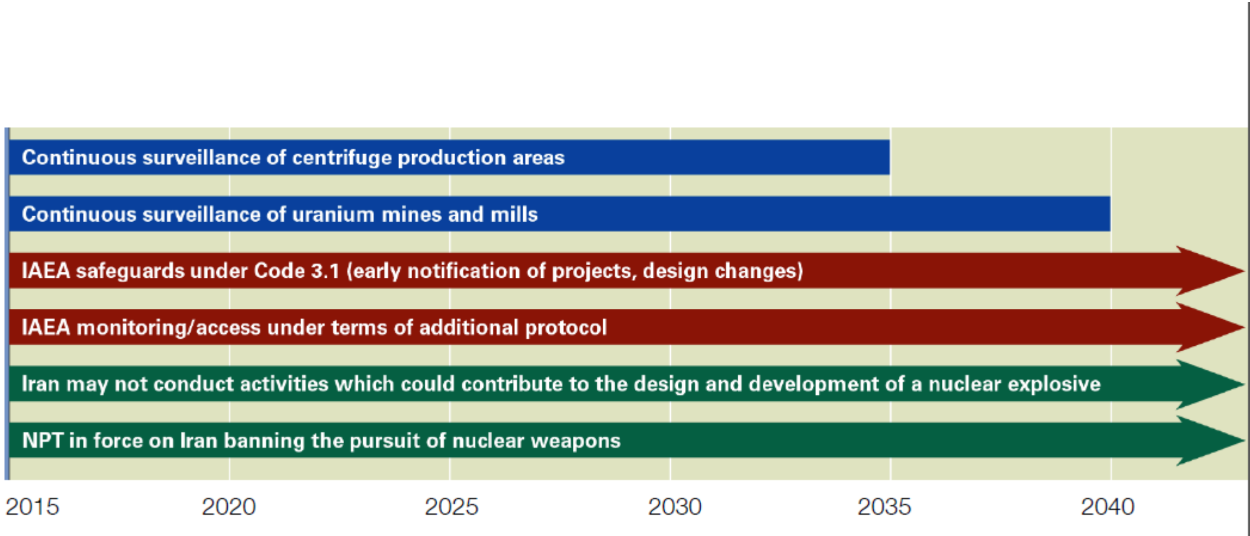


Figure 1. Source: Arms Control Association

In the process of negotiation, Iran shipped out of the country some 98% of its stock of low-enriched uranium, so as to remain below the 200 kg limit of 3.67% uranium set by the Agreement.

The Agreement is 159 pages of mind-boggling detail, with a good deal of room for ambiguity in some aspects, but to my mind it is a great achievement and puts off for a decade or more the time when Iran will have enough enriched uranium for a single nuclear weapon. Moreover, the

Agreement denies Iran the acquisition of plutonium for that type of nuclear arm.

If Iran should denounce the Agreement (just as if they had denounced their membership in the Non-Proliferation Treaty and ejected the IAEA inspectors before the Agreement), Iran could, if unimpeded by a diplomatic or military response, use its centrifuge capacity to enrich uranium. But rather than being a few weeks from having enough material for its first nuclear weapon, it would take most of a year—ample time to mount a diplomatic or military response.

So that is the story of one strategic challenge abated, if not solved, as a result of technical and diplomatic effort involving extensive negotiations within the United States, with its allies in the process—including China and Russia—and with the adversary, Iran.

However, some of these constraints expire in 10–15 years; during this time a key objective for the United States should be to use contacts and conversations with Iran to encourage its continued support of the Non-Proliferation Treaty, and to reduce the capacity for nuclear destruction in the world, through Iran's greater integration with the West, and perhaps through reduced security threats in the region. This is a precious opportunity that should not be squandered. For instance, before the end of the Agreement period, Iran might opt for international participation in its expanded centrifuge plant for commercial power-reactor fuel. Yes, a non-nuclear Iran can cause trouble, as it has in Yemen and Bahrain, but a nuclear Iran can do that and far worse.

Since the signing of the Agreement in 2015, Iran and the United States have been on opposite sides of the conflict in Syria, adding to the problems posed by Iran's supply of arms that are used in attacks on Israel. This has led to calls for the reintroduction of sanctions on Iran's missile program, or otherwise pressuring Iran to abandon activities that are contrary to U.S. interests. To my mind, the United States should oppose such activities by Iran, but it would be counterproductive to abandon the protection offered by the Agreement.

North Korea

As a member of the nine-person Commission to Assess the Ballistic Missile Threat to the United States (Rumsfeld Commission), in July 1998 I concurred in the commission's judgment that any of the three emerging powers of that time—Iraq, Iran, and North Korea—

> "would be able to inflict major destruction on the [United States] within about five years of a decision to acquire such a capability (10 years in the case of Iraq)."

We have already discussed Iran. Iraq is no longer in that category, but North Korea definitely is.

In its five underground nuclear explosion tests, North Korea has apparently achieved explosive yields on the order of 10–20 kilotons[1], and may have

1 (in its test of September 9, 2016)

incorporated, or may soon incorporate, “boosting” technology, in which the exponentially growing neutron population in the exploding fissile material is boosted suddenly to a higher level by the rapid fusion of deuterium and tritium within the fissile core.

In February 2017, North Korea tested a solid-fuel missile, which, if the technology is transferred to its medium- and long-range missile program, will make these weapons more robust, easier to conceal, and potentially, with a shorter burn time, more difficult to intercept in flight. North Korea has long sold short- and mid-range ballistic missiles to other states, and has recently offered for sale lithium metal highly enriched in Li-6, indicating that North Korea has no shortage of the source material for producing tritium for boosted fission weapons.

Why is North Korea—with its population of 25 million and per capita GDP of only $1,800[2]—a problem for the United States? The answer lies in the Korean War, which ended, in July 1953, in an armistice rather than a peace

[2] CIA World Factbook.

settlement, so there is still an armed confrontation between North and South Korea, with the United States allied to South Korea and China to North Korea. The United States based nuclear weapons in South Korea from 1958 to 1990 and still has 28,000 military personnel deployed there.

It is generally felt that the North Korean leader, Kim Jung-Un believes that the United States would take any opportunity to depose him, if necessary by force, and that North Korea must preserve and expand its military capability in order to prevent this.

The United States has been deterred from solving this problem militarily because half of South Korea's 50 million population is in the Seoul area, within range of North Korean guns and short-range rocketry. If North Korea were to initiate a shooting war, making political and economic demands as a condition to bringing it to an end, there would surely be a massive military response, but no one knows how much damage would be done to South Korea before the confrontation ended. Now that North Korea has a stock of perhaps 20 nuclear weapons, the potential damage to South

Korea would be much greater, and North Korea could lash out against Japan as well.

North Korea, in turn, has also been deterred from military action—by the threat of massive US retaliation, as well as by sporadic intense negotiations. The United States is concerned (perhaps overly so) about the benchmark that would be constituted by a long-range missile capability to deliver a few nuclear weapons against the mainland USA. This threat is nothing new, in view of the long-standing vulnerability of U.S. coastal cities to attack by North Korean short-range missiles launched from ships near U.S. shores. Deterrence still works, but might be at risk if North Korea's leadership feels that the United States, with some defensive capability, is preparing a preemptive strike.

It has been proposed[3] also by former Defense Secretaries William J. Perry and Ashton B. Carter, that intercept be made "left of launch"—that the

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[4] "If Necessary, Strike and Destroy," *The Washington Post*, June 22, 2006.

United States should destroy the test vehicle for a North Korean ICBM, while it is on its launch pad and not moving at all.

The best approach may be to work with China to provide enhanced sanctions against North Korea, to persuade it not to test missiles to a range beyond 2,000 km and not to conduct further nuclear explosion tests. Success is not assured, and both defense and the promise of deterrence by retaliation against actual use of these weapons are essential. A reduction in the U.S. military presence in South Korea could also be considered, as part of a negotiation to bring North Korea into compliance with U.N. Security Council resolutions.

U.S. nuclear weapons

Our own nuclear weapons can constitute a major threat to the United States—not primarily because of the risk of an accident here or in allied countries, but because they can provoke instability and the use of large numbers of weapons of enormous destructive power.

My involvement with nuclear weapons began in 1950, continuing to the present day. In recent decades this has largely been through work by the JASON group of consultants to the U.S. government in support of the Department of Energy's Stockpile Stewardship Program (SSP).

Since the last U.S. nuclear weapon explosive test, in 1992, each year the directors of the three nuclear weapons laboratories—Los Alamos, Livermore, and Sandia—certify that the existing nuclear weapons stockpile is safe and reliable. By means of extensive experiments and tests without nuclear explosions, and with enormous computational capability, we know far more about our nuclear weapons than in the days of nuclear explosive testing, but there is always the danger of going beyond our certain knowledge and making changes, intentional or not, which will imperil the reliability of the weapons, or cause unexpected problems.

The very scale of planned expenditures in the Department of Defense and the National Nuclear Security Administration is itself a challenge to our national security, with plans to spend some $340 billion in DOD and $300 billion in NNSA over the next 25 years to modernize and upgrade the nuclear warheads and the their delivery systems—the strategic bombers, the silo-based ICBMs, and the submarine-launched ballistic missiles (SLBMs). Time after time, the U.S. Government has committed to a new weapon or to a modernization program that then becomes unaffordable, resulting in the procurement of a far smaller number of vehicles or weapons—a form of unilateral disarmament.

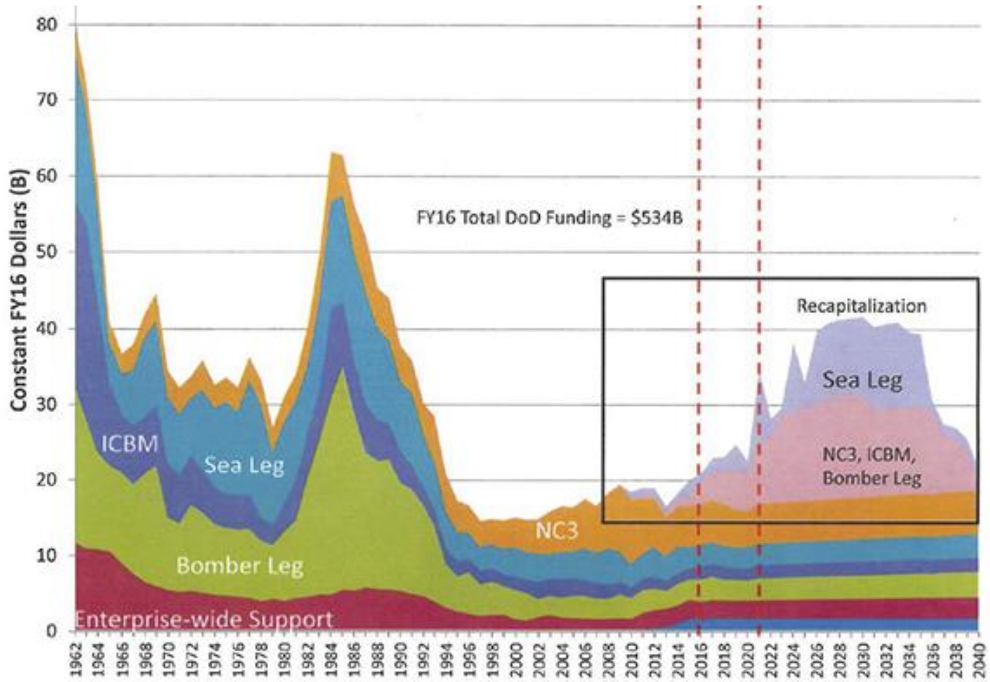

Figure 2. Historical and projected U.S. Department of Defense expenditures on nuclear-weapons delivery vehicles and nuclear command, control and communication (NC3). The two historical peaks are associated with the Kennedy–Johnson and Reagan Administrations. The projected peak is associated with plans for new strategic bombers,

ballistic-missile submarines and ICBMs.[4] This does not include expenditures by the National Nuclear Security Administration on nuclear-warhead modernization. (From a forthcoming article by Steve Fetter, Richard Garwin, and Frank von Hippel, to appear in *Physics Today*.)

My own judgment is that a course oriented toward realizing economies can substantially reduce this cost, provide needed improvements sooner, and avoid competitive strategic expenditures in other countries.

My second point it that one must distinguish the role of the U.S. ICBMs (the Minuteman missiles) as regards Russia, from their role as regards nuclear targets in the rest of the world. Russia has enough land-based multiple-warhead missiles (both in silos and as mobile missiles) with sufficient accuracy to destroy all of the 450 Minuteman silos, and this may happen at the outbreak of nuclear war. That very prospect is likely to lead

[4] Department of Defense, Cost Assessment and Program Evaluation, January 2017, https://www.armscontrol.org/files/images/TriadModernizationCosts1.png. The blue band at the bottom that begins in 2012 is funding that DOD has committed to the National Nuclear Security Administration. Most of NNSA's costs for nuclear-warhead modernization, which, by themselves, amount to about $10 billion per year, are in the Department of Energy budget.

to the launch of all of the Minuteman against their pre-planned targets—most of them, apparently, the offensive (or retaliatory) nuclear weapons in Russia, thus ensuring devastation on both sides, in the vain hope of reducing the damage that would be done to the United States by Russian nuclear weapons.

According to the late Robert Peurifoy—who died in March 2017, after a long career at Sandia National Laboratories and a second one as consultant to the House Armed Services Committee's Nuclear Weapons Safety Panel—U.S. nuclear weapons today are not significantly different from those that were designed and tested in the 1960s. The two-stage radiation-implosion hydrogen bombs of that era were much safer than even much lower-yield single-stage nuclear weapons, and met many requirements for 100-percent reliability and zero-percent unintended explosion rate, to exaggerate only slightly.

At a time of reduction in numbers of weapon delivery systems, it makes sense to determine the individual margin to failure for each weapon and retain the better ones, rather than replace the entire force—many prematurely. Even better results can be obtained by identifying the best subset of components, and reassembling a smaller number of weapons from them. But few such tools are employed; for instance, such an evaluation exists for the solid-fuel missiles of the U.S. Navy's SLBMs, but not for the solid-fuel elements of the Minuteman.

In short, I favor preserving U.S. nuclear warheads by further life-extension programs, and removing 80% of the Minuteman ICBMs from launch-on-warning status.

Cyber threats

In this ranking of dangerous strategic threats, I put cyber first, and this even without including the potentially effective influence of disinformation and propaganda. The cyber threat is probably also the most obdurate.

The cyber threat is so serious because of the enormous dependence in the United States on computers, and their necessity even to aspects of society that may not present a computer or communication interface to the public. Furthermore, unlike the challenges from nuclear weapons in North Korea, potential weapons in Iran and elsewhere, and our own ready-to-fire nuclear-armed Minuteman, cyber attacks on the United States take place every day, perpetrated by criminals, terrorists, and nation states, with some overlap among them.

There is a strong overlap of the capability for cyber attack with that of cyber espionage, as practiced extensively by Russia, China, the United States, and just about every other country in the world. The United States is not happy to lose information, trade secrets, and valuable data through the intercept of its communications by other states, or from penetration of its computers, whether this is done by remote access from the Internet, or by "close access" by hands-on intervention.

A National Research Council report of 2009[5] provides an early summary of the field. The threat to our society has greatly increased with the ubiquity, now, of the Internet and the increasing penetration of computers into all aspects of modern life.

This is about to escalate further with the rapid expansion of the Internet of Things (IoT)—the proliferation of Internet-connected speakers, voice-actuated personal assistants, thermostats, controls of lighting, and the like. There is every indication that the Internet will soon have 100 billion individually addressed gadgets worldwide, augmenting the threat in two ways: First, there are that many more nodes that can be co-opted in a "botnet"; and, second, the protection of IoT gadgets is far less effective than that of even a residential PC, which can have anti-virus suites, automatic software upgrades, and the like. Some cyber threats are very simple, such as a distributed denial of service (DDoS) attack—in which as many as a million individual IP addresses are commanded to send brief

[5] Technology, Policy, Law, and Ethics Regarding U.S. Acquisition and Use of Cyberattack Capabilities (Washington, D.C.: National Academy of Sciences Press, 2009)

signals to a target address, flooding it with so many incoming messages that it cannot handle real ones, or maybe any at all. Criminal botnets are organized as a business, by cyber criminals who have no interest in the specific targets of their crime, but simply rent the tools to perpetrators.

Beyond this simple exfiltration of data, and the installation of tools that use the targeted computer system or computer system network to do the selection of data to be exported, there are the further threats of "preparation of the battlefield," which could be practiced by nation states, in preparation for a possible cyberwar or cyber component of kinetic conflict.

Actual damage to the computer system itself was practiced against Saudi Arabia by Iran in 2016, and against Sony Pictures in 2014 by North Korea. In a different category is the computer-directed transfer of funds, as apparently was practiced by North Korea, and, beyond that, to cyber-augmented sabotage, such as shutting off power transmission lines, with the causing of a massive flood by opening sluice gates from a major dam, or the over-pressuring of a gas pipeline, as practiced by elements of

the United States against the Soviet Union, apparently in retribution for their theft of industrial control software.
The picture is indeed grim, because of the many current practitioners of cyber skirmishes, and the fact that economic collapse can be produced by targeting less sophisticated and less well protected computer systems.

As with any threat, the first means of nullification is thought to be "defense," invoking the image of walls and shields, and, of course, there is a lot of defense against cyber penetration and cyber attack. In the case of nuclear weapons, the destructiveness of a single nuclear weapon so far exceeds that of a high-explosive bomb of the same weight that after the early 1950s primary reliance has been placed on deterrence rather than defense. This is not because deterrence is preferable or more moral, but because defense at the required level of effectiveness has been considered infeasible. Deterrence, and its more sinister sibling, compellence, involved manipulating the views and actions of decision makers by the promise of imposing unacceptable costs.

Two recent papers attempt to provide solutions to the cyber threat in this mold, one by Joseph S. Nye[6], who asserts that *deterrence* in cyberspace can be achieved, at least in part, by *threat of punishment*, by *defense* (preventing significant gain from the act), by *entanglement*, and by *norms*. But to what extent and against whom?

A current discussion from the point of view of the U.S. Department of Defense is afforded by its Defense Science Board.[7] This report provides useful information, such as,

> "The United States views cyber espionage as a legitimate activity, and undertakes it extensively; yet, just as with espionage conducted by human spies, there should be both limits and consequences to being caught."

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[6] "Deterrence and Dissuasion in Cyberspace**,"** Joseph S. Nye Jr., *International Security* Winter 2016/17, Vol. 41, No. 3: 44–71.

[7] *"Report of the Defense Science Board Task Force on Cyber Deterrence,"* co-chaired by Dr. James N. Miller and Mr. James R. Gosler (February, 2017) casts the challenge and the solution as deterrence: "*Deterrence by denial* operates by reducing the expected benefits of attack, while *deterrence by cost imposition* operates by increasing the expected costs."

The report cites as examples of significant cyber operations: the 2015 theft by China of 18 million personnel records from the White House Office of Personnel Management, which included security investigations; the 2016 Russian hack of the Democratic National Committee and emails of various public figures, and the disclosure of such material on Wikileaks, with the intent of influencing the 2016 Presidential election; and the 2014 cyber attack by North Korea on Sony Pictures, either for compellence or in retaliation for a Sony film about the North Korean leader.

All of the deterrence solutions discussed depend on reliable, and probably publicly credible, identification of the perpetrator ("attribution"), possibly on a short timescale—with no apparent path to this goal.

What to do, then, until the (cyber) vaccine arrives?

The greatest threat to U.S. security would not seem to arise from an attack directed by the Russian government or the Chinese leadership, as such attacks can, in principle, be deterred by threat of retaliation, whether in the cyber or another domain, even given the imperfection of attribution. Rather, the danger could be greatest from a nihilist or terrorist group that would derive no direct benefit from the devastation it sowed in U.S. society. But even Russia or China could not be expected to abstain from cyber warfare in the presence of armed conflict.

Many potential crimes in U.S. society are prevented not so much by hardening the target, but by near-elimination of the benefit to the perpetrator. Thus, almost any one of us could be murdered outright, and there are many ways of doing that which would hardly expose the perpetrator to certain capture and punishment. But for the most part, the motive could be to obtain ransom from not carrying out the threat, and this requires the ability to transfer money or other material of universal value to the perpetrator. Thus, it is believed that a significant reduction in drug trafficking (or at least an increase in the price of drugs) was effected by the elimination of all U.S. currency denominations above the $100 bill. You can't put $1 million in hundred dollar bills in your pocket, unlike the few minutes it took me to carry three $10,000 bills a hundred meters from the bank to a law office in downtown Manhattan in 1955. Well, it wasn't $1million, but it could have been.

Against the cyber threat of societal destruction, improved likelihood of attribution would help to deter the most able perpetrators. Against the others, various forms of defense are probably the best approach. Yes, norms and agreements can help. But not against the cyber nihilist or cyber terrorist.

Knowledgeable government and non-government organizations know pretty well the path to take to a more robust Internet-like system. But there are major and sophisticated forces on the other side—including some of the same organizations—that see profit in maintaining "transparent" systems, which are incidentally hard to secure against cyberattack.

Many of the threats involving the public Internet are exacerbated by the business model of "cost-free" access and advertising support. A fee-for-service Internet could be offered that is free from the near-universal commercial intercept of the interaction with websites; it would also be much more responsive, while still allowing distributed caching and access to large files.

An added complication with cyber security is that most of the infrastructure and capability are in the private sector, not the domain of government, and yet government is held responsible for and has an interest in protecting the nation from existential threats. Space and cyber share this characteristic.

Much more needs to be done, and quickly. The Department of Homeland Security has much of the responsibility for creating and coordinating solutions to the cyber threat to society, government and critical infrastructure. The current status may be viewed at its site.[8] Beyond bringing existing systems up to current best practices, real research must be expanded in harnessing artificial intelligence to discover and fix

[8] https://www.dhs.gov/topic/cybersecurity

vulnerabilities, in creating provably secure programming systems, and in automatic logging and alarming of threats internal to the networks.

Closing Remarks

I have tried to give some background as well as some specifics on these strategic challenges for the immediate future—to some of which we have no early solutions, but for which rational individuals and governments together could lessen their likelihood or potential consequences.

For most of these challenges, the work of our intelligence community is key, as is its interaction with the Congress and the Executive and, ultimately, with the commercial world.

Comparing the vulnerability of our finely tuned industrial and commercial society with that of a century ago, we see that technology has brought enormous benefits and also a great fragility against concerted attack, or even natural events such as a geomagnetic storm induced by solar activity.

To inflict starvation and disruption, the cyber threat need not actually destroy much of value, except connectivity. And much of the malign impact can come from a simple loss of confidence— bank failures, lack of trust. A single firm may undergo bankruptcy or even use it as a tool, but bankruptcy is not an option for the United States.

Most of the problems we face need mutual esteem, confidence, and collaboration; without those features the society we have built will collapse.

[Blog] All Things Nuclear

Reentry of North Korea’s Hwasong-15 Missile

David Wright, co-director and senior scientist | December 7, 2017, 2:53 pm EDT

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Photos of the Hwasong-15 missile North Korea launched on its November 29 test suggest it is considerably more capable than the long-range missiles it tested in July. This missile’s length and diameter appear to be larger by about 10 percent than July’s Hwasong-14. It has a significantly larger second stage and a new engine in the first stage that appears to be much more powerful.

While we are still working through the details, this strongly implies that North Korea could use this missile to carry a nuclear warhead to cities throughout the United States. A final possible barrier people are discussing is whether Pyongyang has been able to develop a reentry vehicle that can successfully carry a warhead through the atmosphere to its target, while protecting the warhead from the very high stresses and heat of reentry.

Here are my general conclusions, which I discuss below:

1. North Korea has not yet demonstrated a working reentry vehicle (RV) on a trajectory that its missiles would fly if used against the United States.
2. However, there doesn't appear to be a technical barrier to building a working RV, and doing so is not likely to be a significant challenge compared to what North Korea has already accomplished in its missile program.
3. From its lofted tests, North Korea can learn significant information needed for this development, if it is able to collect this information.
4. While the United States put very significant resources into developing sophisticated RVs and heatshields, as well as extensive monitoring equipment to test them, that effort was to develop highly accurate missiles, and is not indicative of the effort required by North Korea to develop an adequate RV to deliver a nuclear weapon to a city.

The Hwasong-15 RV

When the photos appeared after North Korea's November 29 missile launch, I was particularly interested to see the shape of the front of the missile, which gives information about the reentry vehicle (RV). The RV contains the warhead and protects it on its way to the ground. It appears the Hwasong-15 is carrying an RV that is considerably wider and blunter than that on the Hwasong-14 (Fig. 1).

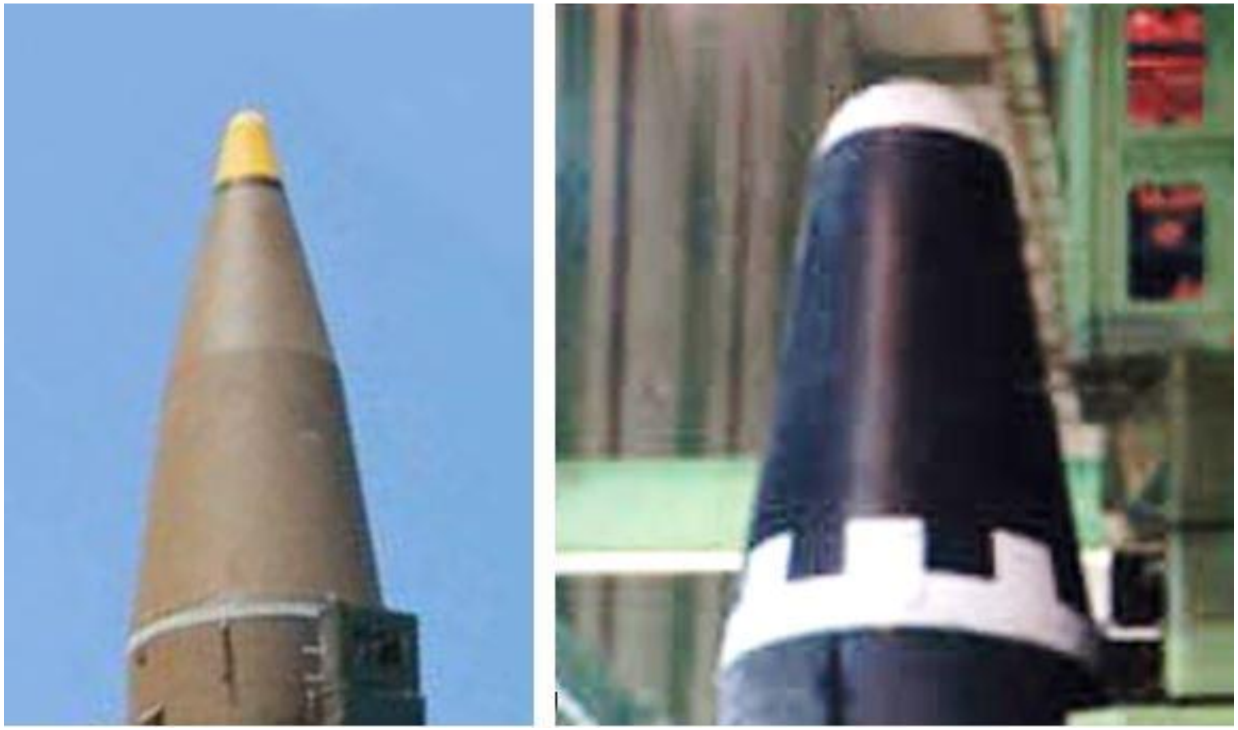

Fig. 1. The RVs for the Hwasong-14 (left) and Hwasong-15 (right), roughly to scale. (Source: KCNA)

This fact has several implications. A blunter RV can clearly accommodate a larger diameter warhead, and the warhead can sit farther forward toward the nose of the RV. This moves the center of mass forward and makes the RV more stable during reentry. (This drawing shows how the cylindrical nuclear weapon in the

US Titan RV, which was roughly the same size and shape, although much heavier, than the Hwasong-15 RV may be.)

A blunter nose on the Hwasong-15 RV also helps protect it from high atmospheric forces and heating during reentry. Here’s why:

As the RV enters the atmosphere, drag due to the air acts as a braking force to slow it down, and that braking force puts stress on the warhead. At the same time, much of the kinetic energy the RV loses as it slows down shows up as heating of the air around the RV. Some of that heat is transferred from the air to the RV, and therefore heats up the warhead. If the stress and/or heating are too great they can damage the RV and the warhead inside it.

A blunter RV has higher drag and slows down in the thin upper parts of the atmosphere more than does a slender RV, which continues at high speed into the thick lower parts of the atmosphere. This results in significantly less intense stress and heating on the blunter RV. In addition to that, a blunt nose creates a broad shock wave in front of the RV that also helps keep the hot air from transferring its heat to the RV.

Fig. 2. This shows two low-drag RVs being placed on a Minuteman III missile, which can carry three RVs. (Source: US Air Force).

A rough estimate shows that if the RVs had the same mass and flew on the same trajectory, the peak atmospheric forces and heating experienced by an RV similar in shape to the Hwasong-14 nosecone in Fig. 1 would be roughly four or more times as great as that experienced by a blunter Hwasong-15 RV; those on a modern US RV, like that on the Minuteman III missile (Fig. 2), might be 20 times as large as on the Hwasong-15 RV.

The tradeoff of having a blunt warhead is that when the RV travels more slowly through the atmosphere it reduces its accuracy. In order to get very high accuracy with its missiles, the United States spent a tremendous amount of effort developing highly sophisticated heatshields that could withstand the heating experienced by a slender, low-drag RV.

For North Korea, the decrease in accuracy due to a blunt RV is not particularly important. The accuracy of its long-range missiles will likely be tens of kilometers. That means that it would not use its missiles to strike small military targets, but would instead strike large targets like cities. For a large target like that, the reduction in accuracy due to a blunt RV is not significant.

What could North Korea learn from its recent test?

Press stories report US officials as saying that the reentry vehicle on North Korea's November 29 test "had problems" and "likely broke up" during reentry. If true, this implies that the RV used on this flight could not withstand the strong drag forces as the RV reached low altitudes.

It's worth noting that the drag forces on the RV during reentry on the lofted trajectory would be more than twice as great as they would be on a standard trajectory of 13,000 km range flown by the same missile (Fig. 3). This is because on the flatter trajectory, the RV flies through a longer path of thin air and therefore slows down more gently than on the lofted trajectory. It is therefore possible the RV might survive if flown on a standard trajectory, but North Korea has not yet demonstrated that it would.

However, given the estimated capability of the Hwasong-15 missile, North Korea appears to have the option of strengthening the RV, which would increase its mass somewhat, and still be able to deliver a warhead to long distances.

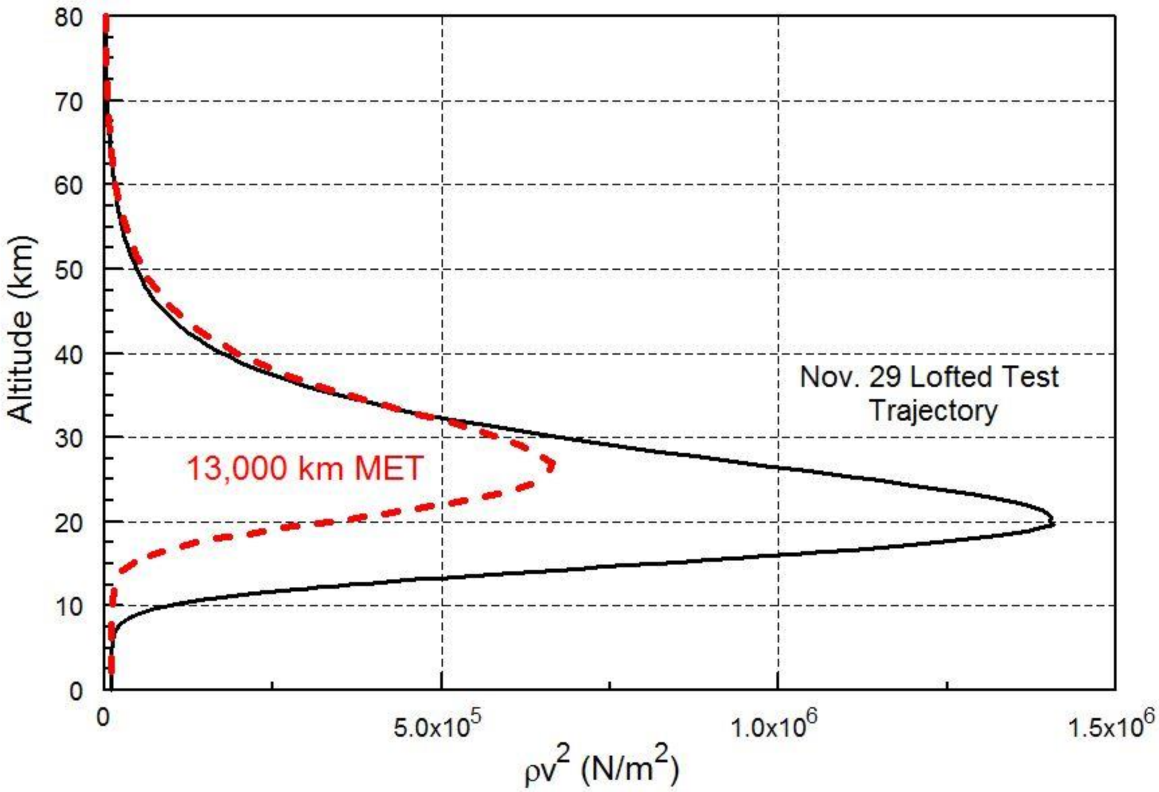

Fig. 3. This figure shows the atmospheric forces on the RV with altitude as it reenters, for the highly lofted test on November 29 (black curve) compared to the

same missile flying a 13,000 km standard trajectory (a minimum-energy trajectory, MET). The horizontal axis plots the product of the atmospheric density and square of the RV speed along its trajectory, which is proportional to the drag force on the RV. The calculations in all these figures assume a ballistic coefficient of the RV of 100 lb/ft^2 (5 kN/m^2). Increasing the ballistic coefficient will increase the magnitude of the forces and move the peaks to somewhat lower altitudes, but the comparative size of the curves will remain similar.

The situation is similar with heating of the RV. The last three columns of Fig. 4 compare several measures of the heating experienced by the RV on the lofted November 29 test to what would be experienced by the same RV on a 13,000 km-range missile on a standard trajectory (MET).

	Maximum atmospheric force on RV	Maximum heating rate at RV surface	Total heat absorbed by RV	Heat Soak time
Nov. 29 lofted	2.1f	2q	Q	τ
13,000 km MET	f	q	1.2Q	1.6τ

Fig. 4. A comparison of RV forces and heating on the November 29 test and on a 13,000 km-range trajectory, assuming both missiles have the same RV and payload. A discussion of these quantities is given in the “Details” section below.

These estimates show that the maximum heating experienced on the lofted trajectory would be about twice that on a standard trajectory, but that total heat absorbed by the RV on the two trajectories would be roughly the same. Because the heating occurs earlier on the RV on the standard trajectory than on the lofted trajectory, that heat has about 130 seconds to diffuse through the insulation of the RV to the warhead, while the heat on the lofted trajectory diffuses for about 80 seconds (Fig. 5). This somewhat longer time for “heat soak” can increase the amount of heat reaching the warhead, but North Korea would put insulation around the warhead inside the RV, and the heat transfer through insulators that North Korea should have access to is low enough that this time difference is probably not significant.

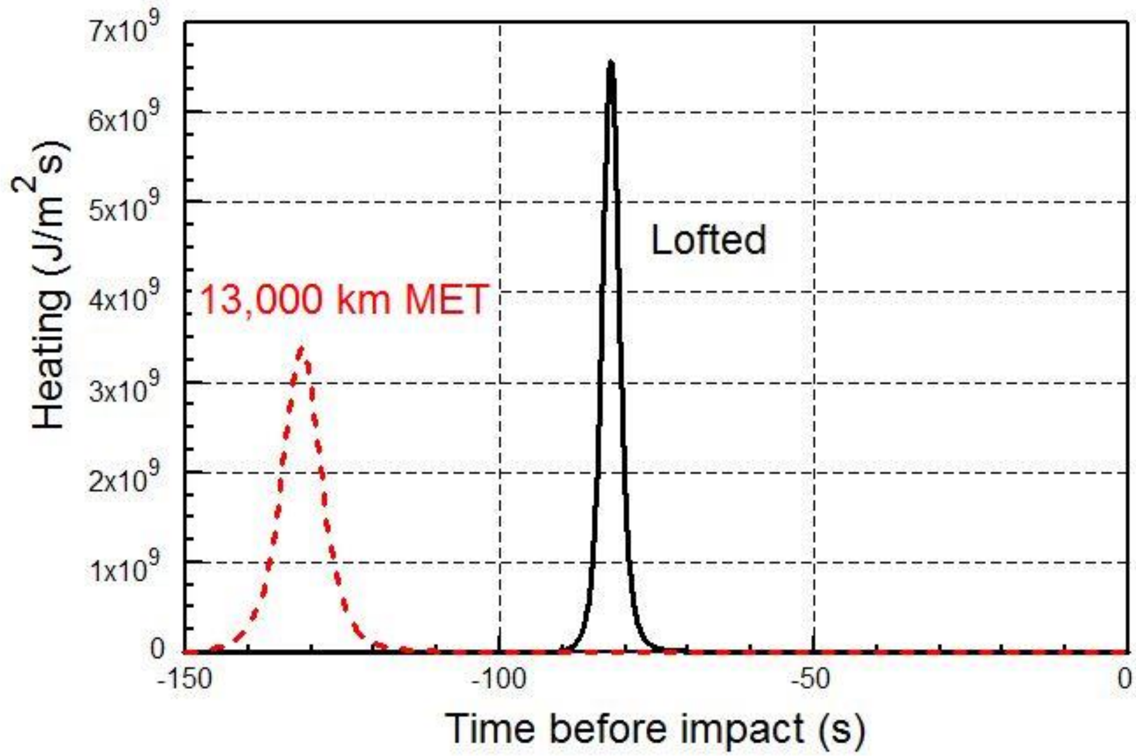

Fig. 5: This figure shows how the heating rate of the RV surface varies with time before impact on the lofted and standard trajectory. The areas under the curves are proportional to the total heat absorbed by the RV, and is only about 20% larger for the MET. The vertical axis plots the product of the atmospheric density and the cube of the RV speed along its trajectory, which is proportional to the heating rate on the RV.

Fig. 6 shows heating on the two trajectories with altitude.

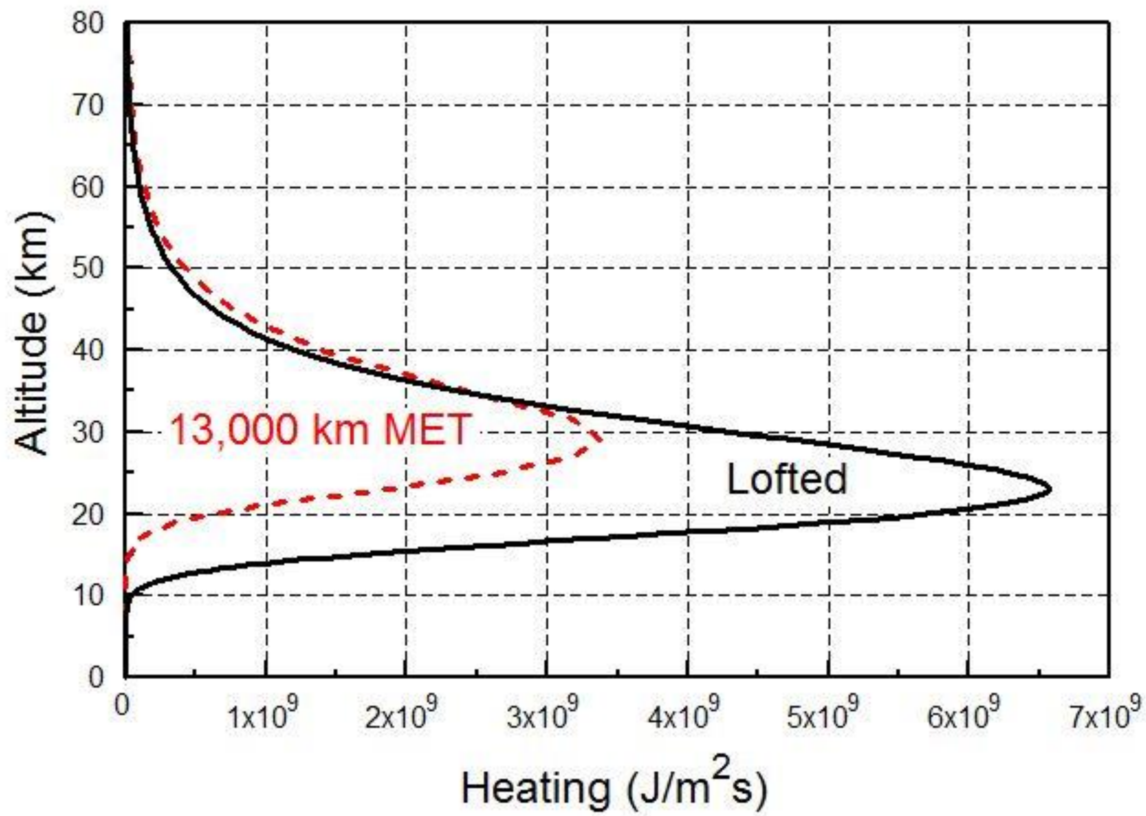

Fig. 6. This figure shows the heating of the RV with altitude as it reenters.

These results show that if North Korea were able to demonstrate that its RV could survive the peak drag forces and heating on a lofted trajectory, it should also be able to survive those on a standard trajectory. As noted above, the estimated capability of the Hwasong-15 missile suggests North Korea would be able to increase the structural strength of the RV and its heat shielding and still be able to deliver a warhead to long distances.

There is still some question about what information North Korea may actually be getting from its tests. One advantage of testing on highly lofted trajectories that fall in the Sea of Japan is that the RV can presumably radio back data to antennae in North Korea for most of the flight. However, because of the curvature of the Earth, an antenna on the ground in North Korea would not be able to receive signals once the RV dropped below about 80 km altitude at a distance of 1000 km. To be able to track the missile down to low altitudes it would likely need a boat or plane in the vicinity of the reentry point.

Some details

The rate of heat transfer per area (q) is roughly proportional to ρV^3, where ρ is the atmospheric density and V is the velocity of the RV through the atmosphere. Since longer range missiles reenter at higher speeds, the heating rate increases rapidly with missile range. The total heat absorbed (Q) is the integral of q over time during reentry. Similarly, forces due to atmospheric drag are proportional to ρV^2, and also increase rapidly with missile range.

The calculations above assume a ballistic coefficient of the RV equal to 100 lb/ft^2 (5 kN/m^2). The ballistic coefficient $\beta = W/C_dA$ (where W is the weight of the RV, C_d is its drag coefficient, and A is its cross-sectional area perpendicular to the air flow) is the combination of parameters that determines how atmospheric drag reduces the RV's speed during reentry. The drag and heating values in the tables roughly scale with β. A large value of β means less atmospheric drag so the RV travels through the atmosphere at higher speed. That increases the accuracy of the missile but also increases the heating. The United States worked for many years to develop RVs with special coatings that allowed them to have high β and therefore high accuracy, but could also withstand the heating under these conditions.

Based on the shape of the front of the Hwasong-15, I estimate that the drag coefficient C_d of its RV is 0.35-0.4. That value gives β in the range of 100-150 lb/ft^2 (5-7 kN/m^2) for an RV mass of 500-750 kg. The drag coefficient of an RV similar in shape to the front of the Hwasong-14 is about 0.15.

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Posted in: Missiles and Missile Defense Tags: hwasong-14, hwasong-15, missiles, North Korea, nuclear weapons

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David Wright, physicist and co-director of the UCS Global Security Program, is an established expert on the technical aspects of arms control, particularly those related to missile defense systems, missile proliferation, and space weapons.