

The secret of the SOVIET HYDROGEN BOMB

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**Was the first Soviet
thermonuclear device really
a step in the wrong direction?**

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No bomb design has been as much maligned or otherwise disparaged as the first Soviet thermonuclear weapon. Detonated in August 1953, the bomb, officially tested under the name RDS-6s but usually known as *Sloika* or “layer cake” (the name Andrei Sakharov coined for it), was nothing to sneeze at. Shown in figure 1 and able to be dropped from aircraft, it released the explosive equivalent, or yield, of almost half a megaton of TNT. The result was a blazing fireball with 20 times the power of the bomb that leveled Nagasaki, Japan.

But when discussed today, the Sloika is almost immediately qualified by US experts as not a “true” hydrogen bomb. The downgrading is a curious reflex, one with interesting cultural and nationalistic origins. At one level, it is a technical determination: The bomb’s design did not allow it to be scaled up to near unlimited explosive yields that true hydrogen bombs would allow, and it differed from what has become the foundation for all modern thermonuclear weapons, the famous US-developed Teller–Ulam design.

Historically, there was also a political reason to downplay the weapon. In the 1950s a lot was at stake for a US government official to say exactly when the Soviets first had true thermonuclear capability or that their first H-bomb was a militarily useless weapon and a dead end from a design standpoint. Decades later, the downplaying of the Sloika remains emblematic of how that phase in nuclear history is spoken of by US historians.

But a perusal of Soviet-era sources released in the past decade and of several new and obscure publications that have come from the Russian weapons establishment has convinced us that the disparaging view is incomplete. The new sources seem to point to two contrary views: First, the Sloika was, in fact, seen as a useful weapon in its own right, even if it was inefficient; it was not “cobbled together” just to make a statement, as some American scientists thought at the time. Second, it was also not as much of a nuclear dead end as it was perceived and is still claimed to be: Rather, it appears to have been

absolutely crucial in helping to solve the riddle of how the Soviets developed their later, multistage, multimegaton thermonuclear weapon designs. Indeed, the Sloika is possibly the answer to the most curious question about the Soviet thermonuclear program: How did it develop a form of the Teller–Ulam design only a year after developing the Sloika?¹

Why do we care?

The origins of the reflexive diminishing of the Sloika are found, in part, in an earlier debate in the US over whether

to develop an H-bomb at all. In the fall of 1949, after the first Soviet atomic bomb test (labeled Joe-1 by the US, RDS-1 by the Soviets), a polarizing debate took place among US scientists and policymakers about whether a crash program to develop the H-bomb was the appropriate response to the loss of the nation’s nuclear monopoly. The debate became public by the end of the year, and the resulting publicity prompted President Harry S. Truman in late January 1950 to issue a mandate to the US Atomic Energy Commission to develop thermonuclear weapons. The problem was that nobody knew how to do such a thing. The H-bomb, which would use the power of nuclear fission to initiate substantial reactions of nuclear fusion, was then still an uninvented technology, an idea without an implementation.²

A few days after Truman’s mandate, the UK announced that physicist Klaus Fuchs had confessed to being a Soviet agent. Fuchs had been a key member of the UK nuclear program and had worked at Los Alamos during and slightly after World War II, before the US had stopped all classified cooperation with the British. Newspapers reported that Fuchs may have passed on information about the H-bomb to the Soviets as well. Now the American narrative was a new one: The Soviets had stolen the design for an atomic bomb, not independently developed or reinvented it, and they were possibly galloping ahead. For Edward Teller and others who had argued in favor of developing the H-bomb, the story was a vindication.³

Thermonuclear research in the US revolved primarily

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around one design, later called the Classical Super. The Classical Super was Teller's *idée fixe* and posed difficult technical problems. The basic idea involved using a high-yield nuclear fission bomb to ignite fusion reactions in a mixture of deuterium and tritium, which would generate enough heat to propagate further fusion reactions. The appeal was that arbitrarily large explosions could be generated that way; just add more deuterium. The problem—aside from the fact that it would require large amounts of scarce tritium and a very large fission stage to set the bomb off—was that it didn't seem to work.

In the spring of 1951, US scientists Teller and Stanislaw Ulam, shown in figure 2, made their famous breakthrough. Instead of a reaction that propagated relatively slowly down a tube of material, one fission bomb (the "primary") would detonate inside a heavy chamber that reflects its radiation to compress another, separate fusion capsule (the "secondary") inside a heavy chamber. That scheme, based on the concepts of staging (keeping the primary and secondary physically separated) and radiation implosion (the use of radiation to compress the secondary), became known later as the Teller–Ulam design. From the perspective of most weapons designers at the time, it was a radical departure from the approach taken with the Classical Super.⁴

The first prototype of the Teller–Ulam design was tested in

November 1952 and was known as shot "Mike" of Operation Ivy. Yielding an equivalent of more than 10 million tons of TNT, the prototype vindicated the concept, though Mike was not designed to be used as a weapon. Its extensive cryogenic equipment, designed to keep deuterium in liquid form, meant that it weighed some 80 tons.

Just before the test, a fierce, secret debate about the importance of Fuchs's information began in the weapons laboratories. Fuchs's last contact with the US thermonuclear program was in 1946. Was information he could have gleaned from the program at that time valuable to the Soviets? On one side was Hans Bethe, who argued that the successful Teller–Ulam design differed so much from the original Classical Super design that anything Fuchs could have given them would be at best irrelevant and at worst completely misleading. Poised against him was Teller, who argued that the theoretical distance between the Classical Super and the Teller–Ulam design was not as large as Bethe thought. Furthermore, he pointed out, Fuchs had himself been involved with working on certain lines of research that eventually proved crucial: Fuchs, along with John von Neumann, had worked on a hydrogen bomb design that involved a version of the concept of radiation implosion.⁵ (See the articles by German Arsen'evich Goncharov, *PHYSICS TODAY*, November 1996, pages 44, 45, 50, and 56.)



FIGURE 1. THE SLOIKA, or "layer cake," is the informal name for the Soviet Union's first thermonuclear bomb. Although its casing was roughly similar in shape and size to Fat Man, the US atomic bomb dropped on Nagasaki, Japan, in World War II, the Soviet bomb was 20 times as powerful: It detonated with the explosive equivalent of 400 kilotons of TNT. (Courtesy of the Russian Federal Nuclear Center, VNIIEF.)

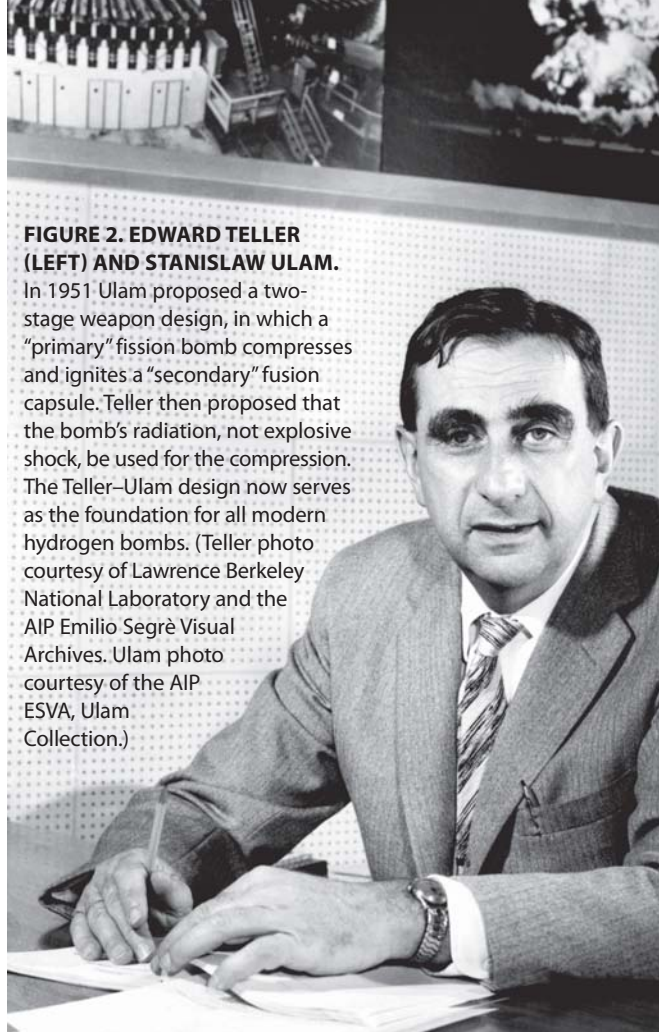


FIGURE 2. EDWARD TELLER (LEFT) AND STANISLAW ULAM.

In 1951 Ulam proposed a two-stage weapon design, in which a "primary" fission bomb compresses and ignites a "secondary" fusion capsule. Teller then proposed that the bomb's radiation, not explosive shock, be used for the compression. The Teller-Ulam design now serves as the foundation for all modern hydrogen bombs. (Teller photo courtesy of Lawrence Berkeley National Laboratory and the AIP Emilio Segrè Visual Archives. Ulam photo courtesy of the AIP ESVA, Ulam Collection.)



The content of the debate was technical, but the reasons for it were clearly political. If Teller was correct, then the US was potentially behind the Soviets in weapons development. In Teller's eyes, it was because people such as J. Robert Oppenheimer stood in the way of his work on the H-bomb in the years after World War II and squandered a potential lead. If Bethe was correct, though, then not only would Fuchs be unable to pass on useful information about later US H-bomb design (since he did not know anything about it), but Oppenheimer would be vindicated for not supporting Teller's early, wrong-footed schemes. That debate started in the spring of 1952, even before the Mike test, and versions of it arguably continue today in any history of the thermonuclear program.

The Soviet Sloika entered the story in the middle of the debate and before the US had tested deliverable versions of the Teller-Ulam design. On 8 August 1953, Soviet premier Georgi Malenkov gave a speech to the Supreme Soviet in which he declared that "the United States has no monopoly in the production of the hydrogen bomb." On 12 August, the fourth Soviet nuclear test, dubbed Joe-4 in the US, was detonated over the Kazakh steppe. On 20 August, *Pravda* published a statement proclaiming that "within one of the last few days an explosion of one of a variety of hydrogen bombs was carried out for experimental purposes" and attributed its "great strength" to a "mighty thermonuclear reaction."⁶

It looked, then, as if the Soviets might be keeping pace with the US, if not beating it: If the Joe-4 test was of a deliverable thermonuclear bomb, then the Soviets could be seen as ahead in the H-bomb race in one sense, because the US Mike device

was an experimental apparatus, not a weapon. More than US pride was in the balance: A leading Soviet program might be a vindication of those who said that the US program had been needlessly stalled.

By September 1953, however, there were reasons to doubt that the Soviets were, in fact, ahead in the race for a deliverable H-bomb. A panel consisting of physicists Bethe, Enrico Fermi, Richard Garwin, and Lothar Nordheim conducted an analysis of the fallout residues from the August test. Their full conclusions are still redacted more than six decades later, but from what has been released, we can see they found that the Joe-4 test used highly enriched uranium, not plutonium, and that it involved "a substantial thermonuclear reaction." They were able to estimate the amount of uranium in the device and the amount of energy release attributable to fusion reactions, and they could speculate on the geometry of the device. They concluded that it was not a Teller-Ulam design but a weapon that had achieved "a high-yield, high-efficiency [fission] reaction with the help of the boosting principle." Bethe would later call the device "a big boosted fission weapon" and "a glorified booster," and he would say that it was clear from the analysis that it was a "single stage" weapon that involved "alternating layers of uranium and lithium deuteride."⁷

The Soviet bomb was therefore not really an H-bomb, if by H-bomb one means something along the lines of the Teller-Ulam design. Instead, it shared characteristics with two other thermonuclear designs the US had pursued. One design, Booster, involved a fission weapon that had a small amount of deuterium-tritium gas injected into its core at the moment of

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its detonation, which generated enough fusion neutrons to cause extra fission reactions.

The other design was one Teller had proposed in 1946 as the Alarm Clock—a weapon that would use spherical layers of fissionable and fusionable fuel in a matryoshka-doll arrangement, one sphere inside the other. The design had serious negatives: Its fusion yield would necessarily be limited, primarily serving to enhance fission reactions, like Booster; the various layers would interact in complex ways that were extremely difficult to calculate with the computing technology of the time; and to increase the Alarm Clock's yield to the megaton scale meant increasing a bomb's radius so much that it would not fit inside a bomber. For Teller, the fact that Alarm Clock's yield could not be increased indefinitely made it less interesting. Like the Booster, it was considered an auxiliary approach to what was then still the main show, the Classical Super.

If Joe-4, the Sloika, was just an Alarm Clock, then it wasn't the main show. If it was a glorified Booster, it definitely wasn't an H-bomb. But the Soviets saw it somewhat differently.

The Soviet view of Sloika

The Soviets called their H-bomb design the Sloika in reference to a layered Russian pastry similar to a napoleon. The code name hints at the bomb's internal geometry: layers of highly enriched uranium, fusion fuel made of solid lithium deuteride, lithium deuteride tritide, and uranium tamper materials, all of which would be compressed by high-explosive lenses. Many details, such as the number of layers, their order, and their relative masses, remain classified.

Declassified documents and imagery indicate that the test device was roughly a sphere, 1.5 meters in diameter, and that it weighed about 4.5 tons. The test device apparently fit into the same casing as the original Soviet atomic bomb and differed from the production-line (military) version of RDS-6s mainly in that the latter used two to three times as much tritium and uranium-235 as the test version and thus would have likely had a substantially larger yield.⁸ In terms of weapons design, that size is not extreme (see figure 1)—it would be roughly the same shape and weight as the US Fat Man bomb dropped on Nagasaki, Japan, in World War II, though with a far more powerful explosion.

The basic problem with the Sloika, from a weapons designer's viewpoint, is that chemical high explosives simply lack the power to compress the entire mass sufficiently for substantial fusion reactions to occur. Such a weapon would also be extremely expensive in terms of enriched uranium usage.

As tested in 1953, the Sloika detonated with an explosive yield of 400 kilotons, of which around 80% of the energy came from fission reactions and 20% came from nuclear fusion. That ratio of fission-to-fusion reactions is less useful in determining a true H-bomb than it might seem: The Mike design, like practically all US H-bombs, relied heavily on a final uranium fission stage to increase its yield, and it had the same fission/fusion ratio as the Sloika. As J. Carson Mark, one of the few US weapons designers not to quibble about the status of the Sloika, argued in an interview: "They managed to get 400 kilotons without going to an unreasonable or even a heavier size. And, they did it by using thermonuclear reactions. Want to call that a hydrogen bomb? Well, why not?"⁹

Where Sloika really loses is in terms of the yield-to-weight

ratio, the amount of energy release divided by the total bomb weight, which is the preferred method by which weapons designers gauge weapon sophistication. At 0.08 kilotons of energy per kilogram of bomb weight, the Sloika was an order of magnitude better than Fat Man, but still an order of magnitude less efficient than the first deliverable US H-bomb designs.

Documents declassified in the past decade give us some insight into how the RDS-6s device was viewed by those who made it. Although privately the Soviet designers also would consider it a glorified booster, they had grand plans for the Sloika. Contrary to US analyses that insisted those weapons could never achieve yields much greater than the 1953 test, the Soviets originally envisioned it as a megaton-range weapon.

But the multimegaton Sloika proved more difficult to develop than Soviet nuclear scientists, including Andrei Sakharov, originally envisioned. Serious problems emerged because a Sloika of a particular diameter could only make efficient use of expensive materials such as uranium-235 and tritium up to a certain yield. By mid 1954 it became clear that within the 1.5-m radius dictated by the size of delivery vehicles, constructing a Sloika with a yield greater than 0.5–1.0 megaton without using costly tritium would be difficult.

Over the next year, some of the Soviet Union's most brilliant technical experts devoted their attention to constructing a cost-effective, multimegaton Sloika. They also explored developing a design with a focus on economy rather than yield. That effort resulted in a new budget-friendly design that was the same size as the multimegaton Sloika but with a yield of only 350 kilotons. Soviet nuclear scientists, however, insisted that the seemingly inferior weapon exploited the full potential of the Sloika concept for maximizing yield while minimizing the need for scarce nuclear materials such as lithium-6, making it vastly more cost-effective.

In September 1953 the Bethe panel produced a lengthy analysis, in which it asserted that weapons on the Sloika principle would scale poorly even if "the yield they have achieved is certainly enough to cause concern." How are we to account for the contrast between Bethe's dismissal of the RDS-6s design and the Soviets' ambitious plans for the Sloika? One possibility is that Bethe's conjectural reconstruction of the weapon's internal geometry was in error, but we cannot be sure, as both Bethe's analysis and the design details of the Soviet device remain classified.

However, given the extreme difficulty the Soviets experienced developing the megaton-scale version of the RDS-6s (dubbed the RDS-6sd), it is also possible that their ultimate design differed very substantially from the weapon tested in 1953. For a predicted yield of 1.8 megatons, it may have incorporated a dissimilar internal geometry, different materials, and counterintuitive features that never occurred to Bethe or other US scientists who lacked hands-on experience with weapons of the Sloika type. Bethe's dismissal of the Sloika may also have been based on the analysis that had been done in the US on the Alarm Clock; although it shared a similarly layered design with the Sloika, it may also have differed in several ways.

By August 1955 both the RDS-6sd and its budget version were ready for testing, but the imminent arrival of a more advanced rival delayed their debut. After struggling to improve the Sloika, the Soviets had finally hit on their version of the Teller-Ulam design. They called it Sakharov's Third Idea, and

gave the prototype the code name RDS-37. A two-stage weapon employing radiation implosion to produce a multimegaton yield, the RDS-37 used about a quarter of the nuclear explosive materials the RDS-6sd used and had the capacity for a much greater yield in a package that the Soviet Union's bombers and missiles could carry. Soviet leaders decided to wait to test the costly multimegaton Sloika until after the performance of Sakharov's new invention could be verified in a live test.

The successful airburst of the RDS-37 on 22 November 1955 sounded the death knell of the RDS-6sd and, in time, all other Sloikas. Deliberately detonated at half its total predicted power, the weapon fit into the same case as the Sloika but released 1.6 megatons of energy. Assuming its weight was similar to the Sloika's, it was a full order of magnitude more efficient and, more importantly, much more flexible for scaling weapon

output both up and down. The handful of RDS-6sd devices were promptly dismantled so their precious lithium-6 and enriched uranium could be incorporated into more modern weapons. The Sloika had passed into history.

The Sloika's legacy

Was the Sloika merely a dead end? The Soviet records suggest not. For Soviet weapons designers, Sloika served as a means of exploring thermonuclear concepts while still producing deliverable weapons that though not as powerful as later developments were large enough to be considered serious city busters. Moreover, reading between the lines of the secret Soviet histories, there are reasons to suspect that Sloika was more important to their program than one might expect.

No doubt the Soviet fission bomb program owed much to

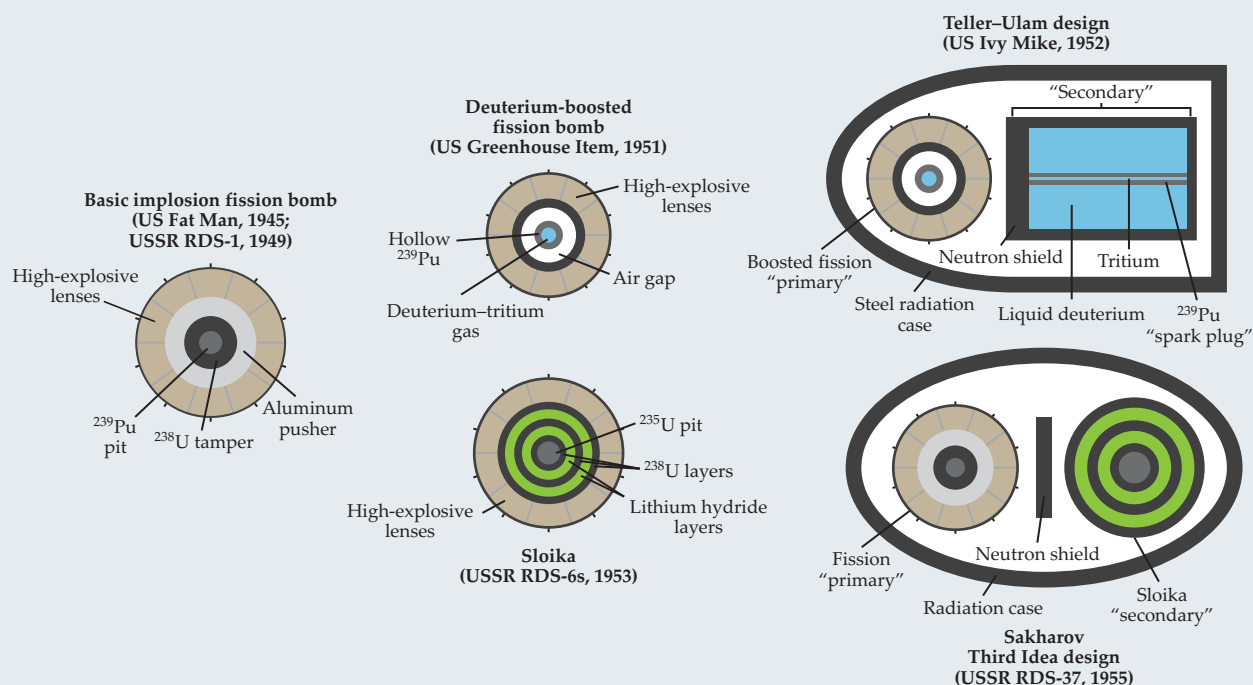
TWO APPROACHES TO THERMONUCLEAR WEAPONS

In a basic implosion bomb, like the one dropped on Nagasaki, Japan, a solid-metal plutonium core is compressed using high-explosive lenses and an aluminum pusher to around 2.5 times its original density. In the deuterium-boosted design, a hollow core of plutonium is injected with deuterium-tritium gas at the moment of detonation, which causes a small number of fusion reactions. Those reactions produce high-energy neutrons that enhance the efficiency of the fission reactions in the core. In the *Sloika* design, alternating layers of lithium hydride and uranium-238 surround a uranium-235 core. The high-explosive lenses compress the entire core

and set off of a fusion reaction that in turn compresses the fusion fuel. The fusion reactions produce high-energy neutrons that induce further fissioning.

These bomb designs are the basic ingredients that the US and the Soviet Union adapted into thermonuclear weapons—also known as H-bombs. In the original US Teller-Ulam design, a boosted fission bomb sits at one end of a heavy radiation case. At the other end sits the thermonuclear charge, a cylinder with a neutron shield on one end, liquid deuterium inside it, and a thin “spark plug” of plutonium mixed with tritium. At detonation, the radiation from the fission bomb reflects off

the inside of the radiation casing and compresses the thermonuclear charge to many times its original density. The compression, in turn, begins a fusion reaction in the “spark plug,” which compresses the fusion fuel from the other side simultaneously. Thus compressed, the fusion fuel is primed for fusion reactions, which contribute significantly to the explosive yield. The reactions produce high-energy neutrons that induce further fissioning in a uranium-238 tamper. Sakharov's “Third Idea” adopts a similar scheme, except the neutron shield is integrated into the overall design, and the Sloika is stripped of its high-explosive components.



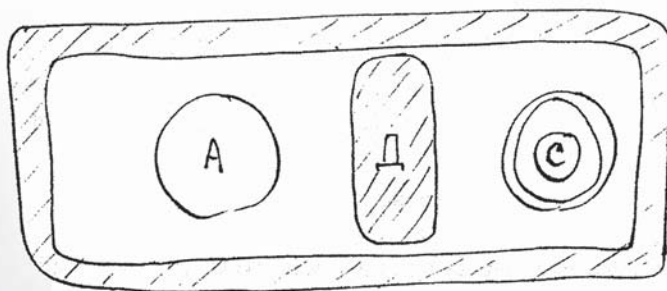


FIGURE 3. ANDREI SAKHAROV is pictured next to the first formulation of the “Third Idea,” a heavy box containing an atomic bomb (A), a neutron shield or diaphragm (Д, the Cyrillic letter for “D”), and a Sloika (C, the Cyrillic letter for “S”). (Sakharov photo from the Russian Federal Nuclear Center, VNIIEF Museum and Archive, courtesy of the AIP Emilio Segrè Visual Archives; diagram adapted from ref. 8, doc. 56, p. 128.)

espionage. The work of spies such as Ted Hall and David Greenglass allowed the Soviet Union to have a reasonably good understanding of what went into the construction of plutonium-implosion nuclear weapons, and its first fission bomb, RDS-1, was a “Sovietized” copy of the weapon dropped on Nagasaki.¹⁰

The Soviets also received some information on US thermonuclear work from Fuchs. Declassified documents from the Soviet archives show that Fuchs gave them extremely detailed accounts of the state of US work as of 1946 and of the work he did with von Neumann. The Soviets did have a research program for the Classical Super design, which they dubbed the *Truba*, or “Tube,” that ran parallel with the Sloika work.^{11,9}

As noted earlier, the Soviets eventually hit upon the two-stage, radiation implosion design known in the US as the Teller–Ulam idea. Although the Soviets called it Sakharov’s Third Idea (see figure 3), internally they noted that exact authorship was difficult to determine. As Lev Feoktistov, a scientist on the project, recalled, “New ideas dawned upon us suddenly like light in a dark kingdom, and it was clear that the instant of truth had come. Rumors ascribed these fundamental thoughts in Teller’s spirit now to [Yakov] Zel’dovich, now to Sakharov, now to both, or to someone else, but always in some indecisive form: likely, possibly, and so on.”¹² The first two ideas were, in order, the Sloika’s layering scheme and the use of lithium deuteride as a fusion fuel; both had been well-documented by 1949.

Both the Third Idea and the Teller–Ulam design differentiate themselves from earlier H-bomb designs in their use of radiation energy as a means of achieving extremely high densities in a thermonuclear assembly (see the box on page 45). As

Soviet designers drew it, the weapon was a heavy box with an atomic bomb at one end and the thermonuclear capsule at the other. In the earliest US Teller–Ulam designs, the capsule was a cylinder with multiple layers: on the outside a heavy tamper, then liquid deuterium or lithium deuteride, and in the center a “spark plug” of plutonium and tritium.¹³

The first record of that idea from the Soviet archives dates from January 1954, a brief memo from Zel’dovich and Sakharov titled “On the use of a gadget for implosion of supergadget RDS-6s.”¹⁴ The memo describes a heavy box inside which an atomic bomb (labeled “A”) sits at one end, a neutron shield (labeled the Cyrillic character for “D”) sits in the center, and what looks like a Sloika (labeled with a Cyrillic “S”) sits at the other end (see figure 3). Along with the title of the paper, the sketch suggests a plausible genealogy of the Third Idea: The Sloika became a second stage of a two-stage thermonuclear weapon, the “supergadget” imploded by the fission “gadget.”

Much remains missing in our knowledge of Soviet thermonuclear developments, but the path to the Third Idea may have been paved in part by the intensive work on the Sloika. The chief practical problem of that device is achieving the high compressions one needs for fusion. If high explosives can’t cause them, what can? A new approach appeared to answer the question: using a fission bomb to compress the entire Sloika, first imagined as a compressive shock, later as radiation implosion. The Sloika, minus its high explosives and simplified a bit, is essentially a high-performance thermonuclear secondary: layers of fusion fuel, tamper, and fission material.

Over the decades many authors have asserted that the Soviet Union somehow learned of radiation implosion from the US rather than developing it independently. In more recent decades, a few accounts have asserted that the Soviets could not have discovered radiation implosion on their own and that a still-unidentified mole must have given away the secret of the H-bomb.¹⁵

Declassified Soviet documents contradict those views. They reveal that the thermonuclear information the Soviets got from spies was of limited value and not responsible for the work on either the Sloika or the later RDS-37 device. There is simply nothing to suggest that the Soviet scientists had insight into US

weapons designs; even after they developed their own two-stage design, Soviet nuclear scientists remained uncertain whether the American bombs operated on the same principle.¹⁶ And if the Russian security services could have taken credit for the Soviet H-bomb, which would serve to delegitimize the dissident Sakharov, it seems likely they would have done so by now.

If just one lesson were to be taken from the history of the Sloika, it may be that in the journey toward invention there is no single path to a right idea. Too often the American case is taken to be the default path of technological development, often because the US did it first and perhaps because it is much easier to document than other countries' programs. But the secrecy involved meant that each national program, to various degrees, reinvented the bomb, and finding some national variances should not be so surprising.

The Sloika, rather than just being a relic, sheds much light on alternative approaches toward a similar technological end.

REFERENCES

1. For more information on US scientists' perceptions of the Sloika, see R. Rhodes, *Dark Sun: The Making of the Hydrogen Bomb*, Simon & Schuster (1995), p. 524.
2. See, for example, G. Herken, *Brotherhood of the Bomb: The Tangled Lives and Loyalties of Robert Oppenheimer, Ernest Lawrence, and Edward Teller*, Henry Holt & Co (2002).
3. Ref. 2, chap. 12.
4. Ref. 1, chaps. 23, 24; K. Ford, *Building the H Bomb: A Personal History*, World Scientific (2015), chaps. 9–14.
5. H. Bethe, "Memorandum on the History of the Thermonuclear Program" (28 May 1952), documents NV0318420 and NV0311423, Nuclear Testing Archive, Las Vegas, NV; E. Teller, "Comments on Bethe's History of the Thermonuclear Program" (14 August 1952), document NV0318421, Nuclear Testing Archive. For information on the Fuchs–von Neumann design, see J. Bernstein, *Phys. Perspect.* **12**, 36 (2010).
6. *New York Times* (10 August 1953), p. 6; H. E. Salisbury, *New York Times* (20 August 1953), p. 1.
7. H. Bethe et al., "Analysis of Joe-4," (11 September 1953); H. Bethe, *Bull. At. Sci.* **46**(8), 8 (1990), p. 8; H. Bethe, quoted in C. Hansen, *The Swords of Armageddon: U.S. Nuclear Weapons Development Since 1945*, 2nd ed., vol. 3, Chuckelea Publications (2007), p. 136; H. Bethe, quoted in ref. 1, p. 524.
8. See, for example, I. E. Tamm, A. D. Sakharov, Y. B. Zel'dovich, in L. D. Riabev, ed., *Atomnyi proekt SSSR: Dokumenty I materialy*, vol. 3, bk 2, VNIIEF (2009), doc. 5, p. 21.
9. Y. B. Khariton, V. B. Adamskii, Y. N. Smirnov, *Phys. Usp.* **39**, 185 (1996); J. Carson Mark, interview by R. Rhodes (undated), transcript available at Voices of the Manhattan Project, www.manhattanprojectvoices.org/oral-histories/j-carson-marks-interview.
10. M. Gordin, *Red Cloud at Dawn: Truman, Stalin, and the End of the Atomic Monopoly*, Farrar, Straus, and Giroux (2009), chaps. 3, 4.
11. Ref. 4, Ford, p. 99.
12. L. Feoktistov, quoted in G. Goncharov, *Phys. Usp.* **40**, 859 (1997), p. 864.
13. Ref. 4, Ford, p. 156.
14. R. B. Zel'dovich, A. D. Sakharov, note to I. B. Khariton, in ref. 8, doc. 56, p. 128.
15. D. Hirsch, W. G. Mathews, *Bull. At. Sci.* **46**(1), 22 (1990); T. C. Reed, D. B. Stillman, *The Nuclear Express: A Political History of the Bomb and Its Proliferation*, Zenith Press (2009), p. 34.
16. A. P. Zaveniagin et al., to the Presidium of the Central Committee, in ref. 8, doc. 170, p. 394. PT

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