Ripple

An Investigation of the World's Most Advanced High-Yield Thermonuclear Weapon Design

✣ Jon Grams

> **President Kennedy:** What about our tests? How would you summarize our tests, as far as . . . so, how would they? If they were talking about our tests would they dismiss them quite as you dismiss theirs?
> **Glenn Seaborg:** I think that they would not be able to understand the sophistication of some of the biggest advances we have . . .
> **Unidentified:** our most advanced idea, namely the Ripple concept, leads to an inherently clean system and maximum efficiency . . .
> **McGeorge Bundy:** It may be worth just a moment to explain what that is. . . . Because that is probably the most important technical development in our own Dominic series.
> **Carl Kaysen:** That's the sort of breakthrough of the Livermore laboratory.[1]
>
> White House Meeting on the Dominic Nuclear Test Series,
> 5 September 1962

In 1962, the United States conducted the last in a series of atmospheric nuclear test operations that began in 1945. The most important—and still most highly classified—tests were of a concept that, 60 years on, constitutes what is arguably the pinnacle of thermonuclear explosives technology: the Ripple concept devised by Lawrence Radiation Laboratory (LRL).[2] In all probability, the Ripple device was the most advanced full-scale fusion device ever tested, with efficiency levels an order of magnitude greater than current designs. This

1. Meeting on the Dominic Nuclear Test Series, 5 September 1962, in Tape 20, Box MTG, President's Office Files, John F. Kennedy Presidential Library (JFKL), Boston, MA.

2. The facility now known as Lawrence Livermore National Laboratory (LLNL) was founded in 1952 as the University of California Radiation Laboratory at Livermore. It was renamed the Lawrence Radiation Laboratory in 1958. This name lasted until 1971, when the laboratory was given its current name. Throughout the decades, LLNL has always been referred to in short form as "Livermore," which will be used as shorthand throughout this article.

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research note seeks for the first time to establish the technological and historical significance of the Ripple concept within the broader context of the U.S. nuclear weapons program. The article also looks at the concept of a "clean" nuclear weapon and its significant role in the politics of nuclear weapons and in the evolution of strategic deterrence. Guidance on technical aspects was provided by Carey Sublette, administrator of the Nuclear Weapon Archive.[3] Off-the-record interviews with former Livermore Laboratory directors John S. Foster, Jr., and John Nuckolls provided additional insight. Given the technical complexity of the subject and a desire to keep length reasonable, it is assumed that the reader has a rudimentary knowledge of nuclear weapon history and design principles.

Operation Redwing and "Clean" Weapons

To help explain the significance of the Ripple concept and the context in which it was devised, we begin with this 1955 letter from then Secretary of Defense Charles E. Wilson:

> Until the CASTLE (1954) tests confirmed the feasibility of megaton yields at comparatively small cost, military economy in the atomic weapons field had been largely dominated by blast effects and means of maximizing these (effects) in relation to design and delivery costs. As important as these blast considerations still are, we are now confronted with perhaps even more important considerations in the radioactive by-products field. Stated broadly, the problem appears to be that of maximizing the military effect at the desired time and place, and minimizing such effects where they are not desired. While blast effects are essentially instantaneous and local, the radioactive effects may cover very large areas and may persist for very long periods ranging, in fact, from days in the local fallout effects to many years in atmospheric contamination effects. In other words, radioactive effects force us to bring time in as an additional dimension in dealing with this problem. Moreover, the areas subject to lethal radiation are so large, that in planning the use of these weapons we must carefully weigh the damage to friendly as well as enemy installations.[4]

The importance of this letter lies in its recognition that blast effects are only one part of a much larger equation when dealing with nuclear weapons. The

3. The Nuclear Weapon Archive is an online, nongovernmental compilation of open-source documents and commentary on nuclear weapons history and technology.

4. C. E. Wilson, Secretary of Defense, to Lewis Strauss, USAEC, 5 March 1955, quoted in Chuck Hansen, *Swords of Armageddon Version 2*, CD-ROM (Sunnyvale, CA: Chukelea Publications, 2003), pp. 78–79.

issue of radiation and fallout played a significant role in the next Pacific test series and charted the course for new developments in nuclear weapons technology.

The lessons learned and questions raised in 1954 by Operation Castle, the first high-yield thermonuclear weapon test series conducted by the United States, were the subject of the next high-yield series, Operation Redwing, in 1956. Highlighting growing public concern, the issue of fallout took center stage. Between the conclusion of Castle and the beginning of Redwing, the nuclear weapons laboratories were directed to focus their design efforts in two specific areas: first, improving device yield-to-weight ratios and reducing overall size and weight to enable delivery by ballistic missiles; and second, nuclear weapon designs with fission byproducts reduced to the absolute minimum achievable.[5] Development of a "clean" nuclear weapon was proposed:

> A "clean" weapon was one designed to either minimize or greatly reduce the radioactivity of the particulate debris resulting from its detonation. A "conventional" weapon, on the other hand, was one which was designed without special efforts to reduce or minimize fission products or other radiation resulting from its detonation.[6]

Designing a clean nuclear weapon was a difficult proposition. The multiple crucial roles played by fissile material in the Teller-Ulam design (the basis for all thermonuclear weapon designs to this day) limited how "clean" a weapon could be.

> Our development objective should be to develop a weapon whose fission radioactivity will not be such as to (deposit) serious fallout outside the blast and thermal mortality areas. This means that we can tolerate a percent or two fission yield. It will probably be very costly of materials, difficult and time-consuming to narrow the fission yield from a few percent to a fraction of a percent.[7]

A "standard" thermonuclear weapon has a minimum fission fraction of no less than 50 to 60 percent. In the relatively low-yield weapons that currently

5. Expressed as energy yield in kilotons of TNT versus device (physics package) weight in kilograms or kt/kg.

6. Memorandum for K. E. Fields, General Manager, USAEC, from J. H. Morse, Jr., USAEC, Subject: Standardized Weapon Terminology, 1 March 1957; and Memorandum to K. E. Fields, General Manager, USAEC, from Brig. Gen. A. D. Starbird, USA, Director of Military Application, USAEC, Subject: Standardized Weapon Terminology, 5 April 1957, both quoted in Hansen, *Swords of Armageddon Version 2*, p. 263.

7. Memorandum for Lewis Strauss, USAEC Chairman from Brig. Gen. A. D. Starbird, Director of Military Application, USAEC, Subject: Clarification of Certain Matters Relative to Cleanliness in Weapons, 11 July 1957, quoted in Hansen, *Swords of Armageddon Version 2*, p. 291.

constitute the U.S. arsenal, the fission fraction rises to over 80 percent, a direct result of a focus on minimizing physical dimensions.

In 1958, amid a steadily increasing pace of atmospheric nuclear tests after years of failed negotiations with the Soviet Union on limiting such tests, the U.S. and Soviet governments initiated a moratorium that lasted three years. Weapons design continued but without the benefit of testing. In April 1960, General Alfred D. Starbird, director of military application for the Atomic Energy Commission (AEC), asked the Livermore and Los Alamos laboratories to predict what could be accomplished over the next few years in nuclear weapons technology if testing were resumed. Livermore's Edward Teller and Harold Brown predicted that by 1965 a 50-megaton yield would be possible from a device weighing only 6,000 pounds—an approximately 350 percent increase over the most efficient weapon ever built, Livermore's own B-41.[8] These figures represented a yield-to-weight ratio of 18.4 kilotons per kilogram (kt/kg), thus exceeding the total raw energy content of plutonium and obliterating the "Taylor Limit" of six kt/kg of device weight (the most advanced weapon in the arsenal today, the Livermore/Los Alamos W-88, registers in at around 1.5 kt/kg).[9] Los Alamos Director Norris Bradbury saw things differently:

> Bradbury also replied, stating that in his opinion, things were less optimistic than Teller seemed to feel and: "In short, nothing has occurred in the last year and a half to change my own opinion regarding the extent of weapons gains possible with limited testing or even unlimited testing. I am much less optimistic than Teller on both points."[10]

Bradbury's response, depicting the prediction made by Teller and Brown as wildly optimistic and frankly unachievable barring some unforeseen breakthrough, offers a glimpse of just how significant a leap forward the Ripple concept would be. The audacity of the prediction was highlighted by Bradbury five years earlier:

8. William Ogle, *An Account of the Return to Nuclear Weapons after the Test Moratorium, 1958–1961* (Las Vegas: U.S. Department of Energy, Nevada Operations Office, October 1985), p. 186.

9. Los Alamos physicist and weapons designer Theodore Taylor pegged the maximum practical limit for the yield-to-weight ratio of the Teller-Ulam concept at 6 kt/kg. This theoretical limit is widely accepted to this day; primarily because the purposefully compact, relatively low-yield weapons in current arsenals simply cannot approach such efficiency levels.

10. Ogle, *An Account of the Return to Nuclear Weapons*, p. 186.

> It should be clearly recognized that what the AEC now has in its LASL [Los Alamos Scientific Laboratory]-Livermore weapons research complex is almost precisely identical with the "competition" set up for aircraft manufacturers in the design of a new plane. All the designs submitted are basically the same because aerodynamics is a science and not an art, and no manufacturer will propose to produce an airplane which will fly twice as far, twice as fast, for half the weight his competitor will propose.[11]

With the Ripple concept, Livermore was proposing to do precisely that.

A new problem appeared at this time: the anti-intercontinental ballistic missile (AICBM), a term later simplified to anti-ballistic missile (ABM). The ABM threatened the previously unquestioned invulnerability of intercontinental ballistic missiles (ICBMs) to interception. The initial solution to this more serious problem consisted of two parts. The first was to allocate a portion of the already limited payload capability of the ICBM to penetration aids, or "decoys," to fool ABM guidance systems. The second was to detonate the warhead at the minimum effective altitude of the penetration aids in order to close the window of vulnerability to interception. The following excerpt from the 1963 Joint Task Force Eight (JTF-8) scientific report on Operation Dominic details the solution of this problem as one of the objectives of the Ripple program:

> The objectives of the Ripple concept were to investigate new ranges of yield-to-weight ratio possibilities in the design of high yield thermonuclear warheads [Deleted]. . . The Department of Defense is extremely interested in obtaining maximum yield warheads in the 3,000 to 10,000-pound weight class for use in the larger missiles. High yields with smaller weights will allow a larger percentage of the payload to be allotted to penetration aids and also permit penetration from substantially higher altitude while providing a yield which would create the desired ground damage. . . . The growing concern over the ability of our strategic missiles to penetrate enemy defenses has developed a requirement for penetration aids which must be included in the payload. For larger missiles such as the Atlas, Titan I and Titan II, it might be possible to allocate a small fraction of the payload weight to penetration aids which would assist in successful penetration to altitudes in the neighborhood of 50,000 feet. However, detonations at such high altitudes will not create the desired damage on the ground unless substantially higher yields are available at useable weights.[12]

11. N. E. Bradbury, Director, LASL, to Brig. General K. E. Fields, Director of Military Application, USAEC, 22 September 1954, quoted in Hansen, *Swords of Armageddon Version 2*, p. 25.

12. "Report by Commander Joint Task Force Eight to the Chairman, United States Atomic Energy Commission and the Joint Chiefs of Staff on the 1962 Pacific Nuclear Tests (Operation Dominic)

Teller himself had urged research in this direction in December 1961:

> On December 7, responding to the president's request, Teller pointed out the surprises that we had already seen in the Soviets' progress to date, commented that . . . we should work on high yield warheads that could do damage at high altitudes, hence reducing the effectiveness of the Russian missile defense system.[13]

As the JTF-8 scientific report relates, this solution dictated the use of extremely high warhead yields (in excess of 35 megatons for detonations at 50,000 feet) to create the same degree of blast damage as a typical low or sub-megaton range warhead detonated close to ground level for a given surface area. Furthermore, these very high yields would need to be obtained with no increase in warhead weight to enable the use of current and projected ICBM systems; namely, the Atlas F and Titan II (Minuteman was entering service at this time but could not carry payloads in this weight category). This would require a technological leap surpassing the sum total of all the gains that had been made in the previous twelve years of thermonuclear weapons development.

The method by which the Ripple concept was arrived at reveals a novel divergence from the typical pattern of nuclear weapon development. The story begins in 1955, when 24-year-old John H. Nuckolls joined Livermore as a thermonuclear explosives designer:

> I was introduced to Teller's radiation implosion scheme in the summer of 1955, after I left Columbia University Physics Graduate School to accept a position in Livermore's Thermonuclear Explosives Design Division. I learned that matter can be highly compressed when subjected to the enormous pressures generated by a nuclear explosion, and that high densities are essential for practical TN [thermonuclear] explosives.
>
> As a 24-year-old assistant to Harold Brown, the 26-year-old TN Design Division Leader, I studied nuclear explosives and weapons design code development and use.[14]

In 1957, at the behest of LRL director Brown, Nuckolls began directed research into the concept of fusion as a potential source of clean energy. The initial idea involved the periodic detonation of a "clean" one-megaton thermonuclear devices confined in a large, shielded, water-filled underground

Enclosure L Report of Scientific Summary," Headquarters, Joint Task Force Eight, Washington, DC, 4 June 1964, pp. L-B-1-1–2, available online at https://www.dtic.mil.

13. Ogle, *An Account of the Return to Nuclear Weapons*, p. 314.

14. Guillermo Velarde and Natividad Carpintero Santamaría, eds., *Inertial Confinement Nuclear Fusion: A Historical Approach by Its Pioneers* (London: Foxwell & Davies, 2007), p. 4.

cavern to produce energy through thermal conversion of trapped steam. One device could provide seven days' worth of power generation. This was impractical and prohibitively expensive, particularly because of the required use of fission primaries for each thermonuclear device.[15] Nuckolls therefore reduced the size of the cavity and sought to eliminate the nuclear primary. Most significantly, he found that large yields were not necessary, that a small thermonuclear explosion contained in a relatively small, purpose-made chamber could provide the energy required. This proved doubly beneficial as only a very small amount of thermonuclear fuel could (potentially) be ignited by a non-nuclear primary or "driver." The next requirement was a high-potential thermonuclear fuel that was optimized for the non-nuclear driver. The answer lay in a deuterium-tritium (DT) mixture (tritium has the lowest ignition temperature of any available thermonuclear fuel).

> Could very small DT burning fusion explosions be ignited without an A-bomb? [DT burns 100 times faster than D.] In the late 1950s, John Foster, Fission Weapons Design Division Leader, invited me to attend meetings of his special group focused on how to ignite DT fusion explosions without use of an A-bomb. Physicists Ray Kidder, Jim Shearer and Jim Wilson were members of this group. Kidder developed useful approximations to the conditions for ignition of a small DT mass confined by a pusher [a dense metal shell].[16]

The "pusher" mentioned here is the same concept as the heavy metal tamper used in the secondary of the Teller-Ulam design. The small DT mass is essentially a minuscule thermonuclear (TN) secondary.

> Beginning in early 1960, I used the weapons programs' latest radiation implosion and TN burn codes to explore the feasibility of igniting a DT fusion microexplosion with a tiny radiation implosion. I postulated that a "non-nuclear primary" could be invented to energize a tiny radiation implosion.[17]

Nuckolls's initial ideas for a non-nuclear primary or "driver" included a plasma jet, hypervelocity pellet gun, and particle beam. However, the appearance in 1960 of the first working laser provided what would become—and still is to this day—the non-nuclear driver of choice. With this last piece of the puzzle, the concept of inertial confinement fusion (ICF) was born.

Even though the basic ICF concept was now established, significant challenges remained in designing a high-performance DT "microfusion"

15. Given the peak inventory of some 32,000 nuclear weapons, such a plant could provide energy for hundreds of years.

16. Velarde and Santamaría, eds., *Inertial Confinement Nuclear Fusion*, p. 6.

17. Ibid.

secondary, or *target*, that would produce the yield gains required for efficient energy production. The key process in achieving compression levels of the magnitude required was X-ray ablation of the target surface, the same process used in a thermonuclear secondary. In this process, X-ray energy vaporizes the target surface, driving plasma out from the surface at such extreme velocities that it acts like an inside-out rocket and compresses the target from all sides.

> Driving pressures of several hundred megabars and implosion velocities of hundreds of kilometers/second can be generated by ablation with several hundred eV [electron volts] radiation temperatures. At these temperatures, material sound speeds are several hundred kilometers/second, comparable to the implosion velocities required to isentropically compress DT to more than one thousand times liquid density. One-thousand-fold compression of a sphere can reduce the required driver energy by nearly one-million-fold.[18]

What had now become problematic was the high density, non-fissile heavy metal pusher/tamper that compressed the DT fuel.

> The pusher limited the gain because its mass was up to one hundred times larger than that of the DT. To achieve high gains (100 and greater), the pusher had to be eliminated and the implosion energy had to be minimized.[19]

Eliminating the pusher was another major departure from the fundamental Teller-Ulam principle. The next step was to achieve isentropic (or near isentropic) compression:

> To minimize the implosion energy most of the DT must be near isentropically compressed to high densities. The Fermi energy of DT compressed one thousand fold is only one percent of the ignition energy (i.e., the thermal energy at 10-kilovolt ignition temperature). The ignition energy is only one percent of the fusion energy at 30 percent burn-up. Consequently, the fusion energy generated can be 10 to the 4 times larger than the Fermi energy of the compressed DT. The gain can be further increased by igniting a relatively small fraction of the DT mass in a hot spot near the center of spherical convergence. *Fusion yields can then be amplified by TN propagation from the hot spot into a much larger mass*

18. Ibid., p. 9. In an email communication from May 2014, Carey Sublette explained: "Isentropic means that the fuel mass is efficiently compressed—very little heating (net entropy increase) occurs and essentially all of the compression energy goes into increasing its density. A very intense single shock delivers about half of its energy as heat, and half as compressive work, which is unacceptable for this purpose. Instead, a series of shocks starting with a very slow initial shock that compresses without heating is needed. The term 'isentropic' literally means that the entropy of the system does not change as it is compressed. This condition achieves the highest possible density of the compressed fuel, and consequently the most efficient burn."

19. Velarde and Santamaría, eds., *Inertial Confinement Nuclear Fusion*.

> *of DT*. Even with one percent efficient implosions, the energetics is extremely favorable.[20]

These principles allowed a high-gain, pusherless target configuration to take shape.

> I developed an ablatively driven spherical rocket implosion to compress DT to high densities *without use of a pusher. A sustained ablatively driven implosion is made possible by use of a sustained driver input and a suitable ablator*. Optimum pulse shapes make possible very high isentropic compression of most of the DT while igniting a central hot spot. The temperature of the hot spot is amplified by adjusting the pulse shape so that a strong shock is generated near zero radius, and by using a hollow target design containing low-density DT gas.[21]

What does this optimized pulse shape look like? A description can be found in *The Physics of Inertial Fusion*:

> Fast and nearly isentropic compression, however, can be achieved by superimposing a sequence of shocks. In principle, going to the limit of an infinite number of shocks of infinitesimal strength each, rapid isentropic compression to arbitrary density is possible. However, each shock in the sequence has speed larger than its predecessor and therefore will catch up with it after a certain time. Therefore, the temporal increase of the pressure creating the shock sequence has to be shaped carefully such that shocks coalesce at the same time.[22]

Achieving isentropic compression required temporal modulation (time-controlled energy release with intentionally varied intensity of the driver energy), or "pulse shaping." Nuckolls's research into pulse-shaping increased efficiency gains even further: "In a series of 1961 calculations, I explored the potential of strong pulse shaping. With near ideal pulse shapes, very high-gain, pusherless, near isentropic, low temperature radiation imploded fusion capsules that ignite propagating burn are feasible."[23] By the spring of 1962 and the buildup to Operation Dominic, Nuckolls had these two technologies in hand—pusherless high-gain fusion targets and driver pulse shaping.

> Livermore was focusing all possible efforts on responding to high yield Soviet atmospheric nuclear tests (including a 57-megaton explosion). Our goals were

20. Ibid., pp. 9–10; emphasis added.

21. Ibid., p. 10; emphasis added.

22. Stefano Atzeni and Jürgen Meyer-ter-Vehn *The Physics of Inertial Fusion: Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter*, International Series of Monographs on Physics, Vol. 125 (Oxford, UK: Oxford University Press, 2004), p. 52.

23. Velarde and Santamaría, eds., *Inertial Confinement Nuclear Fusion*, p. 10.

to eliminate the potentially catastrophic first strike instability in nuclear deterrence and to search for technological surprises. A low level of work on ICF continued.[24]

On 30 August 1961, in the midst of the Berlin crisis, Nikita Khrushchev announced the Soviet Union's withdrawal from the nuclear test moratorium. Two days later, the Soviet Union resumed atmospheric testing.[25] Two months later, on 30 October 1961, the Soviet Union detonated the largest nuclear device ever built, the RDS-220 "Tsar Bomba." With a yield of approximately 57 megatons and a fission fraction of only 3 percent, this device revealed a mastery of both high-yield and "clean" weapon design. (The Soviet Union's largest test prior to the new series had been three megatons.) The result of a crash program, the device was overbuilt and relatively pedestrian from a technological standpoint, using a lead tamper for the second and possibly third stages (similar to Livermore's B-41). Nevertheless, at full "dirty" yield (120 to 150 megatons), the approximately 50,000-pound device would have hit the 6 kt/kg "Taylor Limit" that had hitherto been approached only by the B-41. This test was followed by four additional tests of different designs in 1962 of 19, 20, 21, and 24 megatons. Most, perhaps even all, of these devices were "clean."

When President Kennedy took office, he pledged to maintain the testing moratorium implemented by the Eisenhower administration. However, strong pressure for a response to the Soviet tests came from all quarters, including Congress and the public. Soviet advances in nuclear weapons technology, which up to this point had lagged significantly behind the U.S. state-of-the-art, were seen as a direct threat to the deterrent capability of the United States and its allies. Consequently, preparations were begun for the resumption of testing in the Pacific as soon as possible. Operation Dominic commenced on 25 April 1962. With 36 tests carried out, *Dominic* was the largest and most ambitious test series ever conducted by the United States.

The pressure was on to catch up and if possible surpass—with some technological breakthrough—the recent Soviet gains in the area of high-yield weapons, a potential threat to first-strike stability. This was the point when Nuckolls, applying his ICF research, proposed the Ripple concept:

24. Ibid., pp. 11–12.

25. From 1 September 1961 through 25 December 1962, the Soviet Union conducted 138 atmospheric tests. Sixteen of these tests were larger than three megatons, and five were significantly larger than the largest U.S. test ever conducted (Castle Bravo at fifteen megatons) and were also "clean." The largest test had a yield of approximately 57 megatons and was 97 percent clean. Though fairly conventional and conservative in design, this remains both the highest yield and one of the "cleanest" nuclear tests ever conducted.

> Meanwhile, I focused on technological surprises. In April 1962, a few months before the scheduled end of the atmospheric test series [Dominic], I proposed a nuclear test of a radical high-yield TN design so fantastic that my colleagues thought it was an April Fool's–day joke. In this radical design, a high-performance TN secondary was imploded with a highly optimized pulse.[26]

Here we pass into the realm of educated guesses and probability as classification comes into play. Based on the available evidence, we can reasonably conclude that the Ripple concept is nothing less than the direct application of nascent inertial confinement fusion technology to full-scale thermonuclear explosive design, the key features being a high-gain pusherless spherical secondary of thin, hollow-shell design imploded by a temporally shaped, highly optimized X-ray pulse from a compact, highly efficient fission primary. The optimized pulse would also enable hot-spot ignition of a centrally located container of DT gas, acting in precisely the same fashion as a fission spark plug but without the weight. In short, the Ripple concept is essentially a nuclear-driven, scaled-up, high-gain ICF fusion explosion. The key to making the Ripple concept work is the highly secret and extremely complex pulse-shaping mechanism that transforms the single, strong X-ray burst from the primary into a series of precisely timed shocks (the pusherless secondary would also contribute to efficiency by drastically reducing device weight). Sublette's work, published in the online Nuclear Weapons Archive, provides some clues as to what this mechanism might look like:

> The idea here is to tailor the energy production in the primary so that the desired pressure-time curve [pulse shape] is produced directly. The functional form of fission energy release (an exponential function) actually does match the desired functional form of the [pulse shape] fairly well. The problem is that the time constant of a reasonably efficient fission system is simply too short. By the time a low pressure shock created by an early stage of fission has propagated a substantial distance (a few millimeters, say) the intense shock from the final stages of fission will have caught up with it.[27]
>
> A barrier between the [primary and secondary] compartments made of opaque (high-Z) material [can control] the rate at which energy flows from the primary to the secondary.[28]

26. Velarde and Santamaría, eds., *Inertial Confinement Nuclear Fusion*, p. 12.

27. Carey Sublette, "Modulated Primary Energy Production," in Nuclear Weapons Frequently Asked Questions (NWFAQ), version 2.26, last updated 13 March 2019, http://nuclearweaponarchive.org/Nwfaq/Nfaq4-4.html#Nfaq4.4.4.

28. Carey Sublette, "Compartmented Radiation Cases," in NWFAQ, http://nuclearweaponarchive.org/Nwfaq/Nfaq4-4.html#Nfaq4.4.4. The term "high-Z" refers to elements in the atomic table with higher atomic numbers (the letter "Z" is commonly used for atomic number).

> The barrier would be driven forward at a very high velocity by the ablation shock, and preventing it from damaging the secondary would be a significant problem. One possible technique for addressing this problem would be to place a shield made of X-ray transparent low-Z material (lithium, beryllium, or boron for example) between the barrier and the secondary to absorb the impact of the barrier remnants.[29]
>
> Many variations on this idea are possible. Varying the thickness or the composition of different parts of the barrier could provide a more carefully tailored release of energy. Thermal energy could be diverted into "radiation bottles" by unimpeded flow through a duct or pipe before release to the secondary. Multiple barriers or baffles could be used to control the rate of energy flow.[30]

Sublette's analysis also seems to confirm the Ripple's thin, hollow-shell secondary design: "Hollow shell secondaries would be essential for use with primaries that rely on modulated energy release to create efficient compression."[31] The known dimensions and weights (high volume with low weight) of the Ripple devices corroborates this hypothesis. We know that all (four) Ripple devices tested used the advanced Kinglet primary.[32] The use of the Kinglet is particularly intriguing because of how new the design was at the time and, more important, because of its very small yield in relation to the yield of the Ripple secondary: no more than 10 to 15 kilotons and, based on data from the Dominic Tanana shot, as little as 2.6 kilotons (this for a secondary with yield greater than 10 megatons). For comparison, the conventionally designed 9-megaton W-53 required a 100-kiloton primary *plus* a fissile tamper and sparkplug in the secondary.

What is the significance of the name Ripple? Up to this point, Livermore's standard practice had been to name all thermonuclear secondary designs after wind instruments; examples include the Bassoon, Cello, Fife, Oboe, Calliope, and Tuba devices. The departure in naming Ripple underscores the radical nature of the design. The word "Ripple" is clearly descriptive of the non-linear pulse shape that is key to the concept.

It was only by accident that the Ripple concept was even tested at all. The schedule for the Dominic test shots had been set before April, with no time for inclusion of a test device that had yet to be designed, let alone built.

29. Ibid.

30. Sublette, "Modulated Primary Energy Production."

31. Carey Sublette, "Thermonuclear Weapon Designs," in NWFAQ, http://nuclearweaponarchive.org/Nwfaq/Nfaq4-5.html.

32. The Kinglet was an advanced, highly compact, two-point primary used operationally in the W-55 and W-58 warheads.

However, repeated failures of the missile-borne high-altitude-effects shots being conducted at Johnston Island resulted in the extension of the Christmas Island test operations from June into July.[33] This provided the opening Livermore needed.

> Foster dispatched me to Washington to support approval of a nuclear test of my scheme. I was accompanied by Roland Herbst, a theoretical physicist and experienced weapons designer. I briefed AEC Chairman Glenn Seaborg, and my former boss, DOD's R&D leader Harold Brown. President Kennedy approved the nuclear test—the last experiment in the test series.[34]

On 2 July, President Kennedy personally authorized the firing of the first Ripple device as the Pamlico event, initially set for 7 July.[35] Nuckolls had little time and limited resources with which to work, to say nothing of the difficulty of designing and fabricating a radically new concept.

> I was the lead nuclear designer and this was my first nuclear test. Not nearly enough time or computer resources were available. Livermore's nuclear design experts believed success was impossible. [John] Foster and [Peter] Moulthrop were notable exceptions. I severely constrained the nuclear design to minimize calculations, to use parts that could be rapidly fabricated, and to avoid or overpower failure modes. Nuclear design, engineering, and fabrication were completed in two months. (Today, years would be required.) Invaluable assistance was provided by my sole assistant, Ron Theissen, a technician on assignment from the Computation Department. Several other designers volunteered to assist. Day and night, Ron and I punched IBM cards as inputs for hundreds of one dimensional calculations. Although the device was an extreme design, enough computing time was available for only a few simple two dimensional calculations.[36]

The importance of this test is underscored in a letter from U.S. Deputy Special Assistant for National Security Affairs Carl Kaysen to Sir David Ormsby Gore, ambassador of Great Britain:

> The President has authorized the firing of the Ripple device as the Pamlico Event. . . . This test, if successful, will permit the achievement of much greater

33. Operation Fishbowl—the high-altitude-effects portion of Operation Dominic—was conducted at Johnston Island, approximately 700 miles southwest of Hawaii. Only five of nine shots were successful. All failures were attributable to missile malfunctions.

34. Velarde and Santamaría, eds., *Inertial Confinement Nuclear Fusion*, p. 12.

35. As in Operation Redwing in 1956, all nuclear tests conducted as a part of Operation Dominic were named after Native American tribes.

36. Velarde and Santamaría, eds., *Inertial Confinement Nuclear Fusion*, p. 12.

> yield-to-weight ratios in weapons. While technically it embodies a different concept than the [deleted—unknown?] it is designed to achieve the same result. It can be viewed as a substitute for it. In terms of the group of categories that we gave you on 27 February, this falls in the first class of advanced concepts.[37]

On 11 July, the 9,162-pound Ripple device was air-dropped from a B-52 and detonated at an altitude of 14,330 feet, yielding 3.85 megatons. The "physics package" was a cylinder 123.4 inches long and 56.2 inches wide. The predicted yield was 3 to 5 megatons. Nuckolls witnessed the test in person and described the event and the reaction of his Livermore colleagues:

> On a pre-dawn morning in early July 1962, I observed the multi-megaton yield *"Pamlico"* explosion of my device from a Christmas Island beach at the Joint Task Force Eight Pacific nuclear test site. We wrapped in white sheets to avoid thermal radiation and wore dark goggles. Fifty miles distant, a B52 had dropped the parachute retarded nuclear device. Suddenly, we were stunned and dazzled by the multi-megaton pulse of intense light and heat radiated from the three-kilometer fireball. Night became day. The giant mushroom cloud surged upward and stabilized at an altitude of 80,000 feet. The Soviet spy ship was steaming over the horizon.
>
> Foster sent the director's car to meet me at the San Francisco airport. Later, he hosted a dinner/musical celebration at San Francisco's Palace Hotel.
>
> My colleagues were amazed at my beginner's luck and counseled me "quit while you are ahead." But, I resonated with the creative optimism of Lawrence and Teller. I had no fear of failure. Foster's rule was if you don't fail half the time, you aren't trying hard enough. His dynamic spirit inspired Livermore. "You can excel! I want to run so fast anything the Soviets build will be obsolete."[38]

Riding the wave of this initial success, Nuckolls and his assistants immediately set out to refine and optimize the Ripple design, beginning work on the Ripple II and Ripple III devices.

The JTF-8's report to the AEC discussed the nature of Pamlico and underscored its significance:

> [Pamlico] was a test of a new concept. . . . This event, the final event in the Christmas Island Air Drop Series, was a physics investigation [deleted]. . . . It

37. Carl Kaysen to Sir David Ormsby Gore, 2 July 1962, p. 1, reproduced on Nevada Test Site CD-ROM (Las Vegas, NV: NNSA/NSO Nuclear Testing Archive, 2012). Henceforth, this CD-ROM will be referred to as just "CD-ROM" along with information about the particular documents contained on it.

38. Velarde and Santamaría, eds., *Inertial Confinement Nuclear Fusion*, pp. 12–13.

> was a highly experimental [deleted] device, designed and built by the Lawrence Radiation Laboratory in a month's time. . . . It is felt that this shot, through further design experimentation, may lead to warheads of higher yield [deleted].
>
> The objectives of the Ripple concept were to investigate new ranges of yield-to-weight ratio possibilities in the design of high yield thermonuclear warheads. . . . The very gratifying results opened up new ranges of possibilities in the design of high yield thermonuclear warheads.[39]

A letter dated 10 August 1962 from AEC Chairman Seaborg sheds further light on Pamlico, highlighting the radical nature of the Ripple device:

> The [Ripple] device, discussed in my letter to the President, deserves additional comments. To achieve the highest possible yield-to-weight ratios in nuclear weapons, high potential thermonuclear fuels must be burned efficiently [deleted].
>
> Based on the success of the Pamlico test [deleted] the Lawrence Radiation Laboratory has indicated that the [Ripple] fuel system designs can be refined and, with further testing, produce prototype weapons [deleted].
>
> The *Pamlico* event was a test of unique advanced principles relating to high efficiency thermonuclear burn resulting from [deleted]. Preliminary data indicates that the [Ripple] device performed about as predicted. With further testing, the [Ripple] concept may be applied to future weapon design and thus provide appreciable improvements in thermonuclear weapon efficiencies.[40]

Pamlico was intended to be the last airdrop of Operation Dominic, but an unforeseen event altered the situation just two weeks later:

> During the evening of July 25, 1962, a Thor IRBM [intermediate range ballistic missile] was destroyed and burned on the pad on Johnston Island. There came then an approximate two-month interval of no testing at Johnston Island, which allowed the laboratories to think a little bit more about their problems in developing high-yield devices.[41]

This accident occurred during the Bluegill Prime high-altitude-effects shot. The Thor missile, which was to carry a W-50 nuclear warhead to an altitude of 160,000 feet, exploded on the launch pad and destroyed the

39. "Report by Commander Joint Task Force Eight," 4 June 1964, pp. L-A-24-1, L-B-1-1.

40. Glenn Seaborg, Chairman, USAEC, to the President, 10 August 1962, attachment to Leland J. Esworth, Commissioner, USAEC, to Honorable McGeorge Bundy, Special Assistant to the President for National Security Affairs, the White House, 10 August 1962, quoted in Hansen, *Swords of Armageddon Version 2*, pp. 429, 432.

41. Ogle, *An Account of the Return to Nuclear Weapons*.

launch complex, contaminating the area with plutonium.[42] The cleanup and reconstruction halted Dominic operations for nearly two months. This development prompted the AEC's director of military applications, Brigadier General A. W. Betts, to contact Livermore and Los Alamos on 27 July and raise the possibility of further atmospheric tests. Livermore responded with its usual enthusiasm:

> On August 2, [LRL director] Foster advised Betts of the LRL desire to conduct further atmospheric detonations during Dominic. [deleted] He went on to note that the Russians had announced their intention to conduct further atmospheric tests during August, September, and October and said, "The Laboratory should make every effort to prepare and test their most useful and urgent experiments." He added that LRL was starting the design and construction of the [Ripple II and Ripple III] devices.[43]

Los Alamos all but opted out, contributing only one medium-yield test of their Thumbelina device for the Chama shot. Bradbury's response on 8 August was in line with Los Alamos's past approach.

> Any device we could possibly prepare in the prescribed time scale would be a very ragged affair, far from optimized, and of problematical behavior. We would not recommend its testing at this time, but could regard an initial version as a very appropriate candidate a year from now following adequate calculational study. . . . It would appear to us that the only justification for trying to get bits and pieces together in the suggested time scale would be on the basis of early word from you that we should act on the assumption that further atmospheric testing in the next year or two is quite unlikely.[44]

On 6 August, Harold Brown, who had become DOD's Director of Defense Research and Engineering under Defense Secretary Robert McNamara, asked the AEC to "examine the possibility of developing a test device, at an early date, that would provide the maximum possible yield in a weight of approximately 6,000 pounds."[45] The subject of this request was the Titan II, the newest and largest U.S. ICBM. The warhead for this missile was the

42. L. Berkhouse et al., *Operation Dominic I Nuclear Test Personnel Review* (Washington, DC: Defense Nuclear Agency, 1962), pp. 229–241.

43. Ogle, *An Account of the Return to Nuclear Weapons*, p. 405.

44. Ibid.

45. Memorandum for the Military Liaison Committee regarding a Warhead for the Titan II, 6 August 1962, NV76772, on CD-ROM. Six thousand pounds is the physics package weight; it does not include the firing control unit, reentry vehicle (RV), RV adapter, or penetration aids. The precise four-digit weight number is only partly legible because of typeface degradation.

W-53, developed by Los Alamos and first tested during Operation Hardtack in 1958.[46] The W-53 weighed approximately 6,113 pounds (as tested) and had two yields. The standard, or “dirty,” version yielded 8.9 megatons (the Oak shot); the “clean” version was predicted to yield between 2 and 3 megatons (the Sycamore shot) but fizzled. At 3.2 kt/kg for the “dirty” version, the W-53 had the highest yield-to-weight ratio of any ICBM warhead in the arsenal. When combined with the reentry vehicle (RV), decoys, and RV adapter, this was the maximum payload deliverable by the Titan II to the 5,500 nautical-mile range required to reach the majority of Soviet targets.

On 14 September, Brown received a reply to his query about a maximum-yield device for the Titan II:

> We examined this possibility with the two weapons laboratories and concluded that in the time available to us before the conclusion of DOMINIC it would be impossible to design and fabricate a device that would meet such a requirement. At the same time, however, it was apparent that we had a proposal for a test device, the [Ripple II] that would be a long step in the direction of the development which you had requested. Accordingly, we proposed, and the President approved, the inclusion of the [Ripple II] in the air drop tests to be conducted off Johnston Island.[47]

The reply Brown received had been shaped by a meeting held at the White House on 5 September between President John F. Kennedy and his advisers regarding the progress of Dominic. They discussed which—if any—airdrops of devices should be conducted in the window of opportunity created by the delay in Johnston Island operations. The recording of this meeting has only recently been declassified, and, although some sections are still classified, it constitutes some of the most significant revelations about the Ripple concept ever released to the public.[48] To facilitate scrutiny of this material, I have separated the relevant records into six parts. The named participants other than Kennedy are AEC Chairman Seaborg, National Security Adviser McGeorge Bundy, Deputy Special Assistant for National Security Affairs Kaysen, Secretary of Defense McNamara, Special Assistant to the President for Science and Technology Jerome Wiesner, Secretary of State Dean Rusk, and the head of the National Aeronautics and Space Administration (NASA), James Webb.

46. The last MK-53 nuclear weapon in existence was dismantled in 2010, marking the end of high-yield thermonuclear weapons in the United States.

47. A. R. Luedecke to Harold Brown, 14 September 1962, on CD-ROM.

48. Meeting on the Dominic Nuclear Test Series, 5 September 1962.

Part I

> **President Kennedy:** What about our tests? How would you summarize our tests, as far as … so, how would they? If they were talking about our tests would they dismiss them quite as you dismiss theirs? (Russia)
> **Seaborg:** I think that they would not be able to understand the sophistication of some of the biggest advances we have.
> **Unidentified:** I think one observation that might be made here. And I don't want to put a lot of weight on it; but that is: this 25 megaton shot [Soviet test] being clean can be interpreted. . . I mean, it has significance in various ways. But our most advanced ideas, namely the Ripple concept, leads to an inherently clean system and maximum efficiency.
> **Unidentified:** You don't know whether it is a clean weapon or another weapon that is—
> **Unidentified:** Right. Or [*unclear interjection*] whether it's clean to be clean or whether it's clean [*unclear interjection*].
> **Seaborg:** I'm sorry, I believe it has lead in it. And I think that's quite a different process. I'll check, and I don't have it here, but that's my understanding [the secondary is encased] in lead so that it's not an amazing development.
> **Webb:** With reference to your earlier question, Mr. President, I think probably the single most advanced thing they wouldn't be able to make much sense out of, namely the Ripple, which is of course [being tested at] a very reduced yield and [is] a very complicated device. So, I doubt they could really make any sense of it.[49]

This initial part of the discussion centers on the state of the U.S. high-yield and "clean" weapons technology compared to that of the Soviet Union. Several important points are discussed here, and they are all connected, but each requires an explanation of its particular significance.

1.) *The "clean" 25-megaton Russian test of 5 August 1962 used a secondary with a lead tamper in place of a fissile tamper.*[50]

This same technique was used in all U.S. "clean" thermonuclear weapons from 1956 on. Referred to simply as the "materials substitution method," it resulted in a yield reduction (and therefore efficiency reduction) of 50 percent or more. This means the device was *intentionally*, not *inherently,* "clean." The nature of the Soviet test was highlighted in the conversation to contrast it with the technology behind the Ripple concept, which, as Seaborg stated, did

49. Ibid. The two methods of determining yield and cleanliness from long distance are through electromagnetic pulse measurements and radiochemical analysis of fallout.

50. This is the yield determined from U.S. monitoring of the test. Soviet officials later said their instruments indicated a yield of 21.1 megatons.

not use a lead-encased secondary to achieve its high fusion to fission ratio or "cleanliness." This leads directly to the next point.

2.) *The Ripple concept produced "an inherently clean system of maximum efficiency."*

This means that the Ripple device was not "clean" because it was intended to be "clean"; rather, *it was "clean" because that is how the concept worked*. "Maximum efficiency" implies very high fusion fuel burn-up. Typical fusion burn efficiency for thermonuclear weapons—to this day—is not much more than 30 percent and is far lower for weapons without fissile tampers; that is, conventionally designed "clean" weapons.[51] The extremely high yield-to-weight ratios that the Ripple program aimed at would require *both* high-efficiency burn and a very high fusion percentage to attain such ratios at the given weights.

3.) *The Ripple concept represented the most advanced nuclear weapon design in the United States.*

4.) *The Ripple device(s) were intentionally being tested at "very" reduced yield.*

5.) *The Ripple device was extremely complicated; apparently so much so that thermonuclear test monitoring systems (bhangmeters, etc.) could not decipher its design features.*

Part II

> **Bundy:** And a series of five new atmospheric tests primarily designed to explore further the problem of very high yield weapons with probably low weights. The most important being the Ripple II and Ripple III experiments, I believe.
> **Bundy:** It may be worth just a moment to explain what that is. I should think Lee [i.e., AEC Commissioner Leland Hayworth] or Glenn [Seaborg]. . . . Because that is probably the most important technical development in our own Dominic series.
> **Kaysen:** That's the sort of breakthrough of the Livermore laboratory.
> *One minute, 29 seconds excised as classified information. (Technical description of the* Ripple *concept.)*[52]

Here, the primary importance of the Ripple program within the Dominic test series is underscored, and we learn that it was indeed a breakthrough concept: a revolutionary technology as opposed to an evolutionary one. This is something that had not occurred previously—or since—in thermonuclear weapon

51. Sublette, "Thermonuclear Weapon Designs."

52. Meeting on the Dominic Nuclear Test Series, 5 September 1962.

design. The June 1964 JTF-8 Scientific Report pointed this out: “It was hoped that the United States would achieve, in two quick experiments (Ripple II and III), results exceeding the performance that has been obtained through many years with conventional designs.”[53] In my interview with Foster, he stated that the Ripple design was “it.” *This* was the breakthrough that Teller and Brown were anticipating in 1960.

Part III

> **McNamara:** However, in that case we could start airdrops.
> **Wiesner:** Well, there is a problem though, that the Ripple weapons have to be fabricated.
> **Unidentified:** That’s right.
> **Wiesner:** So you can’t drop them tomorrow. They are still in the laboratory, in development.
> **Unidentified:** These were actually the earliest dates at which they could be made ready.
> **President Kennedy:** You mean and each weapon, in other word—
> **Unidentified:** They are being run through the laboratory right now.[54]

The revelation that the Ripple II and III devices were still in development at Livermore underscores the scramble to prepare additional devices after the success of Pamlico, confirming Nuckolls’s account.

Part IV

> **Bundy:** Mr. President, you asked the question what tests do we take now. I do not find that it’s an unacceptably long list in the context of the various ideas and possibilities and knowledge probably that we have. I agree with the Secretary [of State] that that’s [i.e., Ripple II] the proper test. I think this may be our last clear chance to do this, and I think that there’s a great deal to be said for getting in a posture in which we have clearly found out the things we need to find out, because we may have a year or a year and a half when it’s not easy to find out.
> **President Kennedy:** You think—
> **Rusk:** In fact, a major change in the weight-yield ratio, for example, is very important from a security point of view that [*unclear*].
> **Wiesner:** I think you have to be careful about that because it is my understanding that this test, the Ripple II, will not put you in that position. This will

53. “Report by Commander Joint Task Force Eight,” 4 June 1964, p. L-B-1-1.
54. Meeting on the Dominic Nuclear Test Series, 5 September 1962.

put you in a position to design a weapon, which will require further testing, so that—

Unidentified: No, it will put you in pretty good position.

Wiesner: Except you'll have this one, which will not be the 30 to 40 megaton.

Unidentified: No, that's right.

Unidentified: It might be 15 [megatons].

Unidentified: Yeah.

Wiesner: I understand that. So that I think that should be clear.

Unidentified: But it will be a big gain.[55]

Several noteworthy points are made here.

1.) *The Ripple concept should be tested right away instead of at some future date.*

In Geneva barely a month earlier, the United States and Great Britain had proposed a partial test ban that would outlaw atmospheric and space testing as of 1 January 1963. The Soviet Union had rejected this initial proposal, but pressure was mounting to move as soon as possible in conducting any tests that had to be carried out in the atmosphere or outer space (high-yield devices and ABM effects tests).

2.) *The Ripple II test would be a giant step toward attaining the yield-to-weight ratios promised by a fully developed Ripple design.*

3.) *As shown earlier, the Ripple II test device was seen as a major first step in achieving a maximum-yield device in the 6,000-pound weight category for the Titan II ICBM.*

In my conversation with Foster, he pointed out that dropping the Ripple device from an aircraft was one thing. Enabling the Ripple's extremely sophisticated internal components to withstand the tremendous g-forces and temperatures associated with delivery by ICBM would have been quite another. This reason alone would have justified further testing and development.

4.) *We discover here that the initial predicted yield range for the fully fueled device was at least 30 megatons and as high as 40.*

5.) *The Ripple II test was intended to yield a maximum of approximately 15 megatons, which was intentionally reduced from some much larger yield.*

Fifteen megatons was not an arbitrary number. Prior to Operation Hardtack in 1958, President Dwight Eisenhower had established the unwritten rule that no nuclear test yield could exceed that of the largest U.S. test: the 15 megatons of the Castle Bravo test in 1954.[56] Despite pressure from the

55. Ibid.

56. President Dwight D. Eisenhower to Sterling Cole, House of Representatives, 27 May 1957, quoted in Hansen, *Swords of Armageddon Version 2*, p. 307.

Department of Defense, the AEC, and Livermore, President Kennedy refused to exceed the 15-megaton limit established by his predecessor.[57]

Part V

> **Wiesner:** On the other hand, Mr. President, you want to recall the *Kingfish*-type experiment was one of the basic reasons that we felt we had to resume testing, which was to get [these] effects [*unclear*]. Because of the bad luck we've had in the Pacific [i.e., Thor missile failures] we've not carried out this test. Many of the others, I think, would be cut if you took seriously the criteria we started applying initially, which the secretary has talked about.
> **McNamara:** I would speak to that point, Jerry. I think Ripple III should not be cut.
> *44 sec excised as classified information.*
> **McNamara:** We may have to burst higher than previously anticipated to avoid anti-ballistic missile systems. Therefore, I think Ripple III is an important test as I think Ripple II is an important test. So, I wouldn't cut out either Ripple II or Ripple III. There are others that might be cut; but not those two.[58]

Because of concern regarding Soviet ABM advances, additional space tests were thought to be necessary, so this discussion focused on what other tests might be cut. To complicate matters further, Project Mercury launches were scheduled through May 1963, and the ABM effects tests in space were creating artificial radiation belts and forcing NASA to reschedule launches in the name of astronaut safety. We see here again the importance of testing the Ripple concept over other weapon development. Also, military application of the device is mentioned, corroborating the JTF-8 report of June 1964 by implying that the Ripple concept would allow for high enough yields to maintain effectiveness at the significantly higher burst altitudes required for seamless decoy coverage.

Part VI

> **President Kennedy:** Now, we are concerned, which we haven't talked about much, about radiation [i.e., radioactive fallout from the airdrop tests].
> **Wiesner:** Well, this is why I feel strongly about *Thumbelina*. [*Thumbelina* was on the cancellation list.]
> **Unidentified:** That's where *Thumbelina* helps.

57. Ronald J. Terchek, *The Making of the Test Ban Treaty* (New York: Springer, 2013), p. 4.
58. Meeting on the Dominic Nuclear Test Series, 5 September 1962.

> **Wiesner:** Thumbelina helps a great deal; but the Ripple II and Ripple III will also make a substantial difference. I understand the Secretary's—
> *President Kennedy shuts off the machine.*[59]

Operation Dominic was subjected to a "fission budget," which meant that only a certain percentage of the total yield for the entire test series could be from fission. Therefore, any test devices that had relatively high yields with low fission fractions were helpful in balancing out the many conventional or "dirty" tests. LASL's Thumbelina device was an experimental "clean" secondary design tested in the Chama shot on 18 October. The *inherently* "clean" design of the Ripple devices would add a trivial amount to the fission budget; hence their inclusion in this final discussion about Dominic fallout levels. President Kennedy's concern about the issue of fallout is revelatory of his wider nuclear testing position, which played a role in the ultimate fate of the Ripple program. Brown noted this position in a 1964 interview:

> Kennedy started out with I think instinctive bias against nuclear—not bias, but with an instinctive feeling against nuclear testing. He felt very strongly about fallout, much more strongly, I think, than was justified on purely technical grounds, but obviously that feeling was not a misevaluation of the political situation at all. I think it was a correct evaluation.[60]

The second, delayed phase of Operation Dominic was conducted from 2 October to 4 November 1962. The Soviet Union was at this time in the middle of its largest ever atmospheric nuclear test series, which dwarfed Dominic both in sheer numbers (more than twice the number of tests) and in maximum yields (four devices with yields ranging from 19 to 25 megatons). The Cuban missile crisis period (16–28 October) alone witnessed ten tests by the United States and the Soviet Union, with tests by both countries *twice on the same day* (20 and 27 October). That being said, the crisis in the end had no discernible effect on Dominic test operations.

On 2 October 1962 the Ripple II was tested in the Androscoggin event. The device consisted of a Kinglet primary and the new Ripple II secondary. The weight was 6,647.52 pounds with dimensions of 128.5 by 56.2 inches. The maximum predicted yield was 15–16 megatons.[61] The test was a "fizzle," yielding only 63 kilotons:

59. Ibid.

60. Harold Brown Oral History Interview No. 5, 25 June 1964, in Digital Identifier JFKOH-HAB-05, JFKL, https://www.jfklibrary.org.

61. Hansen, *Swords of Armageddon Version 2*, p. 406.

> In August and September, Ron and I worked day and night to design an even more radical nuclear device. We further optimized the pulse shape to achieve practically isentropic fuel compression. On October 1, this device was exploded in the "Androscoggin" nuclear test conducted in the Johnston Island area of the Pacific. A small percent of the calculated yield was generated. A fizzle!? Everyone believed I had "snatched defeat from the jaws of victory."[62]

Nuckolls set out to determine the cause of the fizzle and began the design of an appropriately modified Ripple II.

On 12 October, Leland Haworth wrote to the president to request a retest of the Ripple II:

> Dear Mr. President. . . Our most recent analysis . . . has contributed valuable information toward a better understanding of these advanced and complex devices. We believe that this understanding will enable us to overcome the design deficiencies [*deleted*]. It is the purpose of this letter to request your approval for a repeat test [*deleted* (of the RIPPLE II device)] in the current Pacific series: an improved device could be ready for firing by October 31. [*deleted*] the experience and information gained from the previous tests will contribute to greater confidence than would otherwise prevail. We believe that the great importance of this concept, which promises marked advances in weight-to-yield ratio of large weapons, justifies the expedited procedure.[63]

In the meantime, the test of the Ripple III was carried out on 27 October as the Calamity event.[64] The Ripple III device, at a weight of 1,830 pounds and measuring 93 by 34.4 inches, was "a further physics investigation to experimentally verify design calculations."[65] "Data obtained from this experiment [*deleted*] would provide a basis for new design concepts for our larger ICBM systems."[66] The test was only partly successful. The predicted yield was three megatons, whereas the actual yield was approximately 800 kilotons. The result indicated partial but nowhere near complete fusion fuel burn.

On 30 October 1962, the modified Ripple II device was retested in the Housatonic event, the last airdrop of Operation Dominic. Nuckolls's revisions resulted in success:

> With less than a month before the test series ended, I reviewed early diagnostic data, recognized my design error, and devised a fix which could be rapidly

62. Velarde and Santamaría, eds., *Inertial Confinement Nuclear Fusion*, p. 13.

63. Glenn Seaborg Collection, NV 177415, on CD-ROM.

64. "Report by Commander Joint Task Force Eight," 4 June 1964, p. L-B-4-1.

65. Ibid.

66. Ibid.

Figure 1. Dominic Housatonic, Ripple II, test 2 (10.0 MT), 30 October 1962. Source: Los Alamos Scientific Laboratory.

> fabricated. Shortly thereafter, a highly successful subsequent test was conducted. Performance increased two-fold over the July test.[67]

The improved device weighed 7,139 pounds, measured 147.9 by 56.2 inches, yielded 9.96 megatons (reported also as 10.0 megatons), and was estimated to be 99.9 percent "clean."[68] The predicted maximum yield is still classified, but, being a re-test, it would most likely have been no higher than the 15–16 megatons predicted for Androscoggin. The test was considered a successful step in further developing the Ripple concept. Five days later, on 3 November, a National Security Council meeting was convened in the Cabinet Room of the White House to discuss Operation Dominic and to draft a public statement announcing the conclusion of the test series.[69] AEC Chairman Seaborg recounted the meeting in his diary:

67. Velarde and Santamaría, eds., *Inertial Confinement Nuclear Fusion*, p. 13.

68. "Report by Commander Joint Task Force Eight," 4 June 1964, pp. L-B-5-1–2.

69. On 4 November, the last test of Operation Dominic (and the last-ever U.S. atmospheric nuclear test) was a small, high-altitude shot called Tightrope.

> The President opened the meeting by inquiring of me whether there was any necessity to test in the atmosphere in 1963. I described briefly the Ripple program and said that further tests of this concept would be necessary before weaponization could be achieved, and that the first such tests could be held next May. Secretary Rusk said that he felt we should maintain maximum flexibility with regard to the resumption of atmospheric testing, and make no statement that would preclude this possibility. On the basis of these facts the President decided that the statement announcing the end of the current atmospheric test series would be silent on the question of possible testing in 1963.[70]

This is the last publicly available record that mentions the Ripple program by name. Seaborg's diary makes clear that a solid four to five months of data analysis and design work would be required for the next phase of the program now that the basic concept had been proven sound. More significantly, further testing would be required to develop the Ripple concept more fully and to weaponize it.

The final Soviet atmospheric nuclear test, a 24.2 megaton "clean" device, was carried out on 25 December 1962. The completion of the U.S. and Soviet atmospheric test series by the end of 1962 spurred new momentum toward an atmospheric test ban treaty after an initial proposal in August 1962 had been shelved. Consequently, any plans for further atmospheric or possible deep space testing by the United States were either put on hold or cancelled outright. Because only relatively low-yield devices could be safely tested underground, the end of atmospheric testing left the Ripple program in limbo.

In March 1963, a general review of Operation Dominic included discussion of the results of the Ripple program, albeit without mentioning it by name:

> Although the United States did not test any devices of very high yields, tests were conducted of designs which could lead to an entire new class of U.S. weapons. These new weapons could have relatively low weights and extremely high yields, with the fission contribution decreased to only a few percent of the total yield, thus greatly reducing the radioactive fallout from such weapons. The yield to weight ratios of the new class of weapons would be more than twice that which can now be achieved in the design of very high yield weapons using previously developed concepts. . . . New warheads—for example, a 35 Mt warhead for our Titan II—based on these improvements, could be stockpiled with confidence.[71]

70. Glenn Seaborg Office Diary, Saturday, 3 November 1962, NV 901423, on CD-ROM.

71. Summary of Results of the 1962 Atmospheric Nuclear Test Series, p. 3, on CD-ROM.

These statements both confirm the viability of the Ripple concept and provide some actual numbers and reference points from which to determine the projected performance of a weaponized device. With the primary as the only source of fissile material in the "inherently clean" Ripple design, the device would be around 99.9 percent clean; for all practical purposes, a pure fusion device. The yield-to-weight ratio would be more than twice that of the most efficient high-yield weapon constructed, Livermore's own three-stage B-41 bomb. The B-41 had a device weight of 9,300 pounds and a maximum (untested) "conventional" yield of 25 megatons, giving a yield-to-weight ratio of close to 6 kt/kg.[72] More than twice this ratio, or approximately 12 to 15 kt/kg, would correspond accurately to the quoted yields of 35 to 40 megatons for the Titan II warhead. Given the admittedly overbuilt and far from optimized devices tested, we can reasonably assume that even higher yield-to-weight ratios would have been attainable if testing in the atmosphere (or deep space?) had continued.

In August 1963, the Limited Test Ban Treaty (LTBT), which banned all nuclear testing in the atmosphere, outer space, or underwater, was signed by the United States, the Soviet Union, and Great Britain.[73] The treaty, a long-time goal of President Kennedy, became effective on 10 October 1963. With the door now closed on atmospheric testing, the Ripple concept could not be brought to fruition. According to John S. Foster, one last attempt was made to salvage the program. In the summer of 1963, he and a few others approached Kennedy with a proposal for limited atmospheric and deep-space testing that would enable a small number of tests to be conducted every other year. Kennedy's reply was, "It's too late for that."[74] Brown recalled that Teller—who was a long-time advocate of both high-yield and "clean" nuclear weapons—was among the group from Livermore advocating for additional tests of the Ripple concept (corroborating Foster's account). The president's public reply to this advocacy was, "There are some people who are just never satisfied."[75]

An additional factor weighed against the weaponization of the Ripple concept for reentry vehicle purposes; namely, size. Despite being unusually lightweight, the Ripple concept required a particularly large volume relative to

72. Theodore Taylor, LASL weapons physicist, established the so-called Taylor Limit, which posits that 6 kt/kg is the maximum yield-to-weight ratio achievable for thermonuclear weapons. Only the MK-41 approached this efficiency level.

73. Underground testing was allowed.

74. John S. Foster, Jr., phone interview, 23 November 2011.

75. Harold Brown Oral History Interview No. 5, 25 June 1964.

standard Teller-Ulam designs. The only ICBM in the inventory dimensionally large enough to carry a Ripple-based design was the Titan II, and even though this class of launch vehicle was relatively new, it was already being phased out in favor of smaller missiles such as the Minuteman. This shift, coupled with a strategy that sought to minimize warhead size in order to maximize numbers, also played a role in the decision to halt development. Seaborg acknowledged as much in an appearance before the Senate Foreign Relations Committee. In attempting to assuage concerns about the LTBT's potential effects on the viability of the nuclear deterrent, Seaborg insisted that development would not slow down, except for "complex, multi-megaton weapons," a clear reference to the Ripple concept.[76] With the ban on atmospheric testing, the humanitarian benefits of "clean" weapons disappeared from the public consciousness, and the Department of Defense quietly terminated plans to convert the stockpile. All existing "clean" weapons were withdrawn from service, and nowadays all remaining weapons are "conventional."

The success and potential of the Ripple program, as defined by experimental validation and analysis, has been clearly established. The following facts put this potential into perspective. When compared to the most modern and powerful ballistic missile warhead in the arsenal today—the 475-kiloton W-88—the Ripple concept offers at a minimum ten times the yield-to-weight ratio and does it "clean." The Ripple concept as it stood in early 1963 was at the very beginning of its development cycle as a potential weapon system. Given further development through testing and complete computational analysis, the Teller-Brown prediction of 50 megatons for a 6,000-pound device by 1965 may have been within reach. In today's technological environment, after nearly 60 years of continual ICF research and petaflop computing, the potential gains for the Ripple concept are staggering.

In our conversation about where the Ripple concept stands today, Foster asked me to consider one use to which it could be ideally suited: near earth object (NEO) deflection. The success of nuclear NEO deflection is directly proportional to device yield and weight. The higher the yield, the shorter lead time required for interception. The tremendous yield-to-weight advantages of the Ripple concept over anything available is unquestionable. Furthermore, the fact that the Ripple is "clean" increases its relative effectiveness, as neutrons—produced in copious amounts by fusion reactions—are the most effective mechanism for NEO deflection or destruction in the vacuum of space. These unique characteristics might make the Ripple concept the

76. Terchek, *The Making of the Test Ban Treaty*, p. 39.

ideal nuclear asteroid deflection device. Would this advantage be enough to overcome the issues associated with development of such a device in today's global climate? Unlike all nuclear explosive devices before or after, the Ripple concept came out of the quest for clean energy, and it is perhaps only fitting that its best use would be a peaceful one.