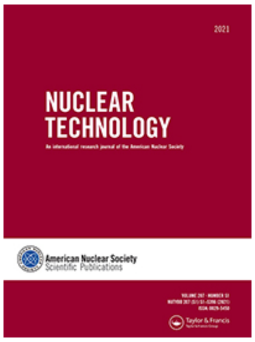

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Technical Paper

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Woolwich, Bruceton, Los Alamos: Munroe Jets and the Trinity Gadget

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Abstract — *Prewar work on the hydrodynamics of explosives and U.S./UK scientific cooperation well beyond Los Alamos contributed to the design of the explosive lenses for the Trinity gadget. Researchers were deliberately brought together and encouraged to share ideas by the leaders of the wartime laboratory. James Tuck, one of the British mission scientists, made particularly interesting contributions in this area, but this paper is not a claim of British or any other individual parentage. Rather, it highlights the importance of collaboration at Los Alamos and more widely.*

Keywords — *Trinity, James Tuck, high explosive, shaped charge, explosive lens.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

Work at Los Alamos on implosion physics for the Trinity gadget[1] and the Fat Man bomb was central to the laboratory's program after mid-1944 (Ref. 2). It built on prewar work, and it succeeded through a combination of theory, calculation, and experiment in making a series of important practical breakthroughs: notably explosive lenses[3] and electric detonators. This short paper looks at one of these breakthrough technologies: lenses. Hydrodynamic phenomena known as jets—tongues or knives of fluid material advancing ahead of the main implosion shock—were crucial and had to be understood in theory and practice. This paper draws together information from published sources and U.S. and UK archives.

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II. MUNROE JETS AND SHAPED CHARGES

The earliest observation of the shaped-charge, hollow-charge, or cavity effect in explosives has been attributed to the eighteenth-century Bavarian philosopher, theologian, and mining engineer Franz Xaver von Baader. Baader saw that leaving a conical or mushroom-shaped space at the forward end of a blasting charge both saved powder and increased the explosive effect. The phenomenon was rediscovered independently several times before Charles E. Munroe, an American civilian chemist working for the U.S. Naval Torpedo Station at Newport, Rhode Island, brought it to wider attention in the 1880s (Refs. 4, 5, and 6).

By the Second World War, experiments in several countries had shown that the shaped-charge effect, now also known as the Munroe effect, could be enhanced by lining the cavity and/or introducing a standoff distance between charge and target. Research was underway, especially to improve the penetration of steel armor and concrete fortifications. Infantry antitank weapons based on the Munroe effect quickly became important. The physical processes underlying the effect were not, however, well understood.

During the war, explosives research at the British government's Woolwich arsenal in London was reorganized and its scientific leadership strengthened. John Lennard-Jones, peacetime professor of theoretical chemistry at Cambridge University, became Chief Superintendent of Armaments Research (CSAR). An Explosives Research Committee (ERC) was established by the Ministry of Supply, then responsible for most UK arms procurements, that brought together leading academic scientists and in-house researchers. Two particular avenues of research overseen by the ERC were important to our story. The first was empirical and theoretical work to understand detonation waves in general, and the Munroe effect in particular, and the second was the requirement for a so-called capital ship or C.S. bomb to sink large warships.

William Payman and Donald Woodhead had been experimenting with and photographing detonation and shock waves for several years at the Safety in Mines Research Station at Buxton in Derbyshire. One of the wartime problems Payman and Woodhead addressed was the shaping and lining of Munroe cavities.[7–10] Geoffrey Taylor,[11] another professor at Cambridge and one of the world's leading fluid dynamicists, became interested in establishing a theoretical basis for the work.

The C.S. bomb, meanwhile, was designed to use an explosively formed projectile to punch through deck armor before detonating its main charge in the bowels of a ship. This was not, in fact, a practical technology. Wing Commander Guy Gibson, who led an unsuccessful raid with C.S. bombs against the incomplete German aircraft carrier Graf Zeppelin in the Baltic in 1942, explained that the bomb "looked of all things rather like a turnip, and like most turnips its ballistics were not very good."[12] Crazy in itself, the C.S. bomb nevertheless inspired a very significant idea.

Harold Poole, a chemist in the Woolwich research department with considerable experience in explosives and rocket propellants, had a keen interest in detonation wave shaping. In September 1942 he proposed to create a flat detonation front at the forward end of a C.S. bomb using "composite charges in which explosives of high and low velocities of detonation are arranged in contact." This flat wave front would then fire a heavy disc forward (downward as seen in Fig. 1), predictably and without breaking up.

High- and low-speed explosives had been mentioned earlier in the context of detonation wave shaping, but Poole's was the first clear suggestion in the United Kingdom, and probably anywhere in the world, of an explosive lens akin to those later used in the Trinity

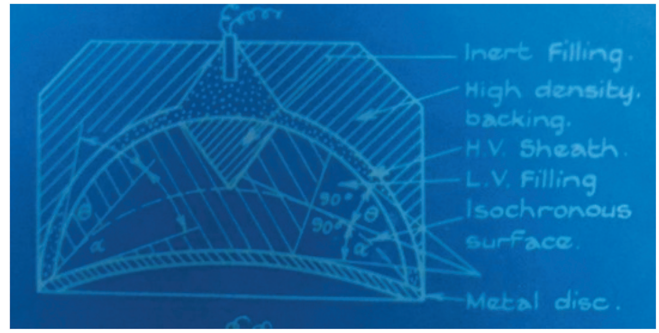

Fig. 1. Drawing from Harold Poole's report of September 1942 proposing an explosive lens. The detonator at the top fires a high-velocity (HV) explosive "sheath" with a part inert, part low-velocity (LV) "filling." An "isochronous" detonation wave front is created, firing the metal disc as a projectile (WO 195/2640, United Kingdom National Archives).

gadget.[a] Baratol and RDX/TNT, an explosive developed in the United Kingdom and also known as Comp B or Composition B, were even suggested in Poole's report as suitable explosives; they would eventually be used in the lenses for the Trinity gadget and Fat Man bomb.[13,14] Woodhead soon showed empirically that Poole's idea would work.[15]

III. JAMES TUCK

At the start of 1943, James Tuck, a young physical chemist from Oxford University, shown in Fig. 2, was

Fig. 2. James Tuck badge picture for Project Y at Los Alamos and (b) at work later in life, from his obituary[24] (Los Alamos National Laboratory).

[a] Unfortunately, it has not been possible exactly to date the work of Elizabeth Monroe Boggs at Bruceton (see Sec. V), although this seems likely to have been in 1943; nor has it been possible to discover whether German or Soviet researchers were thinking on similar lines and if so when.

working as a scientific assistant to Winston Churchill's adviser Lord Cherwell, essentially reviewing the latest discoveries and their defense implications. As he later recalled, "I had all I could stand of other people's research and none to do for myself and by dint of nagging got the chance to try my hand at solving a highly significant scientific puzzle of the time – the Munroe (cavity charge) HE [High Explosive] piercing phenomenon."[16] He joined Churchill's so-called "toyshop," a semi-independent unit under the eccentric Lieutenant Colonel (later Major General) Millis Jefferis, based at Whitchurch in Buckinghamshire. A great fan of secret weapons, Churchill gave much encouragement to Jefferis and his team's inventions, for example, the Hedgehog antisubmarine mortar. A colleague recalled that Jefferis, having "a leathery looking face, a barrel-like torso, and arms that reached nearly to the ground … looked a bit like a gorilla. But it was at once obvious that he had a brain like lightning."[17] As a member of the ERC's subcommittee on shaped charges, Jefferis was part of a United Kingdom-wide collaborative network, and Tuck was set to work with Payman and Woodhead, the Woolwich research department, and Greg Marley and others at the Road Research Laboratory at Harmondsworth near Heathrow airport. Tuck quickly suggested a workable theory for the Munroe effect and wrote a report including perhaps the first flash radiographs of shaped charges.[18–20] The apparatus used for this work is shown in Fig. 3. Flash radiography was not a new technique, but a field emission X-ray tube built by Charles Slack and Louis Ehrke at the Westinghouse Lamp Division in Bloomfield, New Jersey, had become available only in 1941. This allowed microsecond exposure times and made Tuck's work possible. Tuck appears to have been the first to use such equipment specifically to study shaped charges, narrowly ahead of John Clark and Leslie Seely in the United States[21–23] (see Sec. IV).

Fig. 3. Apparatus used for the first flash radiographs of shaped charges in the United Kingdom in 1943. The X-ray source is in the large wooden box on the wall, recording film in the smaller box to the right, and the charge is suspended close to the film box; white detonating cord can be seen above. Several identical shots with slightly different timings were used to build a kind of stop-frame picture of the explosion (WO 195/3650, United Kingdom National Archives).

Taylor reviewed and extended Tuck's theoretical work.[25] Munroe jetting was now understood as a hydrodynamic effect, and the velocity of the jet was related to the velocity of detonation of the explosive used and the properties of the cavity therein. The metal lining of the cavity was shown to separate into a jet, behaving as a fluid, followed by a solid plug of material, as shown in Fig. 4.

IV. ALLIED SCIENTIFIC COOPERATION

At the Quebec conference in August 1943, following a series of ups and downs in the U.S./UK atomic relationship, President Roosevelt agreed with Churchill to combine the British wartime atomic energy project, known as Tube Alloys, with its much, much larger American cousin, the Manhattan Project. This is a well-known story.[26,27] Nuclear historians tend to neglect, however, the wider context of allied collaboration on defense science.

Sir Henry Tizard's mission to the United States in August 1940, in which he carried with him many British secrets including the cavity magnetron, is only one part of this wider picture.[28] Visits by scientific ambassadors were followed by the creation of large permanent liaison offices, notably in 1941 the British Central Scientific Office (BCSO) in Washington, later renamed the British Commonwealth Scientific Office to reflect the involvement of Canada, Australia, and New Zealand. There were many, many areas of cooperation, from radar to proximity fuzes to explosives including RDX, developed before the war in the United Kingdom and now manufactured by new processes in the United States.[29] The BCSO was part of a "Whitehall in Washington," which expanded well beyond research and development into procurement, production, and (inevitably) intellectual property issues. The BCSO and other British liaison offices organized visits, provided diplomatic advice, and distributed many thousands of technical reports in both directions. Equivalent offices were set up in London under the U.S. National Defense Research Committee, later the Office of Scientific Research and Development (OSRD). Cooperation was well and truly institutionalized: An

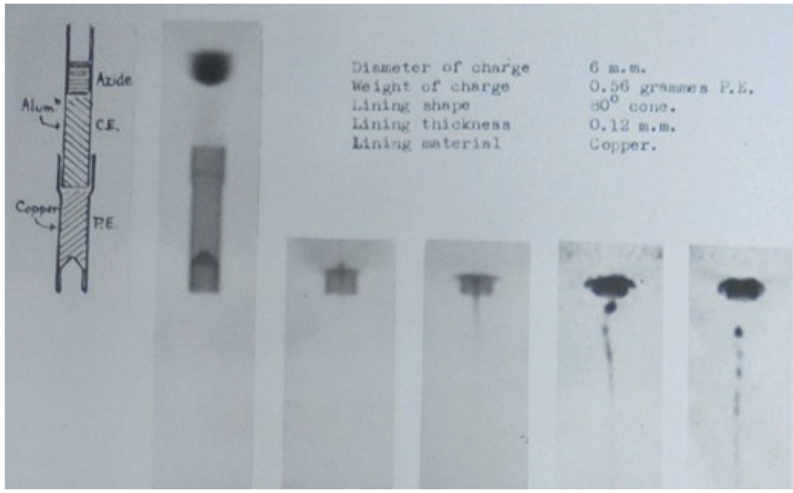

Fig. 4. First flash radiographs of shaped charges in the United Kingdom taken at the Road Research Laboratory for James Tuck in 1943 and showing in five stages (before detonation and after 11, 13, 23, and 28 μs) the formation of a Munroe jet pointing downward here and followed by a small "plug" of solid material (WO 195/3650, United Kingdom National Archives).

estimated 6000 scientific reports were sent from the United Kingdom to the United States and Canada during the war, and 8000 received in return.[30,31]

Explosives researchers in the United Kingdom therefore had access to the resources and ideas of their U.S. counterparts, and vice versa. This was the case well before the atomic relationship settled down into a pattern of harmonious cooperation.

At the long-established Bureau of Mines research site at Bruceton, Pennsylvania—an equivalent to the British site at Buxton—a new Explosives Research Laboratory (ERL) was set up by the OSRD in fall 1940, working on explosives chemistry, rocket propellants, and shaped charges. In May 1943, Seth Neddermeyer, the earliest champion of implosion at Los Alamos, visited Bruceton.[14] Elsewhere, the Ballistics Research Laboratory, established in 1941 at the U.S. Army Ordnance Department's proving ground at Aberdeen, Maryland, expanded rapidly and worked also on shaped charges, terminal detonation ballistics, and high-speed photography and radiography.

Although the flow of ideas back and forth across the Atlantic is hard to follow in detail—whether particular reports were passed and their importance realized, and if so, exactly when—it is clear that UK research was routinely being reported to large distribution lists in the United States. By September 1941, Harvard professor George Kistiakowsky's ideas on detonation and shock wave theory, developed at the ERL, were being debated in the UK explosives research community. And by March 1943, joint meetings on shaped-charge research were being held in Washington. Kistiakowsky and Duncan MacDougall from Bruceton, Garrett Birkhoff from Aberdeen, and other researchers from the DuPont Corporation and various U.S. universities shared their theories and experimental results on the Munroe effect. Clark and Seely at the ERL had been making similar flash X-ray observations to Tuck's. United Kingdom attendees, at least, concluded that the Taylor-Tuck hydrodynamic "squirt theory" explained the Munroe effect, although Kistiakowsky favored a theory of interacting shock waves and DuPont researchers emphasized spalling effects.[32–34]

V. LOS ALAMOS

And so, by a long and roundabout way, we come to the Manhattan Project.[2] Neddermeyer had started a small program of experiments to study implosion physics at Los Alamos in the spring of 1943 (Ref. 3) and was encouraged by his visit to the ERL, but the work lacked attention and priority until energized by the visit of John von Neumann to Los Alamos in September. Following this visit Kistiakowsky, a pioneer of the precision use of high explosives, was head-hunted by Robert Oppenheimer, bringing with him several colleagues.[14] At this point, the implosion program had advanced far enough to get into trouble. When cylindrical implosions were made with 16 points of detonation and a flash photograph taken down the axis of the imploding cylinder, jets of material moving inward were observed instead of a smooth uniform inward motion. The jets occurred at those places where detonation waves from two different detonation points interacted.[35]

One of von Neumann's suggestions was to capitalize on Munroe jets, using shaped charges to power the implosion. However, as experiments continued, it became clear that jetting was the enemy: A symmetrical implosion would be very hard to achieve.

In the first half of 1944, British scientists began to arrive at Los Alamos. They brought good and bad news for the implosion program. Rudolf Peierls, visiting in February 1944, recalled in his memoirs that he had only recently taught himself hydrodynamics in order to prepare a lecture course, but he brought useful new techniques to solve partial differential equations. Peierls's hydrodynamics contribution continued to be extremely valuable, as Morgan and Archer demonstrate (see this issue).[36–38] Taylor, meanwhile, visiting in May 1944, was pessimistic about instabilities at material interfaces.[14]

Also in May 1944, Tuck arrived at Los Alamos, where he found that asymmetries and interactions between detonation waves dominated his conversations. Within weeks he was put in charge of an experimental program to observe explosive lenses by flash radiography. Explosive lenses were not unknown to U.S. researchers. Elizabeth Monroe Boggs at the ERL independently described a concept for an explosive lens.[14,b] But the available sources agree that it was Tuck, familiar with Poole's idea through his work with the wider UK explosives community, who first suggested the use of lenses to smooth the implosion in the atomic bomb. Indeed, "in England, eight months before Tuck's proposal … Poole prepared a complete description of a crude two-dimensional lens to generate a plane detonation wave."[14]

Taylor described lenses as "a suggestion made by Mr Tuck,"[c] also mentioning 32 detonation points specifically, as used in the eventual Trinity test device, and noting that "the question whether a converging spherical detonation wave can be formed in this way is … to be investigated independently at the Bruceton experimental station."[39] By July 1944, a dedicated program of explosive lens experiments for Los Alamos was indeed underway at Bruceton under the name Project Q.[14] In a letter to Cherwell, delivered to the United Kingdom personally by James Chadwick, Tuck noted that "my explosive lenses … didn't get much support here at first but people are starting to get rather frightened now and [Hans] Bethe has got them to start work at [Bruceton]." Tuck was clearly enjoying himself, adding that "I seem to get on quite well with the Americans and we seem to work hard … About twice a week, I go horseback riding in the evening … for 100 USD, you can get a horse that will go like the wind."[40]

Later, Tuck recalled that "the idea of explosive optics captured the fancy of the mathematical physics community … von Neumann came up with an ingenious extension of Huygenian optics which when tested experimentally, seemed to work."[16]

Tuck continued to be involved in experimental work on lenses, and in October 1944 Marley also brought his rotating mirror camera from the Road Research Laboratory to Los Alamos. According to Peierls, Marley later achieved the rare distinction of being audible in the back row at one of the colloquium meetings, presumably a wry comment on the acoustics of the Los Alamos cinema building.

With theoreticians and experimentalists now working closely together, understanding of the nature of jets advanced quickly. Experiments, including X-rays of slabs of solid material by Tuck, and theoretical calculations by Klaus Fuchs, now showed that the jets were not due to the Munroe effect but to high interaction pressures in detonation and shock waves. Seemingly the jets seen in solids were more akin to Kistiakowsky's original concept of shock-wave interactions than the Taylor-Tuck "squirt" theory which, strictly speaking, explained only the behavior of the cavity liner in a shaped charge.

Confidence in lenses ebbed and flowed over time, but the challenges were surmounted. Interestingly, Kistiakowsky recalled many years later that "physicists … with few exceptions, were very skeptical as to whether the lenses would work properly" but attributed this to "a general feeling of superiority by the physicists over the chemists" at Los Alamos.[41] Peierls and Bethe, it appears, were nevertheless also consistent champions of the explosive lens.[14]

VI. CONCLUSION

We have seen that the idea of an explosive lens arose originally in the United Kingdom, in the course of research on shaped charges and the C. S. bomb. Harold Poole at Woolwich suggested the lens, and Donald

[b] Interestingly, Boggs had completed her PhD research before the war at Cambridge working for Lennard-Jones, although in those unenlightened times women were not awarded actual research degrees by Cambridge. Unfortunately, it is not clear what application, if any, Boggs had in mind for her explosive lens

[c] Tuck remained "Mr"—his PhD studies at Manchester University had been interrupted by the war and were never completed.

Woodhead demonstrated its feasibility. Poole and Woodhead were probably slightly ahead of Elizabeth Monroe Boggs at Bruceton. James Tuck derived a theory of the shaped charge, later improved by Geoffrey Taylor, and conducted experiments using U.S. flash X-ray equipment. British and American researchers shared and discussed these results routinely as part of their wartime cooperation on defense science. Tuck was brought to Los Alamos, where he suggested the use of the lens in the implosion gadget and conducted some of the related experiments. His idea was improved by John von Neumann and refined through further calculations and experiments through 1944 and 1945. This work provided a solid practical and theoretical foundation for all work on hydrodynamics in the nuclear weapons program during and after the war. Moreover, the foundational lens work in the Manhattan Project encouraged the further development of precision explosives, and beyond nuclear weapons, was key to developing shaped charges for conventional defense and civilian applications in demolition, energy extraction through fracking, and complex engineering solutions, such as the separation mechanism of multistage rockets.[3]

The Manhattan Project authorities took great care over patenting, more for security than for traditional commercial reasons. Patents have the effect of assigning ownership. This, and the traditional focus of historians and documentary makers on the human stories of invention, has tended to drive interest in establishing the paternity of bombs and bomb components: Who was the "father of the bomb"? Whose was the "eureka!" moment? Patent experts at the time, however, were unable to unravel these questions. Neddermeyer, Tuck, and von Neumann were all credited as inventors of the "method of focusing detonation wave in implosion process (lens assembly)."[42,43]

The extent of the British contribution to the work of Los Alamos has also preoccupied historians. Bethe's comment, coming from a theoretical physics perspective, may be the most interesting on this subject: "It is very difficult to say what would have happened under different conditions [i.e., without the work of the very small number of British scientists at Los Alamos]. However … it is not unlikely that our final weapon would have been considerably less efficient."[44] Explosive lenses closely affected the efficiency of the gadget.

Paternity and the extent of British help are not, however, very useful questions. Reviewing the genesis and development of this breakthrough technology, we see a much more complex picture. Many U.S. and some British researchers, often with highly relevant previous experience, were brought together deliberately at Los Alamos where they freely contributed ideas and hard, often tedious experimental work. Way beyond Los Alamos—beyond even the wider Manhattan Project—an inter-allied network of scientists exchanged ideas on a vast range of defense research, including physics and chemistry, of direct importance to the design of the gadget's explosive components. They also exchanged equipment and techniques, such as the American X-ray equipment used by Tuck to take his original pictures of Munroe charges and the Marley camera taken to Los Alamos. They debated theories and experimental results at joint meetings on shaped charges in Washington and at colloquia and council meetings at Los Alamos. Just as important, scientific leaders—notably in this case Oppenheimer, Bethe, and Kistiakowsky, but also Peierls—championed particular technologies and between them made tough design choices as theoretical and experimental knowledge advanced, sometimes in parallel and in good time, sometimes not.

Collaboration, and not the "lone genius" model, is the key to understanding the explosive lens and continues to be fundamental to nuclear weapons science.

VII. EPILOGUE

James Tuck witnessed the Trinity test on July 16, 1945, making a series of sketches of the development of the mushroom cloud (Fig. 5) and asking rhetorically, according to a later interview with his daughter Sarah, "what have we done?"[45]

Tuck had enjoyed Los Alamos:

> [F]or us, my wife and I, Los Alamos in its heyday had been an unforgettable … experience. The people had been socially congenial, we had a wide circle of friends (the members of the British mission were good and competent but somehow didn't wholeheartedly enjoy the Los Alamos scene, their wives especially, quite as much as we did …).

Back at home, postwar austerity was hard to bear, and in 1950, encouraged by both Edward Teller and Norris Bradbury, Tuck returned to the United States, became a naturalized citizen, and enjoyed a long career at Los Alamos.[16] Although he never completed his PhD due to war, Tuck was named to the Order of the British Empire in the United Kingdom and a Fellow of both the American Physical Society and American Association for the Advancement of Science in the United States.[46]

Birkhoff, MacDougall, and Taylor (now Sir Geoffrey) were coauthors of a definitive paper on the Munroe effect in the Journal of Applied Physics in 1948, based on their wartime collaboration.[47]

Fig. 5. James Tuck's sketch of the Trinity test 3 min after the explosion (CAB 126/250, United Kingdom National Archives).

Harold Poole, author of the first report on explosive lenses in 1942, continued his career in defense research, taking over from William Penney as CSAR in 1950 when leadership of the British atomic weapons program began to monopolize Penney's attention, and retiring as a Commander of the Order of the British Empire.[48]

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