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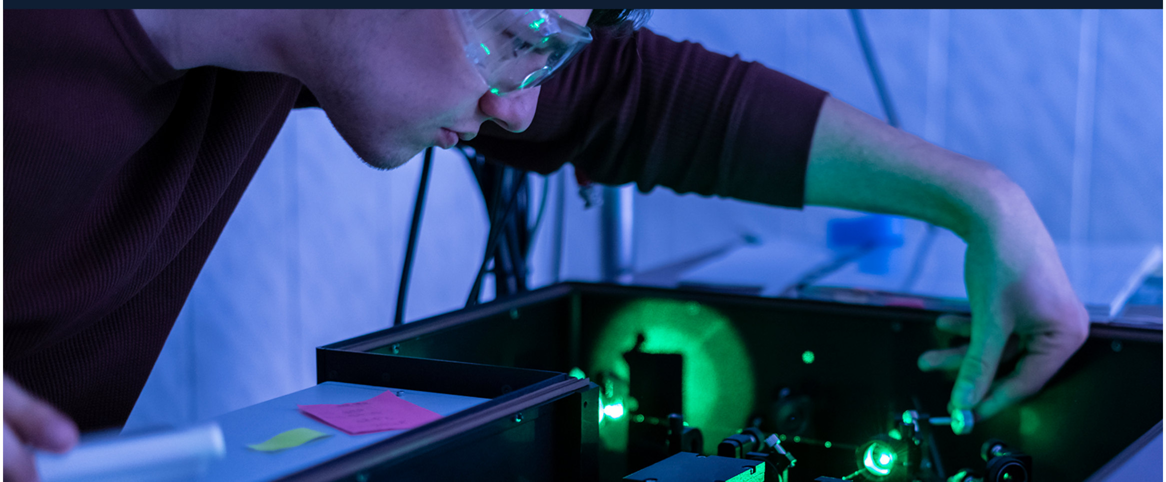

“Peaceful” nuclear explosives?

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On 10 December 1961, a crowd of several hundred people, including officials from the US Atomic Energy Commission (AEC), scientists, reporters, members of the public, and guests from 13 nations, gathered roughly 40 kilometers southeast of Carlsbad, New Mexico, and eagerly waited for the countdown. The nuclear testing moratorium initiated in November 1958 between the US and the Soviet Union had ended four months earlier (see the timeline in figure 1), and Project Gnome, the first nuclear explosive test detonated as part of the AEC's Project Plowshare, was finally about to occur after years of delay. Information acquired from Gnome was intended to support research on using nuclear explosives to produce recoverable energy, to mass produce radioisotopes for scientific and medical uses, and to demonstrate that such devices could be utilized for "peaceful" purposes—Plowshare's primary objective.

At noontime, the 3-kiloton-yield nuclear explosive buried 361 meters deep was detonated and formed an underground cavity chamber of 27 200 cubic meters. As reported in a 22 December 1961 *Time* article, one onlooker described the seismic activity as having "shook up your rattlesnakes" as the earth above the blast site rose almost two meters. Although Gnome was designed to be self-contained, the article reported that an "ominous-looking mushroom cloud" emerged from the shaft opening just minutes after the shot, venting radiation into the atmosphere. It damaged chemical samplers over ground zero and film in nearby cameras. The exit road from the site had to be temporarily closed, and cars in the area were washed down. A moment of nuclear promise evaporated into one of disappointment.

From the 1961 Gnome experiment through 1973, Project Plowshare detonated 35 nuclear explosives in 27 tests. It was organized under the AEC's division of military application in 1957—the same year that the world's first nuclear plant for commercial electricity generation began generating electric power and the International Atomic Energy Agency was established. Plowshare's purpose was to study the technical and economic feasibility of using "peaceful nuclear explosives" (PNEs) for civilian industrial applications. (For a contemporary look at Project Plowshare, see the article by David Lombard, Physics Today, October 1961, page 24.) The name was biblical in nature, chosen to emphasize its peaceful aims: "And they shall beat their swords into plowshares, and their spears into pruning hooks; nation shall not lift up sword against nation, neither shall they learn war any more" (Isaiah 2:4).

The development (and ultimate cancellation) of Plowshare occurred amid Cold War tensions and international negotiations for nuclear disarmament, a national environmental movement wary of "the unnatural creation of man's tampering with the atom" (reference 1, page 7), and heightened public opposition to new nuclear applications. There was also a need for greatly expanded domestic energy production driven by predicted near-term significant

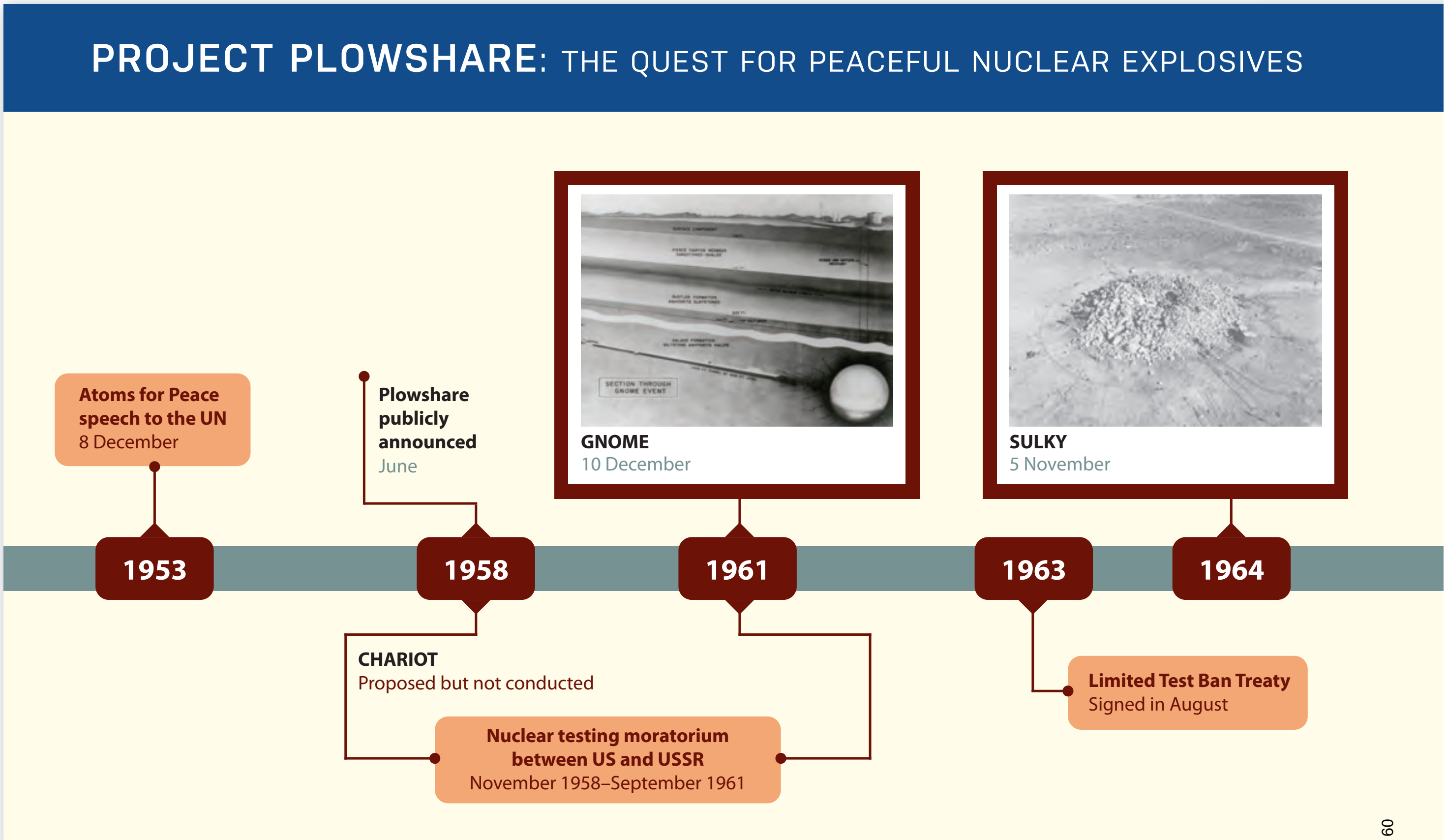

FIGURE 1. PROJECT PLOWSHARE took place among changing political treaties and shifting public opinion on nuclear technology. The timeline shows a small selection of Plowshare and other important events to put the tests into a wider context. (Images courtesy of the US Department of Energy.)

consumptive increases and national security interests, to which nuclear technologies could, in theory, provide economical solutions. The fundamental question of costs—whether to the budget, environment, or public confidence and safety—remained a central challenge to the AEC's efforts to demonstrate that PNEs were indeed worth their while.

Construction from destruction

"Occasional pages of history do record the faces of the 'great destroyers,' but the whole book of history reveals mankind's never-ending quest for peace and mankind's God-given capacity to build," declared President Dwight D. Eisenhower during his Atoms for Peace speech to the United Nations General Assembly on 8 December 1953. "My country wants to be constructive, not destructive." The following year Congress amended the Atomic Energy Act and codified such peaceful nuclear aims into law by requiring that "the development, use, and control of atomic energy shall be directed so as to promote world peace, improve the general welfare, increase the standard of living, and strengthen free competition in private enterprise."

With the dawn of the "peaceful" atomic age, the AEC exercised its dual regulatory and promotional roles to oversee the development of civilian nuclear programs and to encourage and mediate partnerships between the federal government and private sector. AEC officials believed that the key to success of new nuclear endeavors lay in placing the burdens of technological risks and financial liabilities onto private companies through contractual agreements. In other words, it was to be a prime example of the military–industrial complex that Eisenhower would come to warn about in his farewell address. The AEC itself would remain responsible for all aspects of radiation safety. In prepared remarks for an American Institute of Chemical Engineers meeting in March 1954, AEC member Henry Smyth said, "Private industry already is carrying a major share of our enterprise under contract to the Government and is now becoming more and more active on its own initiative. This is as it should be" (reference 2, page 17).

Civilian access to nuclear technology opened the door for new applications. The 1956 Suez Canal crisis motivated Harold Brown, a physicist at the University of California Radiation Laboratory at Livermore (now Lawrence Livermore National Laboratory), to wonder about the possibility of using nuclear explosives to construct sea-level canals as a solution to the international trade disruption (see the map in figure 2). The success the following year of Project Rainier, the first underground nuclear shot, demonstrated that PNEs could produce underground cavities as predicted, which further catalyzed interest from oil, gas, and mining companies. (To read more about the promise of nuclear excavation with Plowshare, see the article by Gerald Johnson, Physics Today, November 1963, page 38.)

Project Plowshare's ambitions were frequently limited by measures put in place for other nuclear programs, regardless of intention. Plowshare was publicly announced in June 1958, only to be curtailed by the three-year nuclear weapons testing

GASBUGGY
10 December

RULISON
10 September

RIO BLANCO
17 May

1965 **1967** **1969** **1973** **1977**

PALANQUIN
14 April

KETCH
Proposed but not conducted
August

National Environmental Policy Act of 1969
Signed into law on 1 January 1970

Plowshare terminated

moratorium that went into effect four months later. The moratorium broke down when the Soviet Union resumed nuclear testing on 31 August 1961 and the US promptly followed suit two weeks later.

Under Project Plowshare, six tests, including Gnome, would be conducted before the Limited Test Ban Treaty was adopted in August 1963. It prohibited nuclear explosions "in any other environment if such explosion causes radioactive debris to be present outside the territorial limits of the State under whose jurisdiction or control such explosion is conducted." To the extent Plowshare experiments could breach that provision, the treaty remained a risk to the program's prudence, although the Soviet Union was administering its own nuclear testing program for peaceful applications.

"The nuclear reactor has become a symbol of the constructive uses of atomic energy; the nuclear bomb, a symbol of destruction. What peaceful end could ever be served by a nuclear explosion?" wondered Brown and Gerald Johnson, also a physicist at the Radiation Lab.[3] The goal of Plowshare was to find out.

How atomic energy could change the world

In its early years, Plowshare was focused on large-scale geographical engineering projects, such as digging harbors, manipulating mountains, and altering watersheds. "We will change the earth's surface to suit us," wrote physicist Edward Teller in *The Legacy of Hiroshima* (page 84), his 1962 book with Allen Brown. Teller was an infamously outspoken advocate of Plowshare during his tenure at the Radiation Laboratory at Livermore. Earlier, in June 1959, while in Alaska promoting Project Chariot, he was quoted by an Anchorage newspaper as saying, "If your mountain is not in the right place, just drop us a card." Such dreams of earthmoving intersected with a galvanized national environmental movement, often marked by the 1962 publication of Rachel Carson's influential *Silent Spring*, which compared the invisible threats of radioactivity with the indiscriminate spread of pesticides and other poisons, an ecological crisis of our own making.[1]

"Unquestionably, the environment has suffered from the actions of man," stated Sam Smith, director of exploration for the El Paso Natural Gas Company, in 1970. "Some of this damage has been unavoidable, some the result of ignorance, and unfortunately, some has resulted from lack of responsibility. . . . However, we must consciously recognize that the expanding population and improved standard of living will require continued modification of our environment" (reference 4, page 21). That observation exemplifies Plowshare advocates' negotiations of PNEs' consequent ecological and biological hazards and to what extent such incurred environmental costs could be justified in their attempts to demonstrate the program's utility.

Project Chariot, an experiment designed to blast a new harbor in Cape Thompson, Alaska, was among the first of those ventures. It was planned as a series of five thermonuclear devices with a 2.4-megaton yield, but the design was later replaced with smaller fission explosives, cutting several million off its price tag. The blasts would create a harbor 823 meters long and 229 meters wide at a site only 300 kilometers from Siberia. Though the project site was repeatedly described as "a barren wasteland" that was "far away from any human habitation," an Inupiat community was located only 48 kilometers from the planned project site, but the AEC repeatedly failed to engage with its residents (reference 5, page 33). Aware of the 1954 catastrophe at Bikini Atoll,

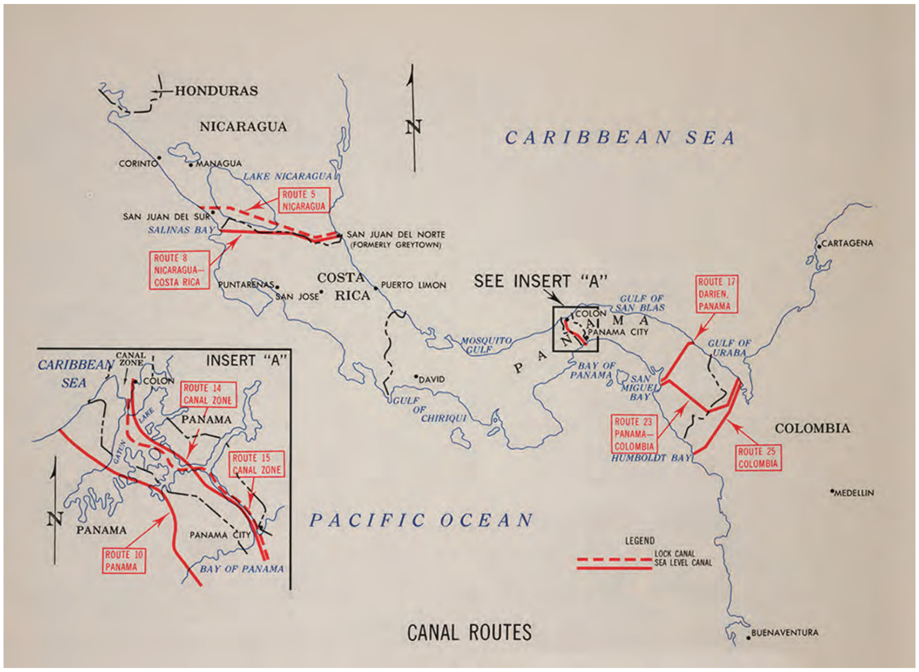

FIGURE 2. SEA CANAL ROUTES. One considered use for peaceful nuclear explosives was the building of canals. As part of the Atlantic–Pacific Interoceanic Canal Study, many routes across Central America were considered. (From ref. 7, page vi.)

the Point Hope residents organized against Chariot. Establishing a village council, they wrote letters expressing their concerns about the radiation hazards and questioning the AEC’s right to use the land for the experiment, especially because they relied on it for hunting caribou. “I’m pretty sure you don’t like to see your homeland blasted by some other people who don’t live in your place like we live in Point Hope,” Kitty Kinneeveauk told the AEC during a March 1960 meeting (reference 5, page 34).

Understanding how radioactivity could travel through and accumulate in an ecosystem was a crucial factor in weighing the biological cost of the proposed excavation. Biologists at the University of Alaska Fairbanks raised concerns that Chariot had no plans for ecological assessments. “It is scarcely too early in the Atomic Age to give considerable attention to the environment which supports man on this planet,”[5] said John Wolfe, an ecologist with the AEC’s division of biology and medicine (reference 5, page 35). The AEC established a Project Chariot environmental studies committee, chaired by Wolfe, to oversee the bioenvironmental program. The end result was a 1200-page publication of 42 environmental studies of the Cape Thompson region,[6] often considered the first environmental impact statement. Such statements have been required since passage of the National Environmental Policy Act of 1969. Importantly, ecological studies confirmed that radiation could be traced from the lichens to the caribou that eat them, to the Inupiat community who eat the caribou. Although Chariot was never formally canceled, it was among Plowshare’s numerous geographical engineering failures.

On 22 September 1964, Congress authorized $17.5 million for the Atlantic–Pacific Interoceanic Canal Study to evaluate construction methods, including the use of nuclear excavation techniques. The commission looked at numerous routes through Panama, Colombia, Costa Rica, and Nicaragua and later conducted field surveys in the countries. But it determined that the use of PNEs to create a “panatomic” canal was not technologically feasible. The unavoidable risk of radiological consequences in foreign territories also exacerbated existing political objections.

In pursuit of a sea-level canal, the US leveraged the PNE as an instrument of technological and engineering prowess for geopolitical gain. US proposals were met with demands by Panama for revisions to the Hay–Bunau-Varilla Treaty of 1903. By 1967 three new treaties were drafted, including one for granting the US rights to build and operate a sea-level canal in Panama, but they were never ratified. In the cover letter to its 1970 Interoceanic Canal Study final report, the commission concluded that “no current decision on United States canal policy should be made in the expectation that nuclear excavation technology will be available for canal construction.”[7]

The Limited Test Ban Treaty’s prohibition on the spread of fallout across international borders also presented issues for the nuclear excavation of a sea-level canal. The AEC interpreted the treaty’s language to mean that only a measurement of radioactivity higher than internationally accepted standards would constitute a violation, and, according to the commission, “there was confidence . . . that the radioactivity effects could be held to insignificant levels” (reference 7, page 34). Fallout patterns were predicted along the potential sea-level canal routes, and the study results suggested that up to 30 000 people could require evacuation. To a large degree, however, the maps were an illusion of control; other Plowshare tests—namely, Palanquin, which released airborne debris that was approximately 2500 m above the unexpected crater, had higher-than-predicted radiation levels, and nearly drifted across the US–Canadian border—cast considerable doubt that the spread of radioactivity subject to changing meteorological conditions could be accurately predicted.

The Plowshare efforts for nuclear-excavated canals were exemplary of the 1960s US practice of deploying state-sponsored technocratic projects to conquer nature “on a scale comparable to waging war.”[8] It became clear that the potential costs of PNEs demanded a fuller evaluation of the environment surrounding the test sites so that the impacts could, in theory, be calculated and mitigated with engineered controls.

Energy problems, nuclear solutions

In the 1950s, signs of an impending energy crisis were evident—a booming population, increasing consumption, and depleting natural resources—and the question was not only how nuclear energy could be part of the solution but how it could effectively compete in the energy market. In a 1954 congressional report on the AEC's proposal for a five-year reactor development program, the pressurized water reactor was ranked as the least promising of the proposed reactor designs for achieving economically competitive nuclear power: "It is clearly of conservative design and has a poor long-term prospect for producing low-cost atomic power" (reference 2, page 3). Nine years later, Teller wrote that "nuclear energy is not yet competitive. It has contributed to the national economy by providing additional incentive for lower cost of the conventional installations."[9]

Market incentives for a more efficient and economical means to increase natural-gas production drove industry participation in Plowshare, but the potential for long-term profits was uncertain. Gas production models suggested that PNEs would be advantageous over conventional extraction techniques—for example, using a hydrochloric-acid solution to dissolve calcium carbonate in a limestone reservoir—because their higher yield would increase the permeability of the surrounding medium and the radius of the chimney formation fracture system (as seen in figure 3), thereby increasing the rate of gas flow. A 1967 report suggested that PNEs used in low-permeability gas fields could increase recoverable natural-gas amounts by adding at least 18 years to the national supply at a fraction of the cost.[10] Project Gasbuggy, the first Plowshare experiment to produce natural gas, was undertaken by the AEC, the Radiation Laboratory at Livermore, the El Paso Natural Gas Company, and the US Bureau of Mines to confirm to what extent that was indeed the case.

Gasbuggy aimed to stimulate the Pictured Cliffs, a low-permeability formation in New Mexico's San Juan Basin where the El Paso Natural Gas Company owned oil and gas leases. The experiment was conservatively predicted to make 67% of the 149 million cubic meters per acre of natural gas recoverable, a sevenfold increase compared with conventional stimulation. It was unclear, however, to what extent the radioactive byproducts would contaminate the natural-gas supply, given that certain gaseous radioisotopes—krypton-85, xenon-133, and tritium—could not be filtered out. According to a 22 September 1967 article in the *New York Times*, before the Gasbuggy shot, a Radiation Laboratory representative at a public meeting told the attendees, from 14 countries, that "current estimates for gasbuggy itself indicate that with regard to tritium, the gas (released by the explosion) will not be suitable for unrestricted use unless diluted with uncontaminated gas." The AEC needed to determine whether use of the gas would result in radiation exposure above normal levels received by the public under the standards set by the Federal Radiation Council before the El Paso Natural Gas Company could sell it. But even if the AEC determined that the natural gas was acceptable to sell, would consumers be convinced of its safety?

After several delays, Gasbuggy was detonated on 10 December 1967. The 29-kiloton explosive created a chamber just over 46 meters in diameter and 101 meters high with approximately 57 000 cubic meters of space. Although the test was successful in that the radioactivity was completely contained in the underground cavity, samples of the natural gas revealed significant amounts of tritium and a dramatic decrease in the percentage of hydrocarbon. Post-shot surveillance by the US Public Health Service showed that the highest concentration of tritium in the environmental samples coincided with the highest daily release rates during initial flaring operations in November 1968, a standard part of the natural-gas extraction process. El Paso was never able to sell the gas produced.

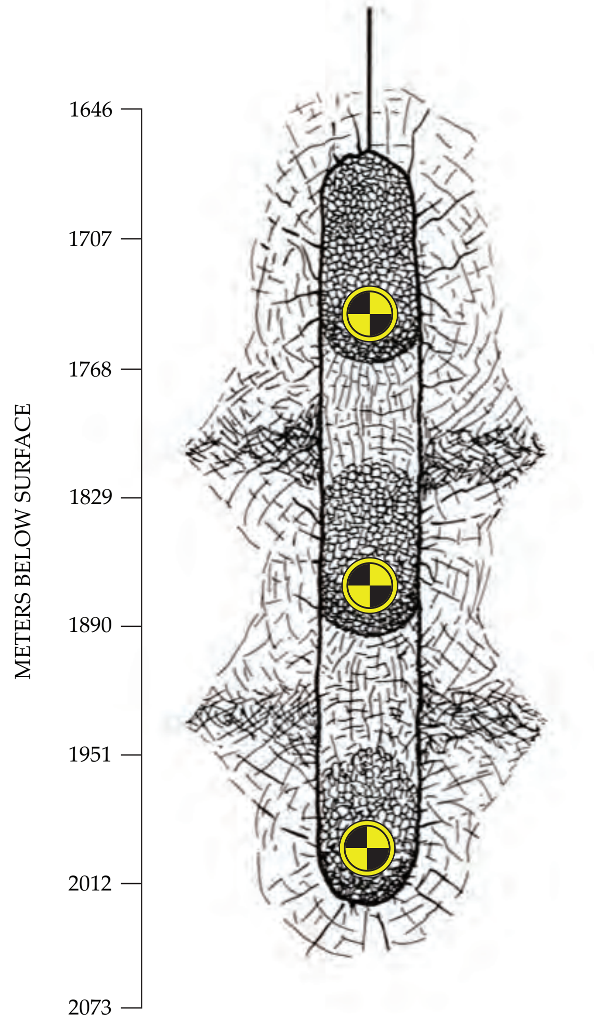

FIGURE 3. PROJECT RIO BLANCO aimed to use three detonation sites in vertical arrangement in order to optimize the yield. (Adapted from J. Toman, H. A. Tewes, *Project Rio Blanco: Phase 1 Technical Studies*, Lawrence Livermore Laboratory, University of California, 24 January 1972.)

Like Gasbuggy, Project Rulison—sponsored by the AEC, the Department of the Interior, and the Austral Oil Company with CER Geonuclear Corp—aimed to test PNEs' effectiveness for gas stimulation in the Rulison Field in Garfield County, Colorado. Under the contract, 90% of the $6.5 million cost would be covered by private industry. Austral Oil had the lease for the land, so no state approvals were required before the shot was detonated, but local environmental groups, including the Colorado Committee for Environmental Information, were vocally opposed to the blast. After several delays because of legal challenges from conservation organizations and unfavorable weather forecasts, the 40-kiloton explosive was detonated almost 2600 meters underground on 10 September 1969. Initial results were positive: The radioactivity was completely contained, and the well produced nearly 6 million cubic meters of gas in one month, equal to six years' worth of production for the region. But

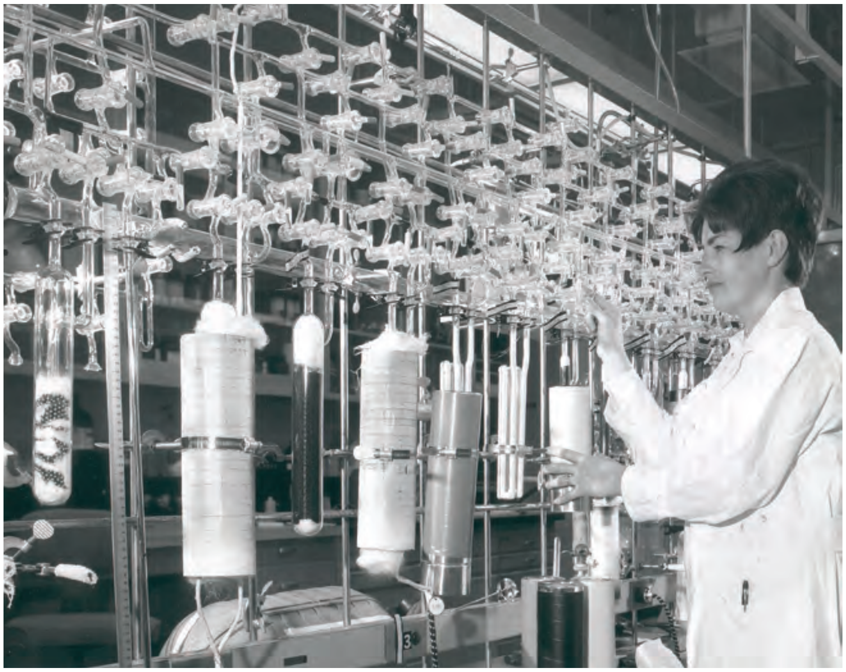

FIGURE 4. LAWRENCE RADIATION LABORATORY, around 1968. The branch at Livermore housed chromatographic gas columns with samples from Project Gasbuggy. JoAnn Rego was one of the scientists who worked in the radiochemistry laboratory. (Courtesy of the US Department of Energy.)

similar to Gasbuggy, the natural gas contained tritium, and the AEC would not permit Austral to sell it. The experiment ultimately cost Austral nearly double the original contract estimate, and the company did not recoup a single penny.

Rio Blanco, Plowshare’s third gas stimulation experiment, was similarly unsuccessful. Scientists began studying a site near Rifle, Colorado, in December 1970. The previous January, the National Environmental Policy Act had been signed into law and required government agencies to prepare an environmental impact statement for “major Federal actions significantly affecting the quality of the human environment” and to solicit public comment. Akin to Chariot, Rio Blanco received a barrage of public scrutiny. A US representative on the Joint Committee on Atomic Energy described it as “an unnecessary waste of the nation’s uranium.” A member of the Sierra Club, a US environmental organization, said, “We are the nation’s guinea pigs in an insane experiment for a few dollars for a few corporate enterprises which includes the AEC.”[11] The final Rio Blanco environmental assessment stated that the amount of tritium to be released during flaring was expected to be less than the amount released during Rulison. The predicted total maximum potential dose to local populations was less than 1% of annual background radiation, an “adverse environmental impact which cannot be avoided.” The report also said that “the development of this technology must be evaluated in terms of whether the benefits derived from the gas production outweigh the economic and environmental costs.”[12]

Rio Blanco was detonated on 17 May 1973, and the results were disappointing: The three vertically placed blasts created separate cavities, as seen in figure 3, rather than one, and no gas could be found in the top chimney. Discovery of cesium-137 immediately put a stop to the post-shot flaring, and the Nuclear Regulatory Commission, established in 1975, would not allow the sale of any gas produced because strontium-90, a dangerous byproduct of nuclear fission, was detected in 1974. The 85% of Rio Blanco’s $8.9 million cost covered by private industry resulted in zero financial gain.

After more than $80 million spent on Plowshare’s natural-gas stimulation efforts, the unique liabilities and risks presented by PNEs proved too costly for private industry’s comfort. “Analysis of the stimulation effects and the attendant costs leads to the conclusion that nuclear-explosive well fracturing at its present stage is not commercially attractive,” said an Energy Research and Dev-elopment Administration representative at a 1976 conference on the future of petroleum and gas production. “Public acceptance of the technology is equally important; it has never been favorable and is downright hostile at this time with no prospect for near-term improvement. The problems are exemplified by voluminous environmental statements.”[13]

Political costs

Three years of collaboration among the Columbia Gas Corp, the AEC, the Lawrence Radiation Laboratory at Livermore (see figure 4), and the US Bureau of Mines to identify a means of providing new natural-gas storage in Pennsylvania resulted in the Project Ketch feasibility study, finalized in July 1967. Ketch would require that a 24-kiloton nuclear device be detonated 1006 meters underground to create a chimney that could provide 13.2 million cubic meters of gas storage. Given that the Appalachian states made up 38.6% of the US’s total natural-gas storage at the time, the region became a priority for the prospect of nuclear-induced storage. Columbia Gas felt Pennsylvania would be particularly accepting of atomic testing, given it was home to the Shippingport Atomic Power Station and had a history of innovative energy production. In his 1 August 1967 letter of support for the project, Maurice Goddard of the Pennsylvania Department of Forests and Waters (now the Department of Environmental Protection) acknowledged Ketch as an opportunity: “If Pennsylvania is to economically supply this important energy fuel to the rapidly expanding industries and population of the Commonwealth throughout the remainder of this century, the amount of gas pipelined . . . will have to be doubled from the present rate of about 683 billion cubic feet annually.”[14]

The proposed Ketch site, located in Sproul State Forest in central Pennsylvania, was primarily chosen for its proximity to major sources of natural-gas production and significant market needs for increased gas storage capabilities—remote from civilization and yet close enough to existing pipelines to make it economical, as the AEC described it. Similar to Chariot, the AEC asserted the marginality of the central Pennsylvania region’s residents by depicting the site as a “hole in the map,” despite its location roughly 48 kilometers outside State College, home of the Pennsylvania State University, and even closer to the nearby towns of Renovo and Bellefonte. Although Columbia Gas repeatedly emphasized that the blast would help stimulate local economic development, it offered little details on the long-term benefits. At the time, Ketch was proposed as nothing more than an experiment in feasibility; there were no long-term commitments from the AEC or Columbia Gas for continued use and operation of the site. A headline in the 23 April 1968 edition of the *Renovo Daily Record* boasted: "If Successful, 'Ketch' will Employ 2 to 4 Men." An editorial in the *Centre Daily Times* on 13 May observed that "the same arguments of economic advantages are being used for Project Ketch that were used for strip mining 20 years ago. Now the long suffering taxpayer must raise the money to try to repair some of the damage so that his environment will be fit to live in."

Many local organizations issued public statements against the experiment. Eventually, the Clinton County Central Labor Union presented the county's commissioners with a 4600-signature petition. A citizens group called People Against Ketch was formed, and its members produced pamphlets and organized a caravan to visit the proposed project site. The AEC and Columbia Gas hosted numerous public meetings in an attempt to mitigate Ketch's ongoing public relations problem. At an April 1968 public forum held at Penn State, questions from the audience lasted for more than three and a half hours. One attendee observed that the others "clobbered" the panel. "Objections appear to be based on fear of the unknown—or partially understood," Ernest Weidhaas, a professor of engineering at Penn State, scribbled in a note to Nunzio Palladino, dean of the College of Engineering and chairman of the Pennsylvania Advisory Committee on Atomic Energy Development and Radiation Control subcommittee on Ketch.[14]

To the residents of Clinton and Centre Counties, Ketch just wasn't worth it. Within three months of the forum, Columbia Gas withdrew its lease application for the Ketch site.

The commercialized atom: At what cost?

Plowshare, fundamentally, was about selling the industrial economic benefits of the peaceful atom. Signs of an impending energy crisis drove market incentives. That created favorable conditions for companies to see the most financial reward from the then newly commercialized atom. But as with the introduction of any new technological application, there are real costs—monetary, environmental, and sociopolitical—initially unforeseen and incurred over time. Nevertheless, the AEC and Plowshare proponents hardly lost faith; they advocated with conviction that something constructive needed to come of a technology capable of such indiscriminate destruction.

Plowshare's defenders remained steadfast that PNEs were an agent of progress driving the future of commercial nuclear capabilities. PNEs were technically sound and economically advantageous, they argued, under the right theoretical conditions. Yet when such grand, visionary ideas were removed from the laboratories and imposed on various environments, initial conditions and assumptions broke down. Despite hundreds of millions of dollars spent on repeated failures to prove any of Plowshare's programmatic aims or reach its goal of becoming a "viable commercial enterprise" (reference 4, page 1), the project was not terminated until 1977.

As Plowshare faded, the idea of using nuclear technology for peace persisted through the construction of nearly 100 operating reactors in the US. Nevertheless, popular enthusiasm for nuclear power faded after the partial meltdown of the Unit 2 reactor at Three Mile Island in 1979. (See "Three Mile Island and lessons in crisis communication," Physics Today online, 5 May 2020.) A "nuclear renaissance" seemingly emerged in the 2000s, however, following passage of the 2005 Energy Policy Act, when the Nuclear Regulatory Commission received applications for combined—both construction and operation—licenses for 29 new reactors. Billions of federal loans were allocated to support new projects at the Virgil C. Summer Nuclear Station, which was ultimately canceled in 2017 due in part to astounding cost overruns, and for two units at the Alvin W. Vogtle Electric Generating Plant. The cost of the Vogtle Unit 3 project alone more than doubled over the course of its lifetime, from $14 billion to over $30 billion.

Such a nuclear resurgence continues through the development of small modular reactors, which have a capacity of less than 300 megawatts electric. Aided by the 2022 Inflation Reduction Act's tax incentives for advanced nuclear deployment, developers of the small reactors are hoping to capitalize on yet another round of the nuclear hype cycle,[15] and they are anticipating that such "deliberately small" designs[16] will not inevitably be subjected to the same economic challenges that are found throughout the history of nuclear technology. Examining Plowshare's varied costs shows that the commercial development of civilian nuclear technologies very much depends on the best price determined by the current political economy—and if private industry is willing to pay it.

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