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TRITIUM PRODUCTION IN PLOWSHARE APPLICATIONS*

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ABSTRACT

Production of tritium by Plowshare explosives is the subject of continuing research and evaluation, with reference especially to the applications now being considered: gas and oil well-stimulation, gas storage, mineral leaching, production of geothermal power, waste disposal, and excavation. About 5,000 to 20,000 Ci/kt of tritium are produced by the fusion reaction, while only about 1 Ci/kt of tritium is produced in the fission process. About 2×10^{23} n/kt escape from both ordinary fission and fusion explosives. Both static and dynamic multi-energy neutronic-group Monte Carlo methods are used to calculate the neutrons escaping into the environment and to evaluate the efficiencies of various internal and external shielding materials in absorbing these neutrons. These calculations are also used to study the effects of rock components, especially lithium and boron, and the rock temperature during the time of neutron capture. In a typical gas-bearing medium,

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about 1% to 3% of the neutrons escaping into the rock will produce tritium. The total residual tritium from the 29-kt Gasbuggy Event was 1400 Ci/kt. Work on reducing this amount has progressed to the point where about 12 Ci/kt were produced in the recently fired 80-kt Miniata Event.

INTRODUCTION

Detonation of a nuclear explosive produces substantial amounts of radioactive materials. A significant component of this material is tritium, and its production has been the subject of continuing research and evaluation within the Plowshare Program. A major goal of the program has been to reduce as much as possible the amount of tritium formed, while developing an economically attractive explosive system for industrial applications.

With the current emphasis of Plowshare shifted from excavation to underground engineering, tritium has become an even more important consideration. In natural gas stimulation and storage projects, for example, tritium could exchange with the hydrogen in the methane fuel.

SOURCES OF TRITIUM

Tritium is produced from two major sources: the explosive itself, and the material and rock surrounding the explosive. Tritium from the explosive comes from the fuel in both fission and fusion explosives.

About 5,000 to 20,000 Ci of tritium can be produced per kiloton by the fusion reaction, whereas only about 1 Ci/kt is produced in the fission process.

In the fusion process, tritium can be produced from a number of different reactions.¹ An example of such a reaction is the $D(D,P)T$ reaction, in which two deuterium atoms fuse to produce a proton and a tritium atom. The $D(T,\alpha)n$ is a fusion reaction yielding a 14-MeV neutron, and in a fusion explosive residual tritium is produced when such neutrons are captured by lithium in the explosive. In the fission process in both a reactor and a nuclear explosive, tritium is produced from ternary fission. Normally there are two fission fragments and something more than two neutrons produced per fission; however, about once every 10,000 fissions, three fragments are formed, one of which may be tritium.

The tritium produced externally to the explosive comes primarily from neutron-capture reactions with boron and lithium. Boron-10 may undergo a $^{10}\text{B}(n,T)2\alpha$ reaction if the neutron energy is greater than about 1.5 MeV. Lithium-6 may undergo a $^6\text{Li}(n,\alpha)T$ reaction; this reaction does not have a neutron energy threshold and thus occurs with very low- as well as high-energy neutrons. Other tritium-producing neutron-capture reactions, i.e., $D(n,\gamma)T$, are normally insignificant when compared with the tritium production from boron-10 and/or lithium-6.

About 2×10^{23} n/kt escape both from an unshielded fission explosive and from a fusion explosive. However, the fusion explosive produces neutrons with energies up to 14 MeV, whereas the fission neutrons have an energy

spectrum peaking at about 1 MeV, with most neutrons below 4 MeV. In general, the amount of shielding material required to capture a given number of neutrons increases with the neutron energy. Thus, less shielding is required to capture the same fraction of fission-energy neutrons than is the case for 14-MeV fusion neutrons. By the incorporation of shielding internal and/or external to the explosive, the neutron output from the explosive, and hence the tritium formed from capture by lithium in the rock, may be reduced.

The total amount of tritium produced, and the relative contribution from each of the sources for any application, would then depend primarily upon the type and yield of the explosive and the composition of the material and rock surrounding the explosive. When a fission explosive is used and boron-containing shielding (i.e., boric acid, boron-loaded polyethylene, or boron carbide) is not used, almost all the tritium produced will come from neutron capture by lithium in the soil. This is the case even when the amount of lithium present in the soil is only a few parts per million (ppm) by weight.

PLOWSHARE APPLICATIONS

Stimulation of Gas and Oil Reservoirs

Many fields exist in which the large quantities of gas and oil present cannot be recovered economically because of the low permeability of the reservoir rock. Plowshare is developing techniques to fracture

the reservoir rock with nuclear explosions and thus increase the permeability.

When a nuclear explosive is detonated underground in a completely contained explosion, it creates a cavity and fractures the surrounding rock out to relatively large distances (a series of five explosives is shown in Fig. 1). This increases the permeability of the rock and speeds the flow of gas or oil. The principle has been successfully demonstrated with one explosive in the Gasbuggy Event in northwestern New Mexico (December 1967, 29 kt) and one in the Rulison Event in western Colorado (September 1969, 40 kt). In addition, the U.S.S.R. has conducted an oil-stimulation experiment using three nuclear explosives.

In this application the main radioactive contaminants of the gas produced are the volatile radionuclides (e.g., tritium and ^{85}Kr) that mix with the natural gas. Tritium is especially important, as some of it replaces the normal hydrogen in natural gas during the explosion and thus is almost impossible to remove. Most other radionuclides, such as ^{85}Kr , could be separated from the gas, if necessary. The nonvolatile nuclei are trapped underground. Thus, a fission explosive is preferred, since it makes considerably less tritium than does a fusion explosive. In this regard, we find that in addition to volatile fission products, tritium from the ternary fission by fission-spectrum neutrons must be considered. Tritium is also produced by neutrons reacting with lithium in the rock.

Fig. 1. Stimulation of natural-gas production extensive fracturing of reservoir rock with nuclear explosives.

Gas Storage

There has been a tremendous growth in the use of natural gas as an energy source. Its advantage over other energy sources, from an air pollution standpoint, should cause this growth rate to continue, provided that proven gas reserves are adequate. Fluctuations in demand for gas from time to time cause a major problem for the gas-distribution industry. In order to avoid having to build large pipeline facilities adequate to supply peak demand, a capability for the storage of large volumes of gas is required. To satisfy this requirement, a contained underground nuclear explosion could be used to create a cavity or chimney in a very tight, unfractured, impermeable formation such as salt or shale at a location as close to the market as is seismically allowable (see Fig. 2). This underground void space could be used to

Fig. 2. Gas-storage reservoirs could be created by Plowshare underground nuclear explosions.

store gas after the radioactivity has been removed, immobilized, or allowed to decay to acceptable levels.

Calculations show that the radionuclides that might cause the greatest problem in this application are tritium, the fission product ^{85}Kr , and, where the detonation takes place in salt, the ^{35}S produced by the neutron reaction on ^{35}Cl . In salt, the lithium concentration is normally small, so most of the tritium will come from the nuclear explosive. The 87-day-half-life ^{35}S could either be reduced by neutron shielding or by merely waiting for it to decay. Whether a fission or fusion explosive were used for creating a gas-storage reservoir would depend partly on the relative radiological safety impact of tritium and ^{85}Kr .

Mineral Leaching

Throughout the world a large number of copper-ore deposits exist where the copper is too deep, or too small in absolute quantity, or distributed too diffusely to be economically recoverable by conventional mining techniques. For those deposits that are deep enough, a contained underground nuclear explosion could be used to create a chimney and fracture zone in the ore deposit (Fig. 3). For oxide ores, an acid solution could then be introduced at the top of the chimney and percolated down through the broken and fractured ore, leaching the copper or other minerals of interest. The leach solution with the dissolved copper would be pumped from the bottom of the chimney to the surface, where conventional separation facilities would remove the copper and return the acid to the top of the chimney for another cycle. A leaching method applicable to sulfide ores involves pumping oxygen down to the bottom

Fig. 3. Plowshare application of an underground nuclear explosion to crush ore for in situ leaching.

of the chimney after the chimney has been filled with water. The oxygen would then oxidize the sulfur in the copper-bearing sulfide ore, to form dilute sulfuric acid. For this application, a fusion explosive may be more desirable, if specific fission products that leach out with the copper are more of a problem than the tritium from the fusion explosive. It is not entirely clear at this time, however, whether either the fission products or the tritium will present a problem, and hence both must be given consideration.

Geothermal Power

In many geothermal areas of the world, a natural system of fractures underground act with a water-circulation system and heat source to form an underground reservoir of steam or hot water. Steam

is obtained by drilling into such reservoirs. In other geothermal areas where steam production is limited because of an inadequate or plugged natural fracture system, an underground nuclear explosion could be used to create a chimney and an associated fracture system (Fig. 4) and to augment existing fractures. Heat might also be extracted directly from the heat source itself when no reservoir or water-circulation

Fig. 4. Plowshare application of nuclear explosives to fracture rock in geothermal areas for development of geothermal power.

system is present. In this case, an underground nuclear explosion would be used to fracture the hot source rock, water would be introduced into this chimney-fracture system, and the resulting superheated steam

would be removed for the generation of electrical power. Here again, the amounts of volatile radioactive species (primarily fission products plus tritium and ^{37}Ar) that might contaminate the steam must be considered.

Waste Disposal

Another underground application under consideration is radioactive waste disposal, wherein the radioactive waste from fuel-reprocessing plants would be stored in underground chimneys created by contained nuclear explosions (Fig. 5).² One or more chimneys would be created at the site of the fuel-reprocessing plant. Radioactive waste would be

Fig. 5. Plowshare proposal for radioactive waste disposal.

injected into the chimney and allowed to self-boil. When it had served its purpose, the chimney would be boiled dry and cemented shut. The heat generated by the waste would then melt the rock, which would dissolve the waste material. When the molten material cooled, the radioactivity would be permanently and insolubly incorporated into the rock. The amount of tritium produced by the explosive in this application is relatively unimportant, because the amount of radioactivity injected into the chimney would be much greater than the amount produced by the nuclear explosive.

Excavation

The chief Plowshare nuclear excavation proposals have been for the construction of a sea-level canal near the present Panama Canal, the construction of harbors—especially in Alaska and Australia, and the use of nuclear craters for developing water reservoirs.

The final report to the President by the Interocean Canal Study Commission³ states that, "Although we are confident that someday nuclear explosives will be used in a wide variety of massive earth-moving projects, no current decision on the United States canal policy should be made in the expectation that nuclear excavation technology will be available for canal construction." Recommendation 7A indicates that, "the United States [should] pursue development of the nuclear explosive technology." Thus, although there is no research currently being carried out by the U.S. in the area of nuclear excavation, this technology may find future application in remote regions of the world.

It should be pointed out that the U.S.S.R. has built a reservoir—which is now in use—with a nuclear explosive (Fig. 6). A movie released by the U.S.S.R. shows a man diving and swimming in this reservoir.

Fig. 6. Reservoir excavated in U.S.S.R. with a nuclear explosion.

Excavation applications require explosives that produce relatively small amounts of fission products and induced activities. Thus, a thermonuclear explosive with a very small yield from the fission trigger must be used, and residual tritium would be one of the main concerns. Extensive neutron shielding is necessary, and materials in and around the explosive that can produce radioactive products of particular biological objectionability are replaced by materials that give fewer undesirable products.

CALCULATION METHOD

Since the tritium production by a nuclear detonation has become such an important consideration, considerable effort has been made in

developing the neutron-activation calculational methods.⁴ To accurately calculate the activation products, a number of parameters must be known; these include the neutron flux level within the materials of concern, the temperature of the materials at the time of neutron capture (since energy from the explosive will heat surrounding materials to very high temperatures) changes in the materials' configuration or geometry resulting from hydrodynamic effects, and both the neutron scattering and various capture cross sections of the materials, including all the constituents of the rock.

Flux level within a certain material is calculated using both static (fixed geometry) and dynamic (changing geometry) multi energy-group Monte Carlo neutronic method computer codes. It is necessary to employ the hydrodynamic code initially, to determine the number of neutrons that escape the explosive as well as the temperature and geometry or configuration of the material and rock surrounding the device. Once these values are known, a static Monte Carlo code is used to transport the neutrons that do escape the explosive throughout the environment surrounding the device.

Once the flux has been determined for a certain region, the radioactive products can then be calculated; the computer code used is ACTIVE. ACTIVE will compute the products of all reactions contained in its cross-section library⁵ for a given material in a zone by multiplying the appropriate cross sections by the flux. The ACTIVE cross-section library contains approximately 800 different reactions. Zonal products are then added to obtain the total activation products at time zero. Since the total activation takes place as a result of a single

burst of neutrons over a very short period of time and the flux levels outside of the explosive are relatively low, decay during activation and second- or multiple-order reactions are not calculated by ACTIVE. Delayed fission neutrons are also not considered, because of their relatively small abundance of less than 1%. The time zero products are then decayed according to their radioactive half-lives to obtain activities as a function of time.

This calculational method is also used to study the effects of rock composition, especially lithium and boron, on the tritium production from the rock and to determine the effectiveness of various internal and external shielding materials.

It should be mentioned that the accuracy of this method depends strongly upon the reliability of the different cross sections employed by the computer codes.⁶ For some materials, cross sections have never been measured, and these must either be calculated by using nuclear models or extrapolated from other known cross sections. In making the transfer from the dynamic to the static case, certain assumptions must be made regarding such parameters as the nuclear temperature and geometric configuration. These also affect the accuracy of the calculations. It is difficult to estimate the cumulative effects of these uncertainties on the calculations; certainly the effects will be different for each specific case. The effect of varying one of these parameters, the soil temperature, will be discussed later in the paper.

TRITIUM REDUCTION

To minimize the amount of tritium produced for any particular application, a fission explosive would be used. This would then establish the lower limit of tritium production as that produced by ternary fission, which is equal to about 1 Ci (0.1 mg)/kt. As has been mentioned previously, there are other sources of tritium external to the explosive, the largest usually being from neutron capture by lithium in the rock. For rock containing approximately 30 ppm (by weight) of Li, which is found in some natural-gas-bearing media, about 1 to 3% of the neutrons escaping into the rock will produce tritium. The amount of tritium that is formed will be dependent on the amount of lithium and other absorbers present in the soil and on the temperature of the soil at the time of neutron capture. We have calculated that temperatures in the range of 1 eV to 1 keV (where 1 eV = 12,000°K) are typical for the rock surrounding the explosives. Within this range, the tritium production rate changes by approximately a factor of 7. Since neutron capture takes place throughout this entire range, the total production varies by only about a factor of 3.

We have previously determined⁷ that borated polyethylene is an attractive external shielding material for Plowshare applications, considering both its cost and its neutronic properties. Employing a shield of this type will reduce the amount of tritium formed in the soil, although some tritium is formed from the boron in the shield. An evaluation as to the effect on the total tritium produced when employing a shield of this type would have to be made for each particular application.

CONCLUSIONS

The total residual tritium from the 29-kt Gasbuggy Event was 40,000 Ci, and the total residual tritium from the 40-kt Rulison Event was 10,000 Ci. Through the design of the LLL Diamond family of underground-engineering explosives, about 1,000 Ci of total residual tritium was expected from the 80-kt Plowshare Miniata Event fired at NTS this July. The Diamond explosive is expected to produce less than 2,000 Ci of residual tritium at yields of 100 kt in a gas stimulation application. It should be understood that these numbers are based on a rock composition that has been observed as being representative of natural-gas-bearing media. A large change in the amount of lithium or other neutron-absorbing materials in the rock could affect the tritium production accordingly.

The large decrease in tritium production from approximately 1,400 Ci/kt for the Gasbuggy Event to 12 Ci/kt for the Miniata Event is indicative of the progress that has been made by the Plowshare Program toward the goal of minimizing the tritium while developing an explosive system that is attractive for industrial applications.

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