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Nuclear Explosions—
Peaceful Applications

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**STATUS OF CONTAINED
NUCLEAR EXPLOSIVE APPLICATIONS**

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149

Contents

Abstract	1
Gas Stimulation	1
Rulison Interpretation	1
Rio Blanco Proposal	3
Wagon Wheel Proposal	5
Comparison of Projects	10
Radioactivity	10
Gas Storage	13
Oil Shale	13
Geothermal Stimulation	18
Chemical Mining	18
Radioactive Waste Disposal	22
Concluding Comments	24
References	29

STATUS OF CONTAINED NUCLEAR EXPLOSIVE APPLICATIONS

Abstract

This paper reviews the status of contained nuclear explosive applications. Particular emphasis is placed on new developments since the last general status report was issued in December 1970. Since the main thrust of the U. S.

Plowshare Program is gas stimulation, that area is emphasized. Five other areas are discussed briefly: gas storage, oil shale, geothermal stimulation, chemical mining, and radioactive waste disposal.

Gas Stimulation

RULISON INTERPRETATION

The Rulison experiment was described by Milo Nordyke in the last general status report¹ and by G. W. Frank.² The cumulative production of dry gas from the Rulison well is shown in Fig. 1. Following a calibration flaring in October 1970, three production tests have been made. The corresponding bottom-hole pressures are shown in Fig. 2. Late in April the well was shut in, and the bottom-hole pressure is presently being measured. A detailed interpretation of this cumulative production and bottom-hole pressure is being made by Don Montan of this Laboratory and will be published later. The early interpretation of this and other data has led to the generalized cross section shown in Fig. 3 (after Don Emerson). Cores, well logs, and pre- and postshot production data have been used in the interpretation. In addition, the electrical cable was pulsed postshot to determine where it had been broken, inferring that

cracking had occurred at that point. The relationship between cavity radius and chimney volume is consistent with the measured yield of 43 kt determined by the Los Alamos Scientific Laboratory. Only 80 ft of net sands appear to have been stimulated.

The chemical composition of the Rulison gas is shown in Fig. 4, which updates the data presented by Smith.³ While prior to detonation some carbon dioxide was predicted to be present in the gas, the high levels measured (shown in Fig. 4) were a surprise. The carbon dioxide comes from the decomposition of carbonate rock. Laboratory experiments have shown that in the presence of silicon such rocks decompose at appreciable rates at temperatures as low as 750°C. Such CO₂ production could be minimized in future experiments by locating the specific shot points in low-carbonate rock. The leveling off of the CO₂ concentration in gas as a function of total gas produced is apparently due to carbon dioxide coming out of

Fig. 1. Cumulative production of dry gas from the Rulison well.

solution in the water in the chimney-and-fracture region. Changes in the concentrations of other chimney gas components are about as would be expected as a result of the combined effects of gas production and rock formation gas in flux. No indication of any chemical reaction involving chimney gas components was observed.

The radionuclide concentrations* measured by Smith³ are shown in Fig. 5 and are about as would be expected to re-

sult from the combined effects of dilution and production. There is no appreciable tritium exchange between the hydrocarbon gas components and water during the course of the gas production. Exchange equilibrium between hydrogen gas and water was established at the chimney conditions existing during production testing. The production of $^{14}\text{CO}_2$ shows the same leveling-off tendency as the non-radioactive CO_2 , indicating similar carbon-14 content in the CO_2 in the gas phase and in the CO_2 effervescing from the water. These are the basic Rulison

* All concentrations have been decay corrected to the time of detonation (September 10, 1968).

Fig. 2. Record of Rulison bottom-hole pressures.

data. Detailed interpretation is in progress and will be made available in the future.

RIO BLANCO PROPOSAL

The CER Geonuclear Corporation has proposed a joint Government/industry experiment called Rio Blanco.⁴ The cross section of Rio Blanco is given in Fig. 6. Three explosives, each with a nominal yield of 30 kt, are planned to be fired simultaneously at depths ranging from 5700 to 6600 ft. The company has proposed a set of measurements (shown in the figure) that would contribute to the technical understanding of nuclear gas stimulation. Our Laboratory has proposed additional measurements—"add-on" measurements—in order to obtain further information. Detailed planning is in progress

for this experiment. We hope that a Government/industry contract will be signed and that sources of funds will be found to make the add-on measurements.

WAGON WHEEL PROPOSAL

The El Paso Natural Gas Company has proposed the Wagon Wheel experiment. In the initial planning phase, considerable effort was devoted to studying the type of rock and to predicting the cavity size and the crushed and shear fracture radii. The details of this study are given by R. Terhune.⁵ The result is shown in Fig. 7. Note the small chimney size predicted. The reservoir section at the Wagon Wheel site is about 3000 ft thick. In order that eventual economic commercial production might be achieved, a way must be found to fracture through the entire

Fig. 3. Rulison postshot interpretation based on cores, logs, gas composition, and production.

gas-producing interval with a minimum number of explosives.

The concept of sequential firing looks promising. Sequential firing refers to the

technique of emplacing a number of explosives in the same hole and firing them in sequence; each explosive is fired after the seismic waves have died down and the

Fig. 4. Chemical composition of the Rulison gas.

chimney has formed from the preceding explosion. A major advantage of this approach is that each explosive can have a larger yield than would be permissible

if all the explosives were fired simultaneously, since an upper yield limit exists for acceptable seismic damage. Another advantage is in the interaction of the shock

Fig. 5. Project Rulison radionuclide concentrations.

PROJECT RIO BLANCO

A Joint Government-Industry Experiment
Proposed by CER-Geonuclear Corporation

Three 30-kt Fired Simultaneously

Late FY 72 Colorado

Experiment Proposed by Company

Determination of Preshot Reservoir Properties
Gas Production Through Emplacement Hole
Calculation of Fracture Zone
Measurement of Chimney Connections with Tracers
Seismic Motion Measurements
Radioactivity Measurements in Gas
Pressure Measurements in Stemming

Proposed LRL R&D Add-On to Measure and Interpret

Dynamic Shock Effects
Early Chimney Pressures and Gas Samples
Chimney Radius, Chimney Interconnections and
Fracture Distribution Caused by Simultaneous
Firing
Reservoir Pressure Gradient

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Fig. 6. Cross section of Project Rio Blanco.

WAGON WHEEL TYPE ROCK 100 KT / DEPTH 10,000 ft

Fig. 7. Predicted result of a 100-kt explosion at a depth of 10,000 ft in Wagon Wheel rock.

waves from the nuclear detonation with an existing chimney. The bottom explosive is fired first, and the chimney is formed as shown in Fig. 7. Then the next explosive above is fired, and the outgoing shock wave will reflect off the void at the top of the chimney. This reflection from a free surface places the rock in tension and causes it to spall downward into the chimney below. This spalling process should cause the first chimney to grow upward to meet the base of the second chimney. Terhune has shown both by

formal calculations and by a comparison with data obtained on cratering shots that the technique looks very promising indeed.

The conceptual design for the experiment is shown in Fig. 8. The technical measurements proposed by the company and additional LRL-proposed measurements are shown in the figure. Sequential firing will, of course, require specially designed nuclear explosives that can withstand the shock of the earlier detonations and still function properly. We believe such an explosive can be developed.

PROJECT WAGON WHEEL

A Joint Government-Industry Experiment
Proposed by El Paso Natural Gas Company

Five 100-kt Fired Sequentially
FY73 Wyoming

Experiment Proposed by Company

Determination of Preshot Reservoir Properties
Gas Production Through Emplacement Hole
Calculation of Fracture Zone
Gas Flow from Each Chimney with Tracers
Seismic Motion Measurements
Radioactivity Measurements in Gas

Proposed LRL R&D Add-On to Measure and Interpret

Dynamic Shock Effects
Early Chimney Pressures
Chimney Radius, Chimney Interconnections and
Fracture Distribution Caused by Sequential
Firing
Reservoir Pressure Gradient

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Fig. 8. Project Wagon Wheel.

Table 1. Comparison of gas stimulation projects.

Event:	<u>Gasbuggy</u>	<u>Rulison</u>	<u>Rio Blanco</u>	<u>Wagon Wheel</u>	<u>Commercial</u>	<u>Commercial</u>
Basin:	San Juan	Piceance	Piceance	Green River	Piceance	Green River
Explosives:	One 29-kt	One 40-kt	Three 30-kt	Five 100-kt	Three 100-kt	Three or four 100-kt
Depth (midpoint) (ft):	4,000	8,400	6,200	10,400	6,200	11,000
Stimulated interval (ft):	286	420	1,350	3,200	2,000	2,400
Gas in interval (billion scf/mi ²):	18	15	75	210	100	170
Pressure (psi):	1,100	3,200	2,750	6,334	3,000	6,000
Permeability (microdarcy):	6.0	9	40	3.4 - 6.8	10 - 40	5 - 10
20-year production (billion scf):	0.9	1.8	22	21 - 33	14 - 31	21 - 35

COMPARISON OF PROJECTS

A comparison of completed and proposed gas stimulation projects is given in Table 1. The 20-yr production estimates have been made by Montan. These estimates depend, of course, on the reservoir characteristics and the volume of gas-bearing sands stimulated. Neither Gasbuggy nor Rulison was planned for 20-yr production, but if they were, Rulison would produce about 1.8 billion cubic feet, compared to about 0.9 billion cubic feet of gas from Gasbuggy. This larger potential production from Rulison results from a 30% thicker stimulated interval and a formation pressure almost three times as high as that at Gasbuggy. The Rio Blanco experiment is projected to give more than ten times as much gas as Rulison because production testing from a conventional well has shown the permeability to be four times higher than for Rulison (40 microdarcy compared to 9 microdarcy) and because three explosives will stimulate more than three times the gas sand interval that was affected by the Rulison detonation.

The Wagon Wheel production is projected to be between 21 and 33 billion

cubic feet, depending upon the actual pre-shot field permeability. This permeability will be determined during the course of the conventional well testing, which is about to begin at the site. Note that the permeability is expected to be in the Gasbuggy/Rulison range, but with five explosives the stimulated interval is about three times thicker than Rio Blanco and the field pressure is about doubled. The last two columns in Table 1 show the projection for commercial gas stimulation in the Piceance and Green River basins. The range, of course, reflects the fact that these two reservoirs vary in their permeability from location to location. Each of the last four columns in Table 1 shows substantially greater production than the columns for Gasbuggy and Rulison do, and that is the challenge of nuclear gas stimulation.

RADIOACTIVITY

The gas from nuclearly stimulated wells does contain a small amount of radioactivity. Every effort is being made to reduce the radioactivity to as low a level as practicable. Tritium is the most

troublesome radionuclide. A special explosive is being designed that is expected to leave less than 0.2 g of tritium postshot. Based on the Gasbuggy and Rulison measurements, it is projected that if such an explosive were used in the Green River Basin the concentration of tritium and krypton in the gas would be as shown in Table 2.⁶

However, for commercial use of this gas, a large number of wells will be needed—not just one. For illustrative purposes, L. Schwartz of this Laboratory has taken the example of a 28-well nuclear field development as shown in Table 3. In the first year it is assumed that 12 wells are in production; in the second year there are 18, in the third year 22, and so on as given in the table. The average tritium and krypton concentrations are calculated by simply averaging the concentrations of the separate wells. Schwartz then calculated potential radiation doses using the

Table 2. Average annual radionuclide concentrations for produced gas from a single well (four 100-kt explosives).^a

Year	Concentration—pCi/cm ^{3b}	
	Tritium ^c	Krypton-85 ^d
1	11	71
2	0.015	0.10
3	—	—

^aAfter removal of CO₂ and water from the gas.

^bpCi ≡ picocurie ≡ 10⁻¹² curies.

^cAssumed:

- 25% of total tritium in chimney gas; negligible exchange of tritium from water to methane after start of production.
- Radioactive decay is negligible.

^dAssumed:

- 100% of ⁸⁵Kr is in gas.
- Radioactive decay is negligible.

Table 3. Average annual radionuclide concentrations for produced gas (28-well field development).

Year	Wells in production	Concentration—pCi/cm ³	
		Tritium	Krypton-85
1	12	11	71
2	18	5.5	36
3	22	3.6	23
4	25	2.6	17
5	26	1.8	12
6	27	1.0	6.4
7	28	0.0007	0.005

Table 4. Hypothetical use of nuclear stimulated gas in Los Angeles (with dilution, 28-well nuclear field).

Los Angeles annual gas consumption	660 billion scf
Production from nuclear field	58 billion scf
Dilution factor	11
Total whole body and gonadal dose equivalents with dilution from tritium and ⁸⁵ Kr in first year (the year of highest exposure)	
Domestic exposure— with dilution	(mrem)
Unvented heating and appliances	2.2
All appliances vented except range	0.3
Weighted average	0.5
Atmospheric exposure— with dilution	
Point of peak concentration	0.2
Population weighted average	0.03
Total with dilution	
Maximum	2.4
Weighted average	0.5

results of a paper by D. Jacobs of the Oak Ridge National Laboratory.⁷ A large, metropolitan area was selected, and the

The map displays a grid of streets with various labels and landmarks. Key features include:

- SCATTERED (100)**: Located in the upper left quadrant.
- EL SEGUNDO (186)**: Located in the center-left quadrant.
- REDONDO (149.611)**: Located in the lower-left quadrant.
- HARBOR (14.008)**: Located in the lower-right quadrant.
- Scale Bar**: Indicates 4 miles.
- Grid Labels**: Various numerical labels are scattered across the grid, including 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900, 950, 1000, 1050, 1100, 1150, 1200, 1250, 1300, 1350, 1400, 1450, 1500, 1550, 1600, 1650, 1700, 1750, 1800, 1850, 1900, 1950, 2000, 2050, 2100, 2150, 2200, 2250, 2300, 2350, 2400, 2450, 2500, 2550, 2600, 2650, 2700, 2750, 2800, 2850, 2900, 2950, 3000, 3050, 3100, 3150, 3200, 3250, 3300, 3350, 3400, 3450, 3500, 3550, 3600, 3650, 3700, 3750, 3800, 3850, 3900, 3950, 4000, 4050, 4100, 4150, 4200, 4250, 4300, 4350, 4400, 4450, 4500, 4550, 4600, 4650, 4700, 4750, 4800, 4850, 4900, 4950, 5000, 5050, 5100, 5150, 5200, 5250, 5300, 5350, 5400, 5450, 5500, 5550, 5600, 5650, 5700, 5750, 5800, 5850, 5900, 5950, 6000, 6050, 6100, 6150, 6200, 6250, 6300, 6350, 6400, 6450, 6500, 6550, 6600, 6650, 6700, 6750, 6800, 6850, 6900, 6950, 7000, 7050, 7100, 7150, 7200, 7250, 7300, 7350, 7400, 7450, 7500, 7550, 7600, 7650, 7700, 7750, 7800, 7850, 7900, 7950, 8000, 8050, 8100, 8150, 8200, 8250, 8300, 8350, 8400, 8450, 8500, 8550, 8600, 8650, 8700, 8750, 8800, 8850, 8900, 8950, 9000, 9050, 9100, 9150, 9200, 9250, 9300, 9350, 9400, 9450, 9500, 9550, 9600, 9650, 9700, 9750, 9800, 9850, 9900, 9950, 10000, 10050, 10100, 10150, 10200, 10250, 10300, 10350, 10400, 10450, 10500, 10550, 10600, 10650, 10700, 10750, 10800, 10850, 10900, 10950, 11000, 11050, 11100, 11150, 11200, 11250, 11300, 11350, 11400, 11450, 11500, 11550, 11600, 11650, 11700, 11750, 11800, 11850, 11900, 11950, 12000, 12050, 12100, 12150, 12200, 12250, 12300, 12350, 12400, 12450, 12500, 12550, 12600, 12650, 12700, 12750, 12800, 12850, 12900, 12950, 13000, 13050, 13100, 13150, 13200, 13250, 13300, 13350, 13400, 13450, 13500, 13550, 13600, 13650, 13700, 13750, 13800, 13850, 13900, 13950, 14000, 14050, 14100, 14150, 14200, 14250, 14300, 14350, 14400, 14450, 14500, 14550, 14600, 14650, 14700, 14750, 14800, 14850, 14900, 14950, 15000, 15050, 15100, 15150, 15200, 15250, 15300, 15350, 15400, 15450, 15500, 15550, 15600, 15650, 15700, 15750, 15800, 15850, 15900, 15950, 16000, 16050, 16100, 16150, 16200, 16250, 16300, 16350, 16400, 16450, 16500, 16550, 16600, 16650, 16700, 16750, 16800, 16850, 16900, 16950, 17000, 17050, 17100, 17150, 17200, 17250, 17300, 17350, 17400, 17450, 17500, 17550, 17600, 17650, 17700, 17750, 17800, 17850, 17900, 17950, 18000, 18050, 18100, 18150, 18200, 18250, 18300, 18350, 18400, 18450, 18500, 18550, 18600, 18650, 18700, 18750, 18800, 18850, 18900, 18950, 19000, 19050, 19100, 19150, 19200, 19250, 19300, 19350, 19400, 19450, 19500, 19550, 19600, 19650, 19700, 19750, 19800, 19850, 19900, 19950, 20000, 20050, 20100, 20150, 20200, 20250, 20300, 20350, 20400, 20450, 20500, 20550, 20600, 20650, 20700, 20750, 20800, 20850, 20900, 20950, 21000, 21050, 21100, 21150, 21200, 21250, 21300, 21350, 21400, 21450, 21500, 21550, 21600, 21650, 21700, 21750, 21800, 21850, 21900, 21950, 22000, 22050, 22100, 22150, 22200, 22250, 22300, 22350, 22400, 22450, 22500, 22550, 22600, 22650, 22700, 22750, 22800, 22850, 22900, 22950, 23000, 23050, 23100, 23150, 23200, 23250, 23300, 23350, 23400, 23450, 23500, 23550, 23600, 23650, 23700, 23750, 23800, 23850, 23900, 23950, 24000, 24050, 24100, 24150, 24200, 24250, 24300, 24350, 24400, 24450, 24500, 24550, 24600, 24650, 24700, 24750, 24800, 24850, 24900, 24950, 25000, 25050, 25100, 25150, 25200, 25250, 25300, 25350, 25400, 25450, 25500, 25550, 25600, 25650, 25700, 25750, 25800, 25850, 25900, 25950, 26000, 26050, 26100, 26150, 26200, 26250, 26300, 26350, 26400, 26450, 26500, 26550, 26600, 26650, 26700, 26750, 26800, 26850, 26900, 26950, 27000, 27050, 27100, 27150, 27200, 27250, 27300, 27350, 27400, 27450, 27500, 27550, 27600, 27650, 27700, 27750, 27800, 27850, 27900, 27950, 28000, 28050, 28100, 28150, 28200, 28250, 28300, 28350, 28400, 28450, 28500, 28550, 28600, 28650, 28700, 28750, 28800, 28850, 28900, 28950, 29

SOURCE: OAK RIDGE NATIONAL LABORATORY

Fig. 9. Gas consumption for the city and county of Los Angeles.

potential dose was computed for a given concentration of tritium in the natural gas. Use of the gas by electrical generating plants, industry, and residents was considered as shown in Fig. 9. When Jacobs' results were applied to the hypothetical 28-well nuclear field, the final dosage determined was as shown in Table 4. The 28-well nuclear field should produce about 58 billion scf, as compared to Los Angeles' annual consumption of 660 billion scf; thus, the gas is diluted by a factor of 11 with gas from other fields. With such

dilution, the whole body and gonadal dose equivalent received during the first year (the year during which the highest exposure is received) averages about 1/2 mrem. This 1/2 mrem is, of course, quite small compared to the range of natural background exposure in the United States (90 to 200 mrem). More details on how these calculations are made are given in Refs. 6 and 7. Here it is sufficient to say that such levels are exceedingly small and appear to be acceptable in the light of current radiation protection guidelines.

Gas Storage

The El Paso Natural Gas Company is actively pursuing the possibility of using a nuclear explosive in salt to create a storage cavity for natural gas. The technology was essentially demonstrated with the Salmon experiment (5 kt in a salt dome in Mississippi) in the U. S. A. and with the 25-kt experiment in a salt dome in the U. S. S. R.

Storage is needed in connection with pipeline systems in many areas of the U. S. A. The particular application that El Paso has in mind was developed by P. Randolph.⁸ Figure 10 is taken from

Ref. 8 and shows the El Paso pipeline system and the desired area for storage in western Arizona. El Paso has drilled at several locations, and very pure salt formations have been found at appropriate depths. At present, negotiations are proceeding to acquire the land rights; when these are obtained, the experiment can proceed. The creation of a storage reservoir should be an important application for nuclear explosives, not only for gas storage, but at off-shore and on-shore sites appropriate for loading and unloading very large oil tankers.

Oil Shale

The United States has an estimated reserve of some 600 billion barrels of oil in the form of oil shale. Competitive economic techniques for recovering this oil have not been developed yet. One promising method is to use the nuclear explosives to break up the shale and to

subsequently retort it in place from the chimney-and-fracture region, thus avoiding the expense of mining. The retort concept is demonstrated in Fig. 11, which has appeared in previous reports. Air is circulated down into the top of the chimney. The hot combustion products are circulated

Fig. 10. El Paso Natural Gas Company's interstate transmission system in the southwestern United States.

ahead of the flame heating the shale up to 715°F. At this temperature the kerogen in the shale breaks down and the oil is released as a mist. When this concept was first proposed, an immediate technical consideration was whether the combustion zone would proceed uniformly down through the chimney. In an attempt to answer this question, the U. S. Bureau of Mines conducted pilot experiments in 10-ton and 150-ton retorts, as pictured in Fig. 12. In the large retort, very large blocks (see Fig. 13) were used to determine whether the presence of such blocks

would upset the combustion front. The results of these pilot experiments indicate that the large blocks in fact do not destroy the uniformity of the combustion front and that the oil is almost completely retorted even from the interior of such blocks. Details of these experiments are contained in the Bureau of Mines papers in Ref. 9. The important conclusion resulting from this work is that efficiencies in oil recovery as high as 70 to 80% can be achieved in the retorts. At present, CER Geonuclear Corporation, working for the Western Oil Shale Corporation, has

IN-SITU RETORTING-OIL SHALE

Fig. 11. In-situ retorting of an oil shale.

Fig. 12. The 10-ton and 150-ton retorts installed at the north site.

Fig. 13. A large 7500-lb shale block before retorting.

developed a proposed experiment in "lean" shale in Utah to determine the chimney-and-fracture configuration. A cross section for the proposed Utah experiment is shown in Fig. 14. Whether oil companies will join in funding this experiment is unknown at this time. One reason why companies have

hesitated to invest in the past is because the Government owns the principal oil shale deposits and no provision exists for private exploitation. However, the Government is making progress in developing a lease program. We hope that a sufficient economic incentive for oil shale companies will develop.

Geothermal Stimulation

In a few parts of the world, electric power is generated from the energy stored as steam or hot water in geothermal reservoirs. As the need for energy increases, increasing attention is being given to the more systematic exploitation of such geothermal energy. The quality and amount of steam that can be obtained from such reservoirs is not always sufficient for an economic operation. In

cases where it is not, it may be possible to use a nuclear explosive to greatly enhance the efficiency of the downhole steam collection system (a nuclear chimney rather than a small drillhole). The geothermal stimulation concept is shown in Fig. 15. In addition, small nuclear explosives may be useful for unplugging wells that have been plugged by deposition of solids in the fracture system near the well.

Chemical Mining

In the mining area it is very clear that a nuclear explosive can break up an ore body; the ore may be removed later by conventional means for processing. A more sophisticated and potentially more economically attractive approach involves the breaking up of the ore body and the leaching of the ore in place. A significant development in this regard is the concept of leaching primary sulfide ores (below the water table) at substantial depths (refer to Fig. 16). (This work has been pioneered by A. Lewis of this Laboratory.) Primary copper sulfide (chalcopyrite) normally leaches so slowly that the process is uneconomic. However, by forcing oxygen or air in under the hydrostatic pressure existing in a flooded chimney, the leach rates are substantially accelerated.^{10,11} In addition, since the oxidation reactions of the sulfide ore as well as of the coexisting iron pyrite are exothermic, the temperature rises, thus accelerating the leaching rate even more. The leaching rates of copper sulfide under these conditions have been measured in

the laboratory. When extrapolated to the nuclear chimney situation, the projections shown in Fig. 17 result. If the nuclear explosive exposes half of the iron and copper sulfides in a 1/2% Cu ore with a py:cp ratio of 1:1, this half would be completely leached in about half a year, with the temperature in the chimney rising to 150°C. If the nuclear explosive exposes a fourth of the iron and copper sulfides, 1-1/2 yr would be required with a temperature approaching 100°C. If an eighth is exposed, 4-1/2 yr are required, and the temperature reaches only 70°C. These are dramatic reductions in leaching times compared to those required with conventional techniques. Thus, the key issues reduce to how much ore is exposed and what circulation can be established with the leached solutions (which determine the rate at which copper can be withdrawn). There appears to be a growing interest by a number of mining companies in this concept. It is quite new, and additional work in the form of pilot leaching experiments is in order before nuclear experiments are undertaken.

NUCLEAR EXPLOSION IN OIL SHALE

FEET

1800

POSSIBLE CHIMNEY HEIGHTS

1900

2000

2100

2200

2300

2400

2500

2600

2700

Fig. 14. Cross section of the proposed Utah experiment.

Nuclear Stimulated Geothermal Field

Fig. 15. A nuclearly stimulated geothermal field.

CHEMICAL MINING FLOODED PRIMARY SULFIDE ORE

Fig. 16. Chemical mining: a flooded primary sulfide ore.

Fig. 17. Projected leaching rates of copper sulfide.

Radioactive Waste Disposal

With the rapid expansion in the number of power reactors, increasing attention is being given to the radioactive waste generated when the nuclear fuels are cycled through a reprocessing plant. In a report by J. Cohen et al.,¹² a high-level radio-

active waste disposal concept is proposed in which a nuclear explosive is utilized. Figure 18 shows that a 5-kt nuclear detonation can be used to produce a chimney prior to the construction of such a processing plant. The block diagram in

**NUCLEAR FUEL
PROCESSING PLANT
(5 TON/DAY CAPACITY)**

**YIELD — 5KT
DEPTH — 2000m
CHIMNEY RADIUS — 11m
MAX. MELT RADIUS — 96m**

**VOID VOLUME
14 million gallons**

LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA, LIVERMORE

100m

Fig. 18. Radioactive waste disposal.

Fig. 19 describes the operation. Waste liquids are poured into the chimney. The heat generated by the radioactive decay boils the water, driving the steam through a pipe to the surface where it is condensed and recirculated back to the chimney. In the example worked out, the thermal power output of the accumulated wastes that are added to the chimney over a 25-year period is shown in Fig. 20. When the waste addition period is over and water is no longer circulated to cool the chimney,

the temperature of the chimney rises and the rock begins to melt. Heat flow theory is used to calculate the radius of melt as a function of time (see Fig. 21). The time sequence is summarized in Fig. 22. Cost estimates have been made that indicate that this method of disposal may be a factor of 5 to 10 times cheaper than the solidification salt mine burial method. This work is described in more detail in Ref. 12, and we are awaiting review and comment on it.

Concluding Comments

There are other contained nuclear explosive applications. The U. S. S. R. has used nuclear explosives for oil stimulation and for the control of gas-well blow-outs.¹³ These are certainly valid applications, and the Soviets are to be commended

for reducing these applications to practice. The U. S. program is concentrated on gas stimulation because of the need for gas in the U.S.A. However, we are technically ready to proceed to the development of other applications as soon as funds are available.

Fig. 19. Generalized flow diagram for an integrated fuel reprocessing and waste disposal system.

Fig. 20. Thermal power output of accumulated wastes.

Fig. 21. Melt radius as a function of time.

Time Sequence

Fig. 22. History of events in the proposed waste-disposal method.

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