Energy and Technology Review

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Energy and Technology Review

ABOUT THE COVER

The welder on the cover, a trainee in our Technology Training Program, is practicing arc welding with a flux-covered rod. Actual practice like this is a starting point for the more advanced techniques presented in the training course. Students receive hands-on experience in various inert-gas and electron-beam welding methods - welding art developed over the years in our government-sponsored programs. These and other technological developments are now being made available outside the Laboratory. For a description of two Technology Training Program courses, see the article beginning on p. 9.

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Briefs

The short items on this page announce recent developments of importance. Some of these items may be amplified in future issues; none of this material is reported elsewhere in this issue.

LASER PROGRAM ACHIEVES HIGHER NEUTRON YIELDS

A major milestone in laser fusion research has been reached with the 2.5-TW Argus laser. On September 30, LLL produced 10^9 neutrons in a laser fusion implosion. With twin 50-ps pulses from the two arms of Argus, the DT-filled targets were imploded and heated to temperatures of about 8 keV, as determined by neutron spectral measurement. This first production of a billion fusion reactions - repeated and surpassed on several occasions - is noteworthy both technically and as a symbol of the rapid progress to date in laser fusion research.

Our higher neutron yields create new diagnostic possibilities. For example, neutron energy is a convenient indicator of temperature in the target's center. Verification of a high temperature is important in confirming that the observed neutrons are from D-T compression and genuine thermonuclear burn. This was first proved in May 1975, using the alpha-particle energy spectrum. Only when a billion reactions are produced, however, are neutrons plentiful enough to permit direct neutron spectral measurement for determining the D-T burn temperature.

As with previous target yields, our LASNEX computer code accurately predicted the billion neutron output. It also predicted the 8-keV target temperature observed through the neutron measurements. Such agreement between LASNEX prediction and experimental results has been a major reason for confidence in the basic soundness of the laser fusion program.

These recent neutron yields are also noteworthy considering that less than two years ago our initial target irradiations were producing only a few thousand neutrons. The sharp increase has been achieved through a multifaceted research program emphasizing computer design in virtually every phase of component development and experimentation.

To demonstrate the scientific feasibility of laser fusion as a power source, however, experiments will have to produce some 10^{18} neutrons - an effort expected to require a laser system at least 50 times more powerful than Argus. To generate power, target irradiations would also be repeated 1 to 10 times per second, with the energy from each microexplosion exceeding the laser energy initiating it by a factor of 100 or more. In the Argus experiments, energy in greatly exceeded energy out. Nevertheless, the neutron yields are encouraging. They help confirm our belief that fusion power plants may begin contributing to the world's electrical power needs about the turn of the century.

NEW GLOBAL OZONE MONITOR

The most comprehensive system to date for analyzing the global ozone shield that protects us from ultraviolet radiation will begin operation here early next year. LLL's Satellite Ozone Analysis Center, supported by the Federal Aviation Administration, will digest detailed satellite measurements of the ozone layer's thickness and other atmospheric characteristics and combine them into global ozone-distribution maps. The goal over the next several years is a clearer understanding of natural and man-made variations in ozone on both global and local scales.

Data will be collected with a new Air Force satellite, which will send more than 68 000 ozone data values per day to Livermore via the Air Force Global Weather Center in Omaha, Nebraska. Personnel at Livermore will perform the numerical manipulations needed to convert these raw data to actual ozone values at specific coordinates. These values will then be compiled into global ozone maps at one- and five-degree intervals for further analysis at LLL and for use by other interested organizations. With these data we will be able to update the total global ozone picture daily. For verification, the satellite ozone values will be checked against readings made by total-ozone monitoring stations in Antarctica, Africa, South America, Australia, Japan, Europe, and North America.

The first satellite will be launched into an 835-km-high circular orbit late this year or early next. As it orbits the globe every 102 minutes, a sensor will measure the total ozone beneath it in 39-km-wide columns. Total ozone will be determined by measuring the amount of infrared radiation emitted at a frequency peculiar to ozone, 9.8 μ m.

A second satellite will be launched six months after the first, orbiting about four hours ahead of this. This second satellite will be of particular value in observing day-to-night ozone changes for specific locations. The rate at which ozone is created and depleted in the atmosphere depends to a large extent on photochemical reactions that are influenced by sunlight.

Along with day-to-night variations, researchers will pay close attention to the effects of occasional, short-term natural phenomena - such as large volcanic eruptions and solar storms - that may suddenly change the ozone creation-depletion balance. The project will also focus on long-term measurements of the earth's total ozone. The goal of this work will be twofold: to establish a baseline against which future measurements can be compared and to detect incipient trends in the ozone level as quickly as possible.

SCIENCE AND TECHNOLOGY

SOVIET EXPERIENCE WITH PEACEFUL USES OF NUCLEAR EXPLOSIONS

The Soviet Union is pursuing an active program for developing peaceful uses of nuclear explosions (PNE). They have reported 16 explosions, with applications ranging from putting out oil-well fires and stimulating oil recovery to creating instant dams and canals. The data reported generally agree with U.S. experience. Seismic data collected by Western sources on explosions outside the known Soviet test sites indicate that the Soviet program is at least twice as large as they have reported. The accelerated pace of these events suggests that in some applications the Soviet PNE program is approaching routine industrial technology.

In any field it is important to maintain a broad perspective, to follow not only what is being done in one's own institution or country but also what is going on throughout the world. This cross-fertilization of ideas accounts for much of the scientific progress of the last 50 years.

In this context it is appropriate to review the accomplishments and plans of the Soviet PNE program. By any measure this program is active and ambitious. Official Soviet disclosures include 16 events designed to develop nine different applications in the petroleum, gas, and minerals industries, as well as in water resources development.

The applications being developed under the Soviet PNE program may be broadly classified as cratering and noncratering. The cratering events include excavation for reservoirs and canals, overburden removal for strip mining, and instant crater-lip dams. The noncratering applications include stimulating oil and gas wells, controlling runaway gas-well fires, breaking up hard ore bodies, and creating large underground storage cavities for gas, oil, or harmful wastes.

Cratering Experiments

The Soviet Union has many water management problems in its vast and varied territory. One of the most spectacular concerns is the level of the Caspian Sea, which has dropped 2.5 m in the past 35 years because of insufficient flow in the Volga River and

increasing water demand in the surrounding area. The prime sources for supplying additional water to meet this need are the rivers that flow northward into the Barents and Kara Seas.

Specifically, the Soviets propose to divert the flow of the upper portion of the Pechora River into the Kama River and thence to the Volga. This would require a 112-km canal and a series of four dams and reservoirs. The northern 65 km of the canal is being considered for construction by nuclear excavation, a project that would require some 250 nuclear charges.

To support this and other water management projects, the Soviets have conducted a series of cratering and row-cratering experiments ranging in size from T-1, an 0.8-TJ (0.2-kt) detonation in sandstone, to the Pechora-Kama row-crater test, using three 63-TJ (15-kt) devices. In between were 1003, a cratering shot in siltstone using a 4.6-TJ (1.1-kt) device, and T-2, a row-charge cratering experimental model of Pechora-Kama using three 0.8-TJ (0.2-kt) devices.

T-1 was a calibration shot for T-2. It was buried in quartzite sandstone at a depth of 31.4 m. The resulting crater was 34 to 40 m in diameter and 21 m deep. According to Russian sources, this is 40% deeper and 25% wider than expected. Because of a shallow water table, the crater filled with water in a few days.

The T-2 Event involved three 0.8-TJ (0.2-kt) devices spaced 40 m apart. The geology was similar to T-1 except that the water table was at a depth of about 5.6 to 6.9 m. The depth of burst for the three shots was 31.4 m, the same as for T-1, giving a ratio for spacing to depth of burst of 1.3. Based on the results of T-1, this would correspond to a ratio of spacing to crater radius of 1 to 1.14, depending on the exact value chosen for the T-1 radius. According to criteria used by the Soviets and the U.S., this spacing should increase the crater radius about 10% without changing the depth.

The actual row crater from the T-2 Event was about 65 m wide and 16 m deep, about 20 to 30% narrower and 25% shallower than expected on the basis of the T-1 crater. The T-1 crater, however, was unexpectedly large. When judged relative to the 1003 crater, for example, the T-2 crater has about the expected dimensions.

The 1003 Event was a 4.6-TJ (1.1-kt) explosion at a depth of 48 m in saturated siltstone rock with an

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artesian water table at 14 to 20 m. The crater initially had an apparent depth of 31 m and an apparent radius of 53.5 m. As the crater filled with artesian water, the loose fallback material sluffed in, decreasing the apparent depth to 20 m and increasing the apparent radius to 62 m within two years.

The original plan for the Pechora-Kama canal was to fire about 250 charges, with no more than 20 charges and no more than 12 PJ (3 Mt) total yield in any one salvo. The desired cross section was originally set at 5000 m², allowing for significant amounts of fallback material to slide into the canal. Recent reports have scaled down this requirement to 3000 m², which would be expected to decrease the required total and individual yields. The Soviets estimate that constructing this canal with nuclear excavation will be 3 to 3½ times cheaper than with conventional earthmoving methods.

The northern 30 km of the proposed nuclear excavation is described as sandstone, siltstone, and argillite rock. The southern part is largely saturated alluvial deposits. Concern over the stability of the side slopes of canals in such deposits prompted the full-scale Pechora-Kama row-charge cratering experiment.

Figure 1 shows a geologic cross section along the alignment of this experiment. The water table was reported to be at 5 m at the northern end of this section and 17 m at the southern end, saturating most of the loose, cohesionless alluvial sediments. The underlying rock consists of interbedded sandstones, argillites, and marls.

Three 63-TJ (15-kt) charges were emplaced at a

depth of about 127 m, putting two of them within the underlying rock and the third at 5 to 10 m above the alluvium-rock interface. The scaled depth of burial was somewhat greater than optimum, but the high water content and the sandy, unconsolidated structure of the overlying material made it reasonable to expect very dynamic cratering action. From north to south, the spacing between the charges was 163.1 and 167.5 m, for a spacing-to-depth ratio of 1.3. This spacing ratio would be expected to increase crater radius by 10% without affecting crater depth.

The produced crater was about 700 m long, 340 m wide, and 10 to 15 m deep. The final pan-shaped configuration resulted from extensive slumping of the crater sides, which increased the width at the expense of the depth. This behavior was expected, although the degree of slumping was hard to predict.

The Soviets reported that the sides of the crater stabilized quickly at a slope angle of 8 to 10 deg. Some observations indicate the crater is actually deepening slightly. The Soviets consider the final crater adequate as part of the ultimate canal and a convincing demonstration that nuclear excavation in a weak, saturated alluvial medium is feasible.

In a related development, the Soviets carried out 1004, a cratering event with a yield estimated from Soviet reports at 525 ± 63 TJ (125 ± 15 kt) and a depth of burst similarly estimated at 178 m. This shot was placed immediately adjacent to a river bank so the crater lip would dam the river to form a large reservoir. Figure 2 is a composite of two frames from a Soviet movie. It shows the crater filled with 7 million cubic metres (5700 acre-ft) of water and a reservoir

Fig. 1. Geologic-lithologic cross section along the alignment of the Pechora-Kama Event. Elevation here is presumably above sea level. The three nuclear explosives are indicated as 1-B, 2-B, and 3-B. This was a full-scale test of row-charge cratering for the Pechora-Kama canal, an ambitious project to divert the Pechora River from its northward course to the Arctic Ocean and channel its waters into the Kama River and from there into the Volga River and the Caspian Sea.

As indicated in this figure, the soil in the southern part of the proposed nuclear excavation is loose, sandy, unconsolidated material, saturated with water. Concern over the stability of the sides of such an excavation in this material prompted the test, which produced a broad, shallow crater of adequate cross section.

Fig. 2. Photomontage of two frames from a Soviet movie, showing the reservoirs backed up behind the crater-lip dam formed by Event 1004. The crater on the right was formed by detonating a 525 : 63-TJ (125 : 15-kt) device about 178 m below the surface in a saturated medium consisting of interbedded sandstone, siltstone, shale, and conglomerates. Initially the crater volume was 7 million cubic metres, but slumping of the loose material on the sides has reduced this by about 25%. The outer reservoir, on the left, contains about 10 million cubic metres. A narrow channel was dug to connect the two reservoirs and flood the crater.

backed up behind the crater lip containing another 10 million cubic metres (8100 acre-ft).

The medium in which this shot was detonated is characterized as interbedded layers of sandstone, siltstone, shale, and conglomerates, with a moisture content of 12%. Immediately after the shot the crater had an apparent radius of 204 m and an apparent depth of 100 m. These dimensions compare fairly well with the 420-TJ (100-kt) Sedan crater (194-m depth of burst, 185-m apparent radius, 98-m apparent depth).

When the crater filled with water, the slopes shifted substantially. About 1.7 million cubic metres of rock slid in, mostly from the south side, reducing the apparent crater depth to 83 m and the apparent volume by 25%. The crater is reported to have stabilized in this configuration and at last report continues to stand as a useful reservoir.

Figure 3 compares U.S. and Soviet cratering data for apparent crater radius. The U.S. and Soviet curves appear to be very similar. Points are plotted for a number of U.S. shots, together with points for 1003, 1004, and T-1. The radii of events 1003 and 1004 appear to be quite consistent with previous U.S. and Soviet data for weak rocks containing 6 to 10% water.

In addition to these water-management projects, the Soviets have described a very large proposed nuclear excavation to remove the overburden from a nonferrous metal deposit. The climate and economic geography of the area are described as being similar to the far north but with frequent earthquakes. A total of 2.3 km³ of overburden must be removed; the Soviets feel 0.9 km³ can be removed with a 4-PJ (1-Mt) row-charge nuclear excavation at a cost of about 5 kopecks/m³ (6.5¢/m³). This would result in a saving of over one billion rubles (\$1.4 billion) compared to excavation by conventional means. (For a comparison of the scale of this project, over the last 65 years only 1 km³ has been excavated by conventional means from the huge Kennecott mine near Bingham, Utah.)

Noncratering Experiments and Applications

The noncratering applications of nuclear explosions investigated by the Soviets are both more numerous and more varied than the cratering experiments. They range in yield from a modest 4-TJ (1-kt) explosion in granite to test rock-fracturing capabilities to two 130- to 170-TJ (30- to 40-kt) explosions to seal off two large and destructive runaway gas wells. In

Fig. 3. A comparison of U.S. and Soviet curves relating scaled depth of burst and scaled apparent radius. The U.S. events are named; the Soviet events are 1003, 1004, and T-1. Several of the U.S. events fall closer to the Soviet curves than they do to the U.S. curves, but 1004 falls on the U.S. curve. Actually, both curves are within the normal scatter pattern for such events.

between were two multicharge events to stimulate oil-well production and a series of four salt-formation shots culminating in a 50 000-m³ (300,000-bbl) industrial gas-condensate storage facility.

The two runaway gas wells, although they were close together and involved similar geologic structures, were quite distinct in the ways they failed and in the problems of sealing them off. The first of these wells was No. 11 in the Urtabulak gas field in Southern Uzbekistan. On December 1, 1963 this well went out of control at a depth of 2450 m, venting over 12 million cubic metres of gas per day through its 20-cm casing. Formation pressures in this area are about 27 to 30 MPa (270 to 300 atm).

Many attempts were made over the next three years to cap the well at the surface or to reduce the flow and extinguish the flame. As a result of these attempts, however, the gas leaked into adjacent wells where its high H₂S content caused serious safety problems. Through all this time the loss continued unchecked at about \$25 million per year. Sealing the hole from

an adjacent hole by injecting cement or by chemical explosions was not regarded as feasible because Hole No. 11 had not been surveyed before it went out of control.

In the fall of 1966 a slant well was drilled to come as close as possible to Hole No. 11 at a depth of 1500 m within a 200-m-thick clay zone. This depth was considered sufficient to contain the 30-MPa (300-atm) formation pressure. Electromagnetic detection of the steel casing and acoustic detection of the escaping gas indicated that the closure well and the runaway well were 35 ± 5 m apart. A 130-TJ (30-kt) explosive detonated in the slant well sealed the runaway well and put out the flare. No radioactivity above background was detected at the surface during postshot surveys.

About the same time that Hole No. 11 was being plugged, another well in a nearby gas field with similar geologic structure broke loose. The loss of about 1 to 1.5 million cubic metres of gas per day continued for two years, while unsuccessful attempts were made

to seal the well by hydraulic fracturing from a slant-drilled well. Eventually a new slant-drilled well was aimed to intersect the runaway at a depth of 2440 m in a salt formation that overlied the production horizon.

Measurements made after the slant well was drilled indicated that it was within 30 ± 5 m of the runaway. A (70-TJ (40-kt) nuclear explosive detonated in the slant well eventually sealed the runaway, although the flare continued for seven days until all the gas that had been forced into the overlying strata during the preceding two years had escaped. Again, radiation surveys showed no radioactivity above background at the surface.

Another Soviet-tested application is oil-well stimulation. Experience shows that it is hard to get much of the oil from carbonate deposits, most of it stays in the ground. There are a number of secondary recovery techniques that work with varying degrees of success, depending on the nature of the deposit and the character of the oil. These include water and gas injection, fire or hot-water flooding, hydro-fracturing to increase the permeability of the formation, and introducing gas into the oil to reduce its viscosity. Many fields resist such conventional techniques, however, and nuclear detonations offer a possible alternative. The Soviets have tested this idea in at least two different fields.

The first field has been described as a solution-gas-drive reservoir in which the ultimate recovery had been projected at about 25% of the in-place reserves. The reservoir is a limestone reef at a depth of 1 to 1.5 km overlaid by interbedded anhydrite and halite layers. Underneath, the deposit is isolated from a pressurized water zone by a bituminized or oxidized layer 25 to 30 m thick.

Because this field's production was declining in its eighth year, the Soviets decided to try nuclear stimulation. The first stage involved the detonation of two 10-TJ (2.3-kt) nuclear explosives, 200 m apart at depths of 1378 and 1348 m. The explosions were separated by a short time interval.

The second stage of this same experiment involved the detonation of a single 34-TJ (8-kt) charge $3\frac{1}{2}$ months later, 350 m from one of the former detonations and at a depth of 1350 m. The average rate of production from the deposit increased 34%, and the projected recovery factor for the field, based on almost six years of postshot data, has increased almost 50%, from 25% to 35%. Perhaps most significant is the drop in the gas/oil ratio from about

450 to about 150 m^3/tonne immediately after the shots and its persistence at that level for at least $5\frac{1}{2}$ years.

A recent economic analysis of this project, based on the data provided by the Soviets but using U.S. oil-drilling and nuclear-explosive costs and assuming that this project was one of a continuing series, shows that the internal rate of return would be about 30%. Alternatively, if such a project were financed at an interest rate of 10%, profit over the life of the project would be about 180% of the invested capital.

The Soviets reported increased production from 20 wells within 300 to 470 m of the shot points. This and the detection of radioactivity in the wells leads them to believe that the general fracturing area extends 300 to 400 m from the shot points, with some individual fractures extending as far as 800 m. Distances of 300 to 400 m would correspond to 20 to 40 cavity radii. This is many times the 4 to 7 cavity radii generally reported in the U.S. and the 3.7 cavity radii reported by the French for the Hoggar granite.

It should be pointed out, however, that the only U.S. experience in a carbonate medium (the Handcar Event) was in a dry, fractured dolomite, in contrast to the saturated limestone of the Soviet deposit. We would not expect the difference in medium to be so significant, but our limited experience prevents us from resolving the discrepancy.

The oil produced from this field over the six years following the experiment is said to contain only harmless amounts of radioactivity and is reported to be in routine use in the Soviet Union.

A second oil-stimulation project involved a similar carbonate reef that was being produced by water injection. Depletion had cut reservoir pressure in half, and bottom-hole pressures had declined so far that it was necessary to pump the oil.

In an attempt to increase the porosity of the formation, two 34-TJ (8-kt) nuclear explosions were detonated in the middle of the field, one at 1212 m and the other some time later at 1208 m and about 1200 m away from the first shot.

Although no production data have been published by the Soviets, they report that after a year or more of production the seven wells within 800 m from the explosions were producing 30 to 60% more. The radioactivity appearing in the oil was insignificant, and the oil was put into general use a few days after the explosions. Here again extraordinary fracture radii are reported and credited with stimulating the flow of oil.

In a related development, the Soviets claim to have carried out a nuclear gas-stimulation experiment; however, no details have been made available. In

Fig. 4. Cross section of the cavity resulting from a 100-TJ (25-kt) explosion in a salt dome, 590 m below the surface. The cavity has a radius of about 32 m and a volume of 140 000 m³. The puddle at the bottom is resolidified salt that ran down from the walls; it contains the bulk of the radioactive debris.

addition they have proposed a nuclear gas-condensate stimulation project involving three 170-TJ (40-kt) nuclear explosions. The stated aim is to produce a 12-fold increase in gas production.

Another area of active interest to the Soviet PNE effort is underground storage of gas, oil, liquefied natural gas (LNG), and biologically harmful wastes. Their analyses show that gas can be stored in nuclear cavities for one-sixth the cost of surface LNG storage and one-third the cost of washed-cavity storage. For gas-condensate storage, the corresponding cost ratios are one-eighth and one-quarter. Such comparisons appear consistent with the many U.S. cost studies.

Altogether, four separate cavity-forming events in salt formations have been reported in varying detail. These range in size from a well-documented 4.6-TJ (1.1-kt) test explosion at 161.4 m to a 100-TJ (25-kt) shot at 590 m. The latter produced an almost spherical cavity of about 32-m radius and about 140 000-m³ volume (see Fig. 4).

This cavity is very similar to the 21-TJ (5.3-kt) Salmon cavity produced in the U.S., although the higher yield and shallower burial made it eight times larger. Both have a puddle of resolidified salt and explosive debris about 0.35 to 0.4 cavity radii deep in the bottom. Scaling the 17.4-m radius of the Salmon cavity to the yield and depth of the Soviet event gives a radius of 33 m, in excellent agreement with their 32-m radius.

In follow-up experiments, the Soviets report industrial testing of one of their nuclear cavities with both oil and gas. They found that the effective volume for storing liquefied gas condensate was 10% larger than the geometric volume. For gas at 6 MPa (60 atm), the extra volume amounted to 24%. This extra volume presumably comes from the porosity of the fractures radiating from the cavity.

Based on this experimental work, the Soviets made a 50 000-m³ cavity at a depth of 1140 m in a salt layer with a 63-TJ (15-kt) nuclear explosion. The cavity was reentered through the emplacement hole. After flushing and cooling it with natural gas, they tested it at 8.4 MPa (84 atm) for 30 days and found it to be pressure tight. They then filled it with gas condensate and turned it over to industrial use. It is being operated at a working pressure of 8 MPa (80 atm) with gas condensate being removed by gas displacement. Figure 5 shows the wellhead with a phantom link of the same capacity as this cavity.

The Soviets report that there is no significant radioactivity in the stored condensate. Compared to

Fig. 5. The wellhead (in wire cage), all that shows of the $50\,000\text{-m}^3$ (300,000-bbl) storage facility produced by detonating a 63-TJ (15-kt) device 1140 m underground and now used for storing gas condensate. The phantom tank in the background indicates the size of the underground reservoir. Storing the same amount of gas condensate in steel tanks above ground would cost 3 to 5 times as much, use 10 to 20 times as much steel, and occupy 2000 times as much land.

storage in a steel tank, this reservoir costs 20 to 30% as much, uses 5 to 10% as much steel, and takes up 0.05% as much land.

Despite all this interest in petroleum-related development, the Soviets have not neglected mining

applications. In addition to the over-burden-removal project already mentioned, they are looking into using nuclear explosions to break up ore bodies. They conducted a test of unannounced yield and depth of burial in solid granite, similar to the 20-TJ (5-kt)

Fig. 6. Cross section of a proposed scheme for breaking up an ore body with a nuclear explosion. The screening void and the screening undercut are to be mined out before detonation to provide reflecting surfaces that will intensify the shock wave and increase the amount of ore broken. It is expected that this single 7.6-TJ (1.8-kt) detonation would break up about $900\,000\text{ m}^3$ of ore. Of this about $400\,000\text{ m}^3$ would be removed through an access drift below the fracture zone by normal slope-mining methods.

Fig. 7. The locations of presumed PNE experiments and applications within the Soviet Union, 1965 to 1973. Squares indicate the presumed weapons-test areas at Novaya Zemlya (upper right) and near Semialatinsk (lower right). The numbers in the circular dots indicate chronological order. More than half (19 out of 32) of these events took place in the three years from 1971 through 1973. These events were detected seismically; they are presumed to be nuclear events because of their seismic characteristics and their location in aseismic regions. Their distance from the weapons-test areas supports the view that they represent engineering tests and applications of PNE. Their number, widespread distribution, and frequency suggest that the Soviet PNE program has been aggressively pursued and may be approaching routine industrial technology in some areas.

Hardhat and the 260-TJ (61-kt) Piledriver Events. On reentering the cavity they found a chimney height of 4 to 5 cavity radii, a crushed zone extending out to about 2 to 3 cavity radii, and a zone of fracturing, probably the result of tensile failure, extending out 4 to 6 cavity radii. Fractures into which the melt from the cavity had been injected were noted out to distances of 5 cavity radii.

In addition, they are proposing the ore-breaking project depicted in Fig. 6. This project involves placing a 7.6-TJ (1.8-kt) nuclear explosive immediately below a 60- to 80-m-thick ore body that dips into a mountain at about 25- to 35-degree angle. To enhance the natural fracture pattern, they plan to mine horizontal and vertical latticework grids 50 and 70 m from the explosion. These will provide free surfaces within the mountain that will reflect the shock wave as a tensile wave, thereby breaking more rock. They expect this single explosion to break about 900 000 m³ of ore, of which 400 000 m³ can be removed from an access tunnel below the fracture zone by normal slope-mining methods.

Seismically Detected PNE Events

Between 1965 and 1973, there were 32 seismic events in the Soviet Union that, because of the characteristics of their seismic signals and because of

their location away from the normal test sites at Novaya Zemlya and Semipalatinsk, many observers believe to be nuclear explosions related to the Soviet PNE program. Both the Stockholm International Peace Research Institute (SIPRI) and the USAEC published listings of such events.¹

Figure 7 shows the widespread geographical distribution of the events. The squares on Novaya Zemlya in the north represent areas having a large number of events (not included in the 32 mentioned above) and presumably constitute the normal weapons-test areas in the Soviet Union. Another presumed Soviet weapons test area is near Semipalatinsk.

The presumed PNE events indicated by circular spots are numbered chronologically. There were one in 1965, two in 1966, one in 1967, two in 1968, four in 1969, three in 1970, six in 1971, eight in 1972, and five in 1973. The large number of events, their wide distribution, and their frequency all point to an active and diversified PNE program.

Key Words: gas wells – stimulation; nuclear cratering; nuclear excavations; nuclear explosions – peaceful applications; nuclear explosions – Russia; nuclear mining; oil fields – stimulation; oil recovery (nuclear methods); underground cavities; underground chimneys.

TECHNOLOGY TRANSFER IN ACTION

Technology transfer, the process of transmitting new techniques and methods from those who develop them to those who can use them, is as old as history. It has traditionally been a gradual, diffusive, undirected process. Recent developments, however, have provided both the incentive and the means for bringing about rapid, purposeful technology transfers. LLL's Technology Training Program is a case in point. This modestly funded program has trained almost two hundred individuals, benefited scores of organizations, and participated in solving several energy-related problems. The benefits are beginning to spread, ripple-fashion, as our trainees become teachers in their own organizations.

The Technology Training Program is an outgrowth of an ERDA policy to find new ways of communicating information and expertise developed within ERDA laboratories. It operates by identifying areas of technology within the Laboratory that have potential applications outside, organizing the information into brief intensive courses, publicizing the courses and recruiting students from industry and from other government agencies, and presenting the material through a mixture of lecture, audio-visual, and student-participation techniques.^{2,3}

We developed three separate courses, two of which – the technology and applications of welding and bonding and of microcomputers – have been offered during the first year. The response has been enthusiastic, as measured both by continuing heavy enrollments and by student questionnaires completed during each course.

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Fig. 8. LLL classroom. The instructor's lectern is at the right, flanked by two television monitors on each side. At the left, behind the students, are two of the remote-control television cameras. The overhead camera, for viewing materials on the instructor's lectern, is out of sight among the lighting fixtures. This picture was taken from the television control console.

Program Elements

Facilities and Equipment. The classroom building consists of two open-bay trailer modules joined together to form a spacious 18- by 7-m room accommodating 32 students (Fig. 8). The customary desks are replaced with long tables on which the students can spread out large diagrams or other study material. A coffee area at one end of the room provides a center where students and instructors can relax together during breaks, helping to maintain a friendly informal atmosphere conducive to learning. It also helps keep the class close together, reducing time wasted in reassembling the class after breaks.

The lectern is placed in the middle of one long wall to shorten the distance to the farthest student and simplify the seating arrangements. This also provides a clear view for the television cameras while keeping them unobtrusive. Two closed-circuit television monitors on each side of the lectern enhance visibility,

giving all the students close-up views of the instructor and of visual aids material.

The visual aids equipment deserves special mention. In a conventional classroom, the instructor may pause to draw charts, tables, and diagrams on a chalkboard as he needs them, breaking the flow of the lecture. In this classroom an overhead camera, focused on the lectern top, projects such material instantly and without interrupting the lecture.

In addition to improving visibility for the students, the television equipment records the entire lecture on videotape. These tapes make it easy and inexpensive to rerun the course for a new group of students. The tapes are also borrowed by other institutions for their own training programs, multiplying the effect of our effort. To date, 36 organizations have requested these tapes.

An equally important part of our facility is the laboratory space for practical demonstrations and

hands-on training. This is housed in a permanent L.L. building near the classroom trailers. Much of the equipment for these demonstrations and practice sessions is temporary, making it easy to convert the space to other uses between courses.

In some cases we have found it worthwhile to design and produce special equipment for these courses. In the microcomputer course, for example, we found that our standard microcomputer-and-teletype-keyboard terminal was cumbersome and awkward to use in the class. We therefore developed a microcomputer trainer, with a keyboard, to fit into a standard attache case. We made 37 of these units, enough to let each student keep one throughout the course and even take it home at night for more practice on his own time. These teaching-aid microcomputers have proved so successful that dozens of other institutions are copying them in their own shops from our plans.

Student Selection. The enthusiastic response to this training program, with more than twice as many applicants as we can accept, makes it necessary for us to be selective. There is no point in admitting students unless we have a reasonable expectation that they will profit by the experience. It makes sense to exclude applicants who lack the necessary background, those who are already expert, and those whose work gives them little contact with the material to be covered.

In making this selection we follow a two-level approach, evaluating first the organization and then the student. First we determine, by interviews and on-the-spot surveys, what the various organizations (agencies, foundations, educational institutions, companies) need and whether one of our courses, with or without modification, will help them. We try to estimate the impact of their participation and whether the organization will implement the new technology in its operation. Only if these factors are positive is the organization invited to participate. Ninety-one organizations have participated to date.

The next step is selecting the students. This requires extensive interviews, both with prospective students and with their supervisors, to determine individual qualifications and interests. We try to correct any misconceptions about the course content, both to let the students and their supervisors know what to expect and to avoid future misunderstandings and disappointments.

Finally, we receive from each agency and company a rank ordering of its candidates. This information, together with our interviews and surveys, helps us decide which applicants to accept.

Feedback. Our estimates of the effectiveness of our courses are based on many inputs. The continuing flood of applicants, the active and enthusiastic participation of the students, the demonstrated improvements in their skills, all point to a successful training experience. In addition we have confirmation in the form of course evaluations by the students and through reports on the way the students apply their training in the field.

The course evaluations come from questionnaires that we distribute to the students during each course. Students rate the course in terms of its many components: lecture facilities, lecture presentations, student notebook, laboratory equipment, laboratory facilities, laboratory presentations, video arrangements, audio arrangements. The generally good-to-excellent ratings received in these questionnaires are gratifying. Constructive criticism also appears in the questionnaires, pinpointing for us areas that we could improve.

Transferred Technology

We have maintained contact with many of our students to follow their progress in applying their new skills. These applications take many forms: improved products and processes, ways to avoid waste, ways to save energy, ways to salvage parts formerly discarded as scrap.

Figure 9 shows a former student welding a break in an aluminum compressor casting in the Bay Area Rapid Transit (BART) shops. Aluminum is impossible to weld by ordinary methods, for it burns when exposed to air at its melting point. Inert gas welding — the proper method for aluminum — had been tried in the BART shops, but without success. Experience gained in cleaning and preparing surfaces for inert gas welding in our course enabled this student to solve the problem, turning scrapped castings back into serviceable parts at a saving of more than \$900 apiece.

Figure 10 shows a 3.4-m impeller, one of five in the submerged pumps of the California Department of Water Resources's Delta Pumping Plant near Tracy. These pumps raise Sacramento River water 75 m through 4.5-m-diam pipes to the head of the California Aqueduct. They were installed in 1967.

In 1969 inspection revealed severe erosion on these massive impellers. Cavitation (a constant pounding and scrubbing caused by the formation and collapse of air bubbles in the turbulence at the ends of the blades) was eating away the metal. The damage was accelerating; the presence of the cavitation gouges was

Fig. 9. A former student repairing an aluminum compressor casting in the BART shops. Previous attempts to apply this inert-gas welding technique had been unsuccessful. Small details learned in our course made the difference, enabling BART to salvage these castings at a saving of more than \$900 apiece.

Fig. 10. The 3.4-m-diam impeller of one of five submerged pumps at the California Department of Water Resources's Delta Pumping Plant near Tracy. The shiny patches are stainless steel laid down by the MIG welding process, filling deep pits eroded away by cavitation attack. Before taking our training course, the welders made slow progress due to the need for developing an optimum procedure. It was a constant struggle to keep abreast of the damage. After training the welders have been able to nearly double the rate of repair, completely eliminating the unsatisfactory temporary repairs previously made necessary by the demands of the operating schedule.

making the subsequent erosion worse. If the process were allowed to continue the unequal weight loss could cause serious vibration in the delicately balanced high-speed rotating system.

At first the cavities were filled with an epoxy-steel composition. This repair was quick and easy to do, but it gave only temporary relief. Within about 700 operating hours the plastic would begin to fail and the metal would be under attack again. It became a regular semiannual chore to shut down each pump and patch its impeller.

By 1974 some of the cavities were 2 to 3 cm deep, and temporary patching was no longer adequate. A program of permanent repair was started with the best available technology, MIG welding (metal arc, inert gas). Properly applied, this process can lay down layer after layer of stainless steel firmly fused to the impeller's cast-steel blade.

It takes time, however, to lay down 12 to 15 kg of stainless steel weld, and still more time to grind down the rough weld to the required smooth finish. The constant demand for pumping capacity made it necessary to adopt a piecemeal strategy, welding only the worst cavities and retarding the attack on the rest with temporary patches. The result was a constant uphill struggle to keep the pumps in repair.

Last winter two of their welders attended our course and learned improved MIG welding techniques: better ways to hold the torch, to control the heat, to leave a smoother surface that required far less grinding. The combined effect was to nearly double the speed of repairing the impellers. These two students have trained two others, and among them they have caught

Fig. 11. City of San Jose employees learning about microcomputers by working with attaché-case trainers borrowed from LLL. The open construction and exposed wiring help students become familiar with the plug-in components and removes some of the mystery surrounding the computer. A generous breadboard area (white space at student's left) provides ample outlets for connecting experimental equipment or additional computer memory or other accessories. The units are self-contained and portable; students can take them home and continue learning on their own time.

up with the erosion damage. The last of the temporary patches has been replaced with long-wearing stainless steel. In just six months the return on this one application has saved Department of Water Resources many times their original investment in the course.

In still another instance, a City of San Jose consultant from the Urban Technology System, which is funded by the National Science Foundation, heard about and enrolled in our microcomputer course. The hands-on instruction experience using our newly designed attaché-case microcomputer trainer so impressed him that he immediately set up and taught the identical course for San Jose employees using LLL videotapes and microcomputer trainers complete with laboratory experiments (Fig. 11). This San Jose in-house course extended our training, at minimal cost, to 17 engineers, programmers, designers, and technicians. These are the people who are responsible for writing specifications, programming, designing, constructing, and maintaining the San Jose traffic lights and control systems.

The City of San Jose has derived a variety of benefits through having its employees attend this course. Its engineers and designers can now specify exactly what is needed in traffic signal systems and evaluate vendors' proposals and bids rather than having to rely on manufacturers' claims. Programmers are better prepared to write their programs, and technicians will be able to maintain these new traffic control systems after they are installed.

As a result of our training program, San Jose now

has an ongoing program of microcomputer development and will be demonstrating a prototype system early in 1977.

After their in-depth study of the subject, traffic control systems' people and maintenance personnel alike are looking forward to the future installation of microcomputers for traffic control. Among the advantages they see are improved flexibility and reliability, reduced size, modular maintenance, a new data-gathering capability, and lower cost.

As to projected savings, San Jose purchases about two dozen complex traffic controllers per year. These presently cost about \$4500 each. Microcomputer controllers, on the other hand, would cost about \$1500 each in similar quantities. Thus the City estimates initial-outlay savings at about \$75 000 per year, and anticipates further potential savings in reduced maintenance. Finally, installing a series of centrally timed microcomputer controllers along a thoroughfare will enable the signal lights to be coordinated to minimize traffic stop/start conditions, providing a smooth uninterrupted flow of traffic and saving fuel.

The San Jose experience is only one of many. This summer, 22 electronics instructors representing 20 community colleges in California and Texas attended the microcomputer course. Impressed with our attaché-case microcomputer, they decided to adopt our hands-on instruction method for their own classrooms. Since documentation for the trainer has been released for public use, the group elected to have the electronics

department of Diablo Valley College in Pleasant Hill, California, serve as a coordinating agency and to have the school's Electronics Club – a nonprofit organization – purchase the necessary materials to assemble 100 microcomputer units. Presently 16 community colleges are participating in this program, and many hundreds of students will benefit from the technology transfer.

By the end of August 1976, we had received requests for the microcomputer course tapes from 36 organizations. Seven of these had previously participated in our program, the rest had read about it or heard of it in some other way. BART has started

a program, using our tapes and training equipment, that will eventually reach 265 of its technicians. Among the organizations requesting the tapes for welding and bonding are the California Department of Water Resources, the Army Corps of Engineers (San Francisco), and the U.S. Coast Guard. We have cast a pebble into a pond, and the ripples continue to widen.

Key words: microcomputers; microprocessors - equipment; integrated circuits; MIG welding; technology transfer, technology - utilization; technology - commercialization.

FOSSIL ENERGY

UNDERGROUND COAL GASIFICATION IN THE U.S.S.R.

During almost 50 years of experience with coal gasification, Soviet researchers have achieved a large measure of success. Methods they have developed are usable in horizontal and steeply dipping beds, in thick and thin seams, and in a variety of coal types. These methods have been used for generating process heat and electricity at six known sites, three of which are still operational. Although recent large discoveries of gas and oil in the U.S.S.R. have reduced their interest in gasification, the reverse is true here. We can benefit from understanding their process designs and the basis for them.

The Soviets' first field experiments in underground coal gasification were conducted in 1933; since then they have continued to develop and exploit the technology. Only in the U.S.S.R. have commercial coal gasification plants been operated over long periods of time, generating electricity and/or local process heat. Thus it is important for us in evaluating our own effort to understand what their process designs look like and why they have made certain critical design choices.

It is easy to conceive many designs for underground coal gasification that address one particular problem but difficult to create a single design that functions effectively as a system, deals with all problems simultaneously, and can be transferred successfully from one coal region to another. One such design exists in the U.S.S.R. It has been operated repeatedly in a predictable manner and transferred among areas with large differences in the geological nature of the coal seams. Figure 12 shows present and former Soviet coalfield and underground gasification sites; only Shatsky, Angren, and Yuzhno-Abinsk are now operational. The size of the associated power station at Shatsky (see Fig. 13) reflects the magnitude of the Soviet effort.

The purpose of underground coal gasification is to convert coal into a combustible gas by carrying out appropriate chemical reactions underground — in theory a simple process of partial combustion by injecting "blast" (air or oxygen-enriched air) and extracting product gas (carbon monoxide, hydrogen, methane, and tars). Basically, the Soviet plan is to drill

two access holes into a seam — one for injection and the other for exhaust — then to establish a permeable channel between them along the bottom part of the coal seam. Blast is forced down the injection hole and product gas recovered up the exhaust hole while the coal between them is consumed. The production burn begins in the channel; the burn front widens the channel, and roof collapse or subsidence feeds more coal rubble into the combustion region.

Channel Formation Techniques

For successful gasification, the product gas must be able to move freely through the coal. Gas flow is possible with only natural permeability, but enhancement is needed for large-scale gasification. This is due both to the low initial permeability of coal and the fact that cocurrent combustion — the flame front and gas flow propagating in the same direction — tends to plug the coal with liquids that condense downstream from the combustion zone.

The Soviets have successfully employed four different schemes — linking techniques — to enhance permeability. It is the nature and limitations of these techniques that dictate most of their overall process design. The four schemes are directional drilling, countercurrent combustion, electrolinking followed by countercurrent combustion, and hydrofracturing. All four produce narrow, linear channels of high permeability between the injection and exhaust holes. None of them create planes of permeability or increase the permeability of the bulk of the coal seam.

Directional Drilling. Drilling vertical holes into coal seams involves no novel technology. However, an advanced method has been developed in the U.S.S.R.: drilling linkage channels along a seam close to the bottom. For steeply dipping coal beds, the holes are usually straight, starting at an appropriate angle to the surface so that they stay within the coal seam. For horizontal beds, however, the drilling starts at an angle to the surface and curves into the seam. Holes up to 0.3 m in diameter have been drilled 300 m into steeply dipping seams and 100 m along horizontal seams.

Directional drilling is an extremely sophisticated technique and therefore costly. Whenever possible, other less-expensive techniques for horizontal coal

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seams, mainly countercurrent combustion, have been used.

Countercurrent Combustion. The differences between countercurrent and cocurrent processes are very significant when applied to underground coal gasification. In the latter, characterized by unidirectional flame-front and gas-flow propagation, the rate of coal consumption determines the flame-front velocity. Almost all the combustible material in the combustion zone is consumed. Conversely, in countercurrent combustion the flame front moves opposite to the gas flow, its velocity being determined by the rate at which heat is conducted upstream against the flow. The upstream coal is heated and ignited, depriving the remaining downstream,

partly combusted coal (char) of oxygen. In countercurrent combustion not all the coal in the combustion zone is fully consumed.

There are other important differences between these combustion modes, the most significant being that countercurrent combustion tends to burn narrow, fixed-diameter channels whereas cocurrent combustion generally propagates on fairly broad fronts. The reasons are indicated in Fig. 14. If a narrow, highly permeable channel of char or ash extends into a coal seam of much lower permeability, as shown here, the gas flow lines converge at the channel tip. In the region A-B, most of the gas flow is carried by the channel. From B to C, the flow distributes more uniformly across the bed, independent of flow direction. If the

Fig. 12. Soviet coal fields and underground coal gasification sites. Of the nine stations shown at the six gasification sites, only three are now operational: Shatsky, Angren, and Yuzhno-Abinsk.

Fig. 13. View of the Soviet power generation station associated with the Shatsky coal gasification site. The size of this station gives some indication of the magnitude of the Soviet coal gasification effort. (Ref.: P. Skafa, *Underground Gasification of Coal*, Moscow, 1960.)

coal is ignited in the channel near B and the flow direction is from C to A (countercurrent combustion), the flame front at the channel tip (at B) has access to more oxygen than the channel walls further toward A. Thus, as the flame front at the tip progresses toward A, the oxygen-starved walls do not expand greatly, and a channel of relatively small and constant diameter is created.

By contrast, if the flow direction is from A to C (cocurrent combustion), the channel walls are exposed to the highest oxygen concentration, supporting

combustion on the walls and promoting a widening of the channel.

Another important difference is that countercurrent burns carried out in virgin coal are not as subject as cocurrent burns to plugging from condensing liquids or coal swelling.

Thus, countercurrent burn is appropriate for creating highly permeable channels in coal seams but not for gasification in the production phase because it leaves unburned coal. Cocurrent burn cannot be used to form channels but can be used for production

Fig. 14. Channel formation by cocurrent and countercurrent techniques. Gas flow paths are shown as dotted lines.

because of its almost complete burn. Therefore both methods are used: countercurrent combustion for linking, and cocurrent combustion for production.

In practice, the Soviets have achieved countercurrent combustion linking rates of 1 to 3 metres per day by injecting air. Higher linking velocities can be attained with oxygen, but the resulting channels are not permeable enough to carry out satisfactory cocurrent burn. Apparently air has an excellent oxygen concentration for producing an appropriately permeable channel at an acceptable rate.

Electrolinking. Electrolinking uses an electric current to char a channel between the access holes, similar in mechanism to countercurrent combustion. However, certain crucial physical phenomena must be present for electrolinking to succeed. First, the coal must strongly increase in electrical conductivity as it is heated by the electric current. Second, the conductivity of the unheated coal must be reasonably high but much less than that of the heated coal.

Figure 15 shows the electrolinking process some time after power has been applied. Channels have appeared from both electrodes, gradually growing toward the center. These channels are highly conducting. Current is concentrated in them but spreads out over a larger cross section in the unheated

coal. Most of the potential drop, and therefore most of the energy dissipation, occurs at the channel ends away from the electrodes, where the channels are in contact with the less-conducting unheated coal.

Energy dissipation in the channels is minimized by their high conductivity. Energy dissipation in the unheated coal is reduced because the large cross-sectional area carrying the current compensates for the unheated coal's relatively low specific conductivity. The combination of high current density and high resistivity of the unheated coal is found only where the current lines converge on the tips of the highly conducting channels. As the tips heat, the coal chars, increasing its conductivity. Each channel is thus extended until the two channels meet. Usually the channel is then further widened with a relatively fast countercurrent-combustion step before production is initiated.

The primary problem encountered with electrolinking has been in controlling it. In an idealized and uniform media, the link proceeds predictably. However, the direction it follows is strongly influenced by anomalous and unpredictable regions of conductivity that are specific to the local geology.

Hydrofracturing. Where none of the other linking techniques is appropriate for a particular coal seam,

Fig. 15. Electrolinking after process has been under way long enough to establish the forming channels. Dotted lines indicate current, which is concentrated in the forming channels and spread out somewhat in the intervening unheated coal.

the Soviets have formed channels by hydrofracturing. The effectiveness of this technique is independent of the coal's electrical properties and, in contrast to countercurrent combustion, works best with coals of low natural permeability. It also requires far less sophisticated equipment than for directional drilling. However, the lack of directional control is a strong disadvantage.

Essentially the process requires pumping water down a pipe into the coal to form cracks. Sand may be added to the water to prop open the cracks after pumping. The effectiveness is often improved by adding a thickening agent to increase the viscosity of the water; this improves the water's sand-carrying capability and helps to confine the underground gas flow to a few major cracks.

Many studies have been run on the use of hydrofracturing to prepare a coal bed for gasification. However, it appears that this technique has been employed mainly for steeply dipping beds where it is not crucial to ensure either that the cracks form at the bottom of the seam or that they form parallel or perpendicular to the bedding planes.

System Design

Any underground coal gasification process must minimize the loss of both injected blast and product gas. To complicate matters, gas losses increase roughly with the square of the pressure, and maintaining a gas-tight zone is very difficult. Also, when coal is removed the roof must eventually subside, especially where a high fraction of the coal is recovered over a large area; this subsidence forms highly permeable cracks to the formations above, sometimes all the way to the surface, allowing gas to escape from the process zone.

The extent of leakage cracks is unpredictable, thus it is important to design for minimum leakage. In the U.S.S.R. this has been accomplished by operating at relatively low pressures and ensuring, through linking, that the permeability between injection and exhaust holes is always greater than that through subsidence cracks. (Cracks at the surface have also been sealed by bulldozing them full of mud.)

Water intrusion into the gasification area must be controlled. The Soviets have done this with high gas flow rates, generally 3 000 to 10 000 m³/h. This maximizes the channel width and thus resource recovery. It is compatible also with control of gas leakage since high flow rates can be achieved in the Soviet system at relatively low pressure drops because

of the highly permeable channels. The driving pressure seldom exceeds 100 kPa (1 atm).

Directional control of gas flow is essential for reproducibility of the desired attributes of maximum resource recovery or optimum economics (these criteria may not lead to the same system). The Soviets have achieved this control by using highly permeable linkage paths with predetermined spacing at the bottom of the coal seams, rendering the gasification process insensitive to variations in natural coal permeability. Directional control has also ensured that the gas flows into the exhaust hole instead of spreading uncontrollably throughout the formation.

Efficient gas-solid reactions require a large surface area consisting of a rubble zone without bypass channels, the reaction rate being limited by the available surface area of the coal where the initial reactions must take place. In the Soviet system for horizontal coal seams, the linkage channels are at the bottom of the seam so that the flame front undercuts the coal (see Fig. 16). The coal then falls into the void, forming rubble. In their system for steeply dipping beds, rubble is formed by coal falling into the void created at a bottom manifold where combustion is initiated (see Fig. 17).

In a horizontal seam, the natural tendency is for the liquids (water and pyrolysis tars), being heavy, to plug cracks low in the seam and to force the flame front to move preferentially along the top. The coal ash also tends to seal the channel bottom, preventing further coal combustion and sharply reducing the fractional recovery.

The Soviet system minimizes this effect by forming the channel at the bottom of the seam during linkage. The channels are kept hot enough during recovery to drive off any liquids intruding into the region, as well as those formed by pyrolysis. All channels thus remain clear to gas flow, and removal of the liquids as vapors permits recovery of the economically valuable coal tars.

This mechanism for total liquid removal also removes phenols formed by pyrolysis. The phenols are never allowed to condense but removed almost immediately as vapors. A "steam flush" helps: intruding water is vaporized deeper in the coal seam than the phenol is formed, flowing inward toward the channels, picking up the phenols, and effectively flushing them into the hot channel. The quantity of phenols in the ground after gasification is thus minimal.

Fig. 16. Typical channel tip during a production burn in a horizontal coal seam using cocurrent combustion.

Fig. 17. Production burn in a steeply dipping coal seam.

Fig. 18. Plan view of a typical Soviet underground coal gasification system for horizontal seams. The rows here are 25 m apart.

A large share of the cost of underground coal gasification is associated with drilling and casing the exhaust and injection holes. It is obviously important, therefore, to maximize the probability that casings will survive gasification and the subsequent roof subsidence.

Figure 18 shows a typical plan view of the Soviet process for horizontal beds, the dotted lines indicating locations of the underground linkage channels formed at the bottom of the seam by casing the access holes two-thirds of the way down. The injected air is forced to enter and the product gas must exit at the bottom of the seam. Thus the linkage channel at least starts and ends at the bottom of the seam, though it may wander somewhat between the holes.

In this figure the cocurrent-combustion production phase is shown in the direction from row 2 (injection holes) to row 1 (exhaust holes). In practice, however, the gasification is conducted in both directions. The choice depends critically on the exact nature of the roof subsidence, which can create leakage paths for the gas as well as obstruct the gas flow. After completion of the resource recovery between rows 1 and 2, row 3 becomes the injection row, row 2 becomes the exhaust row, and the process is repeated.

A primary problem encountered for thick horizontal seams is that ground subsidence has a tendency to shear off the access pipes. To prevent this, two modifications are made. First, a lateral hole technique is used in which either gas exhaust or injection acts

through holes alongside the gasification zone. The reverse process - injection or exhaust - acts through holes entering the seam in a rectangular pattern directly over the coal. Second, within the framework of this general pattern, all holes are drilled on a slant to keep them out of the subsidence region during their functioning lifetime.

The holes alongside the gasification zone are never affected by subsidence; those in the pattern directly over the coal are not affected until after the coal under them is gasified and they are no longer needed. Thus it is never necessary to operate with a hole that has been exposed to any ground movement or subsidence. A cross-flow component can also be added to the gas flow to help recover mounds of coal that might otherwise be left between channels. In addition, if the slant-drilling portion of this design proves not to be cost-effective, the lateral withdrawal technique can be made to work equally well with a combination of vertical holes and more extended underground linkage channels.

It is important to know how wide the channel will grow. This factor determines the maximum initial hole spacing allowable for 100% resource recovery. Eventually the channel will reach a stable width and expand no more because, as the channel widens, the oxygen transfer rate to the combusting coal faces diminishes but the conductive and radiative heat losses from the faces remain constant or increase. At a specific width, called the critical channel width, it is

no longer possible to sustain combustion on the faces, and the channel ceases to widen.

The critical width is clearly affected by the permeability distribution in the channel after roof subsidence. With air as blast, widths as great as 5 to 10 times the seam thickness have been achieved for thin seams; they have been further increased by enriching the blast with oxygen.

Gas Production

It is very important to operate the system such that the composition of the product gas remains relatively constant with time, maintaining the heating value at a desired level. This is accomplished by ensuring that the hot gases always pass through a zone that is essentially packed with coal rubble. Such zones have a large amount of coal surface area available for reaction, permitting intimate contact between the hot gases and the coal.

The downstream tip section of a long channel during gasification of a thick coal seam is depicted in Fig. 16. (The wider upstream portion of the channel with the additional air injection pipes is not shown.) An essential feature of this region is that more coal falls into the growing void as coal is consumed. This creates a high-surface-area, highly reactive rubble bed that serves as a final reduction zone and is responsible for the uniform quality of the product gas.

Further upstream, the channel may widen to many times the coal-seam thickness. In this area, coal falling into the growing void at the sides of the channel does not have such an important effect on the product gas composition because of oxygen bypass at the channel center. A sampling of the upstream gases in the oxidation zone shows low heating values. However, so long as the tip of each channel has a hot and highly reactive zone of coal rubble through which all the hot gases must flow, the product gas will be reduced and have a high heating value that is uniform with time.

As the flame front advances and the channel width expands, a point comes when the tip zone will no longer hold the gas composition constant. At this time, another section is added to the channel (as shown in Fig. 18) to maintain the required high-surface-area coal zone. The gasification process can thus be continued indefinitely along a coal seam with excellent control over the uniformity of the gas composition. Fractional resource recovery can be controlled by proper spacing of the parallel channels.

There are at least three efficiencies of concern in this process: (a) fraction of coal recovered; (b) fraction of the coal's heating value that appears as heating value in the product gas; and (c) overall energy efficiency of the plant, including the conversion efficiency to electricity and the energy needed to maintain the gasification station. The Soviets have extensively documented the first two but report less clearly on the latter. The fraction of coal gasified varies from 50 to 100%, depending on the particular gasification station and the specific nature of the ground subsidence. Of that actually gasified, 50 to 70% of the heating value appears as heating value in the product gas.

No maximum seam thickness has been observed for these processes since they have operated in seams up to 20 m thick with no indication of approaching a limit. However, it has been found that the heating value of the recovered gas becomes unusably small from seams thinner than 1 m.

The Soviets have also been able to gasify multiple coal layers sequentially, starting from the top seam and working down. This permits more complete and economical recovery.

Evaluation

During almost 50 years of research and application, the Soviets have put as many as twelve underground coal gasification stations on a production footing, three of which are still operational. Their system works, using the product gas to generate local process heat or electricity at a surface station. The system is ideal for supplying electrical base-load demands. Under some circumstances it can be turned on and off in time periods as short as a few hours, thus helping to meet intermittent electrical demands.

Interest in gasification has waned recently, following large discoveries of gas and oil in the U.S.S.R. The reverse is true in the U.S., however, where coal is abundant and often considered our most exploitable resource. We stand to benefit, in evaluating our own effort, from understanding the Soviet processes and the critical design choices that have made them effective.

Key Words: coal - fracturing; coal gasification - effluents; coal gasification - Russia; coal - permeability; coal - pyrolysis; combustion - countercurrent.

Notes and References

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