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MAJOR ADVANCE IN CTR RESEARCH

In mid-July, we attained the highest temperatures ever observed in a major fusion experiment — about 12 to 14 keV — using the 2XIIB magnetic mirror machine. Confinement time was 5 ms, a factor of 12 greater than that achieved by 2X11, the previous-generation experiment. We also observed a plasma density greater than \(10^{13}\) ions/cm\(^3\). These results mark the most significant advance for the mirror program since we obtained our first unequivocal evidence of neutrons from controlled thermonuclear fusion reactions in 1961.

Our results demonstrate that the hotter the plasma, the longer and more stably it can be confined by magnetic bottles of the mirror type. Most plasma losses in our recent experiments were not due to the internal instabilities that have plagued fusion experiments, but were due to the much less serious effects of collisions between plasma particles. We are now altering the 2XIIB to try to extend our results. In particular, we are doubling (to 40 keV) the injected neutral beam energy to investigate plasma stability at temperatures about twice as high as those achieved to date.

In equaling or exceeding all major experimental goals for the 2XIIB, our results strongly support the possibility that a next-generation experiment may be able to demonstrate the feasibility of the mirror approach to fusion. The 2XIIB presently approaches reactor temperatures and densities but does not have the needed confinement time (approximately 1 s for mirror reactors). However, Baseball IIIT, a major companion experiment, uses a superconducting magnet to confine a much lower density plasma essentially as long as desired. A next-generation mirror fusion experiment would also use a superconducting magnet and would combine technologies developed in 2XIIB and Baseball IIIT research. Such an experiment could be in operation in the early 1980's.
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ENERGY PERSPECTIVES

ENERGY - A PLAN FOR ACTION

Dr. Edward Teller has prepared a comprehensive program to meet U.S. energy needs by the year 2000 for the Energy Panel of the Commission on Critical Choices for Americans. In his proposal, Energy A Plan for Action, Dr. Teller calls for a combination of foresight and patience to solve the energy shortage and prevent a serious conflict over energy. His stated objective is to have sufficient energy that is inexpensive, clean, and secure. He examines the interrelated measures needed to ensure U.S. energy self-sufficiency before 1985 - energy conservation and production as well as environmental safeguards - and the financial burdens of these measures. Beyond U.S. energy independence, Dr. Teller finds an equally important goal in energy interdependence, with the nation contributing to the world's economic stability. One step toward this goal is for the U.S. to become a net exporter of coal and oil by 1985 [see frontispiece].

The following excerpts are from Dr. Teller's proposal: illustrations and tabular material are also taken from Energy A Plan for Action. Square brackets denote editorial explanations or summaries of deleted text.

It is urgent to take radical but realistic measures to resolve the interrelated problems of energy, ecology, economics and world stability. The United States has responded successfully to other challenges. The mobilization of our industry during World War II, including a plan to build 60,000 planes, is one example. (Actually, more than 125,000 planes were built in a single year.) Our success in landing a man on the moon impressed the world. Our reaction to the oil embargo was, by comparison, insufficient. When the embargo was lifted and President Nixon declared that the crisis was over, even the little progress in energy conservation and public awareness that had been made began to disappear.

Within the next year, progress can be made by implementing a national conservation ethic, by introducing available energy-saving devices, by removing barriers to increased energy production and by establishing better cooperation among energy-consuming nations....

1985 Target

The main thrust of our proposal is to establish badly needed and realistic objectives and a plan for achieving them by the year 1985. The existence of a plan and public understanding of its objectives will make it easier to accept temporary difficulties and to avert dangerous developments. The elements of the plan include:

- Economic and effective use of energy.
- Substantially increased oil and gas production in known domestic basins.
- Much greater use of coal.
- Public acceptance of and greater use of nuclear energy.

Our purpose is to establish by 1985 a strong energy position that can serve as a basis for healthy development of our economy and that can provide badly needed help to our allies by exporting coal and oil from the United States. We propose to increase production of energy sources not requiring great innovative research. These are oil, gas, coal and nuclear energy. As early as 1980, our oil imports and coal exports may balance if we pursue this program vigorously....[See Table 1 for the 1980 and 1985 targets for domestic energy production and consumption.]

If our target is reached by 1985, the U.S. could export 13% of the energy produced domestically. This would include the export of a little less than three million barrels of oil per day, an amount which may be almost 10% of the expected oil requirements of our allies. In addition, we would export about a million tons of coal per day. These exports should have a moderating influence in the oil market and would suffice to protect any one country among our allies from the effects of an oil blackmail. Even the expectation of a modest U.S. oil export capability could deter the OPEC countries from limiting oil production to conserve oil underground instead of increasing production for export....
### Table 1. Energy demand and supply (all figures in quads per year = 10^{18} Btu's per year)

<table>
<thead>
<tr>
<th>Demand</th>
<th>1973 Actual</th>
<th>1980 Target</th>
<th>1985 Target</th>
<th>2000 Example</th>
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<td>Other</td>
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<td>(b)</td>
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<tr>
<td><strong>Net</strong>e</td>
<td>64.2</td>
<td>74</td>
<td>96</td>
<td>145</td>
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</table>

### SUPPLY

| Liquids                      | 35.2        | 34          | 39          | 50             |
| Conventional                 | 22.2        | 27          | 35          | 30             |
| Shale                        | 0.0         | 0           | 2           | 15             |
| Synthetic                    | 0.0         | 0           | 1           | 5              |
| Imports                      | 13.0        | 7           | 1           | 0              |
| **Gas**                      | 23.6        | 26          | 29          | 25             |
| Conventional                 | 22.6        | 25          | 28          | 20             |
| Synthetic                    | 0.0         | 0           | 2           | 15             |
| Imports                      | 1.1         | 1           | 1           | 0              |
| Converted                    | 0.0         | 0           | -2          | -10            |
| Coal                         | 15.0        | 22          | 33          | 50             |
| Nuclear                      | 0.9         | 6           | 12          | 60             |
| Hydroelectric                | 2.9         | 3           | 3           | 5              |
| Other                        | 0.0         | 0           | 2           | 10             |
| **Totals**                   | 77.6        | 91          | 118         | 200            |

---

aPrimary energy demands - energy consumed by the electric utilities to produce electricity. For non-fossil fuel sources (such as geothermal, hydroelectric and nuclear) energy consumed is the equivalent fossil fuel energy which would be required. This equivalence is based on converting 10,500 Btu of heat to one kilowatt-hour of electricity or at an efficiency of 32.5%.

bEnd-use sector totals exclude electricity consumed. (See Note c.)

cElectricity consumed in this end-use sector which is produced by the electric utilities. Not included in sector totals.

dElectricity consumed in this end-use sector which is produced by the electric utilities. Not included in sector totals.

eElectricity consumed in this end-use sector which is produced by the electric utilities. Not included in sector totals.

fElectricity consumed in this end-use sector which is produced by the electric utilities. Not included in sector totals.

gElectricity consumed in this end-use sector which is produced by the electric utilities. Not included in sector totals.

hElectricity consumed in this end-use sector which is produced by the electric utilities. Not included in sector totals.

iElectricity consumed in this end-use sector which is produced by the electric utilities. Not included in sector totals.

jElectricity consumed in this end-use sector which is produced by the electric utilities. Not included in sector totals.

kElectricity consumed in this end-use sector which is produced by the electric utilities. Not included in sector totals.

lElectricity consumed in this end-use sector which is produced by the electric utilities. Not included in sector totals.

mElectricity consumed in this end-use sector which is produced by the electric utilities. Not included in sector totals.

nElectricity consumed in this end-use sector which is produced by the electric utilities. Not included in sector totals.

oElectricity consumed in this end-use sector which is produced by the electric utilities. Not included in sector totals.
Costs

The cumulative capital expenditures required to carry out this program up through 1985 are approximately $840 billion [1973 dollars*]. This amounts to a yearly investment of almost $80 billion in energy alone, which is about four times what we have spent for this purpose in the past. [The distribution of these investment needs is summarized in Fig. 1.] We believe that this is the most difficult condition that needs to be fulfilled if our plan is to be realized although heavy expenditures will be required in any case during the next decade. In order to finance this plan, other capital intensive programs may have to be cut back and capital formation must be stimulated both by direct and indirect government action. It may be necessary to increase the fraction of the gross national product going into private investment. How we do this and what we are willing to sacrifice for this purpose are critical choices connected with any energy plan.

Beyond the $840 billion of capital expenditures, about $40 billion will be required for research and development. This corresponds to an annual research and development expenditure of about $4 billion (an amount not very different from the present practice if spending by government and by industry is included). The present research and development expenditures are not in an ideal balance. Industry emphasizes developments that are to bear fruit in the next couple years. Government research, on the other hand, is oriented toward the next century. More should be done to take care of the next 10 years. If we emphasize better exploitation of fossil fuels (better drilling equipment and advanced methods of fuel recovery) and short-term development of nuclear reactors (greater safety and a switch to abundant thorium as the main fuel), together with other medium-term developments, the cumulative expenditure of $40 billion for research and development will be an excellent investment.

Conservation

[Consumption can be influenced more rapidly than production. As shown in Table 1, the 1985 target for domestic energy demand is 103 quads. This increase from the 75.6 quads consumed in 1973 represents a lower annual growth rate than that of the past decade. To meet this demand target, we will have to constrain energy consumption; therefore conservation is a must.]

We must begin at once a serious and continuing effort to conserve energy—particularly oil and gas. At the same time our economy must remain vigorous if our targets for 1985 are to be reached.

The most serious problem is petroleum and this is exceedingly hard to resolve. Continued imports of oil on a large scale would hurt our trade balance, would deprive us of capital badly needed in other areas and would antagonize our allies who would consider us as an unwelcome competitor in the oil market. Import of gas is both expensive and dangerous. Therefore, we must find ways to live with less petroleum.

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*All dollar amounts are given in 1973 dollars.
Direct conservation measures will have the greatest impact on the transportation sector. Such measures include enforcing the 55-mph speed limit, improving automobile gas mileage, using diesel-powered taxis and small trucks in metropolitan areas, and increasing mass-transit support. Electricity generation also is amenable to direct conservation measures. Electric rates must be allowed to rise, assuring utilities a fair return, but the rate structure should be altered to discourage excessive use of electricity, and the industrial use of "bottoming cycles" should be encouraged. Other direct conservation measures include incentives and requirements for better home insulation and the use of sunlight for hot water production, space heating, and air-conditioning.

Indirect as well as direct measures of conservation are needed. Reprocessing of discarded goods must be encouraged. It is even more important to cause manufactured goods to last longer by appropriate fabrication and by maintaining spare parts and repair facilities. The economics of rapid obsolescence are out of date. All of this is so important as to demand action by the government. Such actions may take the form of tax incentives and penalties, mandatory labeling of goods or other regulations.

Altogether, we propose to invest by 1985 $100 billion to save from 5 to 10 quads per year. This corresponds to an investment of more than $20,000 on the average to save a barrel of oil per day in the favorable case and twice that amount in the unfavorable case.* Another 5 to 10 quads per year would be saved by vigorously exercising a conservation ethic and by other means which are not capital-intensive....

**Target Demand**

In the electricity sector, our target is to increase the input from 19.8 quads in 1973 to 33 in 1985. We propose to accomplish this objective largely by increasing the use of coal and nuclear power even while decreasing the use of oil and gas. Reduced oil and gas consumption may be offset by increased consumption of other energy sources such as solid waste and geothermal.

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*We are actually proposing to save more capital on saving a barrel per day of oil than on finding a barrel per day. This is justified both by a decrease of subsequent operating cost and by environmental considerations. [E.T.J]
The residential and commercial sector is to increase from 20.9 quads in 1973 (18.2 of primary fuels and 2.7 of electricity) to 29 quads in 1985 (24 of primary fuel and 5 of electricity). We are proposing a slight decrease in oil consumption, offset by a similar increase in gas demand. The major increase is to be in the use of coal along with greater use of electricity.

The non-energy sector uses include fertilizers, plastics and other petrochemicals as well as asphalt, waxes, lubricants and commercial solvents. In 1973, this portion of our industry consumed 3.4 quads, of which 2.5 were of oil, 0.7 of gas and 0.2 of coal. We are proposing that in 1985, we should consume 6 quads 2 of oil, 1 of gas, and 3 of coal.

This suggestion represents a radical change from the past. Gas could be used in Alaska for non-energy purposes, but the equipment for its use there is presently non-existent. Coal could be used by the petrochemical industries in the U.S. as it was in earlier decades.

[Consumption in the transportation sector is projected to increase only to 22 quads in 1985 from 18.8 in 1973; oil will account for 21 quads.]

**Target Supplies**

Increased domestic supplies of fossil fuels and nuclear power are essential to meet our targets.

**Electrical Energy.** The production of 6.4 quads of electricity in 1973 consumed somewhat under 20 quads. Our target for 1985 is to consume 33 quads in order to produce 11 quads of electricity. This corresponds to an annual increase of slightly less than 4.3% in the consumption of energy for the generation of electricity which is well below the 6.7% average rate of increase during the 1960's. To achieve even this lower average rate of growth, it is necessary to establish a fair return to the utilities so that they can expand and improve their plants.

Specifically, we project the 33 quads consumed by the electric utilities in 1985 will come from the following primary energy sources:

- Nuclear plants will consume 12 quads. This could be accomplished by 1985 if nuclear plants are standardized, if their safety is improved and if nuclear power gains public acceptance, and if, as a result, licensing and siting becomes easier. We recommend special attention be given to determining the feasibility of siting nuclear reactors underground.
- Hydroelectric plants will account for three quads which represents a very small increase over 1973 figures.
- Coal will account for 11 quads. In the case of coal burning plants, it will be necessary to improve the control of stack gases. Still, regulations requiring inflexible nationwide controls on sulfur must be temporarily modified in order to avoid a sharp increase in oil consumption and to encourage the orderly development of the coal industry.
- Gas will account for three quads which is less than was burned in 1973.
- Oil consumption should be decreased to two quads or about one million barrels per day.
- Two quads may be supplied from geothermal sources, from urban wastes and possibly from other unconventional sources.

The total investment of $200 billion in electric plants and distribution systems corresponds to $25,000 per barrel of oil per year used in the generation. If the efficiency of electric generation can be increased to between 35% and 40%, the energy delivered as electricity would cost the equivalent of $70,000 per barrel of oil per year in capital. Although this is a high cost, one must realize that the use of electricity is flexible and in many respects is irreplaceable.

**Oil.** We propose to increase the domestic production of crude oil from 22.2 quads or 10.5 million barrels per day in 1973 to 35 quads or about 16.5 million barrels per day in 1985. This sizable increase requires immediate and thorough exploitation of known reservoirs and includes more complete recovery from existing and from abandoned oil wells. It also requires vigorous development of and production from resources on the Northern Slope of Alaska, including Naval Petroleum Reserve Number 4, and the continental shelf, including the Santa Barbara Channel and the west coast of Florida. These programs require public acceptance which may be forthcoming if proper precautions are taken to avoid oil spills and if methods are perfected to clean up an oil spill, should it occur....
To reach our target, we will have to improve our existing procedure for leasing public lands, placing emphasis on production performance rather than on revenue to the U.S. Treasury. For instance, it might be appropriate to commit an agreed level of funds to the development of the property in lieu of a large lease payment. The government could obtain additional revenue through royalties.

An additional incentive for exploration might take the form of a government guarantee that the price for oil will not be allowed to drop below a “floor,” which is appropriately indexed and which might be set initially at $7 per barrel in 1973 dollars. This price floor should be coupled with an excess profits tax which would apply to all earnings not used for appropriate reinvestments in energy such as exploration, development, research and environmental improvement.

To the 35 quads or about 16.5 million barrels per day of domestic crude production in 1985, we would add:

• One quad or about one half million barrels per day in the form of methanol (which, in addition to other uses, might be introduced as a valuable additive to gasoline). Methanol can be obtained from natural gas or coal. One possible location for production might be at the southern end of an Alaskan natural gas pipeline near Anchorage or Valdez.

• Another two quads or about one million barrels per day produced from oil shale by in situ retorting methods. This is an ambitious target which can probably be reached if early priority is given to appropriate developments.

The proposed rate of oil production may well result in a great reduction of our oil reserves by the end of this century. The development of a method of producing oil from shale could compensate for the gap in oil reserves. It is necessary to push the development of oil shale beyond the pilot plant stage to moderate scale production as early as 1985....

We would thus have a total of 39 quads per year (assuming we import one quad from Canada) or about 18.4 million barrels per day of oil...by 1985, from which amount we could export in oil tankers as much as six quads per year or three million barrels per day. This capability to export oil could have a profound effect on the OPEC and may well blunt the oil weapon....

Gas. President Ford took an important step toward increasing domestic production of gas by proposing decontrolling the prices of natural gas moving interstate. If gas prices are indeed decontrolled, or if the price ceilings are raised to levels approaching the prices of petroleum products, we expect domestic production of natural gas to increase from 22.5 quads in 1973 to 28 in 1985. A considerable portion of this increase is expected to be associated with increased production of oil.

The measures needed to increase domestic gas production parallel those for increasing domestic oil production. They include new procedures for the leasing of public lands, increased production of necessary drilling equipment and appropriate incentives to drill and develop marginal gas wells that are not sufficiently profitable under present interstate price ceilings for gas.

In addition to these 28 quads, we recommend the production of two quads from in situ gasification of coal. Just as the vigorous production of oil may result in the depletion of our oil reserves justifying the accelerated development of shale oil, the danger of depleting our gas reserves through sharply stepped-up production of natural gas should be compensated by the development of in situ gasification of coal. By this technique we could exploit deep, thick coal veins which are hardly accessible or are inaccessible with present methods....

[Two quads of gas are subtracted to produce one quad of methanol, which is needed as an additive to gasoline; one quad is imported.]

The capital expenditure for producing, refining and distributing petroleum (oil and gas) is estimated to require a cumulative capital investment of $300 billion. Since practically all present oil wells and gas wells in the lower 48 states will be exhausted (or will require advanced recovery methods) by 1985, the $300 billion must be considered as the capital needed to produce domestically about 66 quads of petroleum and to construct the additional pipe-lines and refineries which will be required. To establish the production and distribution capability of one barrel per day, or its equivalent in gas, we propose to invest between $9,000 and $10,000 of capital....

Our capability to export six quads of oil per year (little less than three million barrels per day) can be established at a capital cost of about $30 billion.

Coal. It is proposed to increase coal production from 15 quads in 1973 to 33 in 1985. Coal is amply available, but mining equipment, means of transportation, capital and environmental considerations may be serious constraints.
Most of the additional coal will probably come from surface mining in the Western states. Expansion of coal production will require additional equipment (drag lines, drilling equipment, coal movers, tractors and gondola cars) as well as incentives and possibly subsidies which might cover partial costs for some items such as transportation and coal parks near utility boilers.

If the 33 quads per year anticipated for 1985, we could export nine. At present, we are exporting coal mostly for metallurgical purposes. The additional exports discussed here should help to relieve the energy shortage in other parts of the world. Many developing countries can use coal almost as easily as oil. If we appear in the world market as a seller of nine quads per year of coal as well as six quads per year of oil, we will make a profound impression. If other strengths in our economy are maintained (in the fields of high technology and food) we could have the potential to act as a stabilizing factor in the world economy for many years to come.

The capital investment (including environmental expenditures) needed for the export of nine quads of coal will be about $20 billion.

Environment, Health and Safety

The plan we are discussing is compatible with an environment which is greatly improved compared to the present situation. To accomplish this, realistic steps must be taken to improve air quality at an acceptable cost. At the same time, the oceans must be protected against oil spills and the land against abuses which are connected with mining. Finally, serious hazards, which have caused a great deal of worry, must be eliminated.

In order to satisfy the requirements of improved environment and safety, we are proposing a capital investment of $50 billion to be spent by 1985. (The major part of this amount would be spent by the private sector and would influence the price of the final product, that is, the environmental costs would be "internalized".) Approximately one half of the $50 billion would be spent in connection with the production and use of co. Funds are needed to:

- Restore land to an excellent condition after surface mining.
- Remove sulfur from coal and oil before, during or after actual combustion.
- Remove particulate material from the stack gases.

The enforcement of environmental regulations must be timed, and possibly delayed, so as to make it possible to introduce adequately demonstrated, appropriate technological improvements, such as a practical means for ensuring clean stack emissions, in order to comply with the regulations. The initial developments are, to a considerable extent, jobs which may be carried out using government funds. The larger costs associated with purchasing and installing the necessary equipment would, of course, have to be borne by industry.

[A] considerable part of the needed expenditures will have to be dedicated to cleaning up automobile emissions. Too little progress has been made in improving the engines in our automobiles to make them compatible with environmental standards or to improve fuel economy.

Novel proposals such as the stratified charge engine may bring about a great reduction in, but not an elimination of, some undesired byproducts. It might be easier to control the formation of the contaminants in steadily burning, external combustion, or "steam engines" which, instead of steam, use an appropriate organic compound as the working fluid.

Some simpler process such as mixing a little methyl alcohol and possibly water droplets with the gasoline might produce cleaner and more efficient burning in the internal combustion engine. Altogether, improvements of the automobile engine is a wide-open field.

The introduction of electric or hybrid cars (using a gasoline engine and batteries) is another possibility. Hybrid cars will be more expensive but would help considerably to decrease fuel consumption and pollution. It is particularly regrettable that in the last half-century technically oriented research was not strongly supported in the automobile industry. A change in the "life style" of the Detroit factories is overdue. The present slump may act as a badly needed incentive.

Conclusion

The proposal which we present here differs from other recent studies in two important points. One is that with respect to the international situation we have taken a positive stance of achieving not merely independence but interdependence whereby the U.S. will be in the position to make a positive contribution to the world economy. Energy self-reliance before 1985 should be considered as a necessary first step toward a more difficult eventual objective. The longer range objective is to use U.S. influence (as we did in the period following the Second World War) to
establish a viable order in the world and an economic and political climate which is compatible with our ideals, and with the aspirations of the world community....

The other difference is that we are emphasizing some technical possibilities which have not, as yet, received general acceptance. One of these is to incorporate thorium in present nuclear reactor designs to produce uranium-233 as a readily available substitute for other nuclear fuels. Used in this manner, thorium, which is much more abundant and available worldwide, can solve the nuclear fuel shortage problem without a lengthy and expensive development program. The other is the use of in situ processes which, after a relatively brief research and development effort, may well make oil from shale and gas from deep coal deposits available sooner and at much less expense either in dollars or in environmental damage than equivalent surface processes.

Past discussions of the energy problem have either been confined to completely known technologies or have emphasized the longer range technologies that are, hopefully, ideal solutions, but which, in fact, are quite uncertain both technically and economically. We stress a strong technical development program which can produce significant results before 1985 and provide the basis for further substantial progress through 2000 and beyond....

The technological revolution has two consequences. One is to bring about even closer interaction among the peoples of the globe. The world is becoming more crowded and full of danger.

The other is the opportunity to discover new resources so that we need not fight for the necessities of life.

The energy crisis is the latest event in this rapid change. If we manage to solve it there will be other — probably bigger — difficulties to solve.

But at the moment the name of the danger and of the opportunity is energy.

Key Words: coal; coal - gasification; electricity; energy - conservation; energy - consumption rate; energy - forecasting; fossil fuels; geothermal energy; independence project; methanol; natural gas; nuclear power; petroleum; power resources; shale oil.
LASERS AND LASER APPLICATIONS

LASER ISOTOPE SEPARATION OF URANIUM

U.S. capacity to produce isotopically enriched uranium for nuclear power generation is thought to be adequate to meet demands through the early 1980's. However, if additional enrichment facilities are not available then, the projected demand will sharply exceed supply. U.S. plants currently supply 12,000 tonnes of separative work per year. Based on the projected demand for electrical power, their annual output will need to be 100,000 tonnes by the turn of the century. At that time the U.S. will be spending approximately $10 million per day for uranium enrichment. Thus the economic motivation for developing less costly processes than those currently in use is very great.

LLL is investigating new enrichment processes involving laser excitation of the uranium-235 atoms in a stream of natural uranium vapor, followed by separation of the excited uranium-235 from the unexcited uranium-238 atoms. Thus far, natural uranium containing 0.7% uranium-235 has been enriched to reactor-grade uranium containing 3% uranium-235. Initial experiments have yielded 4 mg of enriched material and established the basic principles for future large-scale operations.

The commercial production of enriched uranium is presently accomplished by gaseous diffusion of uranium hexafluoride. The economics of this method are well established: 3 MeV of energy are required for each atom of uranium-235 separated (1.2 TJ/kg); in turn, each atom will produce some 200 MeV (80 TJ/kg) in fission. Isotopic separation by centrifugation is under extensive development on a pilot-plant scale; it is reported to use approximately one-tenth the energy of gaseous diffusion. However, 30-times greater energy efficiency may be possible with laser isotope separation, a process involving the selective absorption of a photon by one of the uranium isotopes.

The physical basis for laser isotope separation is quite simple. The preferred isotope in a stream of mixed isotopes can be preferentially excited by a particular wavelength of laser radiation. Thus by tuning our laser radiation to the required wavelength, we can activate the preferred isotope to an excited state and subsequently extract it by means of a chemical or physical reaction. In principle, the energy required to activate and separate a single isotope need not exceed 10 eV. When laser and process inefficiencies are included, however, the total energy required to separate a single atom may be as high as 100 keV. But this would still represent a considerable reduction in energy consumption over the gaseous diffusion process.

Energy conservation is not the only benefit expected from a successful laser process. The fractional enrichment produced by one stage of a diffusion or centrifuge plant is very small, hence many stages — thousands in fact — are required. Enrichment processes based on photon absorption could complete isotopic separation in one stage, resulting in much smaller, and therefore less expensive, plants.

The abundance of uranium-235 in natural uranium is 0.7%. Tailings from present processes contain about 0.3% uranium-235 — that is, less than 60% is removed. By completely removing the uranium-235 from the ore, which is possible in principle, laser isotope separation would also reduce the projected ore requirement for the 1980-2000 period from 2.2 to 1.3 million tonnes. During this period, the estimated production costs (including capital investments, separation costs, and purchase of uranium) are $135 billion for enrichment by either gaseous diffusion or centrifugation; laser separation shows promise of being significantly less expensive and could yield a savings of $50 to $100 billion.

To meet the projected demand for enriched uranium, major capital investments must be made in existing enrichment processes within the next decade. These processes are extremely capital intensive, requiring $3 to $4 billion to construct a plant that has an annual capacity of 9000 tonnes of separative work. Laser enrichment, however, can potentially reduce this initial capital requirement by a factor of 10. With its combination of reduced energy consumption, smaller facilities, and reduced ore consumption, laser processes can also potentially reduce the total cost of enriched uranium by a factor of two to five or more. Thus, LLL is initiating an intensive program to develop, as rapidly as possible,“Contact James I. Davis (Ext. 4211) for further information on this article.”
laser enrichment processes. The following is a brief summary of two experiments performed at LLL to clarify the basis for future large-scale laser isotope separation work.

Design Options for Laser Isotope Separation

In general, photoseparation processes consist of three distinct steps: introduction of the isotopic mixture, selective excitation, and extraction of the enriched product. Because each step can be implemented in a variety of ways and the various possibilities can be combined, a large number of potential laser processes can be envisioned. However, a survey of possible methods of laser isotope separation generally presupposes that the operation will be performed on gases rather than on condensed phases. This may not be the most desirable commercial proposition, but present knowledge and currently attainable experimental conditions apply best to gases.

Spectroscopic studies of atomic uranium vapor reveal that the electronic energy levels of uranium-235 and uranium-238 are slightly different. The difference is known as the spectroscopic isotope effect and has a magnitude of about 1 part in $10^5$. Although small, such energy-level separations are well within the resolution capabilities of present-day tunable lasers and, by selection of the correct wavelength, it is possible to produce excited uranium-235 atoms in a mixture of uranium-235 and uranium-238. These electronically excited states are not ionized, however, and will, if left alone, revert by radiative energy loss to the normally populated states within a few hundred nanoseconds. Because there are more than 1000 electronically excited states below the ionization threshold, there are obviously many transitions that can be tested for suitability as a primary excitation step.

The isotopic mixture can be introduced either as an atomic vapor or as a molecular vapor or gas. Because atomic spectra have been more thoroughly studied than molecular spectra, a process based on atomic vapor can be readily designed; however, system limitations are considerable. Raised to the temperature required to provide a high density of atoms in the vapor state, molten uranium appears to be a universal solvent; it alloys readily with refractory metals, carbon, and ceramics. We have overcome this problem by the use of special uranium-alloy vapor sources, and significant separation experiments using atomic vapor have been conducted.

Extraction of the selectively excited isotope from the system can be done by either a chemical or a physical process. Processes that use a chemical reaction are especially attractive. Unfortunately, insufficient data are available to propose a workable system. In our preliminary experiments, we have used a physical extraction process, separating ions from neutral atoms and subsequently collecting the ions on a charged plate.

We have tested the feasibility of selective photoionization separation processes in two experiments. The instrumentation used in one of these is shown in Fig. 2. A beam of uranium atoms is generated by thermal decompositions of URe$_2$ at 2100°C (in an oven at the left of the figure); it has a density of $5 \times 10^{10}$ atoms/cm$^3$. The intersection of the photon beams. The atom beam is irradiated (perpendicular to the plane of the drawing) with a dye laser tuned to excite only the uranium-235 atoms. The laser provides adequate spectral resolution to ensure monoisotopic excitation.

Radiation from a mercury arc lamp spectrally filtered by a monochromator provides the ultraviolet radiation for the second step in the photoionization process (see top left of Fig. 2). Ions are electrostatically deflected from the neutral atoms into a quadrupole mass filter.

Isotope Separation Experiments

Laser isotope separation experiments have been performed at LLL using both natural uranium and samples containing about 50% uranium-235. We have used several methods to prove the feasibility of the two-step photoseparation technique; in all experiments we observed isotopically selective photoionization.

In one experiment, the dye laser was tuned to an absorption line corresponding to a uranium-238 transition and stabilized at the absorption peak. A mass scan with the spectrometer gave the upper trace of Fig. 3, where the mass peak current corresponded (before normalization) to about $1 \times 10^9$ ions/s. In this case, no uranium-235 was detected. The second trace shows the mass scan as a function of ion current when the laser was tuned to the uranium-235 transition line and the uranium-238 line is missing. Apart from the clear illustration of isotopically selective photoionization, these two traces show a very interesting phenomenon. Despite the use of 50%-enriched uranium in this experiment, the ion current from the uranium-235 is only 15% the ion
current from the uranium-238 (after separation). This discrepancy is due to the hyperfine splitting that occurs in the particular uranium-235 absorption line. The eight major line components are separated by intervals of 0.3 to 1.5 GHz, so the 30-MHz bandwidth of the laser could be tuned to only one hyperfine component of the uranium-235 at a time. The third trace in Fig. 3 was taken with the uv light on but the laser beam blocked, to demonstrate that the production of ions was not an experimental artifact.

In Fig. 4 we show the results of similar experiments performed with a natural uranium sample. Again, the known isotope ratio of 1 to 140 was further reduced by the inability of the laser to be tuned to more than one hyperfine component in the uranium-235 absorption line.

In more recent experiments, we have enriched macroscopic quantities of natural uranium by irradiating a vapor stream of uranium with two collinear laser beams (see Fig. 5). The uranium-235 atoms were excited by the 378.1-nm output from a xenon ion laser and ionized by uv radiation from a krypton ion laser. The ions were then electrostatically separated from the neutral atoms and collected on a

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**Fig. 2.** Photoionization vacuum chamber used to demonstrate isotope separation.

**Fig. 3.** Mass analyzer output for the laser isotope separation experiments on uranium enriched to 90% uranium-235.
beryllium plate. In about 2 h we collected a 4-mg sample, which was enriched to reactor-grade quality — about 3% uranium-235.

Commercial Potential

These recent experimental results are proving valuable in assessing the commercial feasibility of laser isotope separation for uranium enrichment. With the collection of macroscopic quantities of laser-enriched uranium, a number of the problems basic to large-scale processes, such as the production and excitation of high-temperature uranium vapor, are being attacked. Nevertheless, many unknowns must be addressed before commercial application is in sight.

It may prove that the most attractive commercial system will involve the use of molecular, rather than atomic, vapor. However the experiments described above are believed to be the only ones that have produced weiglable quantities of enriched uranium.

Before the viability of molecular processes can be tested, the complexity of the chemistry and spectroscopy of uranium demands that much experimental and theoretical work be completed. Commercial-scale exploitation of laser enrichment techniques also requires lasers of much higher power than present state-of-the-art devices. Intensive research is continuing at LLL, where the experiments described here were performed as a first step in the evaluation of the commercial potential of laser isotope separation.

Key Words: isotope separation; lasers – applications; lasers – excitation; uranium isotopes U-235 – separation.
In recent months the nuclear counterforce work of Kosta Tsipis of the Stockholm International Peace Research Institute and the Massachusetts Institute of Technology has gained wide circulation. His arguments are grounded on comparing, for the Soviet Union and the U.S., the lethality (or $K$ factor), rather than numbers of missiles or throw weight. The latter parameters, he claims, are irrelevant to a counterforce capability against ICBM silos, whereas $K$, which is a function of yield and accuracy, is a valid measure of potential counterforce performance. Using $K$ factors, he reaches a number of conclusions indicating that the U.S. has and will continue to have counterforce superiority over the U.S.S.R.

We have analyzed the counterforce situation also using $K$ factors, but taking into account several parameters and arguments not included by Dr. Tsipis. Although some of the conclusions of our analysis agree with his, there are significant differences. In particular, we find that by 1985 the Soviet Union could equal the U.S. in counterforce lethality and could have a first-strike countersilo capability.

A number of articles have appeared recently on the nuclear counterforce work of Kosta Tsipis. Among his arguments, which are based on a comparison of the lethality of Soviet and U.S. missiles, Tsipis concludes that, while neither side has a first-strike counterforce capability at present, the U.S. missile arsenal is tangibly superior. He further contends that implementing Secretary Schlesinger's proposed program to upgrade present ballistic missile systems will enable the U.S. to threaten Soviet sites with assured destruction: this superiority, he claims, would seriously jeopardize future arms-limitation agreements between the two countries. In our analysis of the counterforce situation, we have taken into account several factors not included by Tsipis, and thus some of our conclusions differ from his.

The probability that a silo containing an ICBM will survive an attack is a function of a number of parameters. For our counterforce analysis, we included the yield of the incoming warhead, the accuracy with which it can be delivered, the hardness (resistance to damage by overpressure) of the silo under attack, the reliability of the incoming missile and reentry vehicle, and (for an attack with more than one reentry vehicle per silo) the probability that the detonation of the first warhead will destroy those following (fraticide).

The yield ($Y$) and accuracy of the attacking warhead can be combined into a single variable called the lethality or $K$ factor:

$$K = \frac{Y^{2/3}}{\text{CEP}^2}$$

where the accuracy is expressed in terms of circular error probable (CEP), which is the radius of that circle within which half the reentry vehicles fired at the target would be expected to land. The lethality, and consequently the kill probability, increase much more rapidly with improvement in accuracy (decrease in CEP) than with an increase in yield.

In examining Tsipis's analysis of Soviet-U.S. nuclear counterforce, we have found that he interchanges CEP and $\sigma$, another measure of accuracy, making his kill probabilities smaller than given by the correct calculations. Also, although he recognizes the importance of considering reliability and fratricide in a countersilo attack, Tsipis does not include these parameters in arriving at his countersilo lethality numbers. They are incorporated in our calculations, however.

Table 2 gives Tsipis's estimates of today's U.S. and Soviet ICBM characteristics and silo hardness levels. Using these numbers, we computed a series of draw-down curves, which are plots of the forces surviving an attack as a function of the forces remaining to the attacker.

Figure 6 gives the draw-down curves for a U.S. first strike, using Tsipis's force structure (Table 2) and choosing the reliability to be 85% (0.85 probability that the reentry vehicle arrives at the target and detonates there). The curves show, given these assumptions, that the U.S. does not have a first-strike capability, a conclusion Tsipis also reaches. More than 400 Soviet missiles would remain after an attack using all our ICBM's, even with no fratricide.
Table 2. Estimated U.S. and U.S.S.R. ICBM and silo characteristics, taken from Tsipis.^{3}

<table>
<thead>
<tr>
<th>Missile</th>
<th>Yield, TJ (Mt)</th>
<th>CEP, km (naut. mi.)</th>
<th>No. of RV's</th>
<th>No. of missiles</th>
<th>No. of silos</th>
<th>Silo hardness, GPa (psi)^{a}</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minuteman III</td>
<td>700 (0.16)</td>
<td>0.4 (0.2)</td>
<td>3</td>
<td>550</td>
<td>550</td>
<td>7 (1000)</td>
</tr>
<tr>
<td>Minuteman II</td>
<td>4200 (1)</td>
<td>0.6 (0.3)</td>
<td>1</td>
<td>450</td>
<td>450</td>
<td>2 (300)</td>
</tr>
<tr>
<td>Titan</td>
<td>12 000 (5)</td>
<td>0.9 (0.5)</td>
<td>1</td>
<td>54</td>
<td>54</td>
<td>2 (300)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1054</td>
</tr>
<tr>
<td>Soviet Union</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS-9</td>
<td>84 090 (20)</td>
<td>1.8 (1)</td>
<td>1</td>
<td>289</td>
<td>289</td>
<td>2 (300)</td>
</tr>
<tr>
<td>SS-11</td>
<td>4 000 (1)</td>
<td>1.8 (1)</td>
<td>1</td>
<td>970</td>
<td>970</td>
<td>0.7 (100)</td>
</tr>
<tr>
<td>SS-7</td>
<td>21 000 (5)</td>
<td>2.8 (1.5)</td>
<td>1</td>
<td>209</td>
<td>209</td>
<td>0.7 (100)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td>1467</td>
</tr>
</tbody>
</table>

^{a}Hardness overpressure required to kill the target.
^{b}Estimated (by Tsipis).
Figure 7 shows draw-down curves for a U.S. first strike in 1985, assuming that Secretary Schlesinger's Program I is adopted and that the Soviets upgrade their silos. (According to Tsipis, Program I involves doubling the yield of the Minuteman III and submarine-launched ballistic-missile warheads and improving the CEP of the Minuteman III, Poseidon, and Trident reentry vehicles.) Contrary to the conclusions of Tsipis, here again more than 300 Soviet silos would be expected to survive attack; however the exchange ratio\(^4\) is about 2.0.

Figures 8 and 9 show Soviet countersilo capabilities today. Figure 8 is a draw-down curve of a U.S.S.R. first strike against U.S. silos. Obviously the Soviets do not have a first-strike capability. Because the values

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**Figure 8.** Draw-down curve for a Soviet first strike today, assuming the missile and silo characteristics given in Table 2 and a reliability of 0.75.

**Figure 9.** Number of U.S. silos surviving a Soviet first strike as a function of the CEP of Soviet missiles, using the missile and silo characteristics (except CEP) given in Table 2 and a reliability of 0.75. The solid curve assumes that the Soviet SS-9 missiles are used against the U.S. 7-GPa (1000-psi) silos, while the SS-11's are used against the remaining silos; the dashed curve assumes that the SS-9's are used against the 2-GPa (300-psi) silos, with the SS-11's against the remaining ones. The Soviets would have more than 400 missiles remaining after such a one-wave attack.

**Figure 10.** Number of U.S. silos surviving a Soviet first strike as a function of the CEP of Soviet missiles, assuming that the Soviet arsenal has been MIRVed according to the estimates of Tsipis.\(^3\) He assumes that the present SS-9's would be replaced with SS-18's, each with five 4200-TJ (1-Mt) warheads, and the present SS-11's would be replaced with SS-17's, each with six 800-TJ (0.2-Mt) warheads. The SS-18's would be targeted at the U.S. 7-GPa (1000-psi) silos: the SS-17's against the 2-GPa (300-psi) silos. The reliability is taken to be 0.75. After a one-wave attack about 1300 Soviet missiles would remain; after a two-wave attack about 1000 would remain.
Fig. 11. Lethality ($K$ factor) for the U.S. and the U.S.S.R. in 1985 as a function of missile accuracy for an attack in which one warhead is detonated at each silo. The U.S. curve assumes that Minuteman III yield has been improved according to Program I (see Fig. 7 caption) and that the Soviets have 1500 silos. The U.S.S.R. curve assumes that SS-18's carrying 4200-TJ (1-Mt) warheads are attacking 1054 U.S. silos. The two points show the $K$ factors corresponding to Tsipis's estimate of 1985 CEP for each country.
for Soviet CEP are estimates and lethality is such a strong function of CEP, we include a plot (Fig. 9) of surviving U.S. silos as a function of Soviet CEP. This plot also shows that a one-wave attack js not potent enough to be a successful first strike except in the unlikely case that today's Soviet CEP is less than 0.3 km (0.15 naut. mi.).

Figure 10, however, shows the results of one- and two-wave attacks by a Soviet force that has been MIRVed according to Tsipis's estimates, except that we show CEP as an independent variable. This figure shows that, if the Soviets also improve their missile accuracy to 0.3 km, then they could have a first-strike capability by 1985.

Tsipis contends that, if the U.S.S.R replaces its SS-9's and SS-11's with MIRVed missiles and improves their accuracy to the greatest extent he conceives possible, the U.S. will still have counterforce superiority: this conclusion, however, is based on a comparison of total lethality. We believe that comparing the total lethality needed to destroy the silos on one side (with a given probability) with the total lethality the other side possesses is meaningless. To have a first-strike capability against another country's silos, a country needs to have weapons with sufficient yield and accuracy to destroy a silo with a single re-entry vehicle or else be able to solve the problem of fratricide. Until the fratricide problem is solved, only the lethality of one (reliable) wave is relevant (i.e., the sum of the K factors of each RV for a one-detoxated-RV-per-target attack); summing the K factors of subsequent RV's aimed at already attacked silos is superfluous.

Figure 11 shows the 1985 lethality of the U.S. and the U.S.S.R. as a function of CEP for an attack in which one warhead is detonated at each target. As shown, the U.S. may not be ahead of the Soviets in meaningful lethality by 1985. If parity is a prerequisite for strategic arms-limitation agreements, as Tsipis states, then now and 1985 would seem to be propitious times to reach such accords.

CEP is the most important parameter in determining kill probability. Most of Tsipis's conclusions depend very strongly on his assumptions of Soviet CEP. His conclusions about the relative strengths of U.S. and U.S.S.R. ICBM's could be reversed if Soviet and U.S. accuracy is approximately equal. The very tenuous nature of our knowledge of Soviet ICBM accuracy, and the great importance of this factor, should be kept in mind when attempting to determine Soviet counterforce capability.

Key Words: arms control; ICBM (Intercontinental Ballistic Missiles); kill probabilities; Minuteman; MIRV missiles – Russia; nuclear warfare; nuclear weapons – destruction; nuclear weapons – lethality; nuclear weapons – Russia; nuclear weapons U.S.; silos.
Understanding the behavior of rock and other earth media under impulsive loading is useful to many LLL research programs. It is pertinent to the containment of underground nuclear explosions, to seismic evasion analysis (for defining an unknown source of seismicity in conjunction with a total test ban treaty), and to energy programs, such as the in situ coal gasification program, where some earth medium must be explosively fractured or rubblished to increase fluid permeability.

Since 1970, we have been engaged in three areas of research whose final goal is to develop detailed models of rock behavior. We are looking at the relationship of material properties and explosive-energy coupling, at the mechanisms of rock behavior, and at discontinuous processes such as fracturing and rubblishing. Ultimately, we will incorporate our models into computer codes that can be used to design and interpret complex experiments where rock behavior is important.

LLL studies in rock mechanics during the past five years have focused on improving the basic rock-behavior models used in our principal computer codes, SOC and TENSOR. In conjunction with the ERDA Division of Physical Research and two LLL programs, seismic evasion and in situ coal gasification, we have been involved in three areas of research. We are looking at the relationship of material properties to explosive-energy coupling in various earth media, we are trying to develop mechanistic models of rock behavior, and we are examining discontinuous processes.

Our ultimate goal is to tie all research results together into detailed constitutive models that include discontinuities and correlate existing blasting data with properties and behavior of various earth media. Such models can then be incorporated into our computer codes and used to design and interpret field and laboratory experiments involving rock mechanics.

Material Properties and Explosive-Energy Coupling

Our research into the relationship between material properties and explosive-energy coupling started in 1970. The procedure chosen was 1) to select materials exemplifying the properties believed to control coupling, 2) to determine experimentally the behavior of those materials under various types of loading and unloading, 3) to incorporate the experimental data into the computer model to develop constitutive relationships, and 4) to verify the model experimentally.

We chose 14 materials to study: Mt. Helen tuff, Wagon Wheel sandstone, and Indiana limestone — for effects associated with dry porosity; Blair dolomite, Westerly granite, Nugget sandstone, and polycrystalline salt — for material strength and failure mechanism effects; and three frozen soils (two water saturated and one 50% water saturated) to be compared with ice, water, and two nonfrozen saturated soils — for effects associated with the ice-melting phase transformation and with the two-phase system.

Contact Donald B. Larson (Ext. 3475) for further information on this article.

Research into the behavior of rocks under impulsive loading started at the Laboratory some 15 years ago, to provide information for Plowshare applications and to help define seismic sources and nuclear yields. The rock models and material descriptions used in our two principal codes for these studies, SOC and TENSOR, were developed in the early 1960's. Our continuum models evolved directly from the elastic-plastic descriptions used for metals, with some effort made to introduce such items as brittle failures and dilatation. The models include both quasi-static and dynamic data.

Our rock-behavior models have proved reasonably successful at predicting many of the gross effects associated with explosive loading (e.g., cavity or crater size and shock-wave arrival time and amplitude). However, discrepancies and inconsistencies have occurred at times, motivating a more detailed investigation into modeling earth material properties. Also, recent programs at the Laboratory, especially in the field of energy research, have necessitated more precise models for predicting the behavior of rocks. The accompanying article discusses three areas of rock mechanics research at LLL since 1970.
On each of these materials we performed quasi-static compression tests, quasi-static triaxial tests to obtain deviatoric stress, and acoustic velocity measurements to obtain elastic moduli. We also tested the materials in high-strain-rate gas gun experiments; each substance was loaded and unloaded in uniaxial strain, with particle-velocity time histories recorded at two to four locations in each sample. The quasi-static and acoustic data provided initial input and were incorporated into the existing constitutive model in SOC. The SOC model was then revised until the calculated and experimental profiles for the gas-gun experiments matched. Figure 12 shows the effect of such adjustments. The improved match in Fig. 12b is the result of adding a strain-rate term to the comparison in Fig. 12a.

To verify the new constitutive model, a spherical high explosive was detonated in a 0.3-m-cube rock. Both the particle-velocity and stress time histories were measured at various radial distances from the source. Figure 13 compares experimental and calculated curves; in all cases the profiles are in good agreement.

The details of the relationship between material properties and explosive-energy coupling are not yet complete because we are still developing constitutive models for the 14 materials. However, a number of preliminary conclusions can be drawn from the data from these experiments. They suggest that porosity and material strength, especially the cementing of the matrix, are closely tied in determining the effective elastic radius for a spherical energy source. They suggest that two-phase interactions play an important role in attenuating peak values and in determining the shape of wave profiles. They further suggest that phase-transformation, microcrack, and grain-boundary effects are important in determining wave shape.

When our constitutive models are completed, we will use them to compare relative coupling efficiencies and to provide a relationship between coupling and material properties. This relationship should then allow us to predict coupling for nuclear experiments when the properties of the surrounding medium are known.

Mechanistic Models

For a better understanding of the mechanisms involved in our explosive-energy-coupling work, we plan to model rock behavior on a grain-size level and to verify the models experimentally. Because natural rocks are so heterogeneous, we will use well-characterized ceramic synthetic rocks for modeling.
At present, we are describing dry porous materials by two methods: first, with existing models for the collapse of microcracks and pores, and second, by developing a model that includes anisotropic response. We will then relate these two descriptions and include the effects of water. We have also started modeling phase transformations under dynamic conditions. This model will be applied first to the 14 materials used in our explosive-energy-coupling studies and later to more general problems of geophysics.

Experimental samples of two types of ceramic synthetic rocks are being fabricated and characterized. Kaolinite was chosen to simulate a weak, porous rock and alumina to simulate a strong, less porous rock. As part of the characterization, optical and electron microscopy are being used to measure the distribution and size of microcracks and pores and to give details of the grains and their cementing.

The final step in this research will be to extend the modeling to larger inhomogeneities that exist in the earth, using statistical theory.

**Discontinuous Processes**

Beyond improving our continuum models, we are also interested in modeling discontinuous processes because some of the LLL energy programs involve fracturing and rubblist, which are discontinuous. To characterize fracturing and rubblist, we presently use SOC and TENSOR to calculate failure-associated distortional strain, which is the cumulative failure strain from all failures. Previous results suggest that this parameter is related to the extent and degree of failure damage. In the Hard Hat nuclear event of 1962, we found that the observed limit of intense fracture corresponded to a failure strain of about 10%, with the limit of microscopically detectable fracture corresponding to a failure strain of about 1%.

To test the validity of these relationships and to define further the extent and distribution of fracturing, we participated in two series of experiments for the in situ coal gasification program at the Laboratory. In one set of experiments, relatively small cylindrical

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**Fig. 13.** Comparison of experimental and calculated stress and particle-velocity time histories in a 0.3-m-cube rock. The stress profiles are shown in the upper portion. The particle-velocity profiles in the lower portion are for different values of $R/R_0$, where $R$ is the initial position of the gage and $R_0$ is the radius of the spherical high explosive.
Fig. 14. Effects around the detonated explosive in a block experiment. The irregular white area is epoxy that was poured into the postshot explosive cavity. The more regular white area is a postshot hole used to measure permeability. Its diameter is the same as that of the preshot explosive cavity. The circles indicate the calculated cavity and various calculated levels of failure strain. The calculated region of 1% failure strain marks the approximate limit of observed fracturing.

Charges were detonated in coal blocks from 1 to 1.5 m in diameter. In the other, a cylindrical explosive was detonated in a 27-m-thick coal seam at Kemmerer, Wyoming. In both cases, the observed region of fracturing corresponded well to the calculated region of 1% failure strain. Figure 14, a photograph of one of the block experiments, illustrates this agreement.

A calculational and experimental program is now under way to investigate the usefulness of the relationship for multiple-shot interactions. We will do more block experiments this year and hope to do a series of multiple-shot experiments in a coal seam as funding becomes available.

Another experimental and theoretical effort proposed for the very near future will focus on modeling blasting against a free surface. Such research will have particular application to the rubble in situ extraction (RISE) program, where an area in a bed of oil shale is mined and the neighboring shale explosively fractured into the cavity.
Summary

Rock mechanics research in the past five years has become increasingly detailed and precise. We are trying to extend our present continuum models so that rock behavior under impulsive loading can be accurately predicted in the design of experiments. Because the mechanical properties of rocks are highly variable, a closely coupled theoretical, computational, and experimental program of research into several aspects of rock mechanics has been started. When the mechanisms of rock behavior, particularly in discontinuous processes, are well understood, the computer codes can be used to design and interpret a broader range of field experiments.

Key Words: rocks; rocks - effects of explosions; rocks - effects of nuclear explosions; rocks - failure; rocks - fracturing; rocks - nibbling; rock mechanics; soil mechanics; RISE; coal - gasification; seismic evasion analysis; SOC; TENSOR.
Notes and References

1. Copies of *Energy - A Plan for Action* can be ordered from the Commission on Critical Choices for Americans, 22 West 55th Street, New York, N.Y. 10019. The price is $2.00 per copy; checks or money orders should be made payable to The Third Century Corporation.


4. Assuming a cookie-cutter damage function (i.e., the target is destroyed if the warhead detonates within a distance $r_s$ and survives if it does not) and a circular-normal distribution of impact points centered on the target, the probability that a silo will survive, $P_s$, is $P_s = \exp\left[-\frac{1}{2} \left(r^2/a^2\right)\right]$. Tsipis incorrectly uses CEP instead of $a$. This error carries through his equations; because $\hat{a} < $ CEP, his kill probabilities are too small.

5. Tsipis does not define first strike; here we mean either (a) fewer than 250 of the attacked silos remain (there are about 200 cities of 100,000 or more population in the U.S. and in the U.S.S.R.) or (b) the exchange ratio (expected number of silos killed per booster for one wave of an attack) is improved after the first wave (i.e., for a U.S. first strike it is greater than 1.5, for a Soviet first strike it is greater than 1.5).


12. For a description of the RISE program and a summary of current research, see the June 1975 *Energy and Technology Review* (UCRL-52000-75-6), p. 6 and p. 10.