United Nations

A/CONF.35/DOC.2
3 July 1968
Original: ENGLISH

CONFERENCE OF NON-NUCLEAR-WEAPON STATES

Geneva, 1968

Item 4 (c) of the provisional agenda

THE QUESTION OF PEACEFUL EXPLOSIONS FOR THE BENEFIT OF NON-NUCLEAR-WEAPON STATES

by

Theo Ginsburg*

---

* This paper by Dr. Theo Ginsburg, Professor at the Ecole Polytechnique fédérale, Zurich, has been prepared at the request of the Secretary-General. The views and opinions expressed therein are those of the author and do not imply the expression of any opinion on the part of the Secretary-General.

GE.68-12921

CONTENTS

1. INTRODUCTION

Nuclear explosives are a cheap, compact and powerful source of energy. However, the problem arises on how to use this energy for peaceful purposes. For example, can the release of explosion energy of widely different magnitudes be controlled, considering such hazards as radiation, radioactive contamination, shock waves, and air blast?

The early motivation of atomic energy programmes in both the United States and the USSR, and especially the subsequent development of nuclear weapons, was dictated by military necessity. Already in 1946, however, increased attention had been devoted to non-military uses of this new energy source. The achievement of the first thermonuclear explosion in 1949 made it possible to reduce the radioactive emission, which is very difficult to control, and present technology permits cratering explosions with a very low degree of radioactive fallout.

In a statement at a United Nations session in 1949, Andrei Vishinsky declared that the Soviets would develop a nuclear excavation technology. As he then stated, ".... We are raising mountains; we are irrigating deserts; we are cutting through the jungle and the tundra; we are spreading life, happiness, prosperity and welfare in places wherein the human footsteps have not been seen for a thousand years." Some theoretical work was done in this field by Russian scientists in the following years, as can be ascertained from a number of publications. Also very powerful chemical explosions, up to 9,000 tons, were conducted in China for mining purposes.

In the United States the first step in the direction of non-military use of atomic energy was the establishment in 1946 of a civilian Atomic Energy Commission. Ten years later a group of scientists was formed at the Lawrence Radiation Laboratory of the University of California, Berkeley, to explore the whole range of potential engineering applications of nuclear explosives. In 1957 the Plowshare Programme was formally established by the AEC to co-ordinate all research in this field.

An extensive programme of test explosions involving either nuclear or powerful chemical explosives has been conducted under Plowshare. For this purpose the Congress of the United States has allocated some 85 million dollars. Four Plowshare Symposia were held between 1957 and 1964, one especially devoted to scientific applications. The latest selected Plowshare bibliography, dated May 1966, lists 577 articles, books, tapes and films covering the full range of technical, economic and safety aspects of this new technology. The facts discussed in this report are based mainly upon these American sources.

2. SOME CHARACTERISTICS OF NUCLEAR EXPLOSIVES

2.1 Phenomenology of nuclear explosions

There are basically two types of underground explosions currently being investigated for peaceful uses:

(a) Contained explosions: Detonated at such a depth that the force of the explosion does not rupture the surface;

(b) Cratering Explosions: Overlying material is crushed and partly thrown into the atmosphere, creating a crater.

2.11 Contained explosions

In less than one microsecond after detonation, all energy is released with temperatures of several million degrees and pressures of several millions of atmospheres. A strong shock wave moves out radially from the center of the explosion, vaporizing, melting, crushing, cracking and displacing the medium. On the average, these effects will produce approximately 70 tons of vaporized material per kiloton of yield and 350 tons of melt per kiloton.

At the time of detonation the cavity begins to grow by vaporization of the medium and continues to expand as a gas bubble through the melting stage. At this point different phenomena assume importance, depending on the depth of explosion. In a contained explosion the growth of the gas sphere ceases when the pressure within the cavity equals the lithostatic overburden pressure; the gas sphere cools down and the molten rock accumulates at the bottom of the cavity. Some 80 per cent of the radioactive elements created by the explosion becomes trapped in this congealing rock. Usually no radioactive debris reaches the atmosphere.

Minutes or hours after the explosion the roof of the cavity starts to collapse. An essentially cylindrical chimney continues to develop by subsequent collapse until the remaining rock between the top of the chimney and the ground surface can sustain the overburden pressure. If the explosion is fired at such a depth that the chimney rises to the ground surface, a so-called subsident crater is formed. In this case no throwout of material occurs.

The increased porosity and permeability of a large volume of rock material, including not only the rubble-filled chimney but also the zone of increased fracture frequency surrounding the chimney, has different industrial applications.

2.12 Cratering explosions

The first manifestation of a cratering explosion on the surface is the arrival of the shock wave, causing the upper layers of the material to spall off, and forming a dome on the surface. The rarefaction wave, which is reflected at the surface, reaches the cavity while it is still growing, thus allowing the gas within the cavity to start expanding preferentially in the upward direction. The surface is pushed upward until the dome is ruptured and the gases begin leaking into the air, throwing out rock and debris. M st of the dirt and rock falls back to earth in the vicinity of the crater, creating a lip around its rim.

The optimum depth of burial for an explosion of a given yield is that depth which results in the maximum apparent crater dimensions. If the explosion is buried shallower or deeper than the optimum, the depth and diameter of the crater will be smaller.

2.2 Fission and fusion devices

A nuclear explosive may produce its energy by two processes:

(a) the fission of uranium and plutonium;

(b) the fusion of two isotopes of hydrogen: deuterium and tritium.

While most of the radioactive by-products of a nuclear explosion come from fission, neutrons from the thermonuclear (fusion) reactions can induce activity in the materials of the assembly and the surrounding medium.

Most of the radioactivity in a thermonuclear explosion is caused by the fission device triggering the fusion reaction. By lowering the fission-to-fusion ratio or, perhaps sometime in the future by eliminating fission entirely, radioactivity can be cut to negligible levels.

2.3 Energy of nuclear explosions

The units for measuring nuclear explosive energy are the "kiloton" and the "megaton":

1 kiloton (1 kT TNT) = 10^{12} calories = 1.2 million kilowatthours

1 megaton (1 MT TNT) = 10^{15} calories = 1.2 billion kilowatthours

For comparison: The total production of the world's electric power plants corresponds to the energy of a one megaton explosion every four hours.

2.4 Costs of nuclear devices

In 1964 the American Atomic Energy Commission gave some data about the costs of nuclear devices. The AEC projects a cost of $350,000 for a nuclear explosive with 10 kT yield and $600,000 for a nuclear explosive with 2 MT yield. These costs cover nuclear material, fabrication and assembly, and arming and firing services. Not included are safety studies, site preparation, transportation and emplacement.

3. APPLICATIONS OF NUCLEAR EXPLOSIVES

The potential of peaceful applications of nuclear explosives can be divided into four main parts:

(a) Excavation;

(b) Recovery of power and isotopes from contained explosions;

(c) Industrial applications;

(d) Scientific research.

3.1 Excavation

Perhaps the most obvious and direct engineering application of nuclear explosives, and one of the most practical for realization in the near future, is that of excavation. Nuclear excavation is also the most natural extension of the conventional use of chemical high explosives. The general approach to this new technology is to employ the explosion to eject material, thereby forming a crater or a ditch. The result of a single charge would be a circular crater; whereas a row of charges fired simultaneously would result in a ditch. The crater dimensions depend upon the nature of the medium, the yield, number and spacing of charges, and the depth of burst. For example, a kiloton explosion placed 50 meters underground will produce a crater approximately 100 meters in diameter. As a first approximation larger explosions will move proportionally larger amounts of earth. Thus a megaton explosion placed 400 meters underground (and forming a crater of 1000 meters in diameter) will move a thousand times as much earth as the kiloton explosion.

For nuclear excavation technology to advance to the stage where it can be used in large construction projects, theoretical and experimental studies for predicting the effects of cratering explosions in different soils and rocks are needed.

The Soviet Union in recent years has extended the use of chemical high explosives for earth moving up to the "thousands-of-ton-range" in single blasts. Nothing however, is known about nuclear cratering experiments carried out in the USSR. In the United States, the efforts of the Plowshare scientists are directed primarily toward a better understanding of all questions concerning the peaceful applications of nuclear explosives and the development of special devices to minimize costs and radioactivity.

3.11 Soviet high explosive experiments

In 1956 the famous scientist G.I. Pokrovsky published a paper "On the Use of Nuclear Explosives for Industrial Purposes". This report, based on long years of scientific research in this field, is an analysis of the potentials of nuclear explosions for excavation and of the radioactive hazards.

In the same year the largest chemical explosions ever undertaken for peaceful uses were executed under the direction of Soviet specialists in China. Three charges of 1640 tons, 4780 tons, and 9100 tons were fired to strip overburden from underlying ore deposits in order to permit pit mining. These explosions yielded major contributions to the development of theory, pointing the way to further experimentation. To obtain more details on cratering, in 1957 the Soviets conducted a highly instrumented 1000-ton cratering explosion near Tashkent in Central Asia. This experiment proved that "the force of large-scale blasting can be utilized for the construction of canals, ditches, trenches and reservoirs".

The Soviets next concentrated on perfecting the row charge technique. In 1958 the Kolonga River in the Ural Mountains was deflected into a new bed by 30 explosions of 100 tons each, which produced overlapping craters forming a new river bed. The new canal was 1150 meters long, as wide as 100 meters at the top and 25 meters deep. About 750,000 cubic meters of earth and rock were blasted out. The shot was so cleanly executed that no finishing work was needed. Finally, in 1961, a powerful explosion in the northern Caucasus region was reported by Radio Moscow. Tens of thousands of cubic meters of dolomite - a raw material valuable in the glass industry - had been thrown out.

The experiments described here seem to be the logical kind that would be done to determine economic and technical feasibility of extending such methods to the nuclear range. So it is not astonishing that in the last chapter of the report mentioned above, Pokrovsky stated that "on the basis of the many advantages of nuclear explosives we conclude that the time is ripe to begin actual experiments in this field". It is not known, however, whether in the meantime any nuclear explosions for peaceful purposes have been performed in the USSR.

3.12 Nuclear cratering experiments in the United States of America

The Plowshare nuclear cratering experiments began in 1962 with Sedan, a 100 kiloton explosion in alluvium, and with Danny Boy, a 0.4 kiloton device exploded in basalt. In 1964, two small cratering events were completed: Dugout, a 20 ton chemical row charge in basalt; and Sulky, a 0.09 kiloton nuclear cratering experiment also in basalt. A 4 kiloton excavation experiment, Palanquin, was conducted in 1965 in hard, dry rock; and a series of high explosive cratering experiments, Pre-Gondola, were initiated in 1966 to extend cratering experience to a medium of weak, wet clay shale.

In 1965, the Atomic Energy Commission stated that it would need six or seven additional nuclear tests to determine the feasibility of nuclear excavation. Four of these tests would be cratering - two single explosions and two row-charges. Although the ratification of the limited test ban treaty in 1963 complicated the realization of the cratering experiments, the Plowshare programme has continued with meaningful excavation experiments within the territorial limits of the United States of America. It could be shown that with proper design and with sufficient distance to territorial boundaries, cratering experiments can be carried out without causing radioactive debris beyond national boundaries.

The latest of nuclear cratering experiments, Cabriolet, was conducted at the beginning of this year. It was a 2.5 kiloton explosion, and the first of four cratering experiments in the series, to determine the feasibility of using nuclear explosives to cut a canal across the American isthmus.

The first nuclear row-charge experiments, Buggy I and II, are scheduled for 1968. Buggy I will involve the simultaneous detonation of five nuclear devices, spaced 45 meters apart at a depth of 45 meters. It is expected that the resulting channel will be about 90 meters wide, 300 meters long and 25 meters deep. The experiment will provide information on the amounts of radioactivity released by a row-charge explosion. Buggy II will be performed adjacent to the Buggy I crater and will be designed to produce a second ditch to extend the one formed by the first event. A high-yield, single-charge experiment in hard rock, Schooner, is planned for 1969 or 1970.

3.13 <u>Practical applications of nuclear excavation</u>

The great advantage of nuclear excavation over conventional methods is its peculiar characteristic that the explosion not only breaks rock but also moves it a long distance in the process because of its high energy concentration. As a consequence many useful projects can be planned to put this powerful and cheap source of energy to work for the benefit of man. Some of these projects will be briefly discussed here.

3.131 Project Carryall

This is a demonstration project to show the feasibility of nuclear excavation techniques. A 3 kilometer cut through the summit of the Bristol Mountains in Southern California, about 300 kilometers east of Los Angeles, will be produced for the joint use of a double-track railroad and a highway path. This cut is planned to have a maximum depth of 100 meters and a roadway width of 100 meters. The excavation would require 22 nuclear explosives with a total yield of about 2000 kilotons, detonated at two rows of charges separated in time by about six months. Total cost of the project is estimated to be about one third less than conventional coast.

3.132 Harbours

One of the first planned Plowshare experiments, Project Chariot, was designed in 1959 to test excavation row charge techniques. The experiment envisioned the simultaneous detonation of three 20 kiloton and two 200 kiloton devices at optimum depth in order to create a little harbour in northern Alaska near Cape Thompson. This project was never carried out, but the creation of new harbours is one of the most powerful potentials of nuclear excavation technology.

It is a well-known fact that extensive coast lines such as the western coast of Africa, Australia and South America are badly undersupplied with harbours - these areas could realize great economic development with adequate harbour facilities. These coasts adjoin areas of extensive mineral resources, as well as some of the world's most fertile fishing grounds. Well-placed harbours could open these regions to development, but in some cases only nuclear explosives are powerful enough to do the required work.

3.133 A new Panama Canal

Statistics over the past years indicate that the present Panama Canal, which is designed as a lock canal, will be inadequate within the next ten years. Even today the canal is too narrow and shallow to handle big ships. Supertankers and other big vessels have to go around South America. Moreover, merely the maintenance of the locks is very costly.

In 1957, President Eisenhower directed the Panama Canal Company to study the needs for a sea-level canal and to make recommendations on construction methods and costs. The Plowshare group was invited in 1958 to participate in the study, which resulted in a 1960 report stating that a sea-level canal could not be economically justified unless nuclear excavation techniques were used.

Since 1960 studies have concentrated on the conventional conversion of the present Panama Canal to sea level, and on the routes for nuclear excavation which combine the greatest economy with remoteness from concentrations of population. The concept of the much cheaper nuclear excavation is to design buried explosive charges in such a manner that the explosions blow enough rubble out of the channel to leave it sufficiently wide and deep for navigation without any excavation by machinery. The cost saving comes from the low-unit cost of nuclear energy compared to the chemical energy, machinery and labour used in conventional excavation.

The nuclear cut for the Panamanian route would require 300 nuclear charges, ranging in individual yield from 100 kilotons to 10 megatons, with a total yield for all charges of 170 megatons. In each detonation a row of nuclear charges would be fired simultaneously to blast one of the 14 sections of the canal. These sections would be from 2 to 10 kilometers in length, depending on the depth of cut, and require 4 to 50 charges per row.

Estimated cost for the canal through Panama is $650,000,000 and the total time for surveys and construction would be about 10 years. Safety evaluations for radioactivity, air blast and ground shock lead to the conclusion that there will be a close-in region where the hazards are severe and must be handled by evacuation. Outside this region only minor damage may occur.

A final report of the Canal Study Commission is scheduled for late 1969.

The possibility of constructing sea-level canals by nuclear excavation is not confined to the Panama Canal. Two other canals which have not yet been discussed very extensively are a canal cut across the Aleutian chain and a canal constructed on the Kra Isthmus, at the neck of the Malay Peninsula. Both canals would facilitate shortening some sea routes by thousands of kilometers.

3.134 <u>Landslide dams</u>

Soviet scientists have for some years been experimenting with "direct blasting techniques", whereby dams are constructed by purposely creating landslides with chemical high explosives. By proper placement of the explosive the slide is not only triggered but is directed to form a dam of the height and the orientation desired.

A 1958 Russian paper "New Technology and Pioneering Experimentation in the Construction Industry" describes this blasting technique and proposes the construction of a dam having a height of 90 meters and a top width of 60 meters. The detonation of 8,500 tons of high explosive will result in the 500,000 cubic meters of rockfill necessary for the construction of the dam. The goal of this dam is the protection of the city of Alma-Ata from catastrophic floods. Nothing is known about the realization of this project.

Nuclear explosives could be used in two diametrically opposed ways in connexion with landslide dams. Undesirable natural slide dams might be quickly removed by breaching with nuclear explosives. Such a quick-removal technique must be utilized immediately after the formation of the dam to avoid downstream flooding. On the other hand, landslide dams can be created by direct placement of the nuclear dynamite in the canyon wall in the vicinity of the anticipated slide (as is proposed for the Soviet chemical explosives experiment).

3.2 Industrial applications

The world-wide demand for energy resources is constantly increasing, while presently known reserves of hydrocarbon fuels have been steadily declining over recent years. Many large natural gas and oil deposits cannot be recovered with present techniques because the materials are trapped in tight rock formations. Two effects of nuclear explosions which seem to offer the greatest possibility for recovering raw materials locked in such tight reservoirs are: (a) the enormous mechanical energy release that can fragmentize the rock, and (b) the physical effects such as temperature, pressure and radiation which might permit in situ chemical processes. Several American experiments to test the applicability of different techniques based on these effects for industrial purposes are planned in the near future.

3.21 Natural gas and oil stimulation

In many areas of the world natural gas and oil are found in reservoirs rock of such low permeability that hydrocarbon cannot be produced economically from a normal type well. However, the environment produced by a nuclear explosion, with its increased permeability and temperature over a region of millions of cubic meters of reservoir material, could provide a sufficient stimulation of the reservoir and permit economic recovery. The amount of exploitable oil and gas could be enormously increased if all known deposits could be utilized in this manner.

Project Gasbuggy was the first Plowshare experiment to test the feasibility of this technique. The 26 kT explosion took place on December 10, 1967, at a depth of 1,300 meters in a tight, natural gas reservoir. The primary objective of the experiment is to determine the additional amount in ultimate recovery of gas from such an explosion. Results of Gasbuggy will only be known after mid 1968.

There are two other gas stimulation experiments planned similar to Gasbuggy. The results of the proposed Dragon Trail experiment, in a different type of gas-bearing formation, could provide a basis for predicting results at still other locations. Project Rulison would require a larger yield explosion which would be detonated at a depth of 2,500 meters. Because of the greater quantity of gas, this experiment could test a potential commercial field; whereas the Gasbuggy and Dragon Trail projects are of an entirely experimental nature.

Gas stimulation might become one of the first technically and economically feasible applications of the peaceful uses of nuclear explosives. It is expected that if natural gas stimulation is successful it should follow that oil production of tight reservoirs can be increased in the same manner.

3.22 Oil shale development

Enormous quantities of oil are trapped in hard rock thousands of meters underground throughout the world. It is estimated that in the Piceance Creek Basin alone oil shale formations exist containing 320,000 million barrels of potentially recoverable oil. This would correspond to nearly the total proven oil reserves of the world. In Brazil the three best prospective sites are easily accessible near the ground level. Other vast deposits of oil shale occur in Africa, Asia and Europe.

With contained nuclear explosions the extremely tough oil shale could be fractured and then retorted in place. Two methods for this *in situ* process are proposed: (a) igniting the broken rock and moving a combustion zone through it by ejecting air by means of drill holes; or (b) injecting hot gases from an external source to increase temperatures and force the release of oil. These methods of *in situ* recovery would also eliminate the great problem of waste disposal.

An experiment is proposed to test the possible recovery of oil from rock. A 50 kT nuclear device would be detonated 1,000 meters underground in the Piceance Creek

Basin, creating a chimney of about 1.3 million tons of broken oil shale. Assuming 24 gallons of oil per ton of rock, the chimney could contain approximately 75,000 barrels of oil. After the explosion an extensive experiment will be conducted to retort the oil in the fracture zone outside the chimney, as well as within the chimney itself. The preparations for this project, Bronco, would require about five years.

The possible recovery of oil sands in Canada's Athabasca area was one of the first applications of nuclear explosives suggested to the petroleum industry. The high sulfur content of the oil makes conventional recovery uneconomical. Only if the crude oil is produced very inexpensively and in very large quantities would it be worthwhile refining it. An experiment is planned with a 10 kiloton device placed at a depth of 400 meters and about 10 meters below the oil sand zone.

3.23 Mining and leaching

The application of nuclear explosives for mining processes seems to be very attractive from the economic point of view and appears to be one of the major prospective fields for peaceful uses. The potential applicability of nuclear dynamite to underground mining is greatest in the case of large, massive regular-shaped ore bodies too deeply buried for open-pit mining. Nuclear caving may also find application in the mining of ore bodies which cannot be exploited by block caving, or of too low a grade for mining by stopping. The minimum size ore body to which nuclear caving can be economically applied will probably be at least several million tons.

The high permeability of the resultant rubble-filled chimney of a contained explosion in most competent rock will also be applicable to in situ leaching techniques. Copper, gold and other metals and minerals may be extracted from low-grade ore bodies by breaking up the rock and passing a leaching solution through the fractured ore to dissolve the metal or the mineral.

Project Sloop is a proposed experiment to investigate the use of nuclear explosions to prepare low-grade copper deposits for subsequent solution mining. The 26 kT explosion is expected to produce a chimney of broken ore containing about 5,000 tons of copper, assuming a 0.4% copper content. After the detonation, a leaching system and copper recovery plant would be installed and operate for at least one year to obtain processing and economic data.

3.24 Underground storage

The increased porosity and permeability of the rubble-filled chimney of a contained explosion permits the construction of storage facilities for liquid and gaseous material. If the detonation takes place in a thick, relatively impermeable medium, storage could be effected up to pressures somewhat in excess of hydrostatic pressure. A very important application of underground storage is water conservation (see section 3.25).

Due to the increasing use of natural gas more storage capacity is needed than can be met by existing underground storage reservoirs such as depleted natural gas fields and aquifers. Creating large underground chimneys by nuclear explosions appears to be one promising method of providing new storage capacity near the consumer end of gas transmission lines. A feasibility study which examined these ideas led to the proposal of Project Ketch. The experiment would call for the detonation of a 24 kT nuclear device at a depth of 1,000 meters in a thick, impermeable, shale formation. It is estimated that the chimney would store about 40 million cubic meters of natural gas under high pressure.

3.25 Water resources

Water is a vital resource which must be tapped like any other raw material. It differs from most non-organic sources in that on a global scale, it cannot be depleted. The problem is therefore, not lack of water but maldistribution both in time and space. Only a few places in the world receive no rainfall. But unfortunately, local rainfall often occurs all at once, punctuating long, dry periods. In such areas, unless there is a way to store rainwater quickly, the water is lost, for example, Tunisia annually receives about 33 billion cubic meters of water by rain and run off from other countries. Of this, two billions return to the sea, 30 billions evaporate, and only one billion can be used for irrigation and for replenishment of underground water.

Some potentialities of nuclear excavation technique for water regulation by the construction of earthfill dams were described in section 3.134. In addition to the control and conservation of water supplies, nuclear explosives have also been suggested for many other different purposes: to alter watersheds, inter-connect aquifers, create or eliminate connexions between surface and underground water supplies and, where evaporation is too high, create underground reservoirs, as described in section 3.24. One of the most promising suggestions is the use of nuclear explosives to connect the surface with existing potential aquifers. The most notable example of such a locked aquifer is that below the Nile and estimated storage capacity of 500 billion cubic meters, or several multiples of itself, flow annually. Many other aquifers or water basins of different sizes occur throughout the arid regions of the world, but our knowledge about their location and capacity is still very limited. If it is possible to develop a nuclear explosive technology to tap these big water reservoirs, deserts could be changed into fertile land.

3.3 Recovery of power and isotopes from contained explosions

One of the first proposals for the peaceful use of contained explosions was the capture and recovery of thermal energy deposited in a salt dome deep in the earth. In 1962 Project Gnome made it clear that this concept is technically unfeasible, because the creation of a permanent cavity cannot be realized with reliability and the heat energy of the explosion is diffusing rapidly in the permeable material surrounding the rubble column of the chimney. Consequently, different variants have been proposed to use underground explosions for the release of power; namely, by tapping geothermal heat sources of the earth, or by seawater distillation. Moreover, contained explosions permit the recovery of isotopes created by the enormous neutron flux of the detonation.

3.31 Geothermal power generation

Substantial areas of the world have underlying deposits of rock with abnormally high temperatures. In many instances the heat flow of these deposits is as much as ten times that of the normal crust; temperatures of 500°C and higher may be found at depths of some kilometers. The amount of energy stored in this hot rock is very great, so that it seems feasible to mine this heat via an underground nuclear blast.

Deeply buried high-yield nuclear explosives will produce rubble cones with quantities of heat sufficiently large to appear economically interesting. Consider a 5 megaton explosion detonated at a depth of 3,000 meters in rock where the temperature is about 500°C. The chimney will extent upward to approximately 600 meters from the surface of the earth, containing about 400 million cubic meters of fracturized rock at a mean temperature of 350°C. The total amount of available energy of the rubble cone is about five times the energy of the explosive. This heat energy can be gathered at a controlled rate by the injection of water into the top of the chimney and the recovery of the steam via a separate conduit. Approximately 10^{11} pounds of superheated steam can be produced in this way. Approximate calculations show that the rubble cone could supply energy for a 50,000 kilowatt steam plant on a steady basis for about ten years. A problem here may be the radioactive contamination of the steam. If this hazard is to be completely eliminated a less efficient two-loop heat delivery system must be used.

3.32 <u>Seawater distillation</u>

If the primary water pumped down into the rubble cone is seawater, it will be converted into steam and subsequently be distilled into pure water under very favourable thermodynamic conditions. This process can be effected without recourse to the usual, expensive multi-stage distillation. It is hoped that the porosity and permeability of the chimney will be sufficient to contain the salt remaining from the distillation process. The critical point of this project is, again, the radioactive contamination of fresh water.

3.33 <u>Hydroelectric power</u>

Development of hydroelectric power in the desert of North Africa awaits only the introduction of water from the Mediterranean Sea, less than 50 kilometers distant, into two below sea-level depressions. One is the 20,000 km^2 Quatara Depression, as much as 120 meters below sea level, in Egypt's western desert. The other is the 125,000 km^2 Chotts Depression, starting only 30 kilometers from Tunisia's coast. Studies have been made of the possibility of connecting these depressions to the sea by canals so that large hydroelectric plants could be powered by the flow of salt water to form new, shallow, inland seas. It is predicted that natural evaporation from these new seas would reduce their level rapidly enough to assure a continuous influx from the sea for many years.

3.34 <u>Isotope production</u>

The detonation of a nuclear device is accompanied by an intense neutron flux. This powerful source of neutrons can add 15 or more neutrons to a target nucleus within an instant, producing isotopes that would require decades to be produced in a reactor - if they could be produced at all. The recovery of the products of a nuclear explosion is a formidable task. The explosion must be contained to prevent loss of products to the atmosphere. In addition, the shot debris must be recovered and the products separated from it by chemical processing.

The most favourable place for isotope recovery after the explosion is a salt formation, because the solubility of salt in water allows an easy start for aqueous processing, and the relatively low melting point of salt is favourable for molten salt processing. The nuclear explosion will normally produce 500 to 1,000 tons of rubble per kiloton of energy released, so that a separation factor of 10^6 respectively 10^9 is required for the recovery of kilogram respectively gram quantities. However, chemical processes are available that will recover most of the isotopes produced, and further studies may reveal more economical and efficient processes.

A wide variety of isotopes having broad application in the field of science and medicine might be an economic product of contained nuclear explosions.

3.35 Underground retorting

The use of nuclear explosions to retort certain ores underground, producing pure chemical or useful chemical substances on a very large scale, and using the explosion energy as a heat source, is quite simple in principle. But the practical realization of such projects raises such formidable problems that no further research in this field is planned in the near future.

3.4 Scientific research

Many experiments have been performed or are planned in various branches of science to make use of the effects of nuclear explosions. Most of them concern the fields of nuclear physics and geophysics. However, chemistry, astrophysics, meteorology and other sciences also profit from the new and extensive sources of neutrons, neutrinos, plasmas, electromagnetic radiation, radioactive isotopes, shocks and heat supply resultant from nuclear explosions.

3.41 Neutron physics

Nuclear detonations supply a very intense burst of neutrons which in many ways should prove to be superior to conventional accelerators for neutron cross-section measurements. A very attractive application will consist of measurements of highly radioactive samples. Another category will contain certain partial cross-section measurements requiring a great number of neutrons.

On the occasion of the Gnome shot in 1962, a neutron-physics programme was designed to measure the energy dependance of the neutron-activation cross-section of several heavy elements and the resonance-fission characteristics of uranium-235. Due to an unexpected turn of events, not all of the desired neutron research was accomplished. But the achieved experiments gave valuable results, and many experiments are proposed for future detonations. One such experiment will be for the determination of the neutron neutron cross-section, which is very difficult to achieve by more conventional methods.

3.42 Heavy element production

Two new elements (Einsteinium and Fermium) have for the first time been isolated from the products generated by successive beta decay in the debris of the high-yield thermonuclear Mike explosion in 1952. The Par event in 1964 represented a major advance in nuclear explosive production of heavy elements. In spite of the low yield of 30 kilotons it produced a seven fold increase in neutron flux over the Mike event.

While the majority of the transuranic isotopes up to Lawrentium, which is element 103 and the last of the actinide series, have been produced by combination of reactor irradiation and heavy-ion bombardment, the breakthrough to element 104 and beyond may be accelerated by explosion experiments. Starting with element 104 quite new chemical properties are expected so that the tranplutonium chemistry will become richer and more interesting.

3.43 Seismology

The energy released in nuclear explosions is of the same order as energies released in earthquakes. As a consequence, comparison of signals from nuclear explosions with signals from earthquakes has made it possible to obtain a realistic value for the energies released in earthquakes.

Nuclear explosions exactly define the time and location of the event, while the time and location of an earthquake are diffuse. As a result, times of travel of earthquake waves can be much more accurately determined from nuclear explosions than from natural events. Furthermore, nuclear devices can be detonated near positions at which no natural earthquake faults occur, and in this manner new paths of elastic waves can be explored.

Measurements of the intensity of the elastic seismic waves and of their path would permit the settling of many unsolved problems concerning the structure of the earth. As an example, a single nuclear explosion, under favourable conditions of observation, could give an answer to the very important, and until now unsolved, question as to whether or not Antarctica is a continent.

3.44 Experiments in space

Space offers the researcher a great advantage for measuring natural events: it consists of a vacuum over limitless distances. Nuclear bursts could simulate wave behaviour associated with the interaction of dynamic and magnetic phenomena in space. A number of experiments are proposed for measuring the lifetime of neutrons, comparing light velocities at various frequencies and investigating the propagation of electromagnetic waves in strong gravitational and magnetic fields, etc.

4. SAFETY PROBLEMS

Success and failure of the new explosion technology depends upon whether or not it is possible to eliminate certain hazards connected with nuclear explosives. The principal hazards are: (a) radioactivity, (b) ground shock and (c) air blast.

4.1 Radioactive fallout in cratering explosions

Any application of nuclear energy involves the production of certain radioactive materials which could be absorbed by man. The kinds and amounts of radioactivity are dependent upon the type of the nuclear explosion (fission and fusion) and the environment in which it is detonated.

The development of clean nuclear devices would greatly enhance the application of atomic energy in the future excavation technology. Developments so far make it possible to produce explosives within a wide range of yields up to megatons with no more than a few kilotons of fission. Progress has also been made in special emplacement techniques to trap greater amounts of the radioactivity produced in cratering explosions. As an example, consider the contamination of the Sedan event in 1962. A total dose of 0.5 roentgen was measured at a point 100 kilometers from this 100 kiloton cratering explosion. In a similar test using the devices and techniques of today, scientists predict that the 0.5 roentgen limit would not extend beyond 50 kilometers from ground zero. And in the future this limit can be reduced to 20 kilometers or less. Worldwide fallout can be completely eliminated by reasonable choice of the explosion depth.

4.2 Radioactivity in contained explosions

In dolomite and silicate 95 per cent or more of the radioactive particles of a contained explosion are trapped in insoluble glasses. As for the remainder, exchange processes reduce the concentration of radioactivity in ground water to acceptable levels also within a short distance of the explosion site. For different soils further investigations are necessary.

The problem of radioactive contamination in gas and oil recovery must be solved by analysing the different test explosions planned for this purpose.

4.3 Ground shock

The effects of explosion-induced ground motion must be evaluated in planning and executing any nuclear engineering project. For some projects ground motion intensity may dictate the use of less-than-optimum yields to minimize damaging effects.

It has been speculated that nuclear explosions may trigger a natural earthquake. It is not possible to have a natural earthquake, however, without prior storage of strain energy. Scientific opinion is that it would be necessary to conduct an explosion several kilometers deep in an earthquake-susceptible area to be near a zone where the stress might be sufficient for an incipient quake to be triggered. By careful geological investigations of the explosion sites before the detonation, such events can be excluded.

4.4 Air blast from cratering explosions

Explosive devices buried at optimal depth produce only one to ten per cent of the air blast compared to surface detonations of the same yield. But atmospheric temperatures and winds may cause refractive focusing of sound and blast waves, greatly extending the normal range of damage.

Already some relatively weak blast waves have alarmed people by breaking windows, cracking plaster and creating a considerable nuisance. However, compared with radioactivity and ground shock effects, these phenomena cause only minimal problems in nuclear explosive projects.

5. ECONOMIC ASPECTS

The ultimate test of a new technology is its economic and engineering feasibility. The extent of nuclear explosive technology reaches from primitive earth-moving applications and the production of isotopes to the sophisticated opening up of resources which, though known to exist, cannot otherwise be reached. In all cases the economic consequences will be of a far-reaching nature and necessitate investigating for each special application.

Nuclear explosive applications can be divided into two categories:

(a) Projects that can be carried out cheaper and faster with nuclear explosives than with conventional methods; for example, the construction of a sea-level canal through the American Isthmus;

(b) Projects that are not feasible with conventional methods, where the costs to be incurred or the time needed would be exorbitant. In this category belongs the recovery of deeply locked oil in shales or the production of some special isotopes.

The new technology, therefore, is not only concerned with slight, marginal improvements of known procedures; it reduces the time and costs of projects by orders of magnitude. There are not many occasions in the history of technology where similarly extensive, yet discreet, steps can be taken.

It may be worth discussing some indirect benefits of nuclear explosion applications. Transcontinental canals and the construction of harbours could open new trade routes, considerably lowering transport costs and thus making many heavy industries less dependent upon their raw material bases. The creation of new water resources would also have most diverse consequences for agriculture and industry. For certain regions in the world the availability of water might bring profound modifications of economic circumstances. The development of hydroelectric power by nuclear explosives in the desert of North Africa might open vast areas of Egypt and Tunisia to commerce and precipitate human migration. Cratering applications would primarily concern developing countries where earthmoving is now done very primitively. The tremendous transition from hand operation to the immense power of nuclear explosives, bypassing an intermediary state of conventional explosives, is now possible. This is a step of such magnitude that entirely new dimensions of economic activity in these countries would have to be considered.

The number of examples of such indirect benefits provided by a developed nuclear explosive technology could be easily increased.

6. CONCLUSIONS

It is historically accepted that no new technology becoming available to man has ever been rejected. There have been time delays, and there has often been great initial opposition, occasionally of an ideological nature. Difficulties often arose not based primarily upon the new industries or activities.themselves, but because of the assumed or known, direct or indirect, side effects. However, eventually the new devices were accepted and ultimately were introduced on a large scale.

The development of nuclear explosives for peaceful purposes will bring great benefit to mankind. It offers immense promise of adding to man's knowledge of his environment and improving his well-being. More, it works for mankind as an answer to the increasing demand for energy, water, minerals, transportation links and food supply.