Industrial Applications of Nuclear Explosives and Their Relation to Engineering Geology

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I. Introduction

This is not an original paper, but summarizes the work of many investigators in widely varied fields of interest. For detailed discussions on these and many other Plowshare applications, the reader is referred to the Proceedings of the Second Plowshare Symposium of May 13-15 held in San Francisco. For a broader background, referral is also made to the documents listed in the Plowshare bibliography. Copies of individual documents as may be obtained from the agencies indicated in the bibliography. ~~well as the bibliography may be obtained from the Lawrence Radiation~~ Laboratory.

Due to the stringent requirements of time we can only touch briefly on the highlights of the various Plowshare proposals, as they pertain to engineering geology. For convenience these have been placed in four categories.

1. Earth moving
    a. Harbor
    b. Mining
2. Aquifers
3. Petroleum
    a. Oil shale
    b. Underground oil storage

4. Underground power
   a. Project Gnome
   b. Improvement of geothermal sources

II. Applications

A. Earth Moving

CHARIOT

Project Chariot is the proposed excavation of a harbor on the northwest coast of Alaska. It will be our first experiment in large scale excavation by the use of multiple nuclear charges detonated simultaneously or in close succession. Figure 1 shows the location of the proposed harbor excavation site. Although the reasons for selection of this site were based on criteria other than geological, e.g., remoteness, under direct U. S. control, and possible future economic potential, much of the preliminary investigation and support work was of a geologic nature. Figure 2 is a photograph of the Chariot site. Geologists from the USGS, Menlo Park (Kachadoorian, et al, 1958) investigated this region to gather basic geologic data and decide on a promising location. After the site was selected nearly all of the investigatory work in the summer of 1958 was geological in nature. This included:

1. On-shore surface geological mapping
2. Off-shore submarine geological studies
3. Topographic mapping of the land area
4. Hydrographic mapping of the off-shore area.

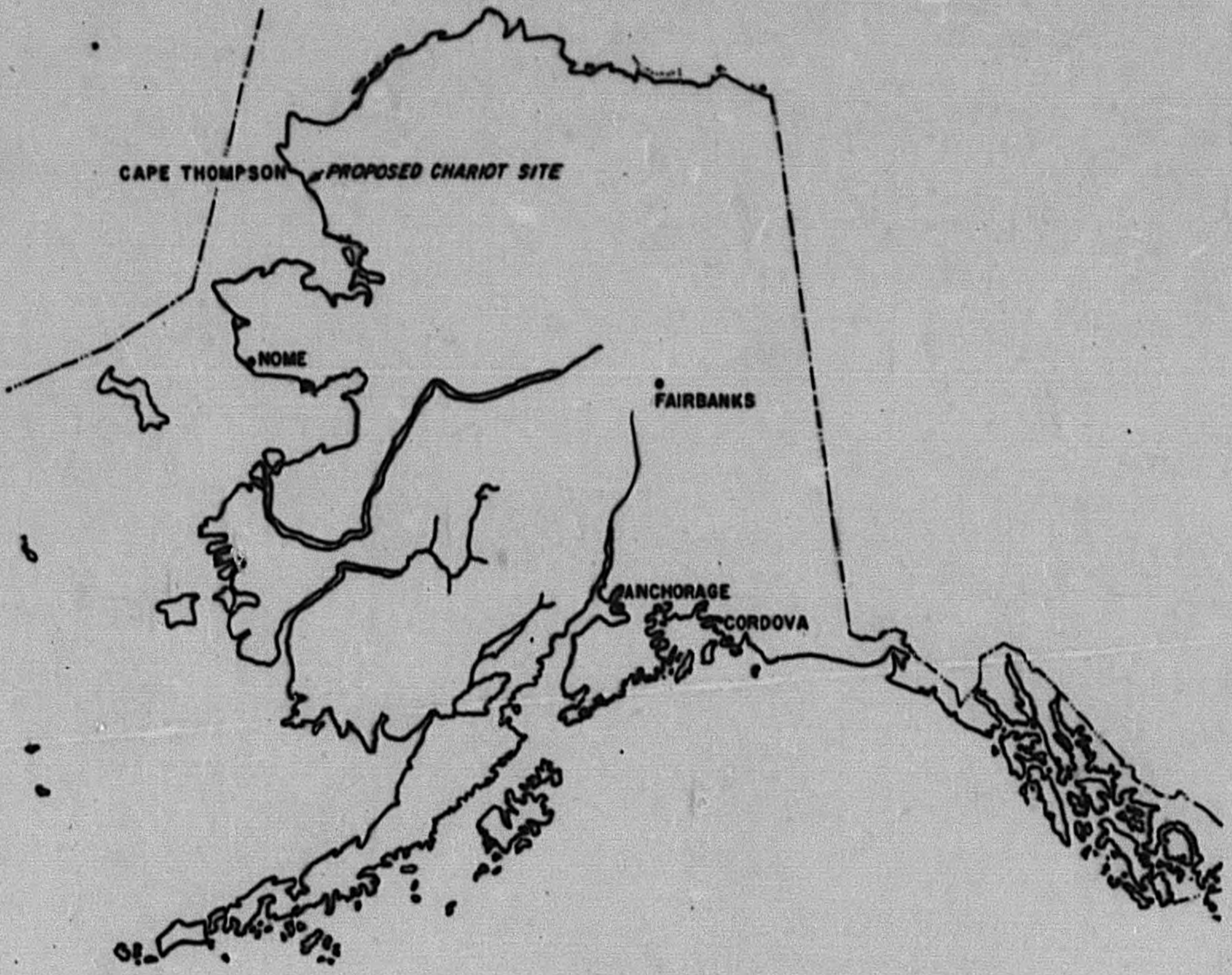

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Fig. 1. Map of the proposed harbor excavation site.

Fig. 2. Photograph of the chariot site.

The surface geological studies indicate as much as 30 feet of alluvium underlain by 500 to 1200 ft. of Jurassic mudstone, siltstone, and graywacke (highly deformed) of the Tiglukpuk formation. Underlying the Tiglukpuk is approximately 200 feet of argillite, fossiliferous limestone, chert and shale, of the Shublik formation of Triassic age. This rests conformably on top of the chert and thick-bedded green argillite of the Permian Siksikpuk fprmation. The base of the section is the Mississippian Lisburne group, a bedded limestone, which is locally cherty and slaty. The Lisburne, where exposed, is in fault contact with the overlying Permian argillite (Kachadoorian, et al, 1958).

Excavating in permafrost, or perenially frozen ground, is of interest from an engineering geology viewpoint. In particular, the two boundaries, upper and lower, are of special concern. The upper boundary is always a problem in the construction of surface structures. We originally thought that the exceeding of the lower boundary would be a problem in device emplacement, as sensitive equipment might then find itself in a wet environment. This fear was allayed in the course of drilling two holes during the summer of 1959, one to nearly 600 feet, and the other to 1172 feet. Since the drilling was entirely in strata which was found to contain not more than 2% water, the problem of the bottom of the hole flooding with water would probably not arise. It is not known if the zero degree isotherm has been reached, because the temperature in the first hole has not as yet returned to equilibrium after the warming effect of the drilling fluid (C. Bacigalupi, personal communication).

Some guesses as to the thickness of the permafrost have been made by USGS personnel. Kachadoorian (op. cit.) believes it to be 500-800 feet. Lachenbruch, in a theoretical discussion of the ocean as a heat source (1957 and 1958), shows that if the shore line has been stable long enough to allow a temperature equilibrium between land and sea to be reached, the permafrost might be aslittle as 250 feet thick near the shore. If, however, the sea has been transgressing, the permafrost will be much thicker. That is, if the heat source of the ocean has not been affecting the adjacent land long enough to allow it to absorb the full quota of heat made available by thermal diffusion from the ocean, then the coastal land will be colder than expected. The second summer's field work indicates the thicker estimate may be nearer the true case (Kachadoorian, personal communication). Evidence of an advancing shoreline was found by Kachadoorian in drowned wave-cut cliffs. But he also found beach gravels inland at elevations of 375 feet above the present level of the sea, indicating the shoreline had at least once transgressed further than its present location. The Pleistocene geology of this region presents many fascinating questions to geophysicists studying heat flow, as well as to engineering geologists.

The main problem confronting the field workers has been the sloughing of the mudstone into the hole. This has occurred due to the two factors predicted by Kachadoorian (1958) viz. the splintery nature of the bedrock, and the thawing of the permafrost by the drilling fluid. It appears that the former difficulty could be overcome as long as the material remained frozen, e.g. after several days of non-operation. But as soon as circulation of the drilling fluid was resumed, the highly fractured nature of the mudstone impaired the drilling progress. (Kachadoorian, personal communication, September 1959).

The depth from the surface to the top of the ice seems to be a function of at least three variables:

--- thermal conductivity of the rock

--- salinity and amount of interstitial water

--- warming by the sun.

In general, the permafrost will be nearer the surface in unconsolidated deposits than in bedrock areas, since the former have a lower thermal conductivity. In addition, the unconsolidated deposits are mantled by vegetation which is an excellent insulator. The depth to permafrost in unconsolidated deposits is of the order of 1 to 2 feet, whereas in bedrock areas this is about 10 feet. On the other hand in modern beach deposits and marine sediments where interstitial water is highly saline, the unfrozen water acts as a heat source, and the depth to permafrost is from 15 to 25 feet below the surface. Areas of poor drainage show a shallower depth to permafrost than those of good drainage. The effect of warming by the sun is seen in the fact that the west facing slopes have a greater depth to permafrost than similar geologic materials on other slopes (Kachadoorian,1958)

The chief problem to be considered is the closure of the harbor entrance by longshore transport of beach materials. Prior to the USGS investigation of the summer of 1958, very little data were available regarding currents, directions of prevailing winds and waves, strength of currents and general climatic conditions of the Ogotoruk Creek area. The conclusions they reached were therefore on the basis of a two summers of data collection. All of the following data are from Kachadoorian (1958, p 28-32): The heavy storms that originate with south easterly winds and which veer southwesterly, present a serious problem. Longshore transport was most active during such storms because the waves struck the beach at oblique angles with a fetch sufficient to create waves of moderate wave-length and height which actively eroded the beach and transported material along the shore predominantly in an easterly direction. At the observed transport rates, a moderate storm would carry material into the harbor entrance at a rate of about 5 cu. yds. per hour.

Phase II of Project Chariot is a continuation and expansion of studies started during Summer 1958, and is being accomplished between June and October 1959. Some information will be obtained during Winter 1959-1960. In addition to the geological, there will be biological and engineering studies and investigations bearing on the radiological and cratering effects on the rock of the nuclear explosion. Phase III could start Summer 1960 with detonation planned for approximately April 1961. The excavation will be accomplished by a nearly simultaneous detonation of 5 nuclear devices. The main bowl of the harbor will be formed by two 200-kt devices buried at an actual depth of approximately 700' and spaced approximately 775' between centers. The entrance channel will be formed by three 20-kt devices buried approximately 375' deep and spaced 408' apart. See Figure 3. Each of these devices will be emplaced in a 36" diameter cased hole, tamped with a high density, low freezing point, drilling mud. These explosives are calculated to produce a harbor with a turning basin approximately 950 yds. long and 550 yds. wide and an entrance channel approximately 600 yds. long and 250 yds. wide. It is anticipated that the cusps of the overlapping circular craters will be minimized so that the sides and bottom will be relatively smooth. Figure 4 shows the approximate

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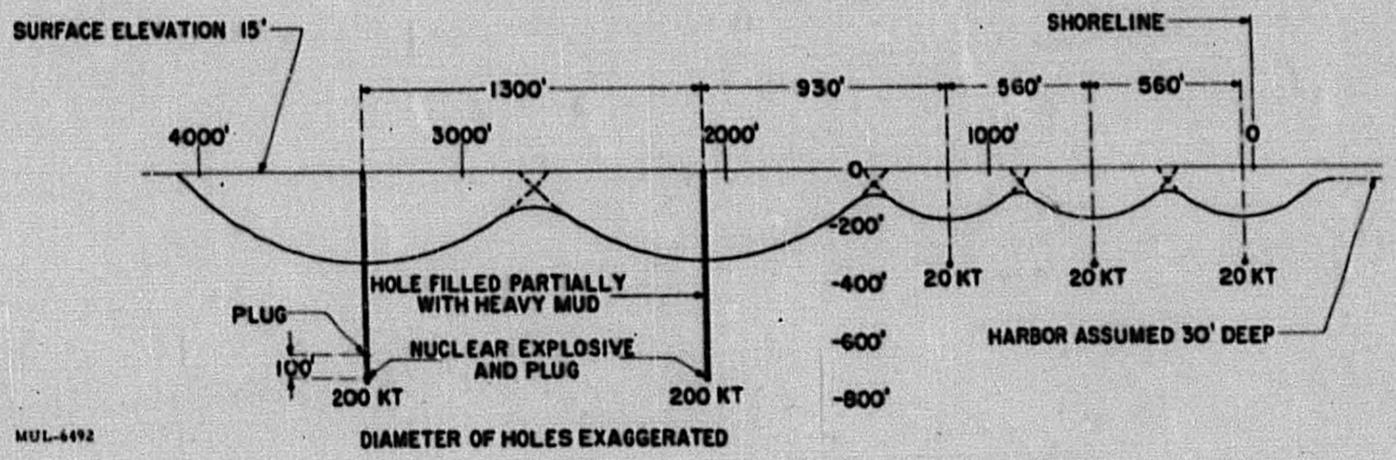
Fig. 3. Proposed chariot project showing to scale experiment.



HARBOR PROFILE

Fig. 4. Harbor profile showing approximate dimensions.

dimensions envisaged in the harbor profile. Assuming a required depth of 30 feet in the turning basin and entrance channel, then the total useful volume of the excavation will be approximately 5 million cu. yds. (Bacigalupi 1959).

It is stressed that Project Chariot is a scientific experiment and does not have to show an a priori economic justification. We hope to gain valuable data on nuclear excavation and radioactive debris containment to be applied to other areas where large volumes are required at minimum cost.

MINING

On the basis of three mining engineering studies (C. R. Adelmann, LRL; F. Smith, and T. R. Young, Colorado School of Mines Research Foundation; R. E. Smith, Sandia Corporation) it appears that nuclear explosives will become economic, or at least competitive with conventional methods when any of the following conditions are operative:

a. a very large size, low grade ore body e.g., a 50 million ton, 0.5% copper ore body (Smith and Young, 1959). This is most economic when followed by in-situ leaching. Figures 5, 6, and 7 offer a diagramatic representation of how this might work.

b. a deep-seated ore body, too expensive to mine by conventional methods. This becomes economical only if it is large enough to warrant a megaton explosion and sufficiently deeply buried to allow an explosion of that magnitude i.e., 1 megaton excavates 30 times as cheaply per unit volume as a 10 kt explosion (Adelmann, C. R., 1959).

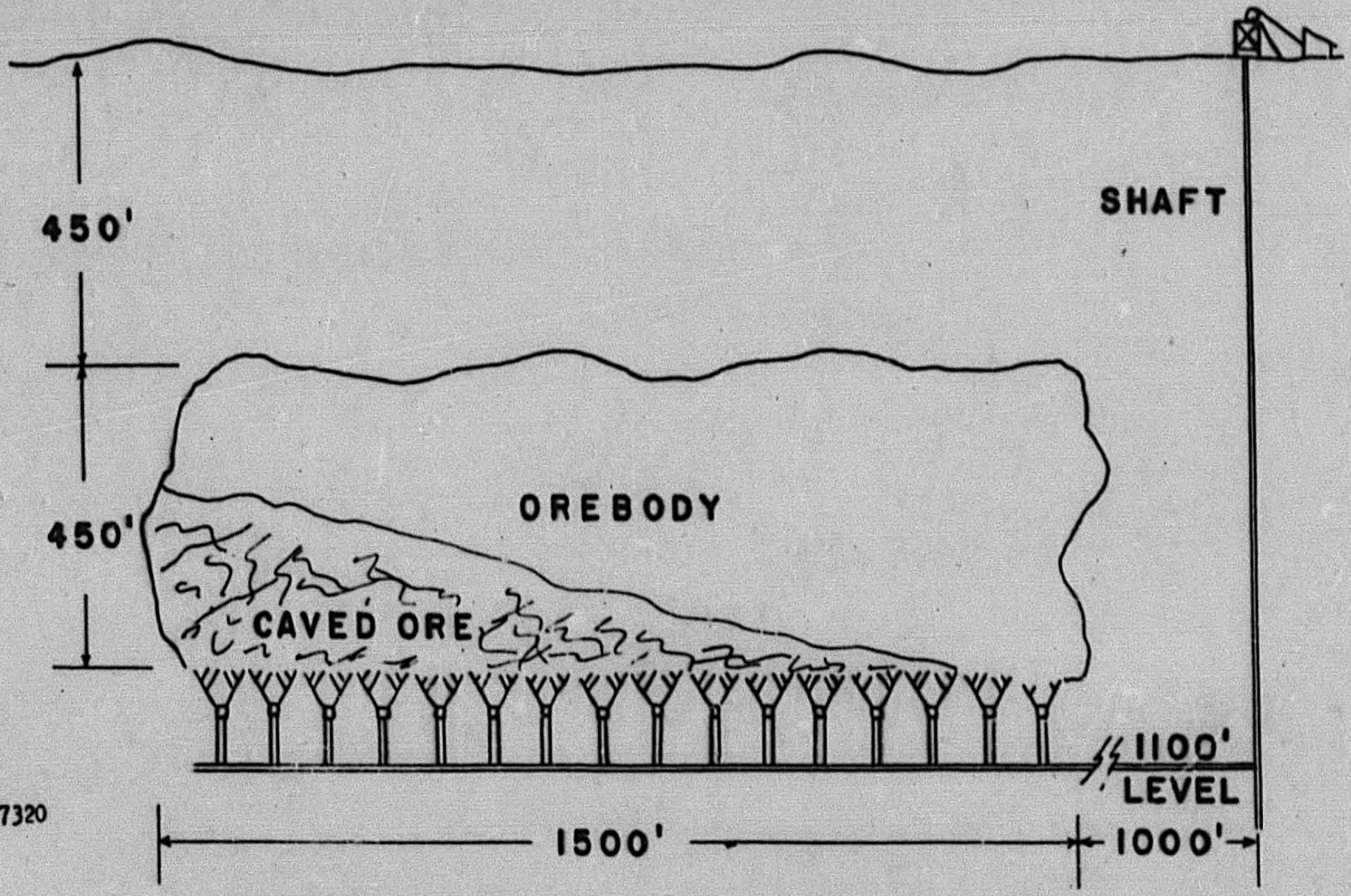


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Fig. 5. Section of ore-body which might be caved by nuclear explosives. (After Smith and Young).

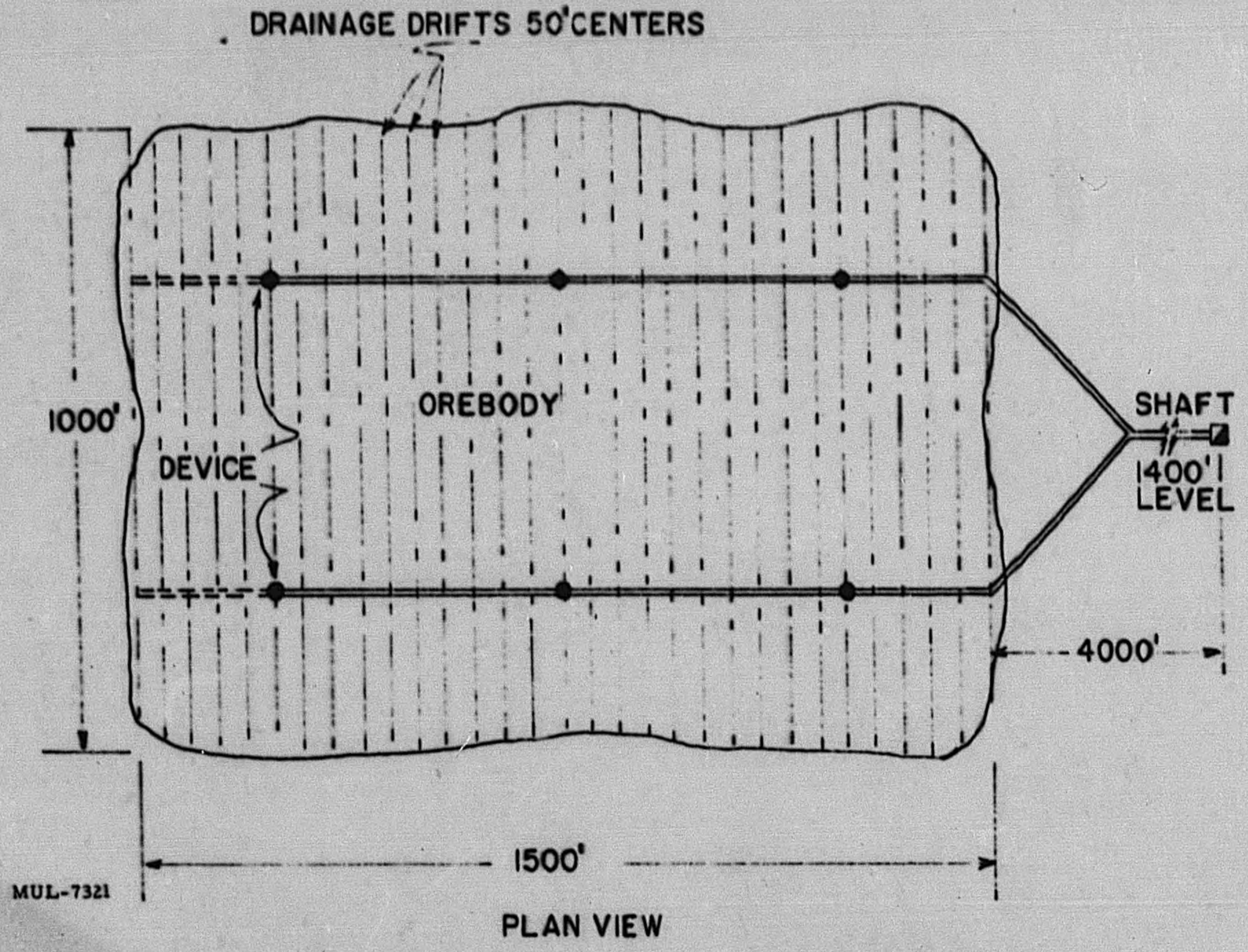

Fig. 6. Plan view of 1400' level of ore body shown in fig. 5. (After Smith and Young).

Schematic illustration of the use of NE to aid ground water problems.

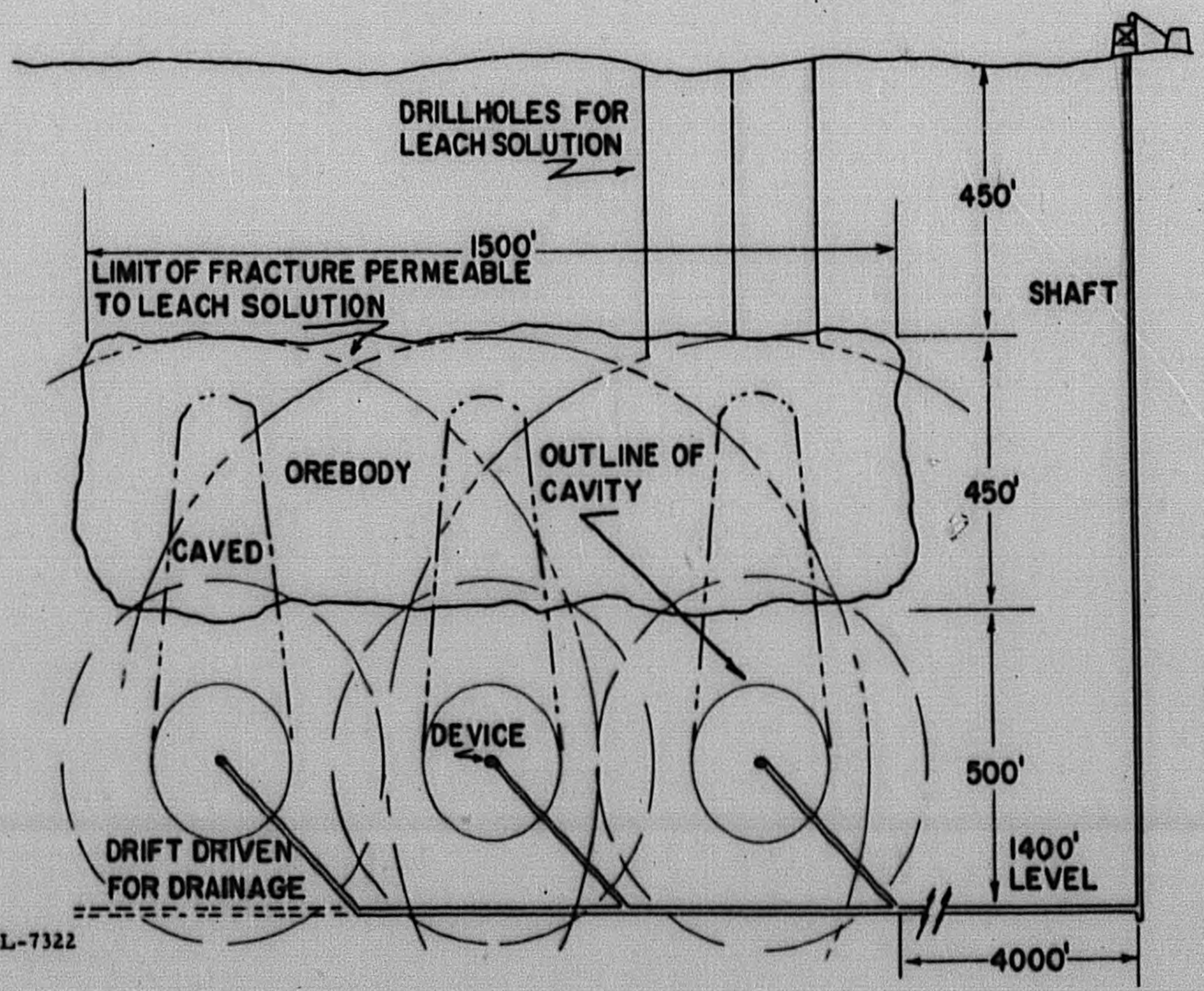

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Fig. 7. Case of permeable layer overlying impervious rock. Shows two possible solutions: a/collecting fresh water in one reservoir; b/using another reservior, closer to the sea or other area of contamination, as a pumping basin.

c. an ore body which cannot be mined by normal block caving methods (Usually a relatively inexpensive technique) due to improper caving properties of the rock, i.e., (1) the ore body will not cave, (2) the caprock does not cave with the ore, or (3) the ore caves in a non-uniform way due to structural irregularities such as faults, dikes, structurally resistant zones, partially caved-in mine workings, etc. The non-caving of caprock is a hazard for the miners, while the non-uniform caving of the ore makes mining operations both difficult and expensive (Smith, R. E., 1959). It is believed that a nuclear detonation would create a nearly homogeneous mass of crushed material by completely fracturing the close-in rock. The advantages that would this accure are the ease of handling of the ore in the transportation systems, and the reduction of crushing costs at the mill.

Several of these workers have called attention to the obvious advantage that N E has over H E in that the former has the two-fold property of eliminating overburden at the same time as shattering ore, in open-pit or quarry type mining operations.

C. R. Adelmann (op. cit.) points out that even if no other justification for NE can be found, the very rapidity with which an ore can be mined is bound to accrue a saving in interest charges and capital tie-up. He cites the Chariot project which will strip an area nearly one mile long, 1000' (average) wide, and 200' (average) deep of 15 - 20 million yards of dirt and rock in a matter of milliseconds. Time may also be the justification for NE when excavation programs must be done in a hurry due to unfavorable winter ice and snow conditions or other seasonal and climatic factors. Speaking about time, Adelmann has further suggested the possibility of speeding up geologic time by chemically initiating a secondary enrichment process in the breccia artifically formed by a nuclear explosion.

B. Aquifers

Studies have been undertaken at LRL to determine the ways in which underground water supplies can be improved with nuclear explosives (Adelmann and Zodtner, 1959). First a word as to why such a grandiose idea should have occurred at all. Two significant effects on the surrounding rocks were noted in underground nuclear detonations at the Nevada Test site: There were formed

1. an area of increased permeability, the "fractured" zone plus the collapsed material from the overlying chimney, and
2. an area of decreased permeability in the "crushed zone", close-in to the detonation point.

These lead naturally to the suggestion that some ground water problems, which are no more than permeability problems, might be solved by inducing this property in a rock by means of an underground nuclear detonation. Most of the ideas since have proposed capitalizing on the increased permeability zone rather than the decreased permeability of the crushed zone.

At the outset it must be emphasized that the hope to create any porosity on a scale large enough to have meaning in the ground-water sense, is a vain one. Anything greater than a purely local small-scale reservoir would probably not be formed with a kiloton device. What is hoped for, is to be able to create permeable channels through impervious layers which bar rainfall or natural runoff from reaching good quifers at depth.

Some of the situations which suggest the possibility of nuclear remedy are as follows:

1. The rather common situation of an impermeable clay, silt, shale, or slate overlying a permeable reservoir in an area of adequate precipitation or surface flow. A permeable conduit properly placed could salvage millions of acre feet from wasted run-off. Figure 8.
2. A water bearing stratum with adequate recharge but so low a permeability that pumping rates are undesirably low. Figure 9.
3. Off channel subsurface reservoirs in areas where surface storage space is meager, or where evaporation rates are extremely high. (In some arid areas evaporation can amount to 50% of the total volume.) Figure 10.
4. The inverse of the situation illustrated in Figure 8, i.e., a permeable stratum overlying an impervious rock, in which the ground water is lost either by underground flowage to the sea, to a poorer quality aquifer, or contaminated by salt water encroachment. In all of these instances one might blast a collecting basin in the lower impermeable rock to collect the good water and inhibit the losses outlined above. Dr. S. Davis of Stanford University (personal communication) has suggested a modification of this idea in the blasting of a reservoir near the area of contamination to be used as a pumping basin. Figure 11.

C. Petroleum

OIL SHALE

Nuclear explosives have captured the imagination of the Oil-Shale researchers, who would like to exploit the mechanical energy of the device

Schematic illustration of the use of NE to aid ground water problems.

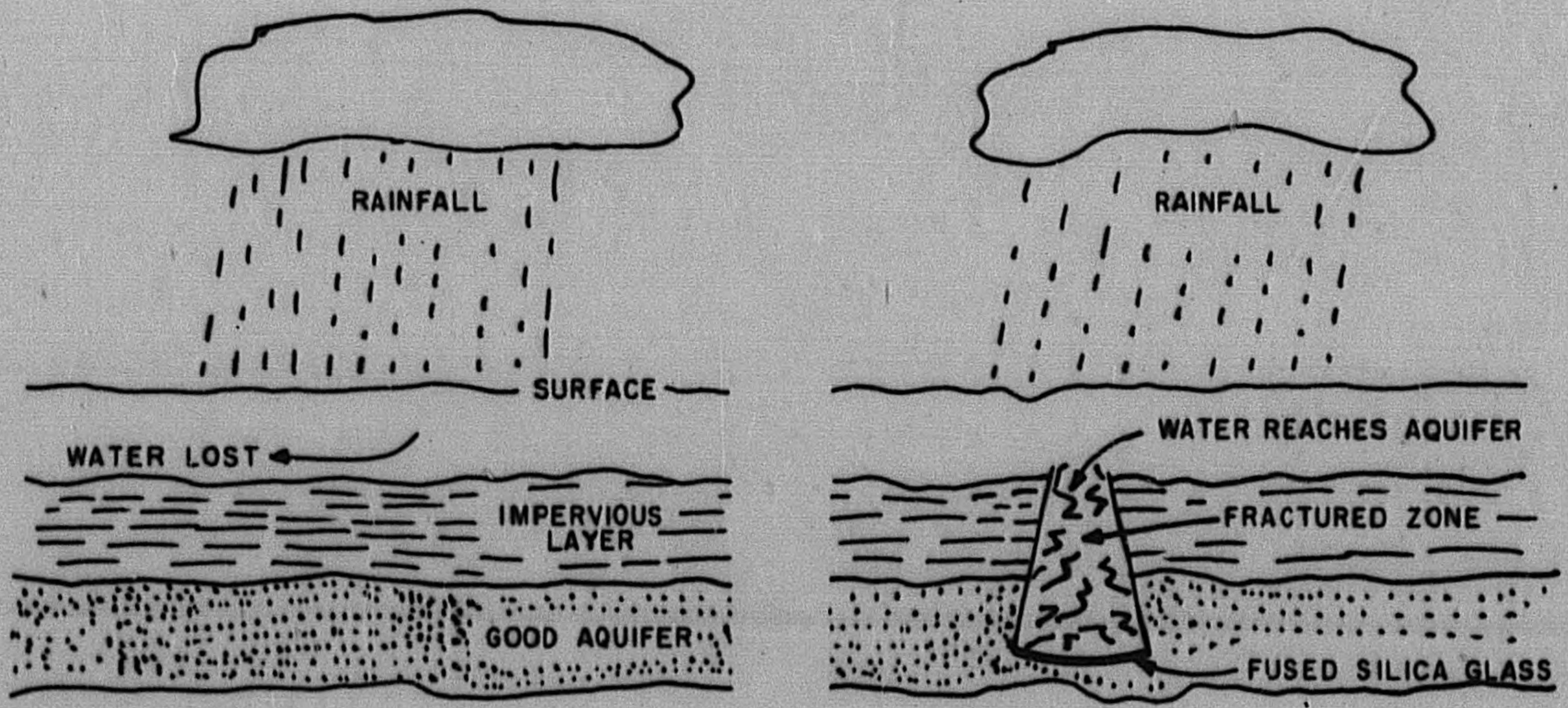

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Fig. 8. Case of impermeable strata overlying permeable rock.

Schematic illustration of the use of NE to aid ground water problems.

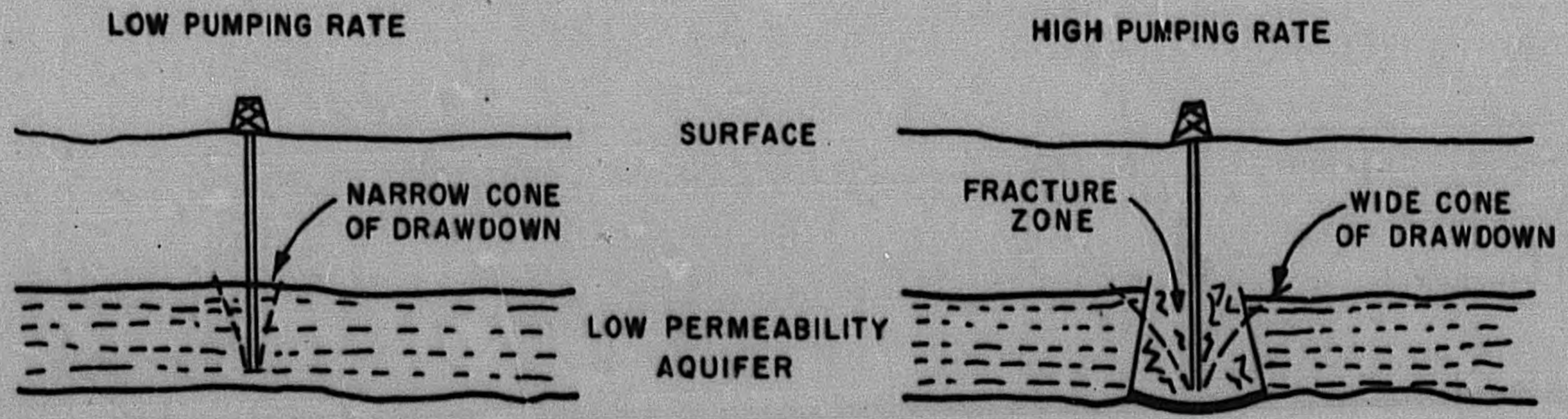

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Fig. 9. Case of water bearing strata of low pumping rate.

Schematic illustration of the use of NE to aid ground water problems.

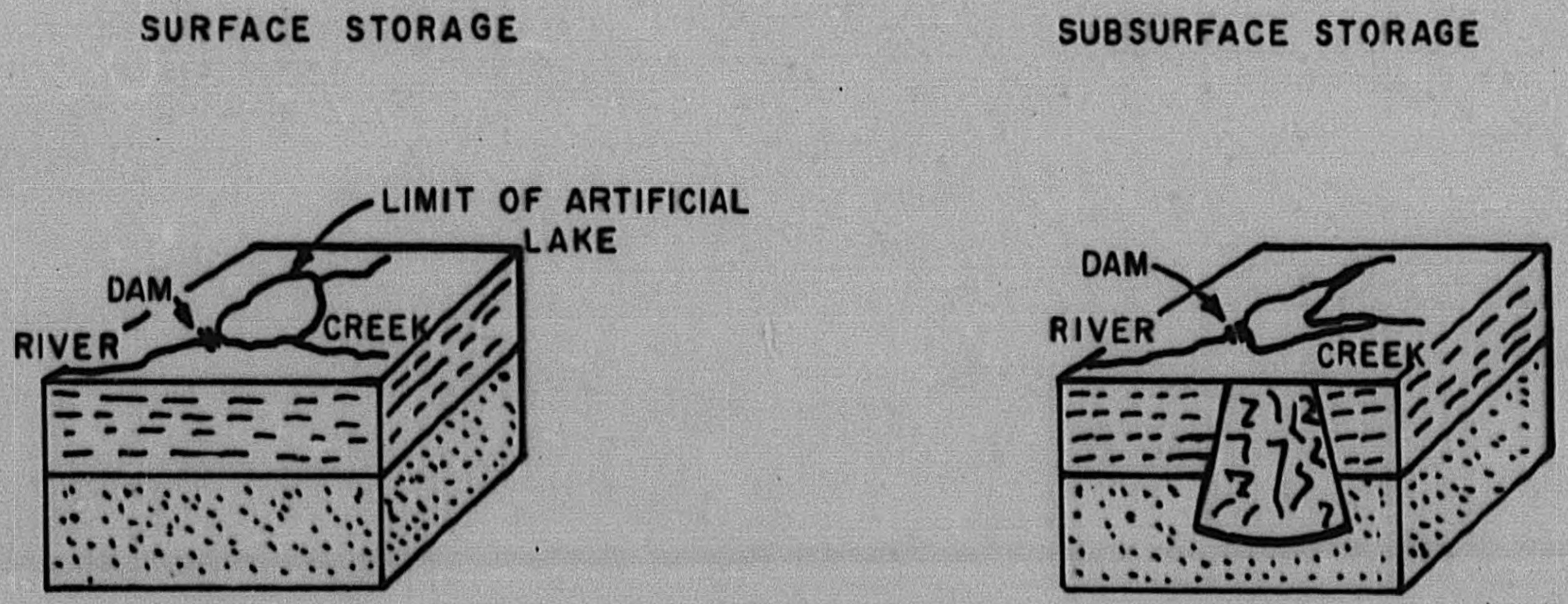

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Fig. 10. Case of off-channel storage of water in subsurface reservoir created by explosions.

Schematic illustration of the use of NE to aid ground water problems.

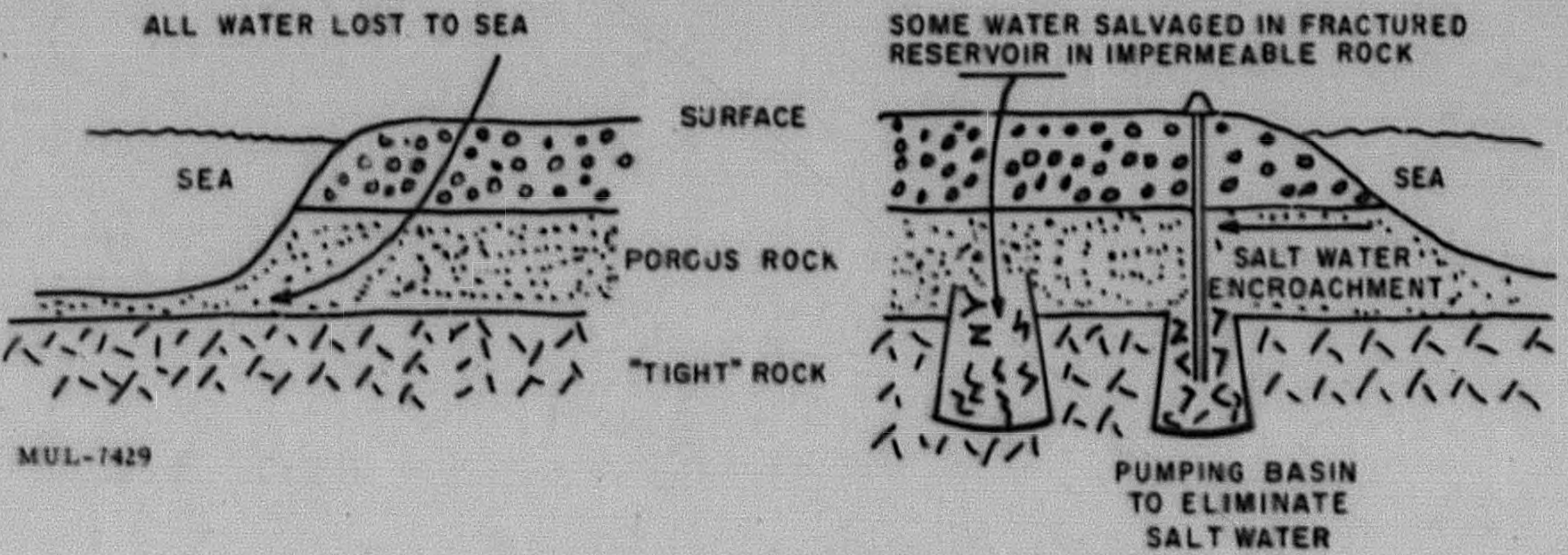

Fig. 11. Case of permeable layer overlying impervious rock. Shows two possible solutions: a/collecting fresh water in one reservoir, closer to the sea or other area of contamination, as a pumping basin.

by utilizing it for removal of overburden and large-scale break-up of ore. Prominent in this research has been Walter I. R. Murphy, the co-ordinator of the Oil Shale research at the Laramie Petroleum Research Center, Bureau of Mines, Laramie, Wyoming. They plan to utilize the heat of combustion of the residual carbon in the shale in an in-situ production of oil from the shale. (Note: The Colorado "oil-shale" is a kerogenaceous marlstone, finely laminated, consisting of dolomite, calcite, feldspar, quartz and illite clay). See Figures 12 and 13.

The following is gleaned from the work of Walter I. R. Murphy (1959). For some time, and with some degree of success, in-situ combustion projects have been conducted in various petroleum reservoirs. These latter differ from oil shale beds in two major features:

1. The nature of the organic material, liquid in one case and solid in the other, and
2. The absence of permeability in oil shale.

It is hoped that a mass permeability might be induced in the shale by the explosion and that the combustion gases, which have to pass through the pores of an oil reservoir, will be able to travel through the induced fissures and cracks in the oil shale.

As an example, there is sufficient potential oil in the Mahogany zone of the Green River Shale to permit economic in situ operation. The porosity of the mineral matrix is in the range of that of reservoirs from which petroleum has been recovered in in-situ projects. The permeability of the shale, however, is zero, since the pores of the mineral matrix are filled with solid organic matter, and the success of the project depends largly on

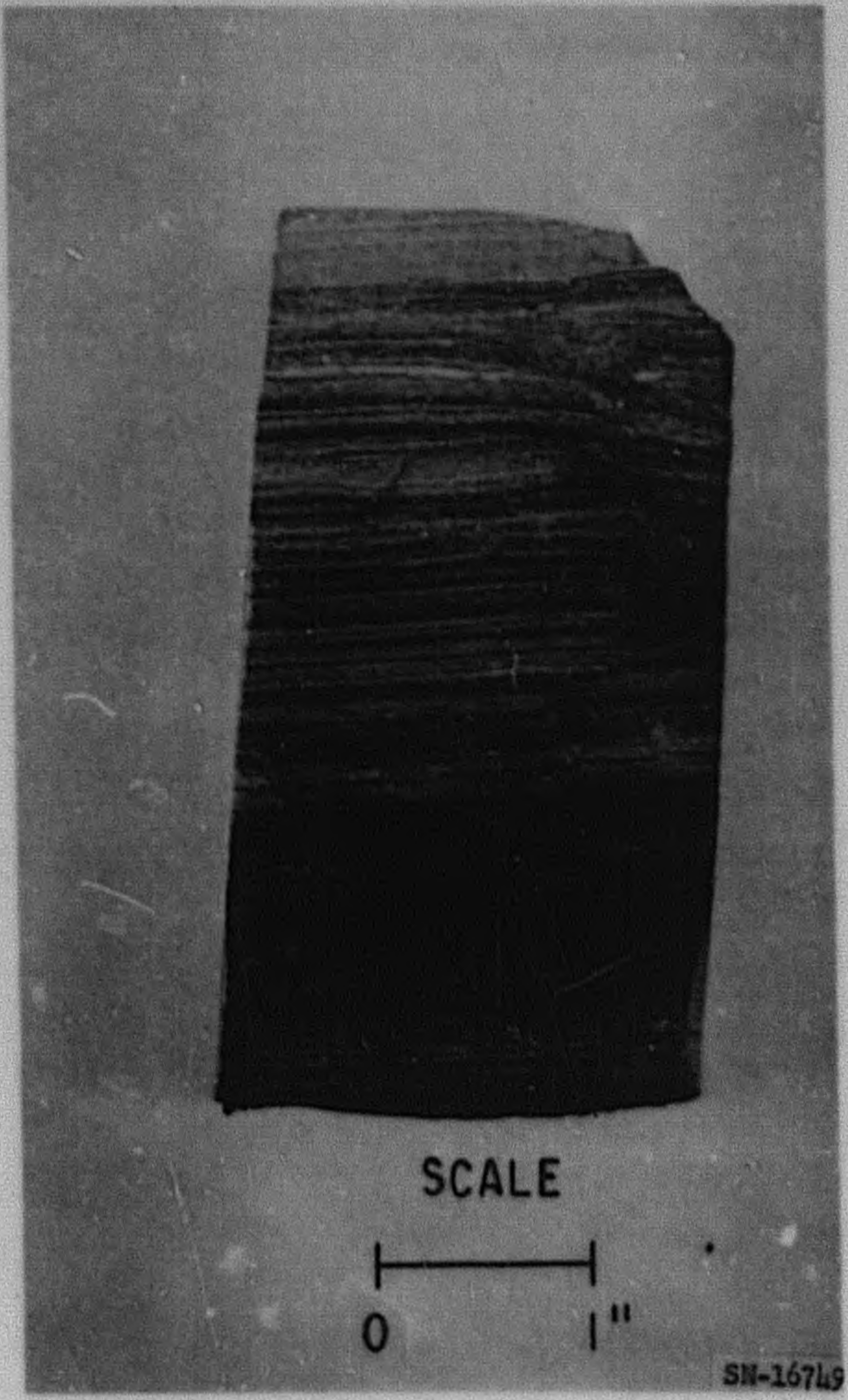

Fig. 12. Photograph of typical Colorado Oil Shale.

(After Murphy).

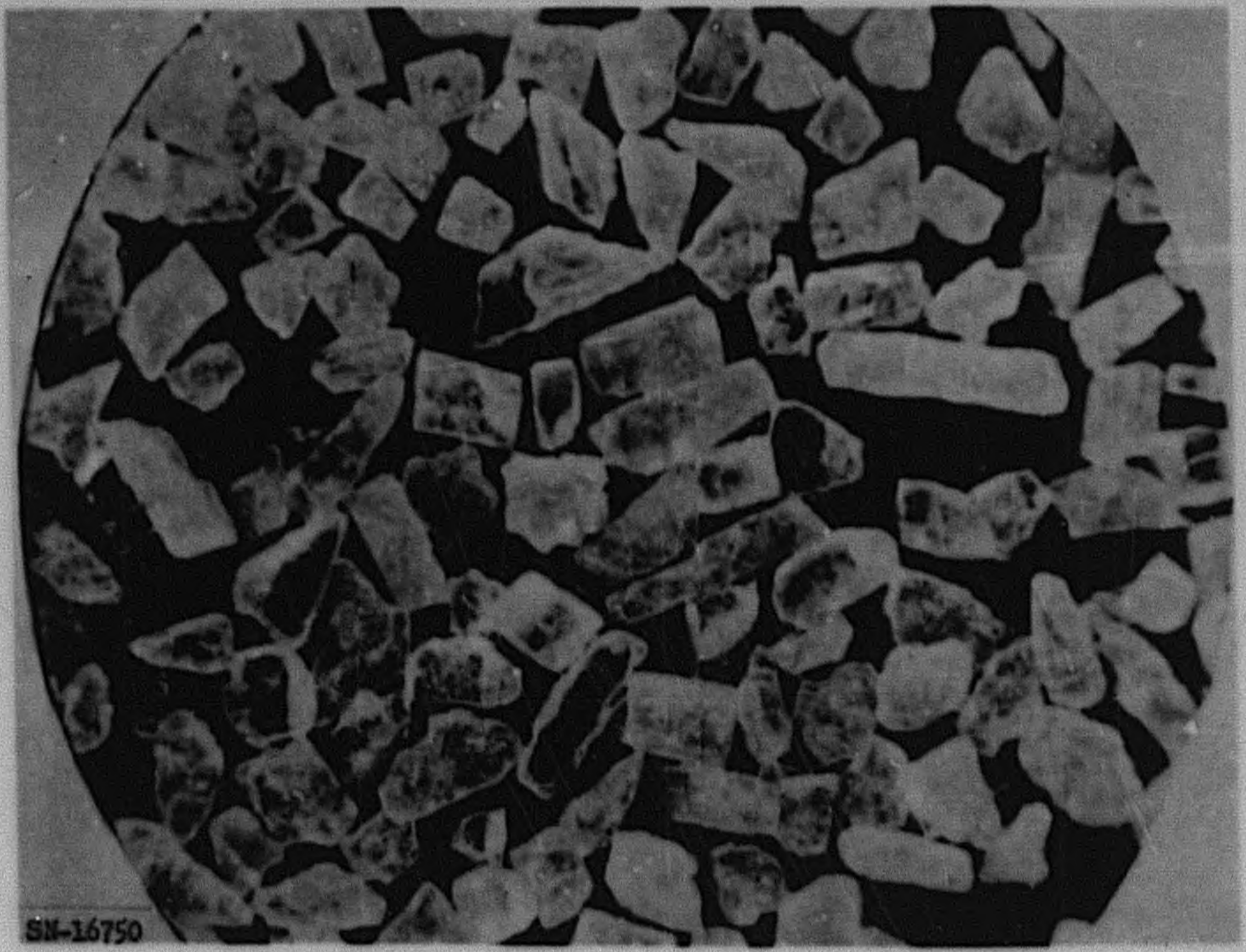

Fig. 13. Photomicrograph of the inorganic particles from the oil shale. (After Murphy).

the extent that mass permeability can be induced by the nuclear explosion.

Briefly, the in-situ combustion process for recovering petroleum involves igniting the oil in a porous reservoir rock and driving a combustion zone through the reservoir toward producing wells with compressed air, with which recycle gas is sometimes blended. Combustion produces hot gases which force the oil and water in the reservoir to producing wells (See Figure 14). As the burning front moves slowly from the air injection well to the production well, several oil displacement mechanisms are operative. Steam produced from combustion and from formation water produces a condensing steam drive ahead of the front. Heat from the steam reduces the viscosity of the oil and promotes displacement. Gaseous combustion products heat the oil and increase its mobility further by dissolving in it, allowing the remaining combustion gases to drive ahead more readily. Mild cracking produces light hydro carbons which blend with the oil to produce a miscible drive. Thermal energy is also transferred to the oil by conduction through the sand ahead of the burning front.

In an in-situ shale oil production process an additional function must be carried out. Oil must be formed by the destructive distillation of the solid organic matter. Heat for this distillation process will come from the combustion of residual carbon, gas, and if necessary, some of the oil. This conversion must be accomplished before the oil can be driven to the producing wells.

The oil that may be formed from the organic content of shales in the Mahogany zone varies from 10 to 75 gallons per ton or 500 to 4,000 barrels per acre-foot. At 900°F the organic material decomposes: 66 weight per cent to oil, 9% to gas and 25% to coke, the latter remaining on the spent shale.

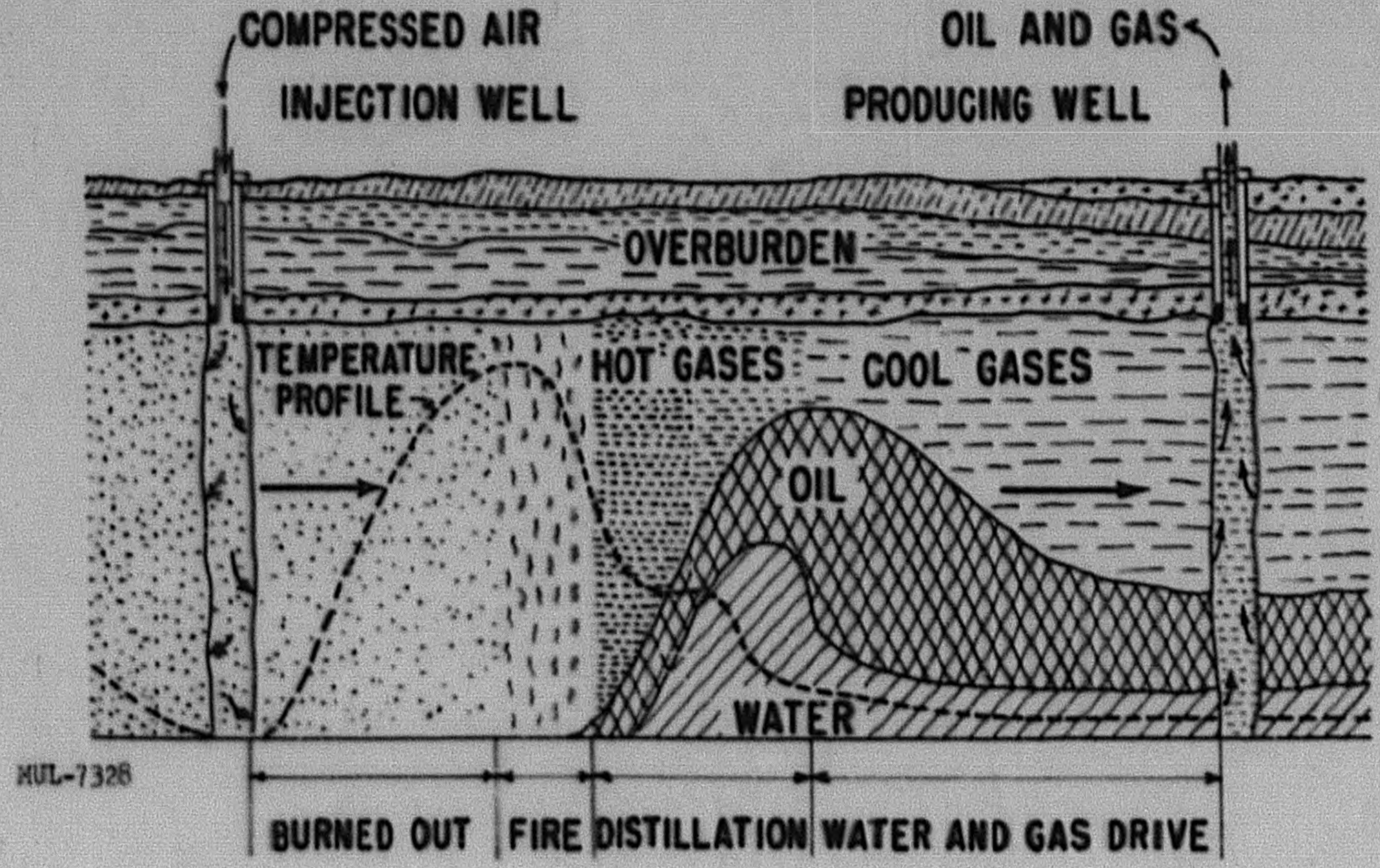

Fig. 14. Conventional method of recovery of oil by in-situ combustion in the more common type of petroleum reservoir. (After Murphy).

Preliminary studies of in-situ shale oil recovery utilizing a 10 kt nuclear device suggest that 300,000 tons or more of broken shale will be produced in a roughly sperical zone of radius 100 feet. If all the heat released by the device were utilized in heating shale to the retorting temperature of 900°F, there would be produced 10 million standard cubic feet of gas and 15,000 barrels of oil. (See Figure 15.). This is probably an optimistic estimate, and the actual values will have to be determined in post-shot investigatory work, before the in-situ experiment is begun. It would be more advantageous if, instead of heating the shale to retorting temperatures, the thermal energy dissipated rapidly through the broken shale raising its average temperature only a few degrees. This would facilitate flow through the mass of high-pour-point oil that will be produced in the combustion phase of the experiment. There will be sufficient fuel available from coke and produced gases to take care of the retorting phase of the project. Figure 16 and 17 show methods by which shale oil may be recovered by in-situ retorting, analogous to secondary recovery processes in petroleum reservoirs.

The oil displacement mechanisms operative in in-situ petroleum projects, will also be important in the shale project with the following exceptions:

1. The condensing steam drive will not be as important in shale as it is in petroleum reservoir due to the shale containing only about 1% water.
2. Miscible drive will be more important in the shale due to large quantities of low-molecular weight-hydrocarbons formed by thermal decomposition of the organic matter.

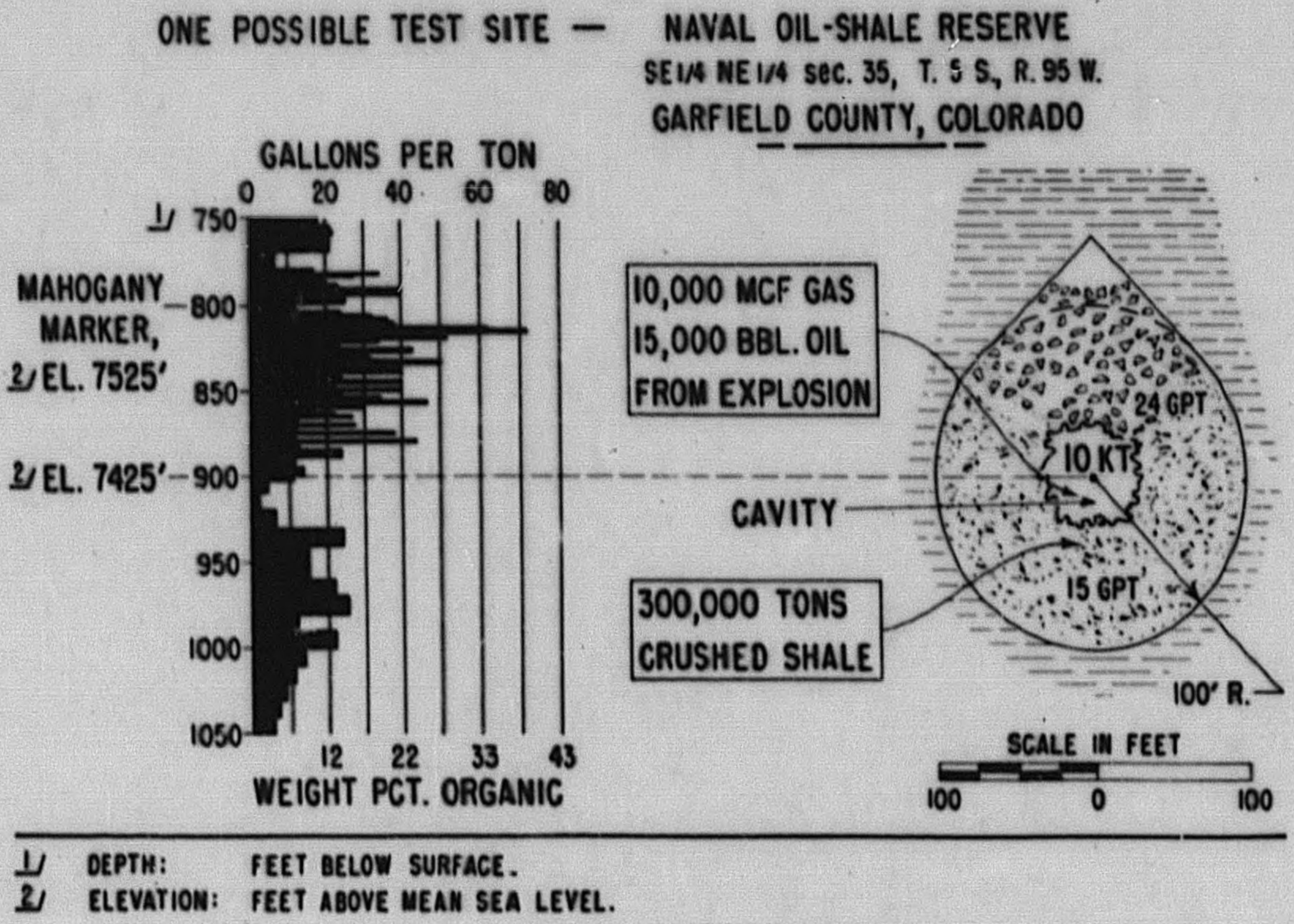

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Fig. 15. Estimated results of a nuclear explosion in Green River oil shale. (After Murphy).

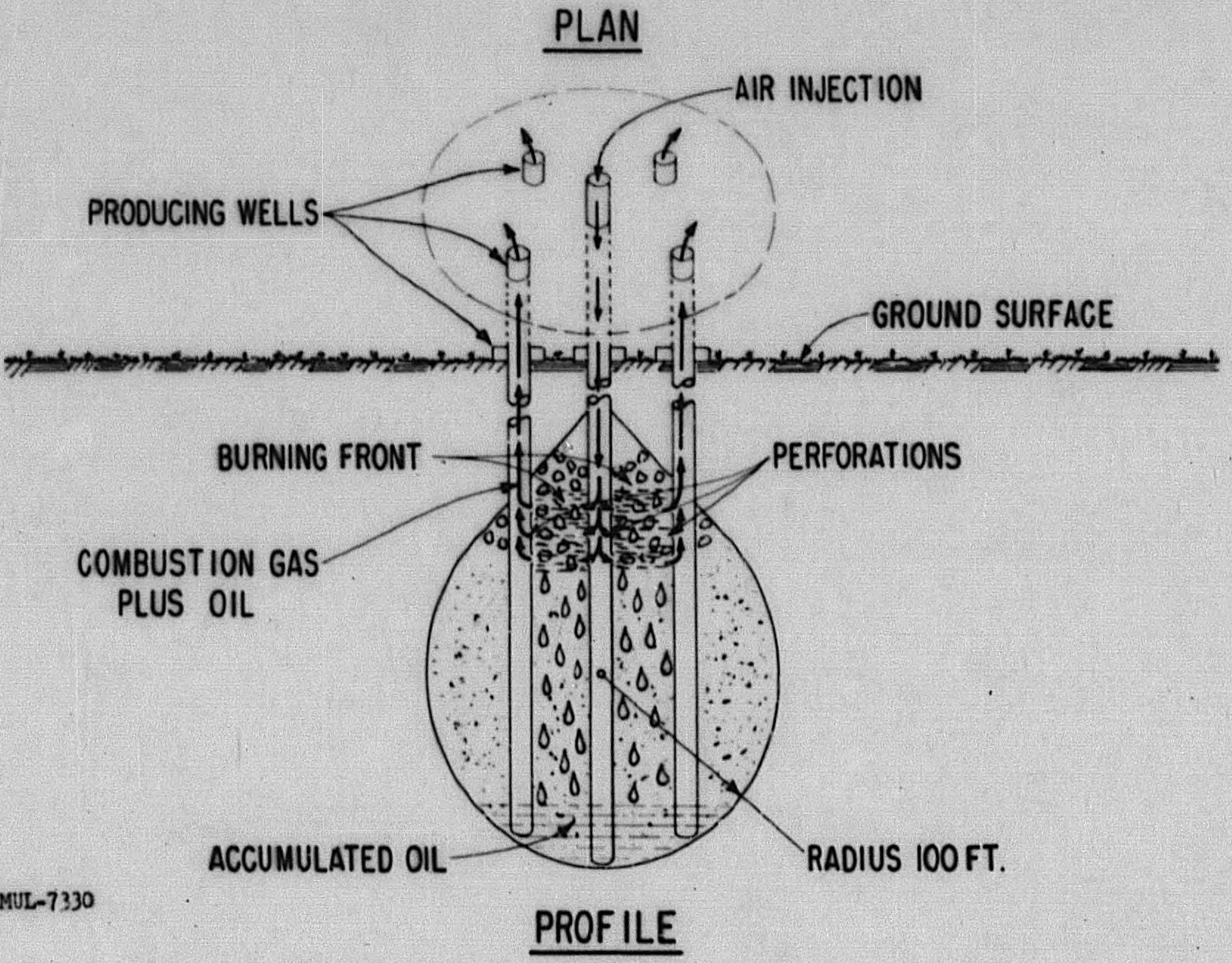

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Fig. 16. In-situ retorting by horizontal sweep. (After Murphy).

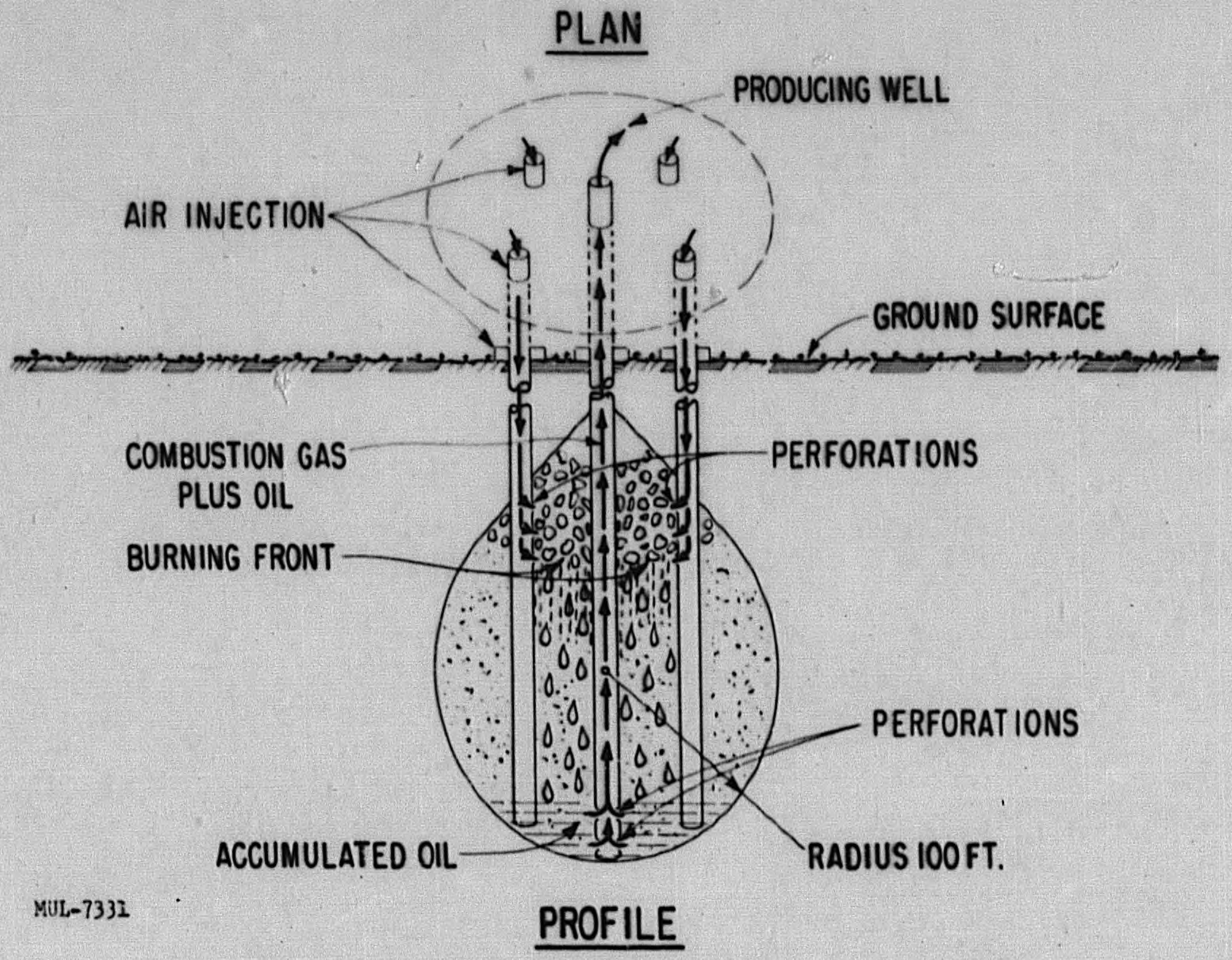

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Fig. 17. In-situ retorting by vertical sweep. (After Murphy).

3. Transfer of thermal energy is mostly by convection through fissures in shale and by conduction and convection through the higher permeability rock of petroleum reservoirs.

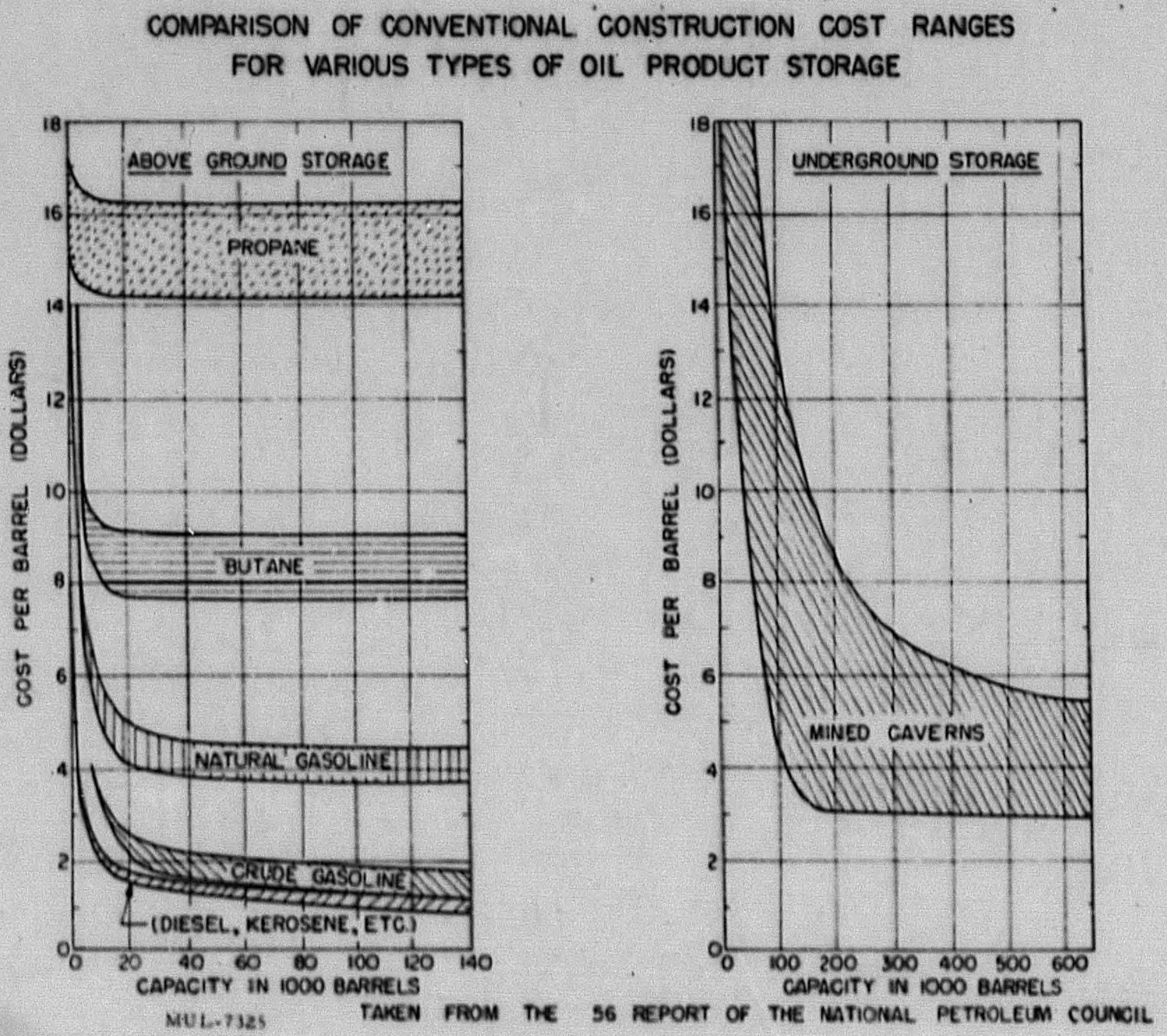
UNDERGROUND OIL STORAGE

Petroleum storage underground has received much attention in recent years, and will probably be even more seriously considered in the future. (Carlson, 1959). The advantage over surface storage are:

1. Lower Cost: $ 5.50 vs. $20 per barrel for liquid petroleum at 250 psi. (See Figure 18)
2. No Need for large quantities of steel.
3. Petroleum unaffected by atmospheric changes.
4. Maintenance and insurance costs less.
5. Industrial accidents less likely.

The construction of underground storage caverns by nuclear methods, while it has exceedingly great advantages, presents a few problems. These latter might be of interest to the engineering geologist.

The type of rock to contain the stored oil is of course the critical factor. The storage area must be blasted in an impermeable rock. It appears likely that the roof of the blast cavity will collapse since the weight of overburden will greatly exceed the strength of the rock. Storage then, will take plade in the pore space between broken rock fragments. If these are small particles, the resultant loss in permeability will make extraction of the oil difficult if not impossible. The feasibility of the scheme, then, lies in the size and uniformity of the resultant rock debris. We have very little actual experience along these lines, but a TV Camera, which was used to scan the cavity that existed above the Rainier chimney, showed fragments of boulder



TAKEN FROM THE 56 REPORT OF THE NATIONAL PETROLEUM COUNCIL

Fig. 18.

(After Carlson).

size. (But, can we extrapolate from tuff to granite as to breakage properties?)

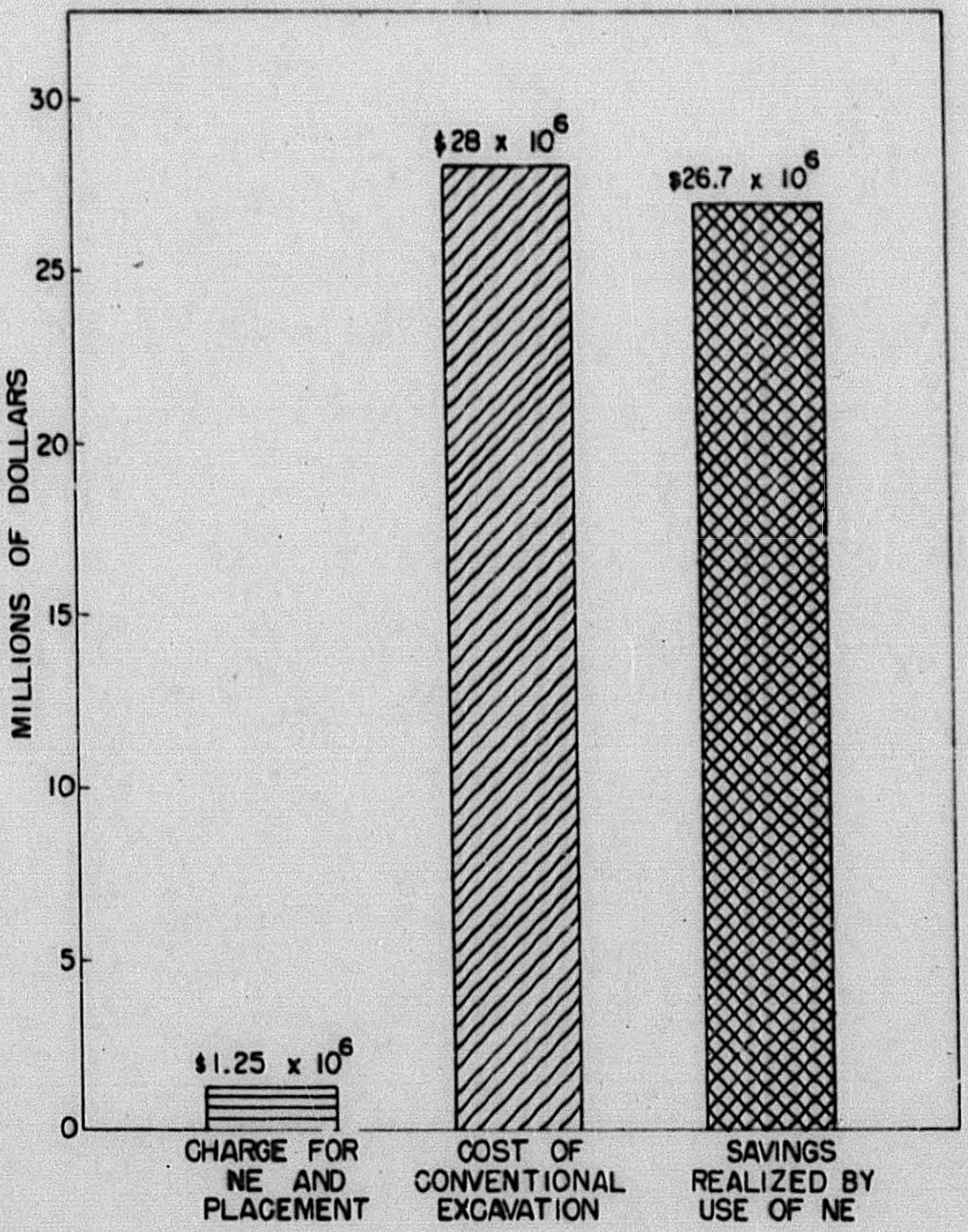
The other two problems to be considered in nuclear excavation, i.e., radiation and temperature, while not strictly speaking, geological in nature, still may have some interest for this group.

Lacking sufficient time to allow the normal radioactive decay to rid the area of undersirable radioactive contamination, this will have to be done by one of several decontamination techniques:

1. Flushing with water. (This may be injected into briny or other non-useful aquifer).
2. Mechanically filtering oil after removal from storage.
3. Disposing of asphalts after distillation at the refinery.

Finally, the temperature of the cavity in an impermeable, low water content rock, will remain quite high for a long period of time. Here again flushing with water might be the answer.

Now to the most striking part of this proposal, the relative costs of nuclear versus conventional methods. (Figure 19 and 20) Note for example the estimated cost of creating a 700,000 bbl. storage capacity reservoir by conventional methods is 28 million dollars, by nuclear it is only 1 1/4 million. This favorable ratio rises geometrically as the megaton range is reached. It has been calculated that a 10 MT explosive will create a 700 x 10^6 bbl. storage capacity reservoir at an estimated saving of 2 billion 798 million dollars!



COST COMPARISON FOR CONVENTIONAL AND NUCLEAR CONSTRUCTION OF A 7 MILLION BARREL UNDERGROUD STORAGE CAVITY - NE OF 100 KT

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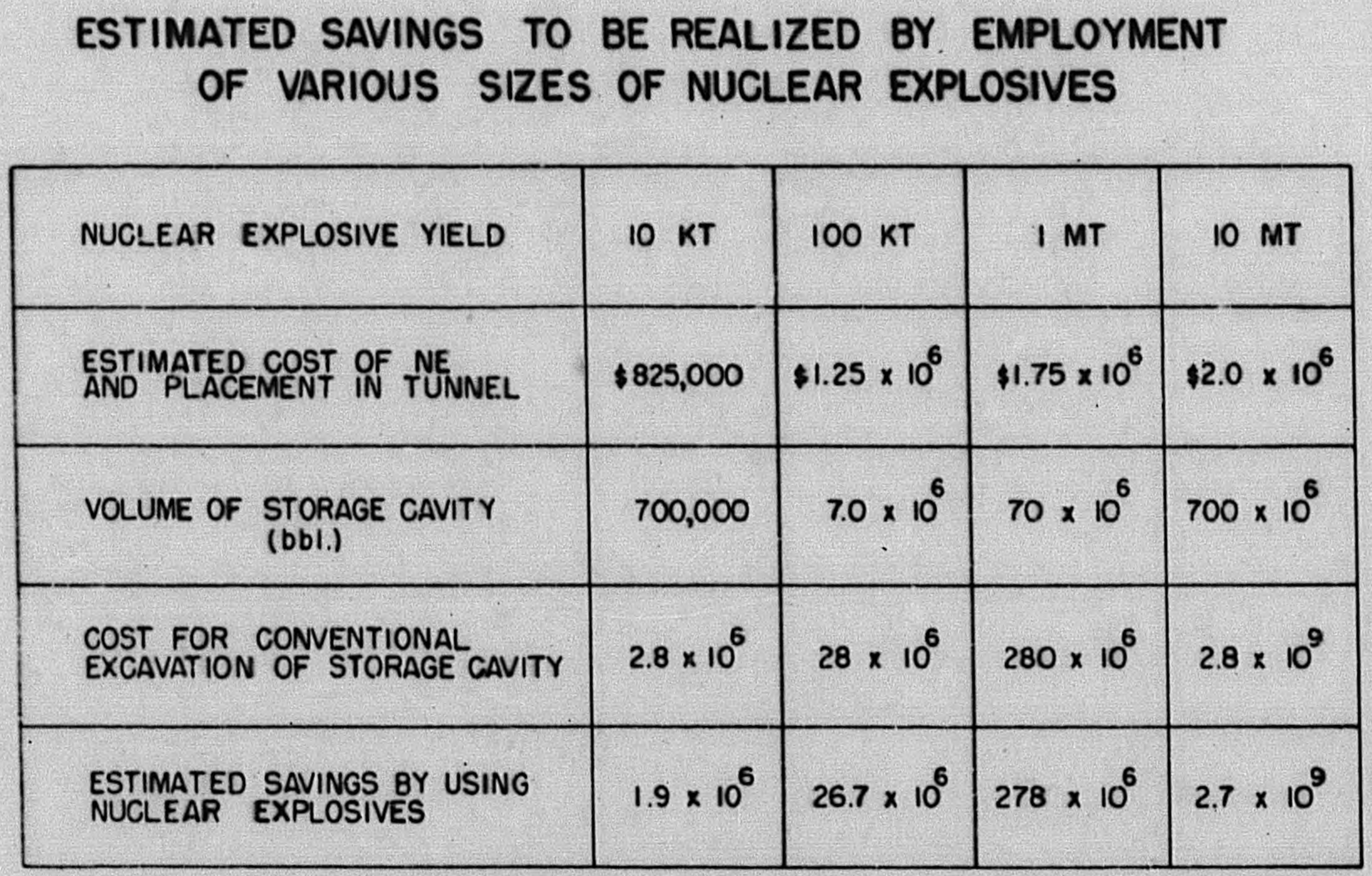
Fig. 19.

(After Carlson).



ESTIMATED SAVINGS TO BE REALIZED BY EMPLOYMENT OF VARIOUS SIZES OF NUCLEAR EXPLOSIVES

NUCLEAR EXPLOSIVE YIELD	10 KT	100 KT	1 MT	10 MT
ESTIMATED COST OF NE AND PLACEMENT IN TUNNEL	$825,000	$1.25 x 10^6	$1.75 x 10^6	$2.0 x 10^6
VOLUME OF STORAGE CAVITY (bbl.)	700,000	7.0 x 10^6	70 x 10^6	700 x 10^6
COST FOR CONVENTIONAL EXCAVATION OF STORAGE CAVITY	2.8 x 10^6	28 x 10^6	280 x 10^6	2.8 x 10^9
ESTIMATED SAVINGS BY USING NUCLEAR EXPLOSIVES	1.9 x 10^6	26.7 x 10^6	278 x 10^6	2.7 x 10^9

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Fig. 20.

(After Carlson).

D. Underground Power:

GNOME

Project Gnome, a 10 kt detonation in a salt bed near Carlsbad, New Mexico, while being a fascinating experiment by itself, holds less interest for the engineering geologist than most of our other experiments. This project has two phases, Isotope recovery, and power recovery. The former interests the chemists, the latter the physicists. The most important function of the geologist so far has been in core identification and groundwater studies. These latter have been for two purposes:

1. Assurance that there will be no contamination of groundwater or surface reservoirs, and
2. ascertaining that the medium in which the detonation will occur will be quite dry. From the Rainier event at the Nevada Test Site it was found that in a medium with a high water content, the temperature is rapidly reduced to the boiling point of water. The Nevada tuff is exceedingly porous, containing on the average 30% void space by volume. These voids are filled approximately 50% with water.

The geology is roughly as follows: The site is structurally on the west margin of the Delaware basin, within the reef zone of the El Capitan limestone reef, so excellently described by Phil B. King in his work on the Guadalupe and Glass Mountains of West Texas and New Mexico. Ground zero will be in the Salado Salt formation of Permian age (Ochoa series), which is overlain by 400 feet of anhydrite, gypsum and siltstone of the Rustler formation (also of the Ochoa series). Resting unconformably on this is 200 feet of Triassic siltstone and interbedded sand of the Pierce Canyon formation. This is separated by an unconformity, from the overlying Pleistocene sands, which are veneered with 10 feet of Recent material.

The detonation will take place in a halite bed at the 1200 foot level, approximately 500 feet below the top of the salt and 700 feet above the lower boundary of the Salado Salt. This guarantees a complete salt environment, and it is believed that fractures resulting from the explosion will not reach the overlying water bearing beds. (See Figure 21) The nearest oil field is 20 miles away. The nearest gas well is 6 1/2 miles, the nearest potash mine workings 8 miles away. The nuclear explosive will be installed by sinking a vertical shaft to 1200 feet and then driving a horizontal adit of 1000 feet, at the end of which the explosive will be set. The 1000 foot length will hopefully safeguard the shaft from the effects of the explosion. The following discussion is from C. E. Violet (1959).

The power program will determine the amount of energy remaining in the shot cavity as available heat, and will study the problems connected with the recovery of heat from this region for power generation. We hope to obtain valuable information on expected cavity size, temperature, and activity from measurements made in connection with other programs. Some of the heat may be recovered by introducing a working fluid into the cavity, either by simply circulating the fluid over the molten salt, or by hydraulic fracturing from nearby holes to establish a circulating path entering much lower in the cavity. Among the heat transfer fluids being considered are dry air and saturated brine. A small electrical generating plant may be installed which would utilize the temperature and pressure of the working fluid to drive a turbine and generator to produce electrical power.

Experiments at Livermore studying various modes of heat extraction have shown that steam generation by depositing water on the molten salt is

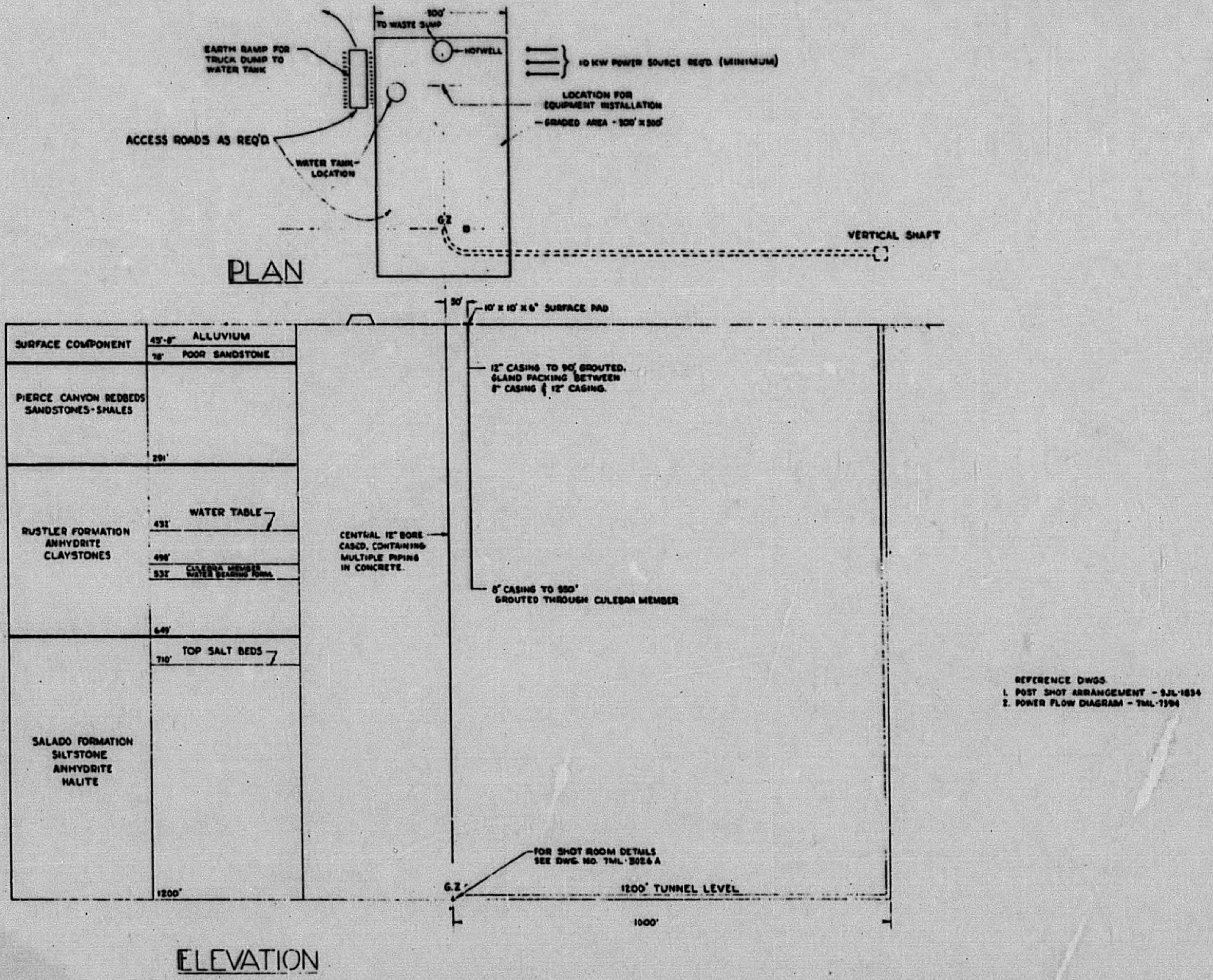

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Fig. 21. Cross-section and plan for Project Gnome.

the most effective method. However, the steam generated was found seriously laden with salt and corrosive acid. They found 30 lbs. of salt per 1000 lbs. of steam, ten times the rate as when air is the working fluid. The pH of the steam is 1.8. Contamination in steam includes salt, HCl, H_2S, and H_2 gas. Severe separation problems were suggested by the <10 micron particles when air was the working fluid.

GEOTHERMAL POWER

Geo-thermal activity has long been a geologic curiosity, only recently has it assumed geologic interest. In Italy 6% of the total electric power generated in the country or 254,000 kilowatts was supplied from geo-thermal sources. In New Zealand, when it was realized that the hydroelectric potential of North Island was rapidly approaching maximum exploitation, studies revealed that geo-thermal power offered the best possibility of future expansion at the lowest cost. Consequently a 250,000 kw plant was completed in 1958. (Carlson, 1959)

The unique advantages of geo-thermal over other sources of power:

1. Fuel is essentially obtained at no expense - magmatic heating.
2. Supply almost inexhaustible, or at least it will survive as long as magma which is heating it. (This may be a geologically short time, but for historic man it is long, i.e., around 10^5 years).
3. Year-round reliability. In some areas, viz. Italy, hydroelectric plants must close down during the dry season.

The role of Nuclear explosives in expanding the use of geo-thermal power has a two-fold application:

1. To create channels through which ground water may reach the heat source, in a known geo-thermal area.

2. To create underground steam cavities, rather than relying on the slim probability of a well encountering a crack from which steam may be exploited.

Figure 22 is a schematic representation of a conventional geothermal steam power plant. Figure 23 depicts what might be done with nuclear explosives in this area.

What has been said previously about induced permeability in the collapsed chimney of an underground nuclear detonation, appears equally promising for creating interconnection between overlying groundwater and sources of magmatic heating. The collapsed cavity itself, with its 10^5 tons of shattered rock from a low Kt detonation looks like a salient possibility for the steam cavity.

In the Thermal Power Company's drilling operation for geo-thermal steam at The Geysers, Sonoma County, California, one hole is presently out of control. Steam is exhausting at an estimated 200,000 lbs/hr. The countryside is blanketed with fine (less than 20 microns) volcanic ash discharged from the blowout. There is no apparent effect on adjacent wells, although this runaway well has been discharging for almost 2 years!

In the rather brief resume presented here we have attempted to acquaint the engineering geologist with the potentiality of the new tool of the "Plowshare" created from a beaten sword. It is hoped you will help us use it to aid man in his ever-increasing struggle to wrest resources from his physical environment.

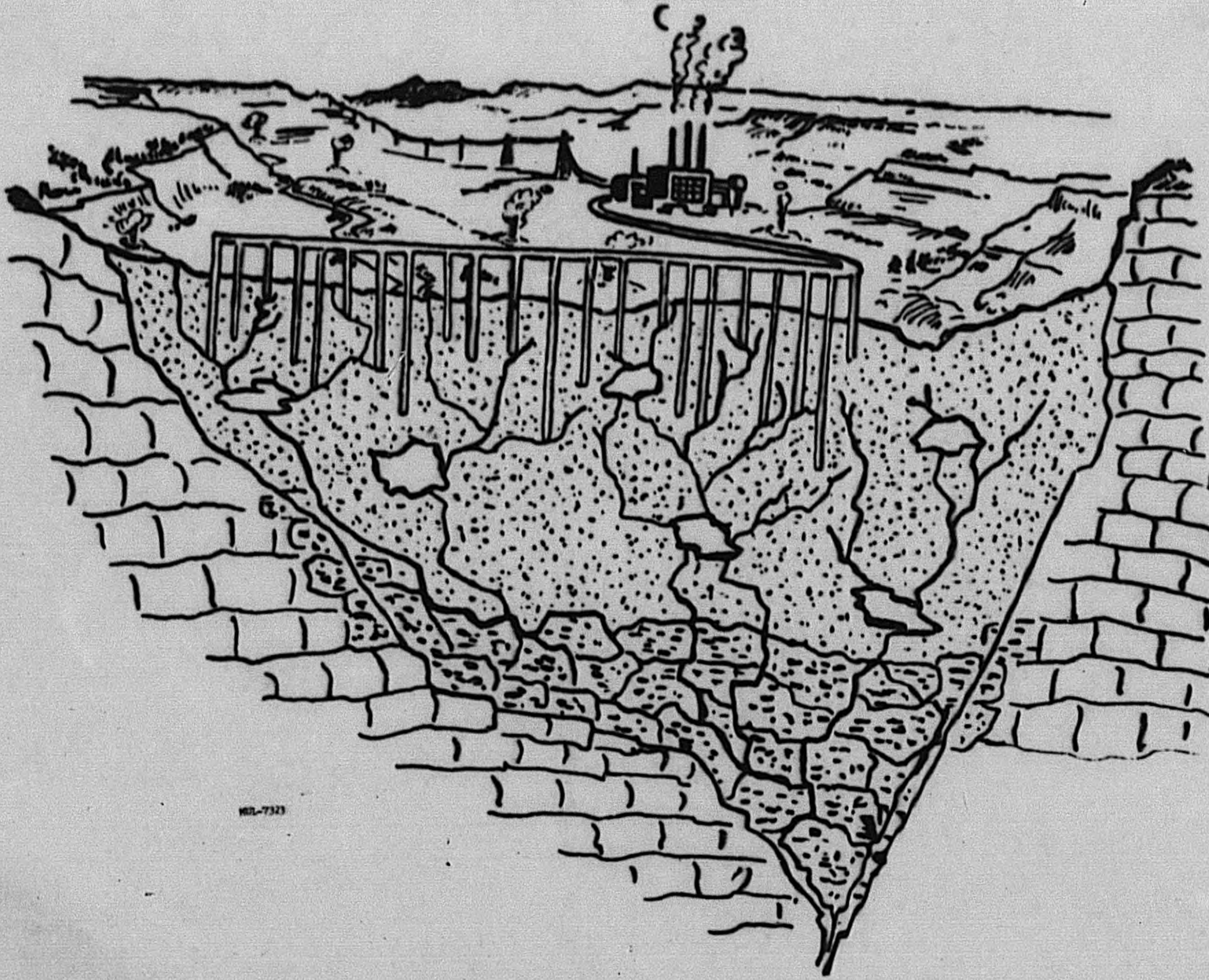

Fig. 22. Conventional Geothermal Steam Power Plant. (After Carlson).

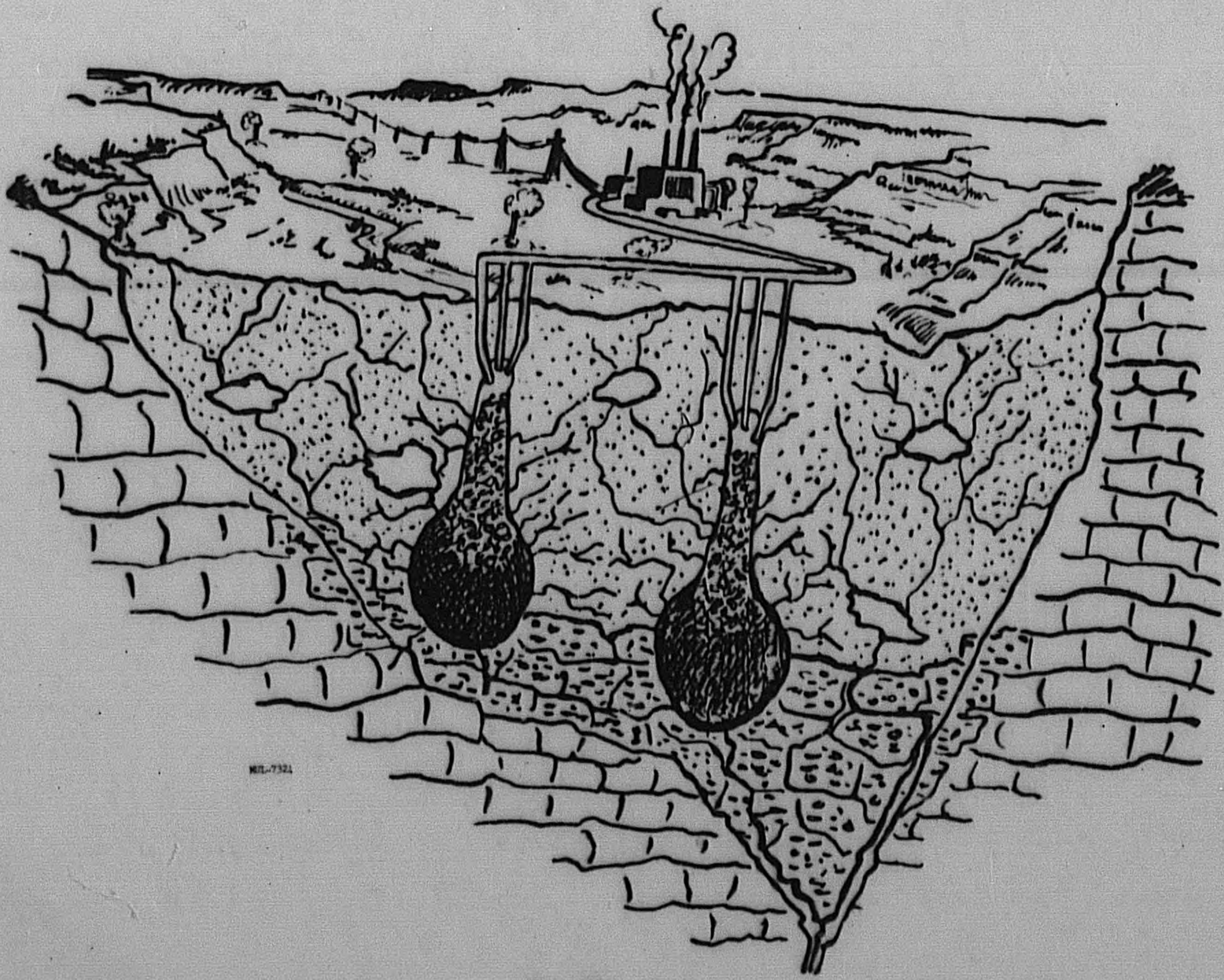

Fig. 23.

(After Carlson).

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