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INDUSTRIAL AND SCIENTIFIC APPLICATIONS OF NUCLEAR EXPLOSIONS

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Nuclear Explosions-Peace-
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UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Livermore, California

Contract No. W-7405-eng-48

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January 19, 1960

Printed for the U.S. Atomic Energy Commission

Industrial and Scientific Applications of Nuclear Explosions*

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In the course of the nuclear weapons development and test program of the Atomic Energy Commission (AEC) and Department of Defense over the last fifteen years, there has been developed a large background of understanding of the phenomenology of nuclear explosions, of the design of nuclear and thermonuclear explosives, and of the operational procedures to safely detonate explosives of large magnitude.

Stemming from the program in recent years have been the successful development of fusion explosions and the demonstrated feasibility of producing such explosions with small fission contributions. These two steps are extremely significant in speculating about the possible constructive uses of nuclear explosives because (1) the fusion fuels are extremely abundant and cheap; and (2) the fusion reaction leads to non-radioactive products and the induced activity can be limited by the use of appropriate absorbing blankets.

In principle, the major problems in application arise from the fission contribution to the energy because the products of this reaction are inherently radioactive; however, in many situations considered, even for purely fission explosions the release of radioactivity to the biosphere can be adequately

* This work was done under the auspices of the U.S. Atomic Energy Commission.

controlled. The technical advances in explosives design, coupled with the large amount of operational field experience in detonating such explosions, have directed attention to the study of possible non-military projects. To this end the Plowshare Program was established at the Lawrence Radiation Laboratory by the AEC in 1957, to explore the feasibility of potential industrial and scientific uses of nuclear and thermonuclear explosives.

The objectives of the program are:

1. The development through experimental and theoretical approaches of the understanding of the basic phenomenology of nuclear and thermonuclear explosions in various environments.

2. The exploration of possible industrial and scientific applications of such explosions.

3. The planning and execution of field experiments to gather additional data, to conduct scientific experiments, and to demonstrate industrial potentialities.

4. The design, development, and test of special explosives appropriate to any desired use. The broad general goals of such a program are to reduce the cost and the radioactivity production of the explosives; however, an additional goal might be the construction of a system for a special purpose, such as isotope production.

An important consideration, of course, in deciding whether nuclear explosives can be afforded for any specific use depends on their costs and the expenses associated with firing them. As a guide the AEC published charges that would be appropriate to providing an explosive and the service of firing for various energy releases. The charges were $500 000 for kiloton (kt) range, $750 000 for tens of kiloton range, and $1 000 000 for megaton (Mt) range explosives. To get total costs of experiments, of course, one must add the construction, operational, and scientific costs. A good illustration of such total costs, including the AEC charges for an explosive, is the Gnome project to be described later, where the total cost will be about $4 000 000. Thus for 10-kt explosions fully instrumented and at a depth to assure containment of radioactivity, total costs up to $5 000 000 might be anticipated.

Information derived from a series of underground nuclear detonations in Nevada has provided a basis for development of theory and for suggesting several possible uses. Some of the explosions were at such shallow depths that craters were produced, which led to the consideration of large-scale excavation projects using nuclear explosions. The other explosions were at various depths beneath the surface, extending from those depths at which only a small fraction of the radioactivity was released to the atmosphere, to those at which no detectable radioactivity was released to the atmosphere. It is the analysis of the effects of these explosions that has led to the preparation and study of several proposals for the next experiments. Three of the experiments are in an advanced state of planning and, hopefully, will be the first three to be conducted. The others are in varying degrees of preparation.

In the following table are listed the nuclear detonations which have been most extensively studied and provide the basis for our discussion. It is important to note that all of these explosions were conducted either as tests of new weapons designs or principles, or for collection of data on military effects. None of the explosions were conducted under the auspices of the Plowshare Program. The first completely contained underground nuclear explosion (code-named Rainier) of September 19, 1957, the study of which provides most of our understanding of such explosions, was conducted to develop a method of nuclear weapons testing which would not release radioactivity to the atmosphere.

TABLE I

Major features of underground nuclear explosions.

Event (and date)		Yield, W (kt)	Medium	Depth, D (feet)	Scaled depth, $D/W^{1/3}$	Measured radioactivity deposited on surface (%)	Crater volume (yd^3)	Crater volume/kt (yd^3)
Jangle-S	(11-19-51)	1.2±0.1	Alluvium	-3.5*	-3.3*	>65	1 650	1 400
Jangle-U	(11-29-51)	1.2±0.1	"	17	16	>80	37 000	31 000
Teapot-Ess	(3-23-55)	1.2±0.1	"	67	63	90	96 000	80 000
Neptune	(10-14-58)	0.090±.020	Bedded tuff	99	220	1-2	33 000	370 000**
Blanca	(10-30-58)	19.0±1.5	" "	835	310	<0.5	0	0
Logan	(10-15-58)	$5.0^{+0.2}_{-0.4}$	" "	830	485	0	0	0
Rainier	(9-19-57)	1.7±0.1	" "	790	670	0	0	0
Tamalpais	(10-8-58)	0.072±.010	" "	330	780	0+	0	0
Evans	(10-28-58)	0.055±.030	" "	840	2200	0++	0	0

*3.5 feet above surface.

**This explosion took place in bedded tuff under a sloping surface 1:3; therefore, the crater is probably larger than would be expected on a level surface.

+No breakthrough to surface but radioactive gases in large quantities leaked into the tunnel.

++No breakthrough to surface but stemming failed, releasing gross fission activity into the tunnel.

The experiment was completely successful and the succeeding underground explosions were part of a development series.

Through extensive drilling, logging, and mining operations the general results of the explosions have been evaluated. A theoretical model has been successfully developed which when set up on the high-speed computers seems to give the proper distributions of energy and correct magnitudes of the mechanical effects. It is convenient to describe the phenomenology in four stages characterized by very different time scales, and the Rainier explosion will be used as an example.

1. Nuclear Reaction (Microsecond Range)

The total energy of the reaction is released in less than 1 microsecond. In the case of the Rainier explosion which had an energy release of 1.7 kiloton (7.2×10^{19} ergs) and took place in a room 6 × 6 × 7 ft containing about one ton of material, after a few microseconds the pressure in the room was 7 000 000 atmospheres and the temperature about 1 000 000°K. Accompanying the large energy release was a burst of neutrons amounting to 2×10^{23}/kiloton of fission energy.

2. Hydrodynamic Phase (Millisecond Range)

Under the influence of the high pressure the room expanded in a few tens of milliseconds to a spherical cavity 125 ft in diameter. The rate of growth of the cavity for Rainier as computed by Nuckolls* is shown in Fig. 1. At this time the cavity is lined with a shell of melted rock about 4 inches thick which amounts to an estimated 800 tons of material. The temperature and

*The data shown in Fig. 2 and Table II were also computed by John H. Nuckolls of this laboratory.

pressure are 1200-1500°C and 40-50 atmospheres, respectively. The shock proceeds outward crushing the rock to a radius of 130 ft and becomes elastic at 280 ft. Beyond that point the elastic wave proceeds until attenuated. For a sufficiently large explosion (~ 20 kt at the Nevada site) the seismic signal can be detected readily at several thousand miles. The shock strength as a function of radial distance is shown in Fig. 2. The calculated partition of energy at this time is shown in Table II.

TABLE II

Partition of energy in Rainier Event.

State	Radii (ft)	Percentage of prompt energy
Gas	0-62	8.2
Liquid	62-62-1/4	19.1
Crushed	62 1/4-130	47.0
Fractured	130-280	21.2
Elastic	280	4.5

3. Quasi-Static Phase (Seconds-Minutes)

The cavity persists for seconds to minutes during which time melted material flows down the sides and drips from the overhead. This stage ends when the roof collapses, at which time, due to rapid expansion of the gas and dilution by cold material falling in, the temperature drops rapidly. The melted rock freezes to a glassy material and collects in a bowl-shaped zone toward the bottom of the cavity. The glass contains 65 to 80% of the gross fission-product activity. The remainder is distributed through the collapsed zone.

Because of the presence of a large amount of water (the rock contains 15-20% water by weight) and the existence of a large permeable zone, the temperature of the hot rock was rapidly reduced to the boiling point of water.

4. Longer-Term Phase (Minutes-∞)

Successive collapse of the cavity vertically, slow thermal diffusion, and radiation decay continues. For Rainier the vertical collapse proceeded upward about 400 ft and then apparently stopped. The temperature distribution measured five months after detonation is shown in Fig. 3.

Detailed geological mapping by coring and mining of the collapsed zone revealed the general structure shown in Fig. 4. The features of interest are the radioactive zone shown at the bottom, the collapsed zone extending from the chimney, and the fracture boundary about 65 ft below the point of detonation to about 400 ft above it. The natural bedding of the tuffs permitted ready visualization of the movement of material into the collapsed cavity. In progressing at about the level of detonation inside the radioactive shell across the collapsed cavity, the rocks grade from a few inches in diameter just inside the shell to several feet in diameter at the center. The boundaries between the rocks were filled with a fine dust which one year after explosion has recemented. A tunnel was driven across the chimney at 100 ft above the point of detonation. This exploration revealed a fractured zone about 10 ft wide at a radius of 75 ft from the vertical axis through the point of detonation. The material within this zone was a very fine rock dust.

In considering all the explosions, the following generalizations are possible for tuff. Extending them to other media must be done with caution.

1. The radioactivity of nuclear explosions in the kiloton range in tuff can be completely contained underground at depths of $D = 400\ W^{1/3}$ ft or greater, where W is the energy release in kilotons.

2. The initial cavity formed by the explosion has a radius of $R = 50\ W^{1/3}$ ft.

3. Initially melted rock, which is converted to glass on cooling, amounts to 500 ± 150 tons per kiloton of energy release.

4. The collapse of the cavity produces a zone of about 70 000 yds^3/kt (120 000 tons/kt) of broken permeable material.

5. The major portion (65-80%) of the gross fission-product activity is in dilute (1 part per 10 million) solution in glass. The remainder (20-35%) is distributed throughout the collapsed zone of the chimney and is deposited on the surface of the broken material.

6. About 30% of the total energy release of the explosion is initially deposited in steam and hot rock at a temperature in excess of 1200°C. The temperature rapidly degrades to the boiling point of water. One year after the Rainier explosion this energy resided within a volume whose radius was less than 80 ft.

One of the striking results of the Rainier study was the fact that such a large fraction (30%) of the total energy was initially deposited in hot debris (> 1200°C). Due to the pressure of large quantities of water, the temperature was rapidly degraded, but what would have been the result in a dry medium? Perhaps the energy could be stored at high temperature long enough to permit recovery, and since the thermonuclear reaction can be made to proceed in explosions, perhaps there would be a chance of recovering energy for power. These observations soon led to the consideration of an explosion in a large natural salt formation which normally is dry (less than 1% water). With more detailed thinking and planning an experiment has been designed, referred to as Gnome, in which it is proposed to fire a 10-kt all-fission explosion at a depth of 1200 ft in a massive salt bed near Carlsbad, New Mexico. The general arrangement shown in Fig. 5 includes a 1200-ft vertical access shaft which is joined at the bottom to a 1000-ft tunnel. The tunnel is terminated in a hook (similar to that used for the Rainier explosion) designed to be self-sealing as far as release of radioactivity to the shaft is concerned.

The basic objectives of the experiment are:

1. To explore the feasibility of converting nuclear explosive energy into sensible and latent heat which will be available as required for the production of electric power.

2. To investigate the feasibility of recovering from natural salt useful isotopes which can be produced by nuclear explosives. The chemical and physical behavior of a large number of elemental species will be studied with no specific attempt to produce useful isotopes.

3. To extend the data on the characteristics of an underground nuclear explosion to a new medium (natural salt) having physical properties in marked contrast to the only medium (volcanic tuff) for which such data are presently available.

4. To conduct several basic neutron-physics experiments (which will be described later).

The experiment is completely designed and, if appropriate authorizations are obtained consistent with the operating schedule, the experiment can be conducted in late 1960 or early 1961.

The Richfield Oil Company, in association with other oil companies and in coöperation with the AEC, has developed an experiment (Project Oil Sand) directed toward releasing oil from the Athabaska tar sands deposit in the province of Alberta, Canada.

These deposits are estimated to contain a quantity of oil approximately equal to the world's proven reserves. Due to the high viscosity of the oil and the approximately 1000 ft of overburden, all attempts to extract the oil from the formation economically have failed. Heating the tar sand to 100°C lowers the viscosity of the oil sufficiently so that it may be possible to pump the oil from the sand. It is proposed to conduct an experiment by detonating a 9-kt nuclear explosive immediately beneath the tar sand formation and use the energy to heat the adjacent tar sand and fracture the interbedded layers of shale, thereby permitting the study of the problems of recovery of the trapped oil. In addition to the direct heating mechanism some oil also may be rendered recoverable by shock heating. Furthermore, the possibility of further recovery by secondary processes can be examined. The geology and proposed placement of the explosives is shown in Fig. 6.

The principal objectives of Project Oil Sand are to gain knowledge that could aid in the economic recovery of oil from the Athabaska tar sand formation through the use of nuclear explosives. The planned detonation, approximately 20 ft below the base of the tar sand formation, will produce a cavity about 250 ft in diameter which will subsequently collapse. When collapse occurs the fractured tar sand and shale formation will tumble into the cavity and be heated by the energy which was deposited locally by the explosion. In Fig. 7 is shown an overlay of the geologically mapped Rainier collapsed zone and the measured temperature distribution. With this input it has been estimated that up to 100 000 barrels of oil might be recoverable from a 9-kt explosion. Based on experience in tuff in Nevada, no cratering, surface subsidence, or breakthrough are expected. Ground-water movements in the proposed area have been thoroughly studied and it was concluded by the Alberta and Ottawa technical committees that there will be no ground-water contamination problem.

On approval by the Canadian authorities and the AEC, Project Oil Sand could be conducted six months from the time authority to proceed was obtained.

A third project is directed toward obtaining more information on the cratering effects of nuclear explosions as part of the excavation program. Project Chariot is a nuclear excavation experiment to be done at a location on the northwest coast of Alaska near Cape Thompson (Fig. 8). To proceed with plans for full-scale excavation projects such as harbors, canals, strip mining, or flood control reservoirs, more data are required on the results of large-yield nuclear cratering detonations and on simultaneous detonations of lines of charges. Such a demonstration of the capabilities of nuclear explosives for excavation projects with greatly reduced release of radioactivity to the atmosphere is necessary before proceeding with earth-moving projects near populated regions.

As presently planned, three 20-kt and two 200-kt nuclear explosives buried at optimum depths for cratering and containment of radioactivity will be simultaneously detonated to produce a single crater which, if desired, will be usable as a small harbor. The proposed layout is shown in Fig. 9. Included in the figure is an outline of how a full scale harbor might appear. The dark circles represent the expected excavations for the two different size charges. The overlay of the proposed experiment is on the topographic survey of the site.

The main objectives of this experiment (Project Chariot) are:

1. Extension of nuclear cratering knowledge to a different medium, to higher yields, and to the effects of simultaneous multiple detonations.

2. To gain new data on the distribution of the radioactivity deposited in the area of the crater and released to the atmosphere.

3. To increase the knowledge of air-blast pressures versus distance from nuclear cratering detonations for deeply buried cratering explosions.

The only reliable nuclear cratering data presently available are for 1.2-kt explosions in alluvial fill at the Nevada Test Site. Project Chariot has been designed to extend this knowledge to yields more consistent with useful excavation projects and to gain experience in a harder medium than alluvium. In addition, Chariot will give important data on the gains to be realized by the simultaneous detonation of a line of nuclear explosives.

The amount of radioactivity released to the atmosphere by a nuclear cratering detonation varies strongly with the depth-of-burst. Based on a 90-ton explosion (Neptune) in Nevada, it appears possible to excavate almost a maximum volume with only 1-2% of the gross radioactivity escaping to the air. In Project Chariot, for which similar scaled depths of burial will be used, it is planned to measure the distribution of radioactivity in the "fallback" material in the crater, on the surface in the vicinity of the crater, on the surface within 100 miles, and in the atmosphere.

In addition to the above, a thorough survey of biological and ecological effects is being made under the auspices of the Division of Biology and Medicine. The biological program is directed toward determination of those factors such as time of year and direction of fallout, such that biological cost will be minimized.

During the summer of 1959, preliminary site surveys, including geological, meteorological, ecological, and oceanographic surveys, were completed.

The three specific projects described above are the only ones in final state of planning. They are still of the nature of proposals and none have yet been released to construction by the AEC. Several scientific experiments that could be conducted using nuclear explosions as sources are described below.

SCIENTIFIC EXPERIMENTS

That nuclear explosions can be employed as a source for a variety of scientific experiments has been pointed out by many individuals. Suggested experiments, to name some, include investigations of the properties of space and the structure of the earth, isotope production particularly transplutonics, neutron resonance measurements, and equations of state at high pressures; these were described at the Second Plowshare Symposium in San Francisco (May 13-15, 1959).[1] Some experiments have already been conducted in conjunction with nuclear weapons development tests. In the Plowshare Program there will be more and better opportunities to conduct such experiments. Now let us examine some of the suggestions.

1. Space Research

The possible use of nuclear explosions as sources to study properties of space has been discussed by several individuals (Argo, Hoerlin, Longmire, Petschek and Skumarich of Los Alamos Scientific Laboratory; Cook of Sandia Corporation; Christofilos of Lawrence Radiation Laboratory; Squire at Aerojet General Nucleonics). That important and spectacular auroral and geomagnetic distrubances can be produced by such explosions was amply demonstrated by the high-altitude explosions set off by the United States in 1958. While the cited detonations were conducted as part of classified military projects, much

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[1] "Plowshare Series: Report No. 2. Proceedings of the Second Plowshare Symposium, Part V: Scientific Applications of Nuclear Explosives in the Fields of Nuclear Physics, Seismology, Meteorology, and Space," Report No. UCRL-5679, available from Office of Technical Service, Dept. of Commerce, Washington 25, D. C.

of the phenomenology has been published. The important characteristics of explosions in space are:

1. One-half of the energy is released as thermal radiation characteristic of source temperatures of several million degrees.

2. One-third of the energy is carried as kinetic energy of the bomb debris.

3. The remaining energy is divided between prompt and residual nuclear radiations.

By using the sharp pulse of thermal radiation, precise measurements of the velocity of propagation of electromagnetic radiation in space can be made, because very long base lines can be used. Squire and Softky suggested an experiment which would establish relative velocities of photons in four frequency ranges: (1) rf ranges (100-1000 Mc); (2) the optical range; (3) the x-ray ranges (few kev); and (4) and the gamma-ray ranges (few Mev). The measured relative velocities should be good to ± 10 meters/sec. To confirm, or deny, the independence of the velocity of electromagnetic radiations on frequency over such a wide band would be important to the theory. The rich source of beta rays can be used to excite the auroras to levels exceeding natural excitations by many orders of magnitude. The advantages in such studies of the capability of predetermination of time and point of injection are obvious. The explosive effects in perturbing the earth's magnetic field provides a means of generating and studying the characteristics of magnetohydrodynamic waves. The nature of the radiation belts and the manner of trapping and injection of particles can be investigated. One interesting suggestion discussed by Los Alamos Scientific Laboratory is the simultaneous detonation of two explosives in space at some separation like 100 kilometers. The two plasmas generated in this fashion would then rush toward each other and interpenetrate, leading to magnetohydrodynamic turbulence.

2. Production of Transplutonic Isotopes

The numbers of neutrons and the fluxes produced in explosions are very high. For example, fission explosions produce about 2×10^{23} neutrons/kiloton and a typical internal flux, which could be used to activate internal targets, would be 10^{23} neutrons/cm^2. Thermonuclear explosions produce about ten times as many neutrons and internal fluxes range from one to two factors of 10 greater than for a fission explosion of the same energy release. Such fluxes are many orders of magnitude greater than are presently available in laboratory sources.

It is important to recall that the discovery of einsteinium (99) and fermium (100) was made possible by their production in the first thermonuclear explosion of 1952. The highest mass number obtained was 255, which resulted from 17 successive neutron captures. This explosion was a weapons development test on the surface, and the samples recovered were minute indeed.

Using a specially designed system and with the flexibility of detonating underground, it is possible to consider production and recovery of milligram amounts of Cf^{252} from a single explosion. Presently under way is a reactor radiation program of several years duration to produce such amounts of this interesting isotope. Californium-252 has an effective half-life of 2.2 years (97% alpha decay, and 3% spontaneous fission) and a partial half-life for spontaneous fission of 66 years. These properties make this isotope unique as a laboratory source for fission neutrons and fission fragments. Furthermore, with appropriate design measurable quantities of an isotope of mass 270, which would be expected to be stable at Z of 104, might be produced and identified.

3. Neutron Resonance Measurements

The measurement of neutron resonances over the past ten years has contributed materially to the development of nuclear theory and has provided cross section data fundamental to the design of reactors. The experimental techniques have generally employed a time-of-flight method but various sources were used to provide the neutrons. Hughes* has compared the several methods used in the past, with what seems to be possible using a nuclear explosion as a source. His general evaluation and conclusions are stated in the following:

The pulsed source planned for the Dubna Laboratory near Moscow, which is a pulsed subcritical assembly, under planned operating conditions for continuous operation, would produce 3×10^{20} neutrons per year. Comparing this number with that number of neutrons available from a nuclear explosion ($\sim 10^{24}$ neutrons), it is seen that 3000 years of operation of the Dubna source would be required to produce the same number of neutrons as a single explosion.

Similarly a comparison with the output of a fast chopper might be instructive. A nuclear explosion emitting 10^{24} neutrons, on appropriate moderation, will produce of the order of 4×10^{10} neutrons/cm^2 in a 1-ev interval at 10 ev at 100 meters. This intensity can be compared with the same flux under the same conditions from the new NRU reactor at Chalk River using the Brookhaven fast chopper. From the measured counting rate at that installation, it can be shown that 10^7 neutrons/cm^2/year are available in the energy interval and distance as above. Thus here also, 4000 years of continuous operation of the fast chopper at Chalk River would be required to provide the same integrated flux available from a single nuclear explosive source.

With these considerations in mind, Hughes has designed an experiment using the 10-kt explosion of the Gnome event as a source to measure neutron resonances for U^{233}, U^{235}, U^{238}, and Pu^{239} in the 1 ev to 1 kev range.

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*D. J. Hughes of Brookhaven National Laboratory.

It is planned to use a 1000-ft long vacuum pipe placed in a tunnel extending radially from the center of detonation for the time-of-flight path. Transmission measurements for each specimen will be made as a function of energy using conventional electronic time-of-flight systems. The output of each of these channels is then compared with an open beam monitoring. It is anticipated that the resolution will be at least four times better than yet achieved in such measurements by any other method.

4. Other Cross-Section Measurements

Cowan (of Los Alamos Scientific Laboratory) during the Fall of 1958 weapons test series in Nevada took advantage of one of the explosions to measure the fission cross section and symmetry of fission of U^{235} as a function of neutron energy. The technique involved mounting a ring of U^{235} on a wheel which was rotated at high speed behind a slit at the time of detonation. The time-of-flight path used was 100 feet. After the explosion the wheel was recovered, and the activities on the ring were measured by counting and radiochemical methods. Ratios of quantities of appropriate isotopes like Ag^{111} $/Mo^{99}$ were compared as a function of energy to get a measure of symmetry of fission.

With the success of this experiment, Cowan has designed a similar experiment to be done with higher resolution on the Gnome event using the 1000-foot vacuum flight path.

With a similar technique, Lindner of the Lawrence Radiation Laboratory intends to measure, in the Gnome event, neutron capture cross sections for several isotopes, including Th^{232}, W^{184}, W^{186}, Ta^{181}, Hs^{180}, and Au^{197}.

The measurements of the angular distribution of 4.4-Mev gamma rays from the $C(n, n'\gamma)$ reaction and the inelastic cross section will be accomplished also on the Gnome event by John Anderson and W. McMaster of LRL. In this experiment a neutron beam impinges on a carbon target at 500 feet from the source. An array of five Čerenkov detectors will be distributed at appropriate angles to detect the gamma rays. The angular distribution will be measured as a function of neutron energy from threshold, 4.8 Mev, up to about 15 Mev with a neutron resolution varying between 0.1 and 0.3 Mev. The use of a nuclear explosive is advantageous because of the completeness of the data that can be obtained over a range where the uncertainties in the resonance structure of carbon make a laboratory experiment difficult.

The overall arrangement of the various neutron experiments for the Gnome event is shown in Fig. 10.

5. Earth's Structure and Seismology

Byerly,* Griggs,† and Press†† have considered several possibilities for the application of nuclear explosions to studies of the earth and seismology. The major portion of the understanding of the internal constitution of the earth has been based on analysis of signals generated by earthquakes. Contributions have also been made using the nuclear explosions set off during weapons development tests as sources (Burke-Gaffney and K. E. Bullen). In 1955 Dr. K. E. Bullen proposed that several nuclear explosions be set off for seismic purposes, but he failed to get sufficient support. However, through the cooperation of the Australian and British governments, the outputs from four bombs fired in Central Australia in 1956 were used to obtain the first reliable information on the depth of the Mohorovičić discontinuity in Australia. The uses of controlled nuclear sources for seismic purposes are many indeed. Major uncertainties

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in usual seismology depending on earthquakes are time, source energy, and location and depth of focus of the generating source. With a nuclear source, on the other hand, the location, time of detonation, and energy release can be accurately controlled. Thus the range of instruments can be properly set, and all instruments can be calibrated before and after the explosion. The travel-time curves then can reveal more detailed information about the structure of the earth because source uncertainties are removed. In addition, the sources can be placed anywhere, and the seismologist need not rely only on signals from active seismic areas.

An important area of the earth in which a source could be used effectively to reveal valuable information is the Antarctic, which is an aseismic* region. Press and Griggs have indicated that a nuclear detonation deep in the ice, at a depth such that there would be no release of radioactivity to the atmosphere, would yield data on the average distribution and thickness of ice, distribution of land mass under the ice, and crustal thickness information. For a sufficiently large shot (100 kt) strong signals would be received all over the world and information on inner and outer core, and other structural details could be resolved. This experiment should be done and should be conducted as an international experiment in the traditions of the IGY and of seismology.

All Plowshare nuclear shots, wherever they are fired, will be announced well ahead of time and fired at specified published times so that the seismic scientific community will be able to take full advantage of the signal.

This is by no means a complete list of possible experiments, but it will serve to illustrate the range of possibilities. The Plowshare Project as it develops can be expected to provide numerous opportunities for an increasing number of scientific experiments as well as for practical applications.

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*Not subject to earthquakes.

ACKNOWLEDGMENTS

The work summarized here was the result of efforts by many individuals in the Plowshare program from several laboratories. Many helpful criticisms and suggestions were made of the manuscript by Dr. D. J. Hughes, Brookhaven National Laboratory, and Dr. Roger E. Batzel, Lawrence Radiation Laboratory. Material was drawn freely from the reports of the Second Plowshare Symposium conducted in San Francisco on May 13-15, 1959.

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Proceedings of the Second Plowshare Symposium, May 13-15, 1959, San Francisco, California, Report No. 2:

UCRL-5675 Part I: Phenomenology of Underground Nuclear Explosions (to be published).

UCRL-5676 Part II: Excavation (to be published about March 1960).

UCRL-5677 Part III: Recovery of Power and Isotopes from Contained Underground Nuclear Explosions (to be published about March 1960).

UCRL-5678 Part IV: Industrial Uses of Nuclear Explosives in the Fields of Water Resources, Mining, Chemical Production, and Petroleum Recovery. (Available from Office of Technical Service, Department of Commerce, Washington 25, D. C.).

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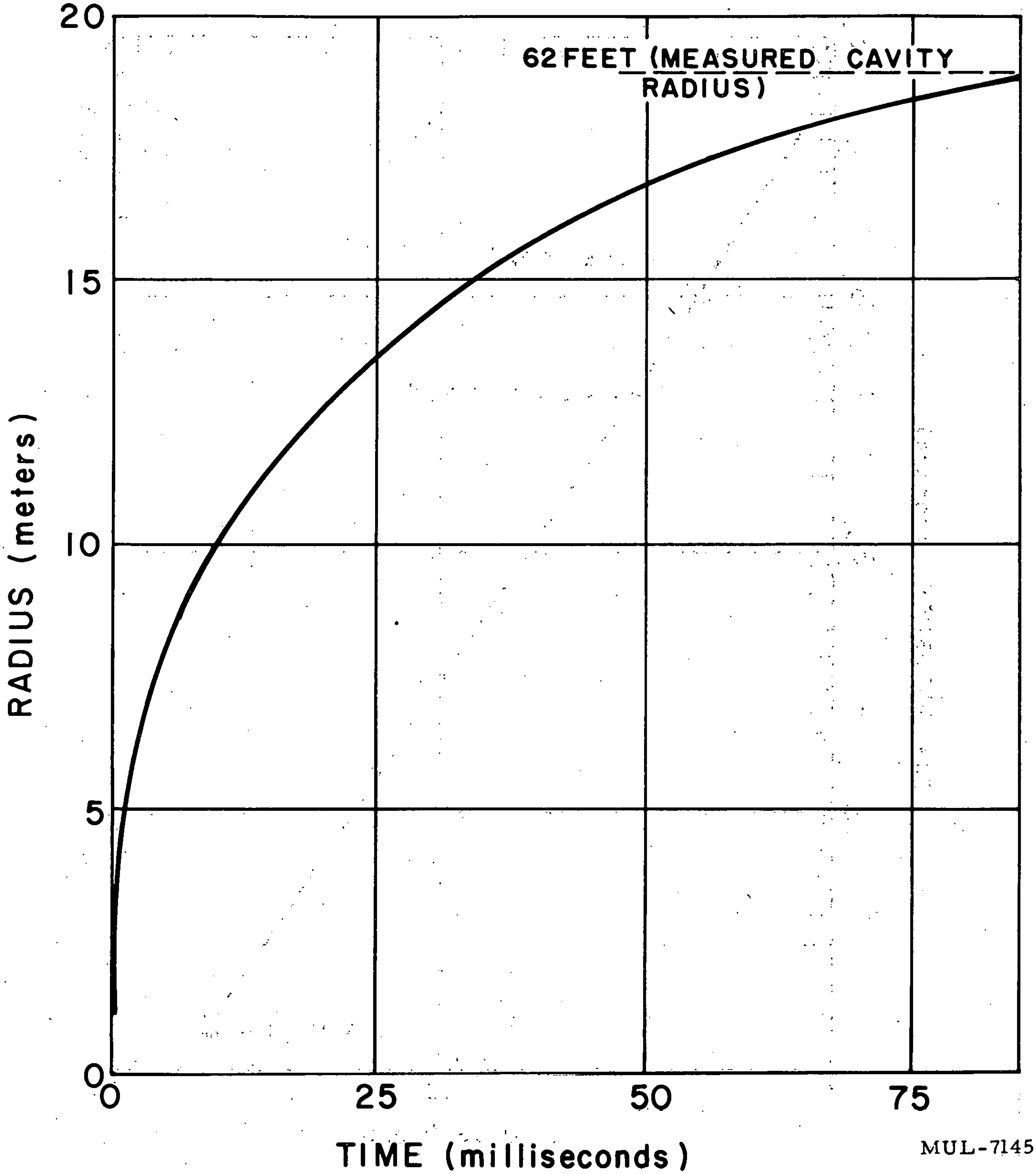


Fig. 1. Rate of growth of cavity. Rainier Event.

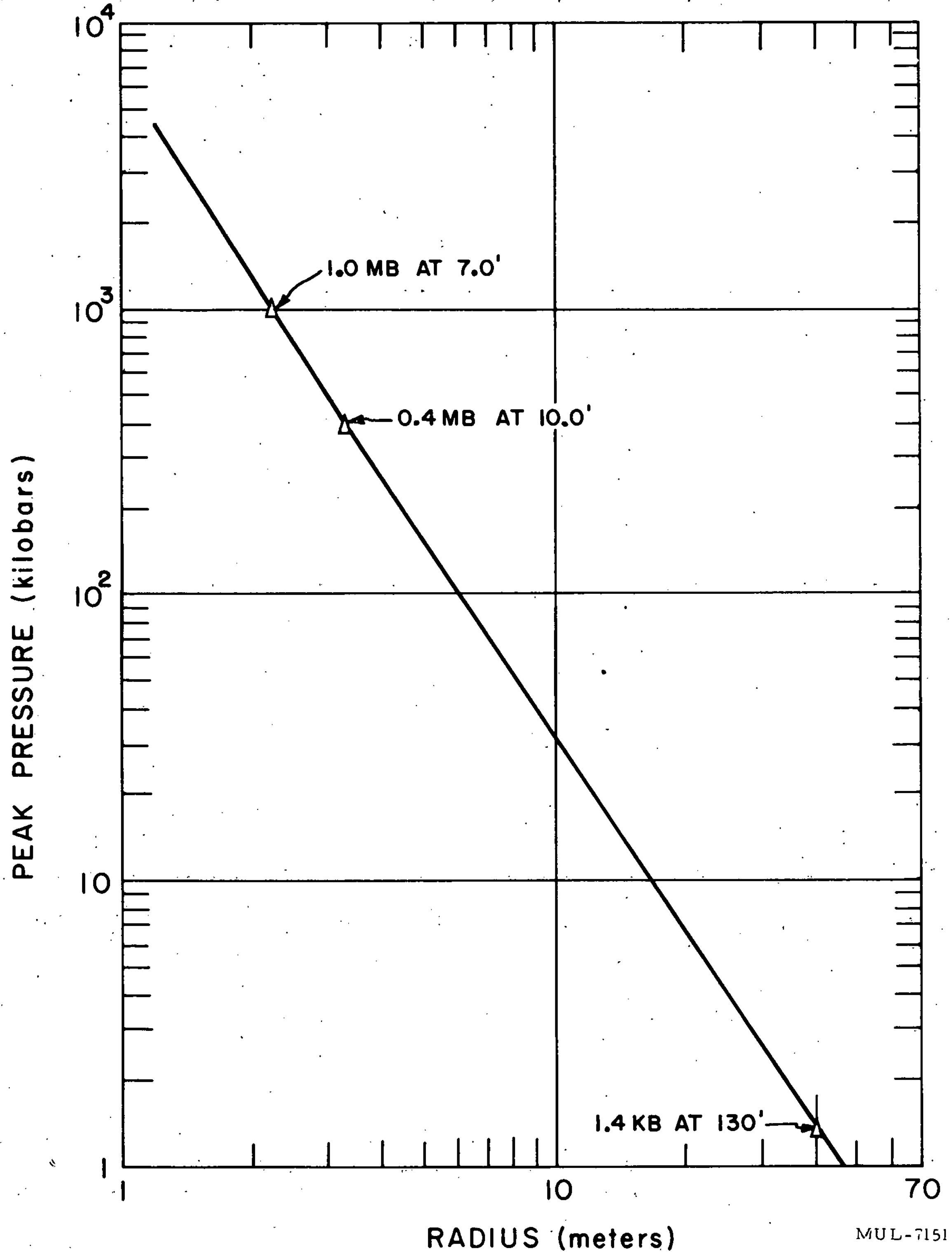


Fig. 2. Shock strength as a function of radial distance. Rainier Event.

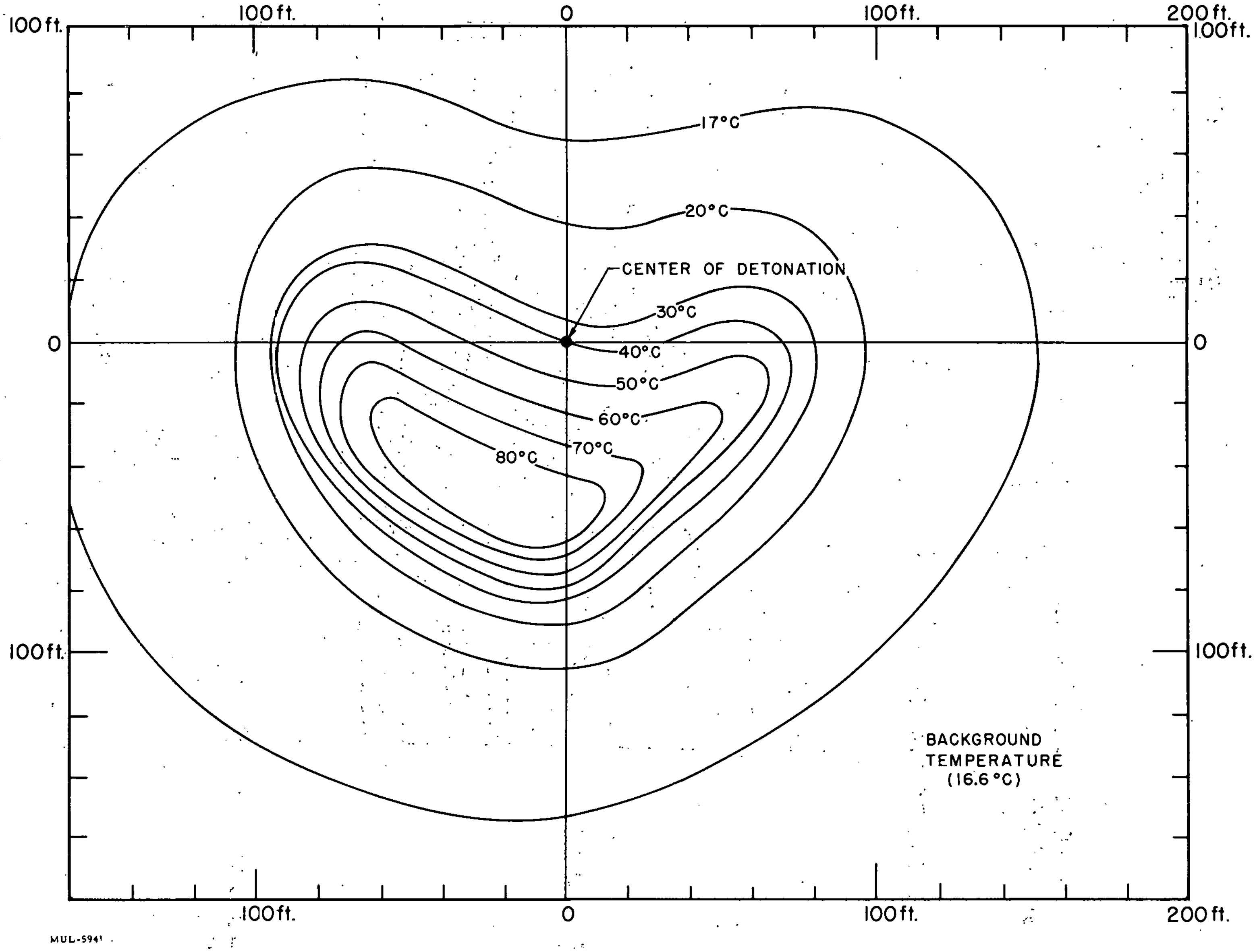


Fig. 3. Temperature distribution five months after detonation. Rainier Event.

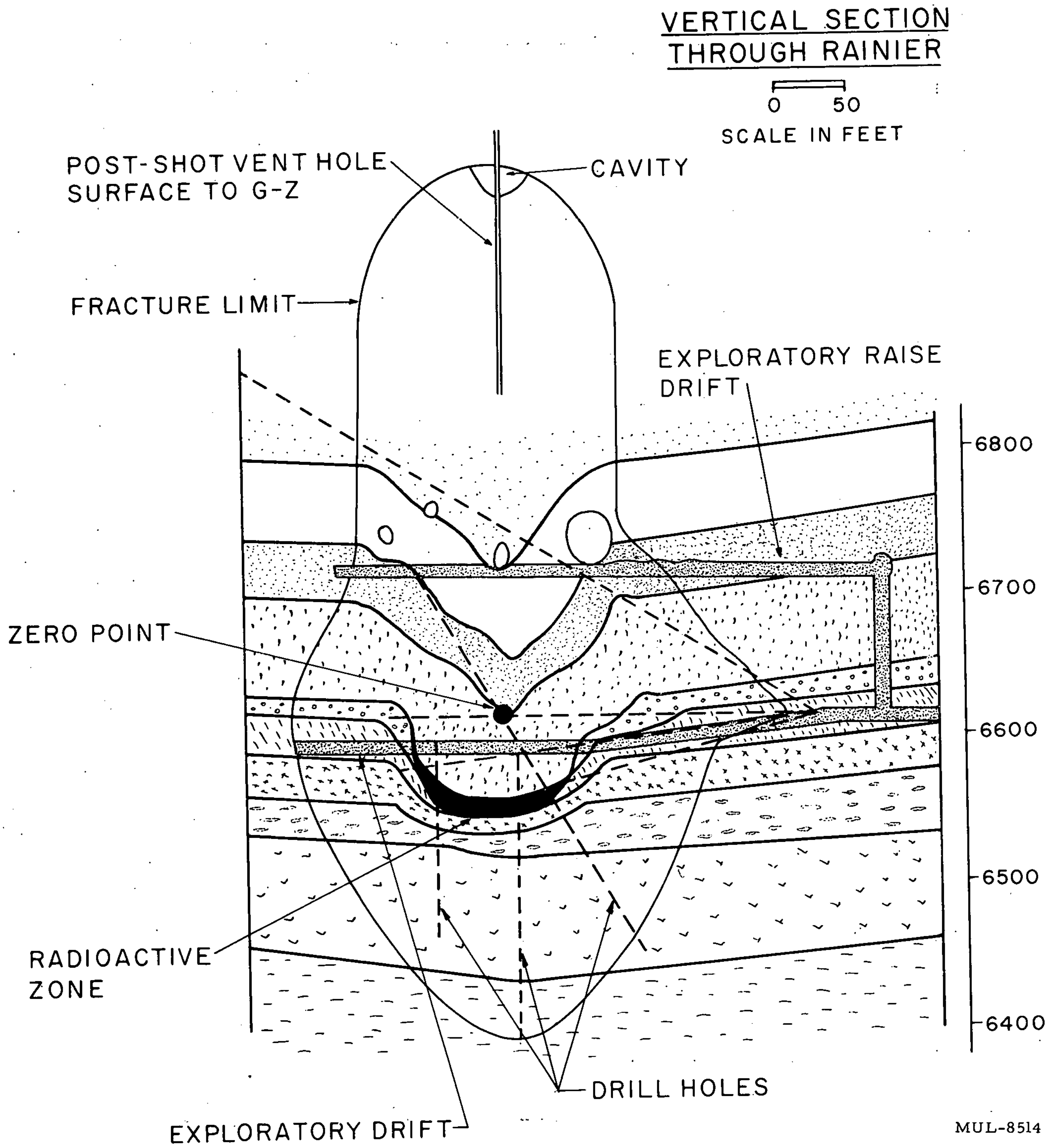


Fig. 4. Vertical section through site of Rainier Event.

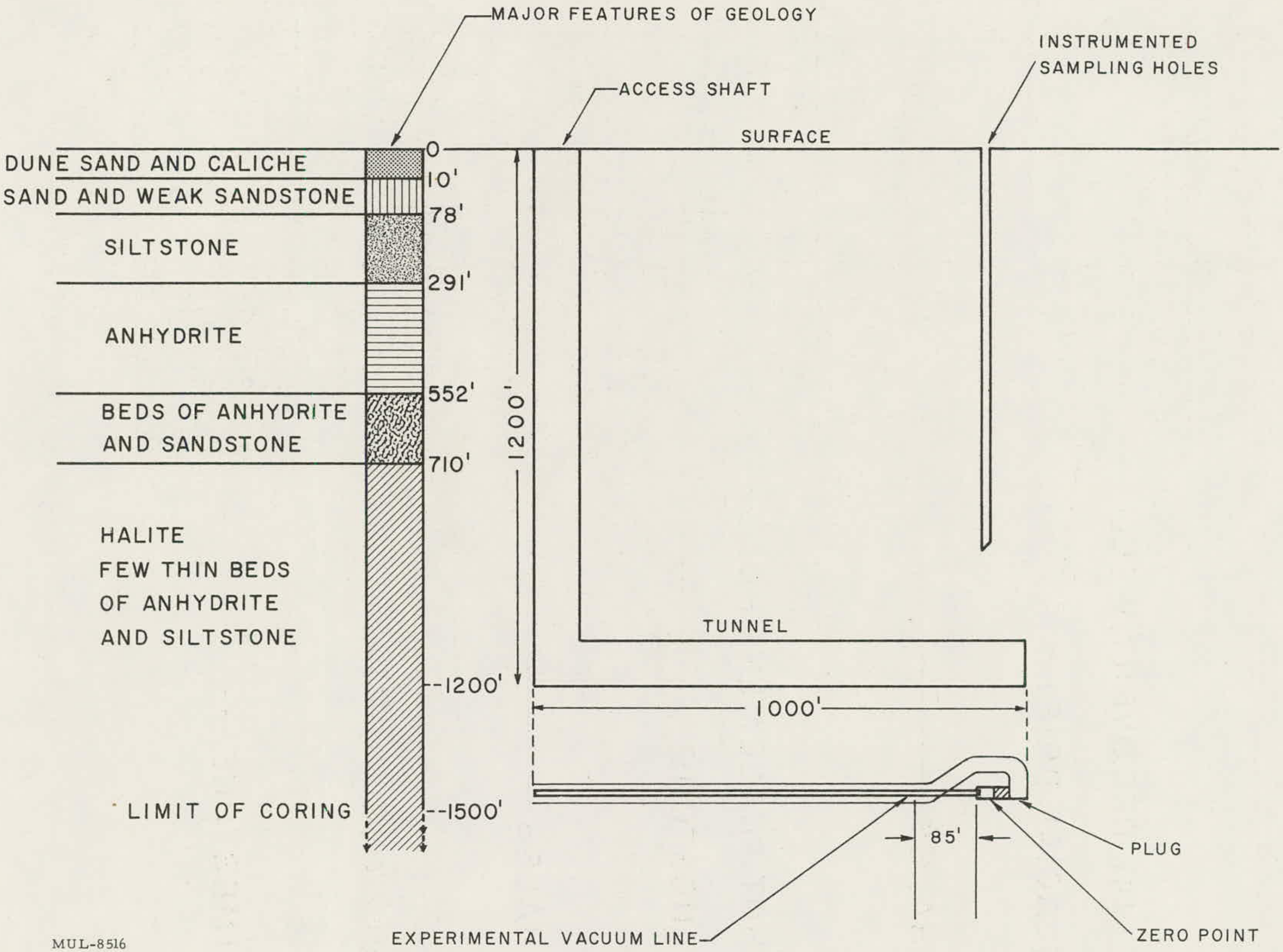
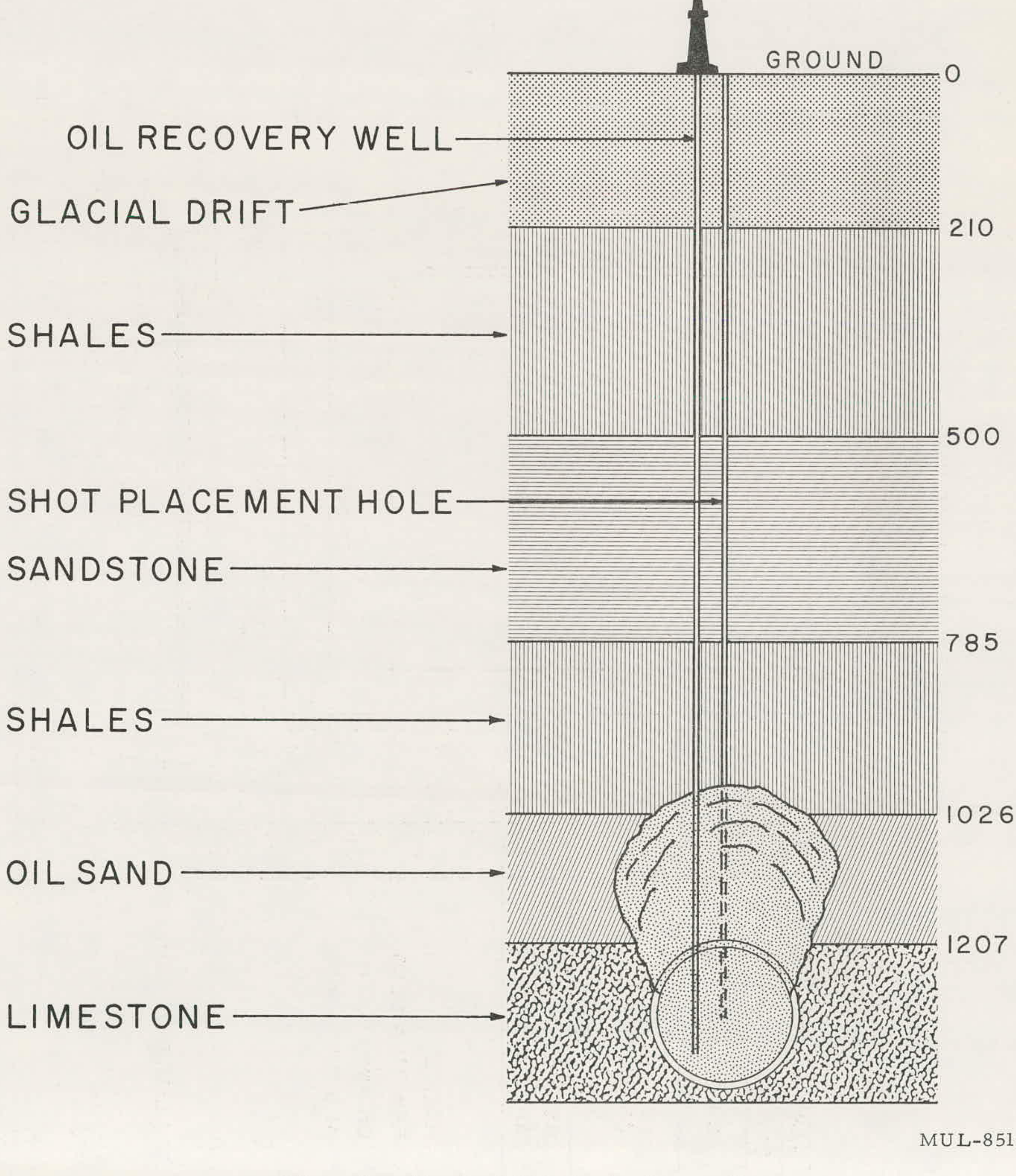


Fig. 5. Schematic layout of Gnome Experiment.



MUL-8515

Fig. 6. Project Oil Sand site section.

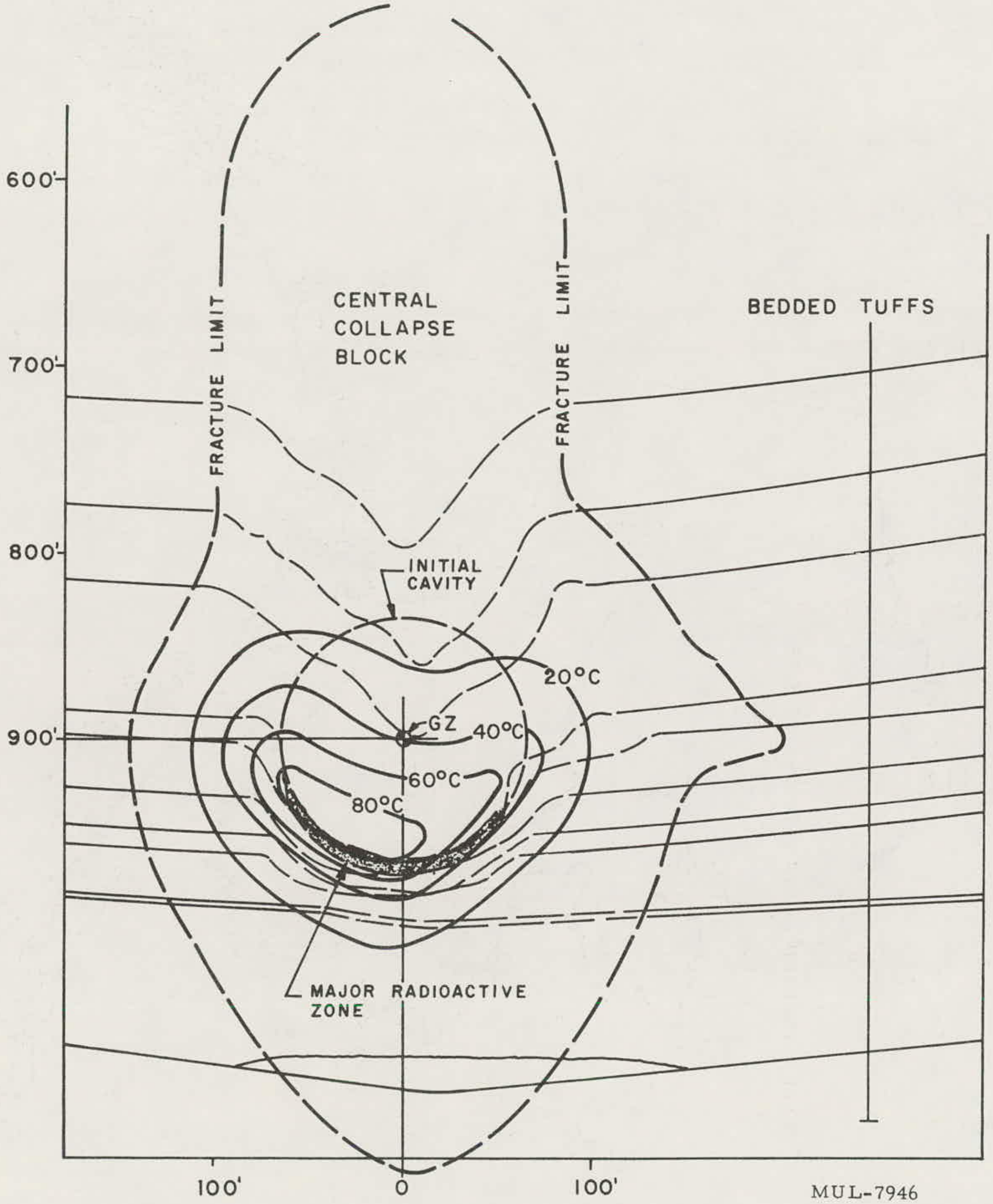


Fig. 7. Relationship of the temperature distribution to collapsed zone of Rainier.

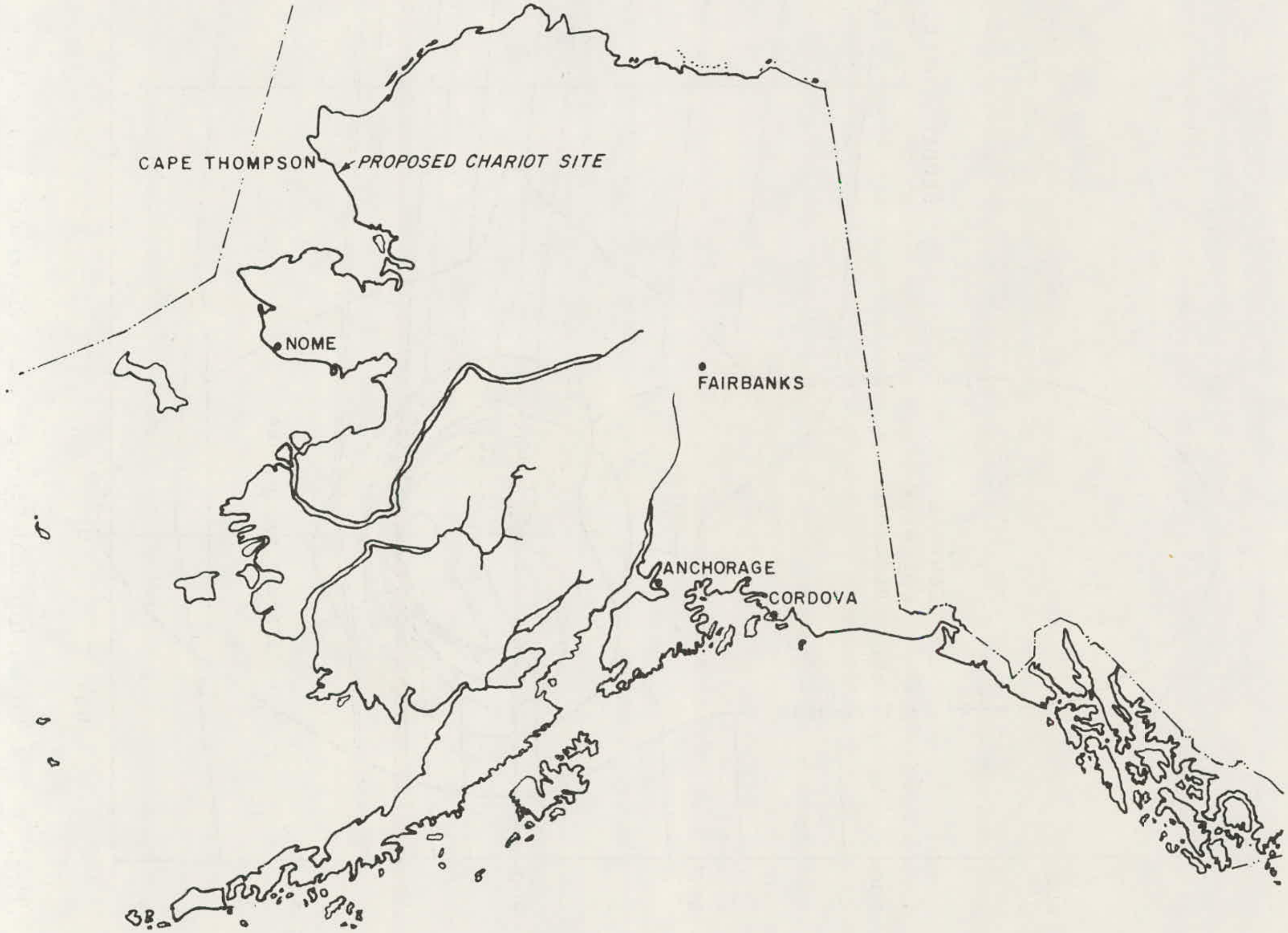


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Fig. 8. Project Chariot site location.

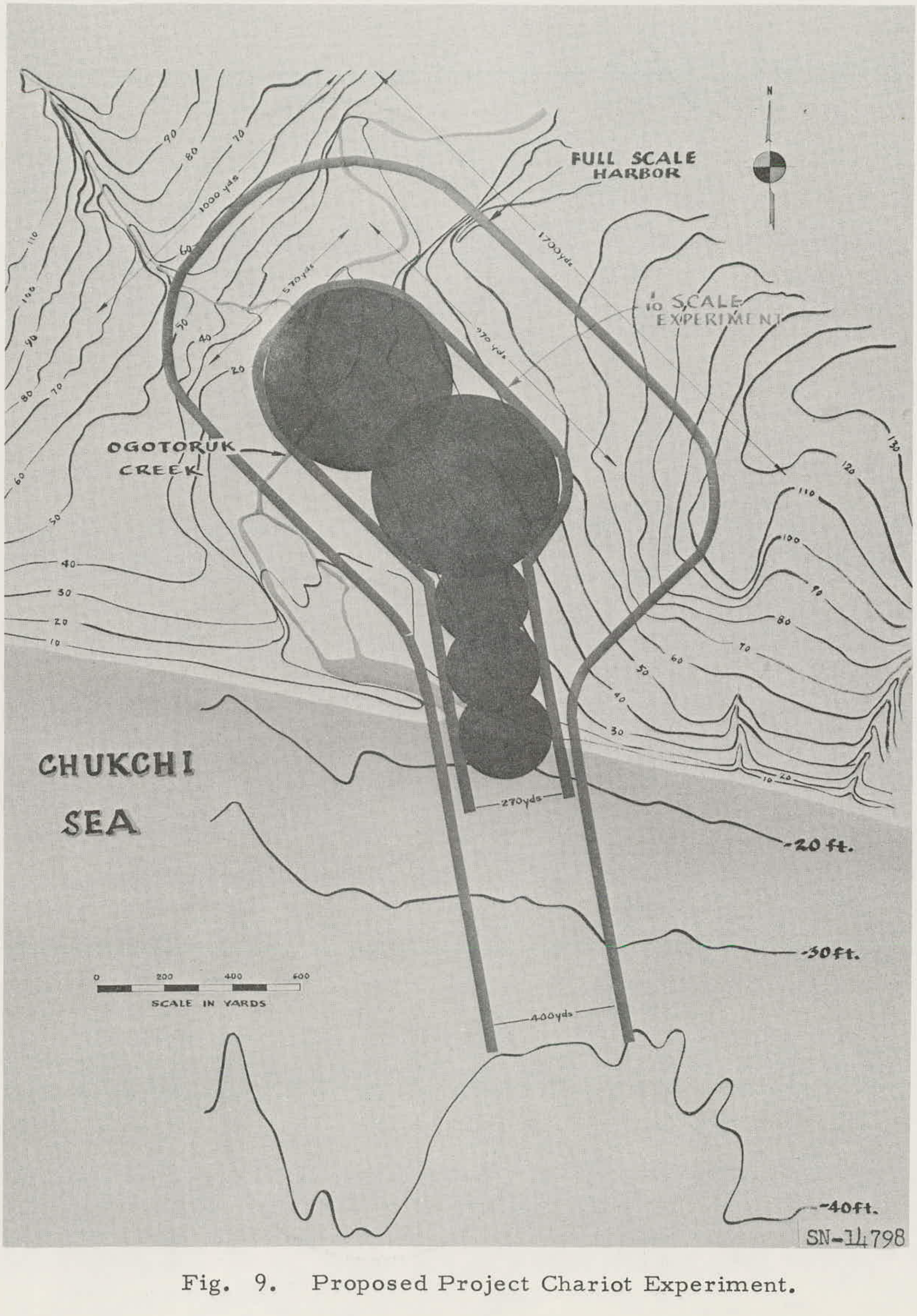

Fig. 9. Proposed Project Chariot Experiment.

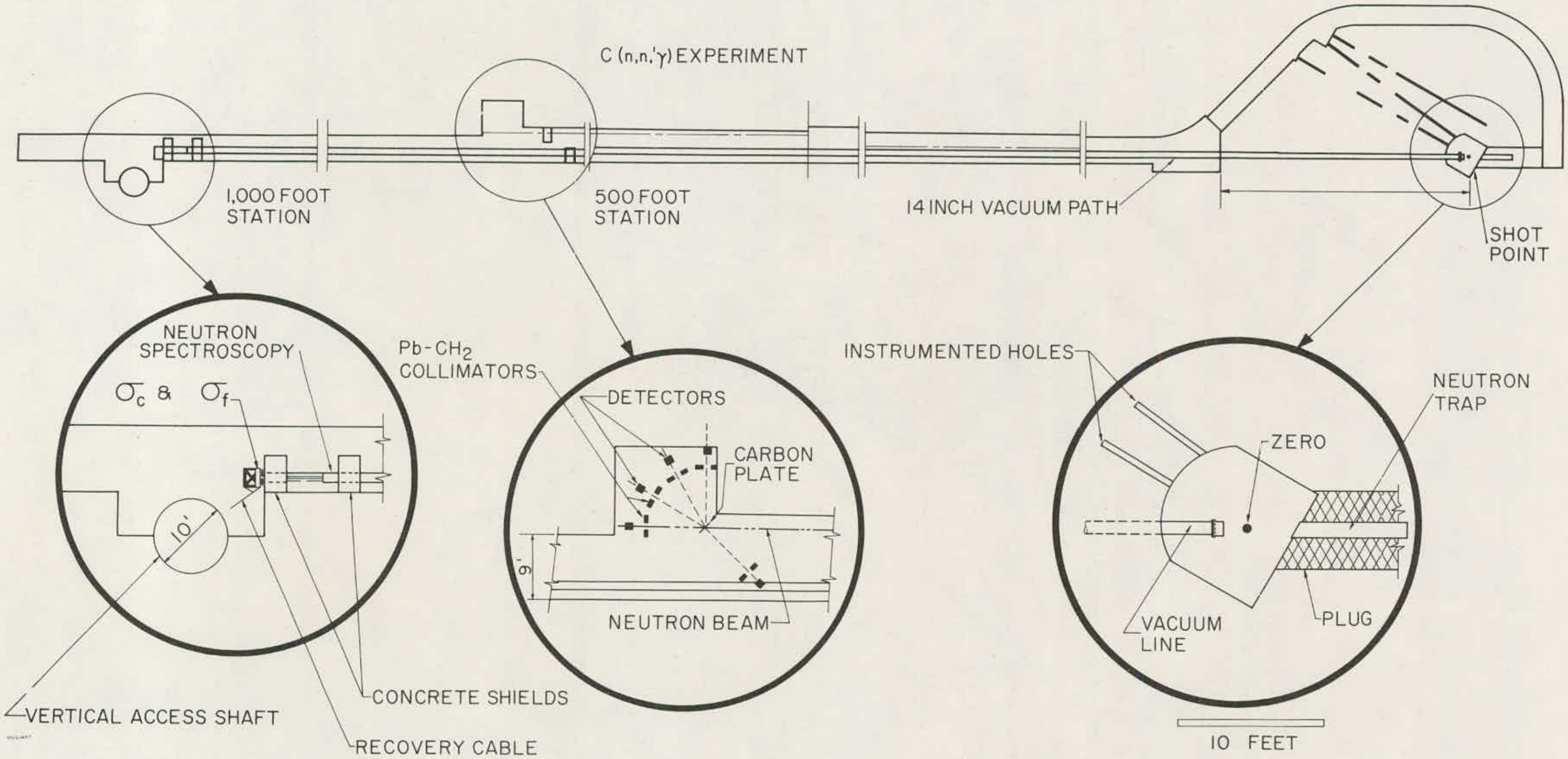

Fig. 10. Experimental arrangement for neutron measurements. Gnome Experiment.

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Report No.	Title
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UCRL-5253	Industrial Uses of Nuclear Explosives.
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UCRL-5623	Radioactivity Associated with Underground Nuclear Explosions.
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	Plowshare Series: Report No. 2. Proceedings of the Second Plowshare Symposium (Held at San Francisco May 13-15, 1959):
UCRL-5675	Part I : Phenomenology of Underground Nuclear Explosions.
UCRL-5676	Part II : Excavation.
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