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CURRENT PROBLEMS IN RESEARCH

Scientific Applications of Nuclear Explosions

Nuclear explosions are uniquely necessary for a number of interesting experiments in basic research.

George A. Cowan

In the first week in July 1959, scientists of various specialties were invited to Los Alamos to discuss the topic "Scientific Applications of Nuclear Explosions." This subject is more narrowly defined than Project Plowshare, which embraces all of the peaceful uses of nuclear explosions, with emphasis on those of predominantly economic importance. It would be very unfashionable to pass up an obvious acronym for the enterprise, and so, to distinguish the purely scientific applications, the term *Project SANE* has been used at Los Alamos.

The meeting was restricted, chiefly to permit the free discussion of design details of nuclear devices under existing information security rules. In recent months some aspects of the topic have been discussed in other reports and journals, and part of the proceedings of the Los Alamos conference has been made widely available on an unclassified basis. Probably as a result, inquiries have been received from outside the Laboratory which indicate a general interest in the subject. In addition current planning for seismic calibration tests with nuclear devices includes proposals for basic research in other scientific fields. Therefore, it seems timely to offer the following brief account of the background and current status of some of these research proposals.

Why Nuclear Explosions?

Nuclear explosions are of interest to the research scientist chiefly as uniquely intense sources of neutrons, neutrinos, plasmas, high temperatures, gamma rays, x-rays, light, shock, and radioactive isotopes. In past years, suggestions have been made periodically for experiments which exploit one or another of these properties. However, during much of this busy period the implementation of such suggestions was not extensive.

Many factors have limited scientific experiments with nuclear explosions. These have included the almost total commitment, in the past, of weapon-laboratory efforts to immediate military needs, the difficulty and expense of field operations, and the restriction of detailed information on the properties and occurrence of nuclear explosions largely to those people most occupied with weapon development. In addition, the experience of performing a complex experiment at a test site and making sure that it will work the first and, perhaps, only available time is enough to persuade most scientists to obtain their data at home in the laboratory if it is at all possible to do so. Consequently, suggestions for making such measurements have not received much attention unless they appeared to have more than ordinary significance and could be performed only with a nuclear explosion and in connection with a scheduled test. Even then, only a very few such experiments have been carried out. However, in recent years an increasing amount of time has been devoted to an examination of the constructive potentialities of these explosions, and at Los Alamos this has resulted in a serious effort to further exploit new opportunities for purely scientific investigations.

Examples of past research based on nuclear explosions help to illustrate the nature of the contribution that such devices can make. The most fundamental property of fission explosions is their ability to transform large fractions of a given element by neutron reactions. An extreme example of this effect was encountered in the 1952 Mike thermonuclear explosion, in which a significant amount of uranium-238 was more than 99 percent destroyed and products of neutron capture of up to mass number 255 were observed (*1*). As a result, radiochemists from three collaborating laboratories identified two new elements (einsteinium and fermium) and greatly expanded existing information on neutron-rich nuclides in the transplutonic region. It was noted that some features of a thermonuclear bomb resemble those hypothesized for exploding supernovae (*2*). The nuclide californium-254, with a spontaneous fission half life of 56 days, was discovered and soon became associated with hypotheses concerning the decay of light from supernovae and mechanisms for nucleogenesis. The fact that neutron-capture cross sections have to remain high even at large neutron ex-

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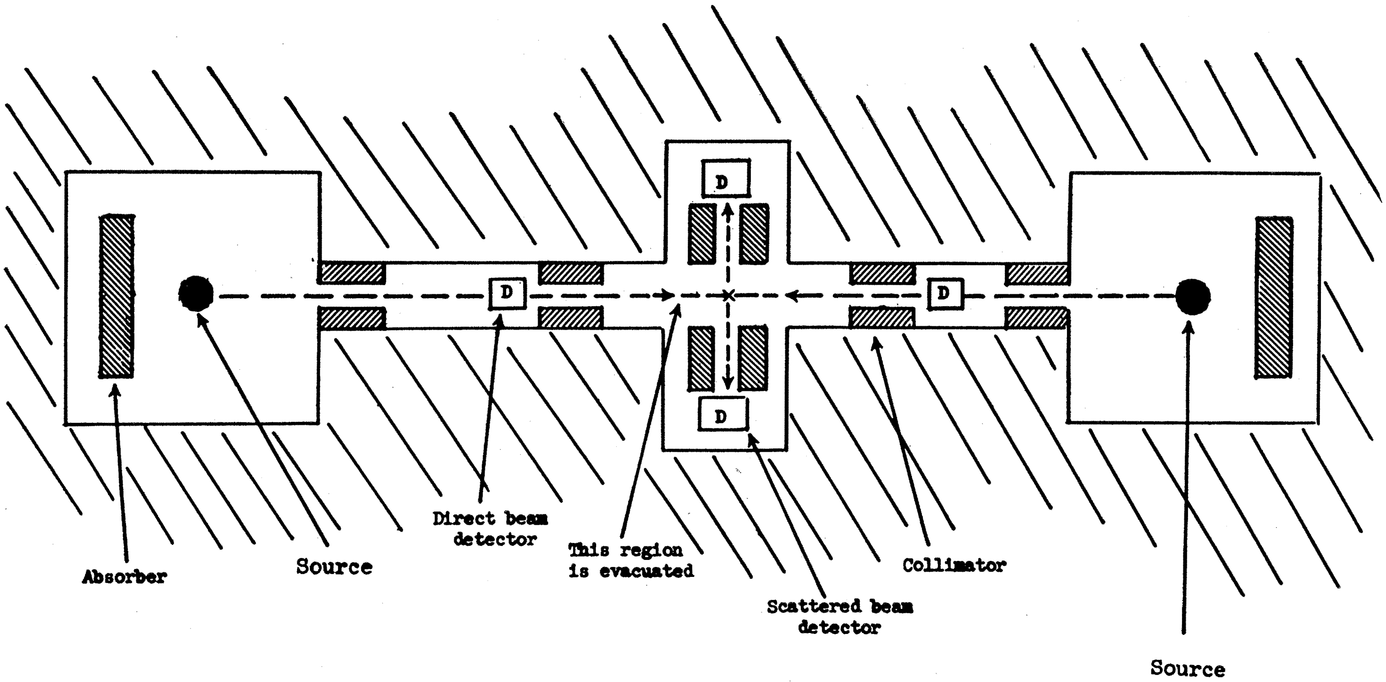

Fig. 1. A proposed method for measuring the *n-n* scattering cross section. Intersecting neutron beams from two 10-kiloton nuclear explosions in an underground tunnel are used. [W. N. Hess]

cess to produce uranium-255 in the amount necessary to account for the fermium-255 measured in the Mike explosion has led to the observation that present mass equations cannot properly be extrapolated to very-neutron-rich nuclides (*3*).

Investigation of the decay schemes of uranium-237, uranium-240, and neptunium-240 has been made possible with samples prepared from nuclear explosion debris (*4*). Similarly, samples from debris have been used to measure the fission cross section of uranium-237. The production of unique radioactive nuclides in quantity sufficient to permit measurement of the rate of world-wide fallout was effected in the nuclear devices exploded in the 1958 Hardtack program; the distribution in fallout of rhodium-102, which was deliberately produced in the very-high-altitude Orange test, is still contributing information on the transport of material deposited in the upper atmosphere. The effects of the high-altitude Argus, Teak, and Orange bursts in 1958, to the extent that they were observed, offered some stimulating data on the interaction of photon, electron, and debris fluxes with rarefied air and the geomagnetic field.

For experiments with neutrons resolved in energy by time-of-flight, an exploding nuclear device offers a very sharply pulsed source (< 1 μsec) of approximately 10^{23} neutrons per kiloton (TNT equivalent energy). This performance may be compared with that of the most advanced laboratory facility we know, which is planned to produce a sharply pulsed over-all source strength of approximately 10^{13} neutrons per second. Thus, the nuclear explosion of a 1-kiloton device is equivalent to approximately 300 years' operation of the laboratory machine. To take advantage of this tremendous flux, a bomb source of neutrons was utilized at Los Alamos during the 1958 tests to measure the symmetry of fission in uranium-235 at many individual resonances in the energy region from 10 to approximately 60 kev (*5*). The potential of this kind of experimental facility in the field of neutron spectroscopy has been enthusiastically described by Hughes (*6*).

Reviews and Conferences

Other possibilities have been considered at this laboratory. In 1957 a classified Los Alamos report was published in which A. Peaslee compiled suggestions from several staff members and consultants (*7*). These included a proposal by S. Chandrasekhar for the measurement of the time-history of excitation of an initially cold gas (for example, Ca or Fe vapor) by high-temperature radiation such as is observed in the corona and high-level chromosphere during periods of high solar activity and in the stellar envelope during a nova-like outburst. Froman and Ulam explored in a little detail the problem of using nuclear explosions for shock-tube and wind-tunnel studies. Taschek briefly mentioned a list of possible experiments, including production of large amounts of short-lived fission products and of transplutonium isotopes in milligram quantities for cross-section measurements; external target irradiations at high neutron flux; tracer experiments in meteorology; experiments of astrophysical interest involving measurements of equations of state and atomic spectra under extreme conditions of ionization, temperature, and pressure; and a study of various nuclear reactions which can be made to occur only under conditions existing in stars and thermonuclear explosions. Tuck considered schemes for observing the interaction of fireball plasmas with magnetic fields. Ulam discussed certain experiments in hydrodynamics, emphasizing the need for information concerning turbulence inside fireballs and possible techniques for producing asymmetric explosions. Interest in the latter subject was promoted by Ulam's suggestion for propelling a large space vehicle with nuclear explosions, a proposal which led to the current investigation called Project Orion.

In the spring of 1959 the Project Plowshare symposium, sponsored at San Francisco by the Lawrence Radiation Laboratory and the Atomic Energy Commission, included a program of papers on scientific experiments (*8*). The topics discussed included the use of nuclear explosions for investigations in neutron spectroscopy, multiple-neutron-capture experiments, studies of debris movement by labeling with unique tracers, scattering measurements with polarized neutrons, measurements of Schwinger scattering and neutron-electron scattering, studies of the interaction of microwave radiation with ionized air, the investigation of certain seismological questions, applications to a number of meteorological problems, and studies of interesting interactions of the products of bomb explosions with the upper atmosphere and magnetic fields.

The Los Alamos meeting provided an opportunity for a somewhat more extended and critical consideration of very much the same subject matter. Conference participants considered experiments in the fields of nuclear physics and nuclear chemistry, meteorology and upper-atmosphere physics, "space" physics, hydrodynamics, and solid-state physics. The roster of invited guests included experts in each of these fields, in order to provide informed comment on the various proposals. Usually rather long discussions followed each talk or group of talks on a given subject. Occasionally there seemed to be general agreement concerning the special merit of a proposal. Most of the talks are summarized in the following paragraphs, although classified details are necessarily omitted.

Experiments in Nuclear Physics and Chemistry

The measurement of the *n-n* scattering cross section seems achievable if nuclear explosions are used as a neutron source. Wilmot N. Hess described the results of some calculations on a possible experimental arrangement (Fig. 1). Two underground 10-kiloton explosions, detonated simultaneously at stations 60 meters apart, would be arranged so as to provide intersecting, collimated neutron beams, and the scatters would be observed as a function of time at right angles to the beam. A precision measurement of scattered neutrons in the energy region 1 to 5 Mev seems feasible if the background from neutrons multiple-scattered into the detectors from walls can be eliminated. Thermalization of the neutron beam to 10 kev is conceivable, but the background problem will get worse. The significance of this measurement is that if charge independence and charge symmetry of nuclear forces are violated, or if effects like the dipole interaction of magnetic moments hypothesied by Schwinger are significant, then the *n-n* singlet scattering length may be expected to differ from the corresponding *p-p* singlet scattering length by a small amount. Doubts were expressed during the discussion about the tractability of the background problem.

The search for improved resolution in neutron spectroscopy and the contribution that can be made by nuclear explosions were described by the late Donald J. Hughes (Fig. 2). Neutron spectroscopy provides a detailed view of the levels in many nuclei in a narrow band (approximately 1 kev) at an excitation slightly above the neutron binding energy (5 to 8 Mev). In this excitation band the level spacing is typically a few volts for medium-weight elements. By measurement of resonances in neutron cross sections, it is possible

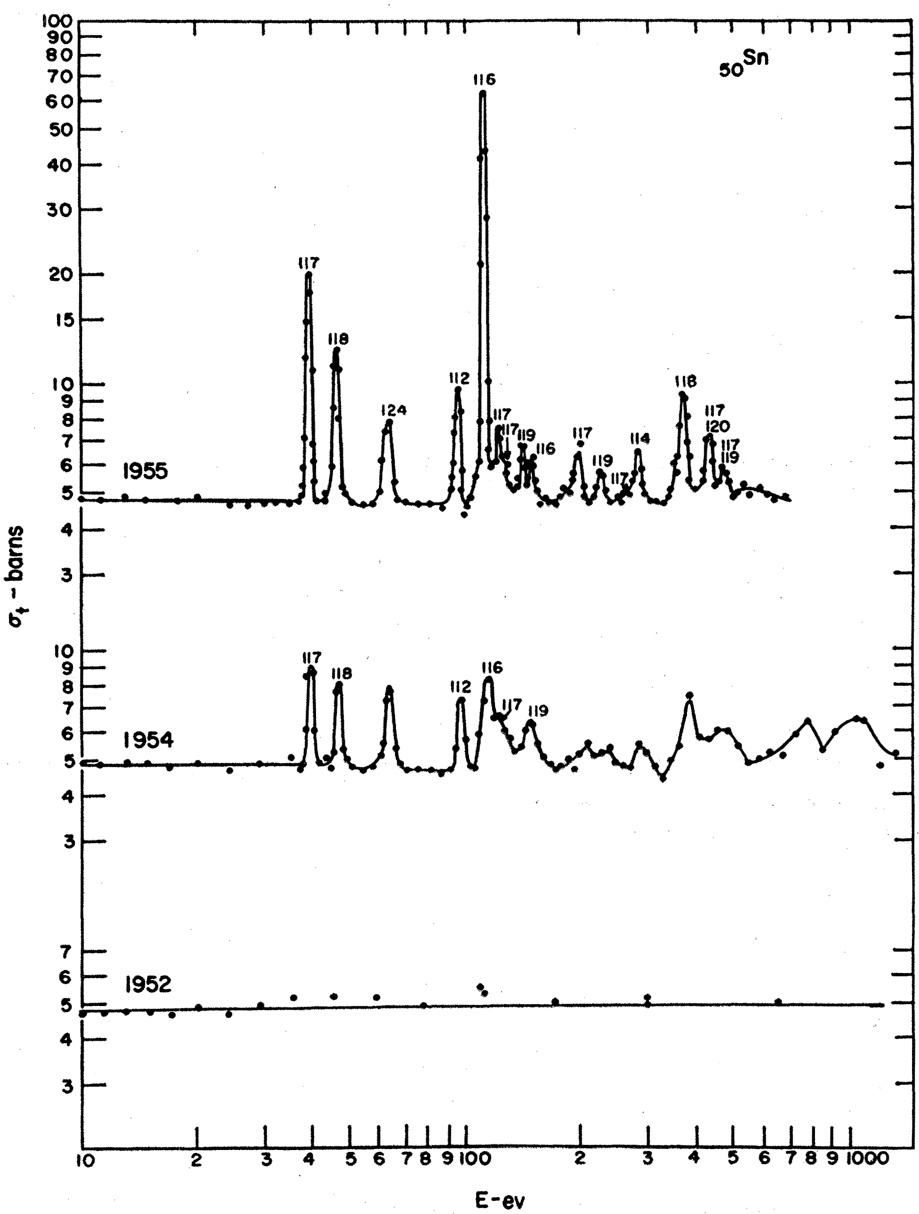

Fig. 2. Improved resolution in neutron spectroscopy is illustrated by the changes in the measured cross section of tin between 1952 and 1955. The use of nuclear explosions as pulsed neutron sources can provide another large increase in resolution. [D. J. Hughes]

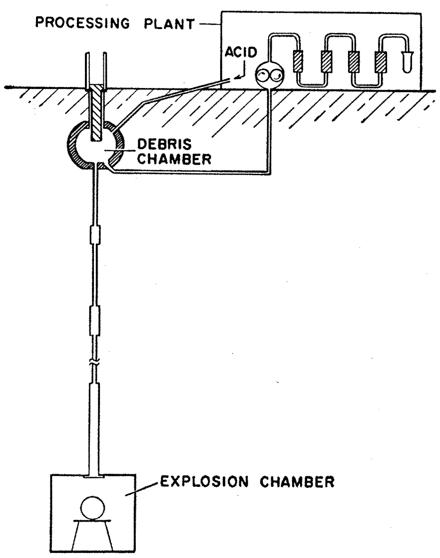

Fig. 3. Underground nuclear explosions can be designed to produce new elements by multiple neutron capture on uranium or plutonium. A processing plant on the surface would quickly recover and chemically identify new nuclear species. [G. A. Cowan]

to determine total level widths, partial widths for various modes of de-excitation, level spacing, and level spins. These results have played an important part in the development of nuclear theory. It has been demonstrated that nuclear explosions will provide external neutron fluxes many orders of magnitude greater than those presently available, or planned, from laboratory sources. No insurmountable experimental problems are foreseen in the use of explosions for making all neutron spectroscopy measurements of interest, with the exception of gamma-ray coincidence measurements. Some experiments which might be performed first with such sources would be a really complete analysis of the resonance behavior of uranium-233, uranium-235, and plutonium-239 in the resonance region. Hughes suggested that about two 10-kiloton neutron pulses a year could provide all the source strength needed for his own experimental program.

In a classified paper Edward Teller described a theoretical approach to the problem of maximizing exposure of a given target element to neutrons. Teller suggested an underground experiment in which a relatively small yield device would produce, at a minimum, 1 microgram of product of mass number 259 and a detectable amount of product of mass number 261.

I presented a classified paper in which it was disclosed that, just prior to the test moratorium, Los Alamos had already begun an experimental effort designed to produce new heavy elements. An existing weapon test in the 1958 Hardtack series was slightly modified to include a region of high neutron flux. Failure of a vital component spoiled the experiment, and further work on the program was terminated by the moratorium. However, it seems quite clear that, with presently known and tested designs, detectable quantities of elements of mass number greater than 260 can be made in devices of relatively low total yield. To avoid atmospheric contamination and to permit rapid recovery and processing of a significant fraction of the debris, it is desirable to explode such devices underground (Fig. 3). Multiple-capture products of the heavy elements can be built by long-term bombardment in piles, but the element-building process is terminated as soon as the lifetime for spontaneous fission and other modes of decay becomes short compared with the lifetime for neutron capture. Heavy-ion bombardments offer a means of building elements of high atomic number, but the products made in this way will always be on the neutron-poor side of greatest element stability rather than on the neutron-rich side. Thus, the thermonuclear explosion can provide a unique insight, otherwise unobtainable, into what is presently believed to be a principal cosmological element-building process.

The extrapolation of known decay and spontaneous fission systematics to unknown, new elements of very high mass number has been used to predict the half-lives of these nuclides and to help identify them. J. D. Knight summarized some of the predicted properties of the undiscovered elements. On the basis of the usual empirical extrapolations, little hope exists for chemically separating and identifying even-even nuclei of mass much greater than 256 or odd-mass nuclei of mass much greater than 259 or 261. This implies an effective limit on building elements in this way at about element number 102. The limit is imposed by the apparent exponential increase of spontaneous fission probability with increasing mass. However, no basic reason is known for excluding the possibility that a region of increasing stability exists, and one might hope to find elements with longer lifetimes before reaching the ultimate limit of successive neutron captures by uranium at about mass number 276, or by nuclei of higher atomic number at even greater mass number. [Indeed, recent work (*9*) indicates the possibility that even at an atomic number of 106, the half-life for spontaneous fission will be many years.]

Meteorology and Upper-Atmosphere Phenomena

L. Machta discussed the two prime applications of nuclear explosions for research in meteorology—to produce tracer activity and to affect the atmosphere by heat or ionization. Studies of transport of radioactivity from previous tests have strongly supported the suggestion that north-south circulation exists in the stratosphere. Some questions which might be studied in the future concern the paths of specific air currents in the stratosphere, the chief regions for injection of stratospheric air into the troposphere, the principal transport mechanism in the stratosphere, and the nature of the "cross wind" transport in the vicinity of the jet stream. Heat from nuclear explosions may be used to study two problems of interest in meteorology—the rise of hot gas bubbles and the effect on the atmosphere of a disturbance convection in the presence of natural convection. Radiations from nuclear explosions also change the electrical conductivity of large masses of air over great distances. Possible important effects of such disturbances have not yet been studied under controlled conditions.

In a paper which remains classified because of some weapon-performance data, E. A. Martell reviewed what is presently known about the mixing history of nuclear debris in the stratosphere and the rate and extent of fallout. He emphasized the need for information concerning debris storage times for altitudes up to several earth radii, and the use of nuclear explosions to supply tracers for these measurements. He also pointed out that, in order to limit fallout, studies in the lower atmosphere might be made with short-lived radioisotopes in small quantity or with naturally occurring sources of radioactivity.

In a group of three classified papers, the phenomenology of the Teak and Orange shots (megaton yield devices exploded in midsummer of 1958, at altitudes of 252,000 and approximately 100,000 feet, respectively) was described, and the scientific questions concerning upper-atmosphere physics which might be answered by similar experiments were catalogued. For instance, Herman Hoerlin pointed out that many aspects of natural auroral phenomena can be simulated by nuclear explosions. Of particular interest would be the extensive observation of the interaction of debris particles with fields in space, with the geomagnetic field, and with the upper atmosphere, and observation of the effects on the radiation belts. Thomas B. Cook, Jr., evaluated the scientific return from a low-yield device exploded at the edge of the atmosphere (Fig. 4). Since energy deposition occurs in three distinct zones of the atmosphere, and at three well-spaced times, from x-ray, neutron and gamma-ray, and debris-particle interactions, respectively, the separate excitations can be studied in considerable detail, preferably by land-based optical instrumentation. Philip L. Randolph presented a detailed theoretical description of the effect on the ionosphere of one megaton of x-ray energy released at 10^5 kilometers from the earth and at the moon. Measurement of the dependence of reflection of various radio frequencies on time and altitude would produce valuable information on the mechanism of recombination of electrons and the decay rate of a perturbation in the ionosphere.

Physics in Space

Two talks were delivered on some possible effects which might be observed as the result of bomb explosions in outer space. Thomas Gold expressed an interest in studying shock waves in space when the input is exactly known. In the vicinity of the sun, shock waves are accompanied by a narrow-band radio noise corresponding to the plasma frequency. Observation of a similar phenomenon in a bomb explosion would add important information to what is presently known about this unexplained effect in solar physics. The possibility of disturbing the geomagnetic field and letting otherwise unobserved particles in space reach the earth, the production of phenomena similar to "whistlers," and uses for the sharp pulse of light or of radio frequencies from a bomb as a radar device were also mentioned.

C. L. Longmire called attention to the probable stability of the bomb debris as a plasma cloud in space and discussed some of the interesting properties of such a cloud. Possible hydrodynamic, hydromagnetic, and radiation-pressure mechanisms exist for accelerating plasma particles in space to really high velocities. Plasmas from two bombs colliding will probably produce turbulence and a magnetic field where none existed before. Hydromagnetic shocks may also be produced by such explosions, and it would be interesting to study their structure. A careful measurement of the electromagnetic signal could conceivably provide information concerning the magnitude of the field in space, particle density, and temperature. In connection with the possible acceleration of bomb debris by radiation pressure, Andrew Skumanich presented calculations which indicated that this mechanism would be unimportant by comparison with hydrodynamic acceleration.

Some novel suggestions were made for using the vacuum and limitless distances of space as a physics laboratory for measuring some of the fundamental physical constants with greater accuracy than would be possible in a terrestrial laboratory. Freeman Dyson explained that a very accurate measurement of the lifetime of the free neutron would help test the validity of various ideas concerning a universal theory of weak interactions between elementary particles. If two rocket-borne neutron detectors a few thousand kilometers apart measured the neutron flux from a nuclear explosion in space, attenuation of the flux would occur because of neutron decay during flight between the detectors. In principle, a highly precise measurement of the

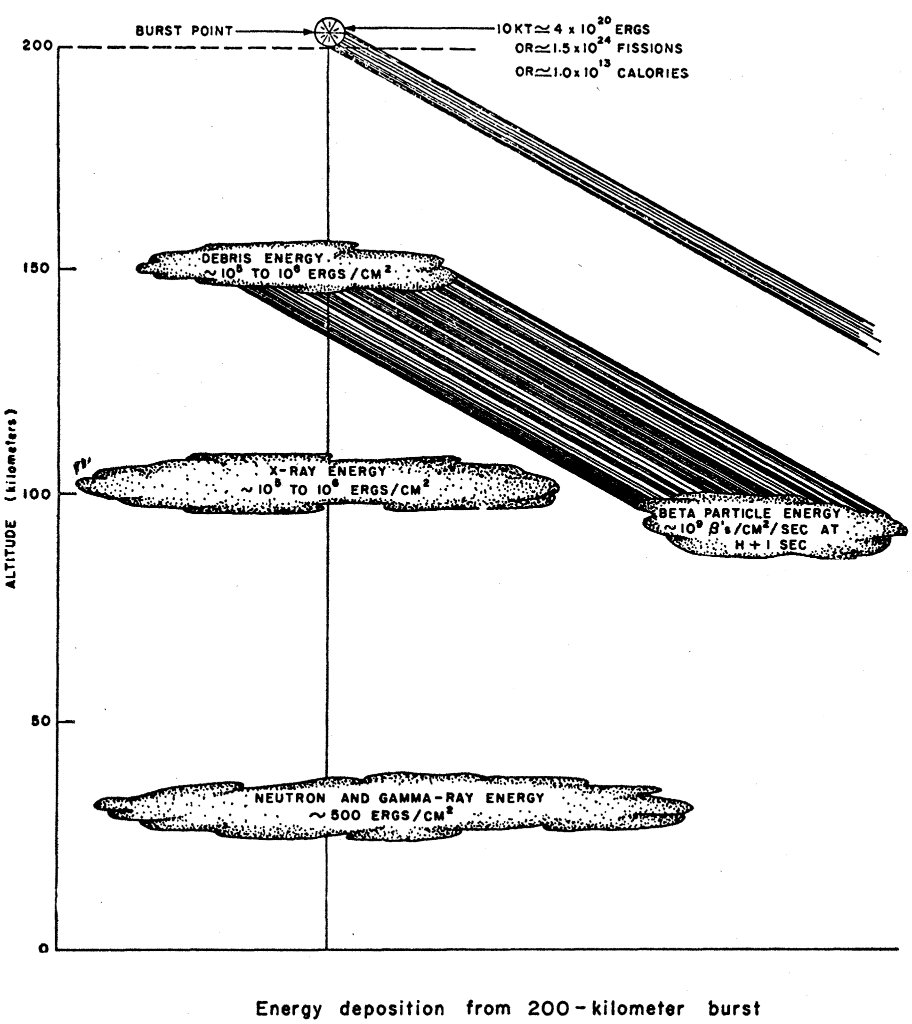

Fig. 4. A 10-kiloton nuclear explosion at the edge of the atmosphere produces x-ray, neutron and gamma-ray, and debris particle interactions with air in three distinct zones at three different times. [T. B. Cook, Jr.]

decay time of the neutron could be made in this way. In a proposal based on a similar idea, Robert K. Squire suggested that the velocity of various frequencies in the electromagnetic spectrum might be measured by time-of-flight of photons from a nuclear explosion at about 10^6 kilometers from the earth. It was stated that the precision of the measurement would be greater by three orders of magnitude than the precision of present data, and the frequency range greater by approximately six orders of magnitude.

Hydrodynamics and Solid-State Studies

Dyson presented a scheme for containing nuclear explosions of up to 50-kiloton yield inside a box on the surface of the ground. Explosion of a large amount of dust, arranged to coincide with explosion of a nuclear device, could provide an efficient heat-sink for the nuclear energy. Heavy plates moving outward into a system of gasbags would take up the first impulse on the walls of the box, and the rapid drop in temperature of the gas would limit the duration of the initial high-pressure pulse to 1 millisecond. The cost of the structure might be several tens of millions of dollars.

Ulam described some hydrodynamic effects which could be initiated by nuclear explosions. He urged investigation of the possibility of producing ionized jets of very high velocity from "shaped" nuclear devices analogous to shaped high-explosive charges and discussed other ideas for the production of asymmetric explosions which could lead to a more efficient utilization of nuclear energy for propelling large space ships. He also suggested that many of the hydrodynamic phenomena in the explosion of a nuclear device might resemble those which accompany the explosion of a supernova and should be studied for their relevance to this problem in astrophysics.

G. J. Dienes offered some notes on the use of very high rates of irradiation with fast neutrons in the study of radiation effects on solids. For many known radiation effects, theory indicates a strong dependence on flux. One would like to produce at a given temperature a certain concentration of defects in a pulse no longer than about 10^{-4} second and study the subsequent motion, disappearance, and aggregation of these defects. Integrated exposures of 10^{17} neutrons per square centimeter, or higher, would be desirable. The use of such a source for investigating the annealing mechanism in metals, enhanced diffusion in metals, solid-gas chemical reactions, and some other phenomena of importance in the study of solid-state problems was discussed.

Some General Observations and Conclusions

Do any of these proposals merit serious consideration? The answer must be based on a difficult mixture of scientific and economic arguments, which the Los Alamos conference tried in part to anticipate, taken together with political arguments, which each reader will supply for himself.

On the affirmative side, one may conclude that some interesting and valuable scientific observations are uniquely available if nuclear explosions may be used for research, and that undoubtedly more thought will reveal more such possibilities. In many cases, radioactive contamination can be minimized by carrying out the experiments underground. In order to provide assurance against evasion of a possible test ban agreement, it should be feasible to conduct at least some of the experiments on a completely unclassified basis and actually increase the opportunities for cooperative research on an international scale.

Some of the nuclear explosions presently in the planning stage for purposes of improving seismic detection, or in connection with other Plowshare Program experiments, can also be used for purely scientific measurements. Perhaps the most easily realized and generally understood scientific use of a nuclear explosion is as a neutron source for external bombardments. If present ideas are carried out, the Project Gnome event (a 5-kiloton nuclear explosion in a salt dome near Carlsbad, New Mexico) will serve as such a neutron source for four sets of physics experiments performed by scientists from several Atomic Energy Commission laboratories. All of these will be experiments with energy-resolved neutrons to investigate various neutron-capture cross sections, the total cross section and fission cross section in several heavy elements, and the basic fission process. These and similar efforts will provide further opportunities to gage the potential usefulness of nuclear explosions in research (*10*).

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10. This study was made under the auspices of the U.S. Atomic Energy Commission.