UNDERGROUND NUCLEAR EFFECTS I

SUMMARY OF GEONUCLEAR EFFECTS

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I. INTRODUCTION

Geonuclear effects are considered here to include all of the interactions between underground nuclear explosions and the surrounding earth material. They constitute a large spectrum of effects that starts with the complex chemistry of the explosion "fireball" and continues in space until the teleseismic signals in the earth have attenuated and in time until the radioactive products have decayed. This paper does not treat the total spectrum but is restricted to those effects which are of direct use to possible nonexcavation engineering projects and the major side effects that could detract from the use of nuclear explosions for such projects. Emphasis is given to possible methods of enhancing the desired geonuclear effects and minimizing the deleterious ones.

Those who have directly participated in developing nuclear explosive technology cannot help but be impressed by the terrific potential for useful work associated with this energy source. Those who have viewed this developing technology from the periphery (the potential industrial market, the concerned public, and specialists in many allied fields) are certainly interested in the potential benefits but cannot help but be impressed by the attendant risks.

Figure 1 illustrates schematically some of the useful geonuclear effects balanced against the associated side effects. More experience and increased knowledge of these effects will affect both project costs and public opinion. These factors will determine how the balance will tilt in relation to specific nuclear explosion engineering projects.

II. GEONUCLEAR EFFECTS

Since this is a very general discussion of geonuclear effects associated with potential engineering applications, oversimplifications and generalities are made which reflect the author's judgments. Exact treatment of the "pros and cons" of geonuclear effects should be restricted to specific applications and specific sites.

2.1. Useful Geonuclear Effects

A considerable amount of theoretical and experimental data and experience exists in this area. Development and engineering can help translate this knowledge into an applied technology. The author believes that this goal will be advanced with increased emphasis on developing methods to enhance the useful effects and control and/or minimize the adverse side effects.

2.1.1. Void Volume

Void volume generated by varying nuclear explosive yields at different depths and in different rock materials can generally be predicted to within about 50% of subsequent measurement if the major element rock chemistry, bulk density, porosity, and percent water saturation are known. With more refined equation-of-state data and strength properties of rock, or previous experience in very similar material, predictions of void volume are within 20% of measured values.

Storage applications are probably most dependent upon knowledge of the void volume produced. Depths for such applications are in the region from 3000 to 5000 ft for natural gas storage (to take advantage of the nonideal compressibility of methane).

There appears to be significant potential for enhancing the cavity volume at a given explosive yield by boosting the working gas (rock vaporized by the explosion) with water added at the time of explosive emplacement. The cavity volume variation as a function of water content can be estimated as follows:[1]

$$V = \frac{RT\,Wm_v}{P\bar{M}}$$

where V = cavity volume in ft^3,

R = gas constant, 2.9×10^{-3} atm-ft^3/mole-$^{\circ}K$,

T = vaporization temperature of SiO_2 at P in $^{\circ}K$,

P = overburden pressure in atm,

W = yield in kt,

$\bar{M}$ = average molecular weight of SiO_2/H_2O gas at T and P in g,

m_v = mass of vaporized rock, 90×10^6 g/kt.

Solution of this equation for Gasbuggy at a 4240-ft depth, a 297-atm overburden pressure, 26 kt, and varying water content of the vaporized rock is summarized as follows:

5% water by wt . . . 2.1×10^6 ft^3 cavity volume
11% water by wt . . . . 2.5×10^6 ft^3 cavity volume
50% water by wt . . . 4.5×10^6 ft^3 cavity volume

The example illustrates the magnitude of potential void volume enhancement with water. Surrounding the explosive with water can also virtually eliminate neutron activation that would otherwise occur from interactions with rock. Production of tritium from deuterium in water is about a factor of 10^{-6} below tritium production from lithium in rock.[(2)]

The engineering methods of producing the space to emplace large quantities of water around the explosive have not been demonstrated. This space may be produced by a combination of underreaming of the emplacement hole, hole expansion and breakage with chemical explosives, and special drilling techniques to remove rubble from the expanded hole. The emplacement concept is illustrated in Fig. 2.

2.1.2. Fragmented Rock

Fragmented rock is defined as that material which has been broken and bulked as a consequence of an explosion. This would be the chimney rubble for deeply contained explosions. The accuracy with which tons of rock broken from single, deeply contained charges can be predicted is roughly proportional to the accuracy of predicting chimney height (assuming the cavity radius can be anticipated with a small error). Without previous experience in a very similar geologic setting or other experimental work, it is possible that predictions could be off by a factor of two or more.

Some qualitative statements can be made about chimney development:

1. Rock that is characterized by high density, low porosity, high strength, and brittle failure will tend to bulk significantly upon breakage and chimney development. This will result in a chimney height equal to or less than the radius of fracturing by the explosion.

2. Rock that responds plastically will not chimney appreciably (for example, salt). However, if the material has a low arch strength, it will form a tall chimney without a large amount of bulking and will chimney higher than a radius fractured by the explosion.

3. Other factors being equal, the chimney height will be less with deep scaled depths of burial for the charges.

4. Other factors being equal, taller chimneys will develop with large yields (greater than 100 kt) because few materials in nature can support the size of the undercutting arch. Also, as the cavity size gets larger, more compaction and less bulking occur with the fragmented chimney material.

There is a need to compile mining experience in a variety of rock materials and different structural geologic settings because such empirical data are very relevant to judging and predicting chimney height. Methods of both enhancing chimney height (for some stimulation applications) and inhibiting chimney development (where overlying aquifers exist) should be developed.

Termination of the upward development of a "nuclear" chimney might be accomplished by using chemical explosives and blasting agents to "pre-split"

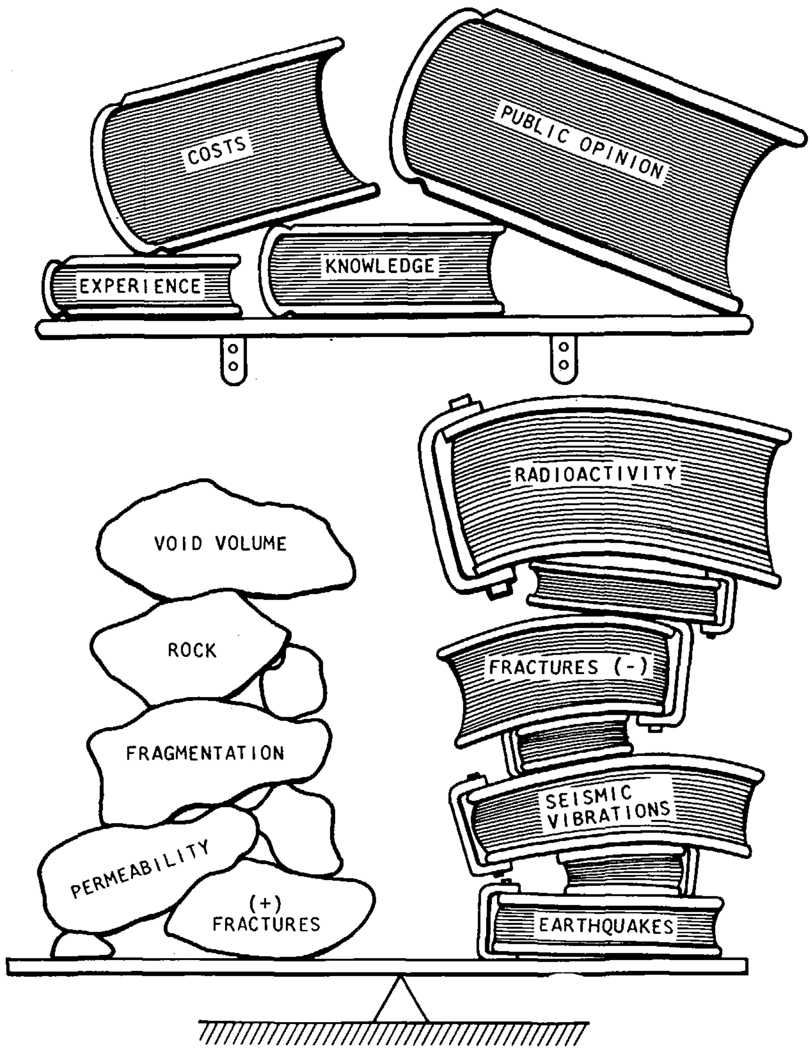

Fig. 1 — Major geonuclear effects of nonexcavation explosions: the "pros and cons".

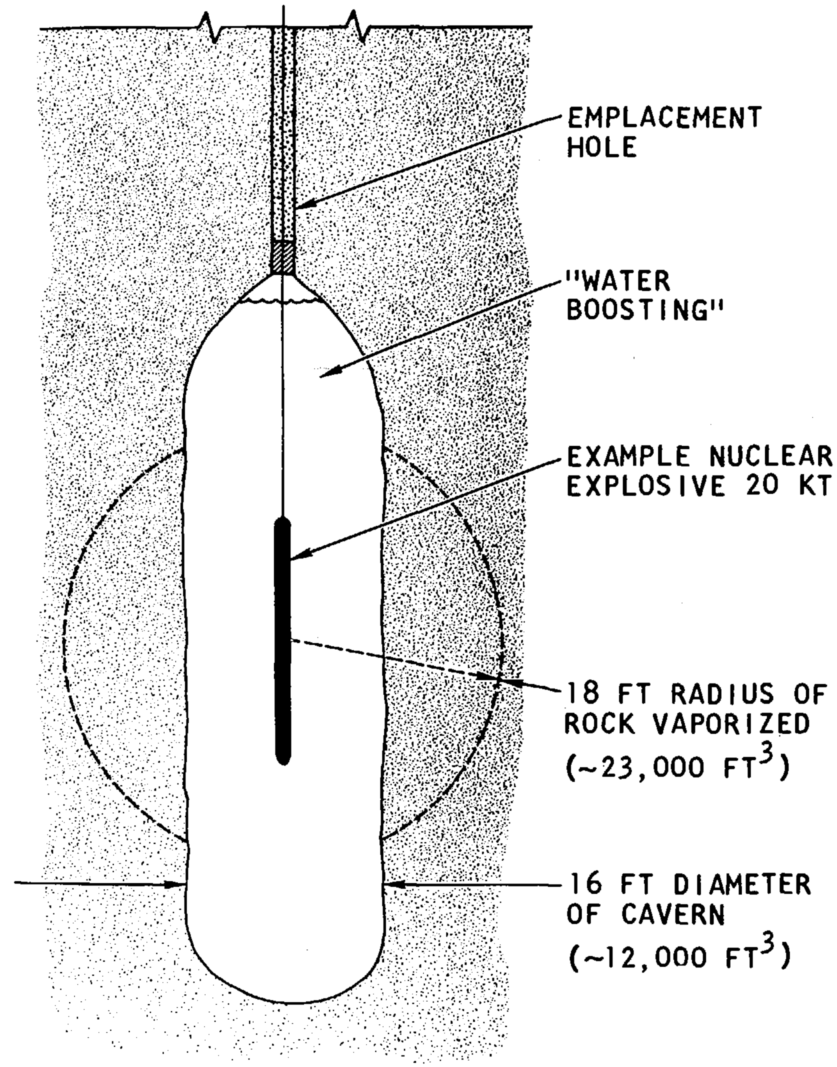

Fig. 2 — Emplacement of a nuclear explosive in an enlarged cavern containing water: "water boosting".

a region where one wants the chimney to stop. This concept is illustrated schematically in Fig. 3. The pre-splitting operation provides a zone of rock with no tensile strength and is expected to terminate the propagation of rock failure induced by the subsequent shot in a manner analogous to conventional pre-split mining methods. The engineering methods for creating space for the large charges of chemical explosives and blasting agents are the same as those described earlier for emplacing water around the nuclear explosive. First the "burn hole" would be produced and then the emplacement space for subsequent surrounding charges. These charges would be detonated using short time delays for optimum breakage.

Figure 4 illustrates a method of enhancing a nuclear explosion chimney with chemical explosives or blasting agents by using delay charges of explosives to propagate normal chimney development. This technique would initiate early chimney development, cause additional rock breakage, and force some compaction of the chimney rubble. The early chimney development would also tend to quench Br^{85} and Se^{85}, which are precursors of Kr^{85}, and thus holds the possibility of reducing concentrations of that gaseous fission product in the chimney gas.(3)

Virtually all of the present nuclear explosive experience related to fragmenting rock is associated with single explosion charges. There are virtually no nuclear explosion effects data, even for single charges in the scale depth range of 200 to 325 $W^{1/3}$ (W = the charge weight in kt). This is a very important region if it is desired to produce maximal amounts of fragmented rock for a given explosive yield and leave the rock broken in place. However, considerable data for both multiple explosive charges and experience in this intermediate scaled depth of burial range have been generated from conventional large-scale quarry blasting.

Figure 5 illustrates a typical quarry shot array with the depth of burial and charge spacing related by the $W^{1/3}$ scaling relation. The row of charges effectively kicks out the toe of the quarry by developing a shear plane to the bench, undercutting the overlying material and also heaving it. As a result, the jointing and other natural weakness in the rock fail, which causes fragmentation to a size roughly defined by the natural distribution of these weaknesses. Quarrying experience illustrates the necessity to consider interacting effects of the distribution and orientation of natural weakness in the rock, the extent of new fractures from the explosion, the depth and magnitude of spall, surface topography, reinforcement of shock waves, and also the coalescence of cavity gas between charges. Understanding the relationship of these factors is important for optimizing the useful work done and evaluating the hazards of vented radioactivity and seismic vibrations from multiple charges.

2.1.3. Permeable Fractures

The value of fractures beyond the fragmented chimney rubble depends in large part upon the useful permeability of those fractures and their frequency and distribution. This is especially true for applications of nuclear explosions involving fluids such as oil and gas reservoir stimulation, in-situ ore leaching, and in-situ oil shale retorting. As yet, there is no theoretical basis for predicting induced fracture permeability, and the experimental data are scarce and limited to a few geologic settings. It is commonly assumed that if rock is

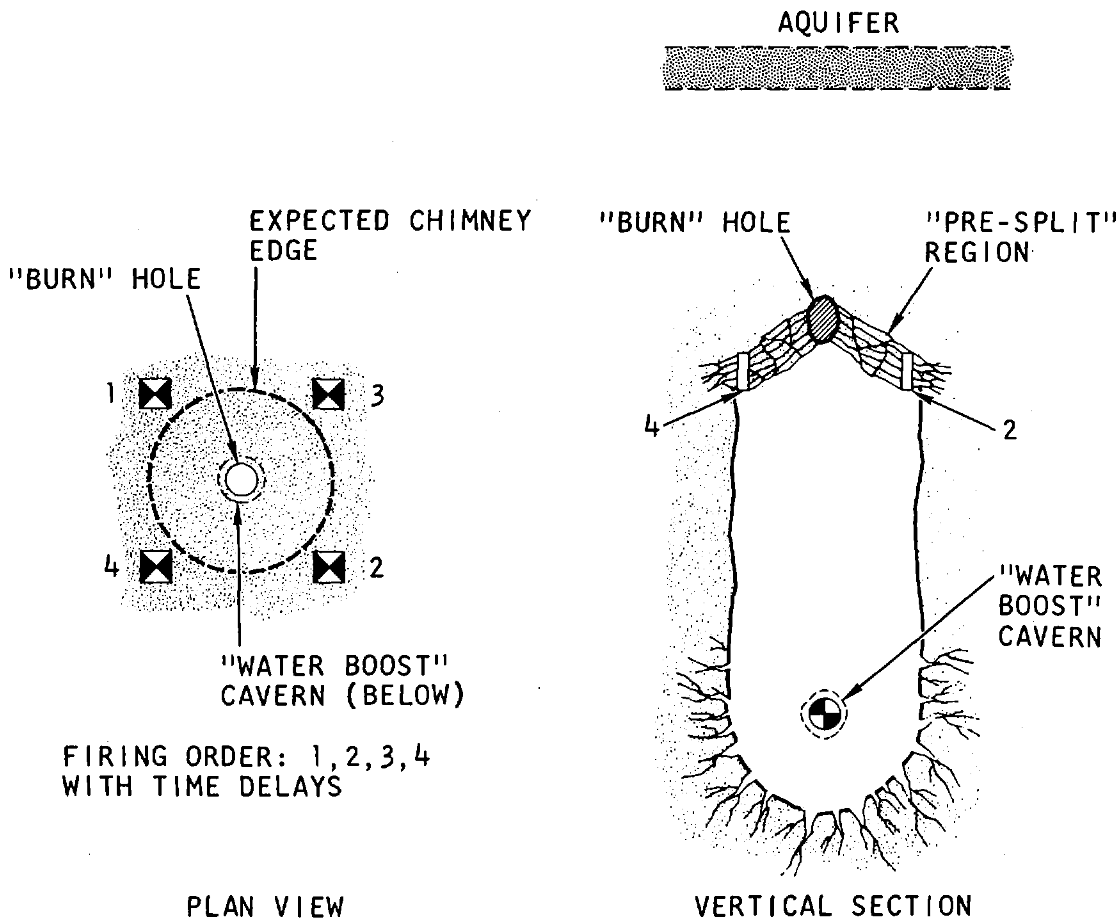

Fig. 3 — Concept for terminating chimney development.

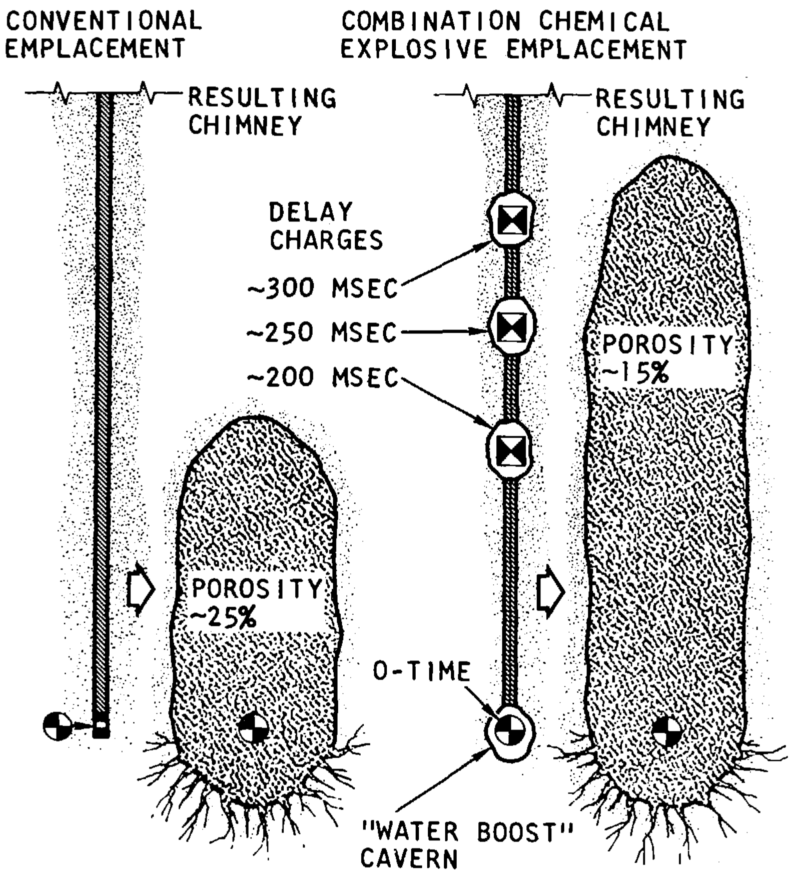

Fig. 4 — Concept for enhancing chimney development.

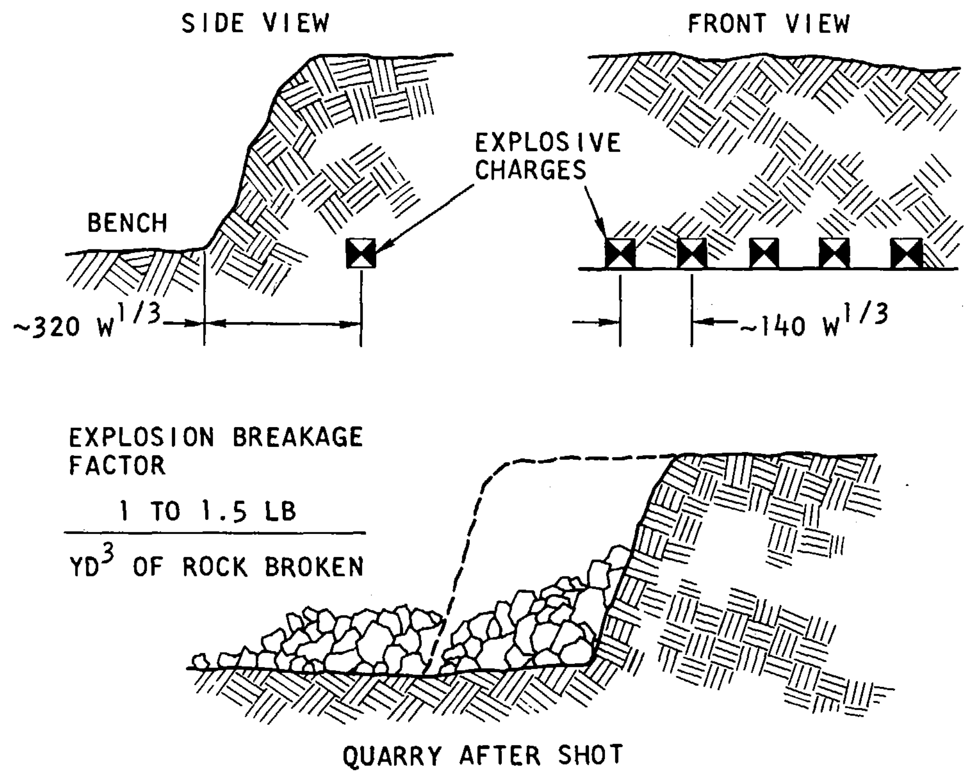

Fig. 5 — Typical quarry, illustrating the cube-root scaling of charge locations.

fractured, it will leak appreciable quantities of radioactivity or, from an optimistic view, the fracturing will allow significant increased flow of natural gas. These are both probably true if the rock undergoes brittle failure and significant differential motion, such as occurs when there is breakage to a free face.

For such applications as rock breakage for in-situ ore leaching or oil shale retorting, it is very desirable and probably an economic necessity to develop intensive permeable fracturing between chimneys. In each chimney, porosity and permeability are going to waste, some of which should be translated into the fractured zones between chimneys. If nuclear explosives were packaged to survive shock loadings up to about 1 kbar, then shooting an array pattern with time delays between detonation of the charges would be possible. Thus, a second charge could break toward the cavity produced by the first charge. This concept is illustrated in Fig. 6. It would be most desirable to build the delay into the explosive package so that there would be no dependence upon external wire leads that could be broken. If the explosive canister cannot provide the required insensitivity to shock, protection could be accomplished in enlarged emplacement holes filled with the appropriate shock-absorbing material.

For applications such as gas reservoir stimulation, the spacing of charges is probably much larger than for the leaching and retorting cases, and thus it is more difficult to enhance fracture permeability. Since most nuclear explosion projects for gas stimulation are intended for low-permeability reservoirs, and the gas in place is in the pore spaces in the rock rather than existing fracture porosity, it is important to establish if there is a threshold permeability below which stimulation by fracturing is of little value. This question should be answered prior to undertaking a full-scale nuclear explosion project.

Another significant question concerns the ability of fractures produced at great depth (4,000 to 20,000 ft) to stay open and keep the useful permeability that is produced by the nuclear explosion. Figure 7 illustrates a method by which fracture permeability as a function of time might be determined before conducting nuclear explosion stimulation tests at a given site. In this method, the vertical hole is drilled below the proposed shot depth for the nuclear charge. The hole is underreamed over a short vertical section, loaded with a few tens of tons of chemical explosive or blasting agent, shot, and cleaned out by the appropriate drilling technique. This creates a void for a subsequent explosive charge to break to. A permeable plug is then set above the void at a point where a whipstock is set. Next, a sidetrack hole is drilled and underreamed at the same level as before, but approximately 20 to 50 ft away. Chemical explosives and blasting agents are then loaded and shot in the hole, breaking and fracturing to the first cavity. Gas can then be circulated under controlled conditions through the fractures to determine the effective permeability produced and monitor changes as a function of time.

2.2. Hazardous Geonuclear Effects

The two major concerns associated with nonexcavation applications of nuclear explosives are, of course, the disposition of the various radioactive species and the severity of seismic vibrations.

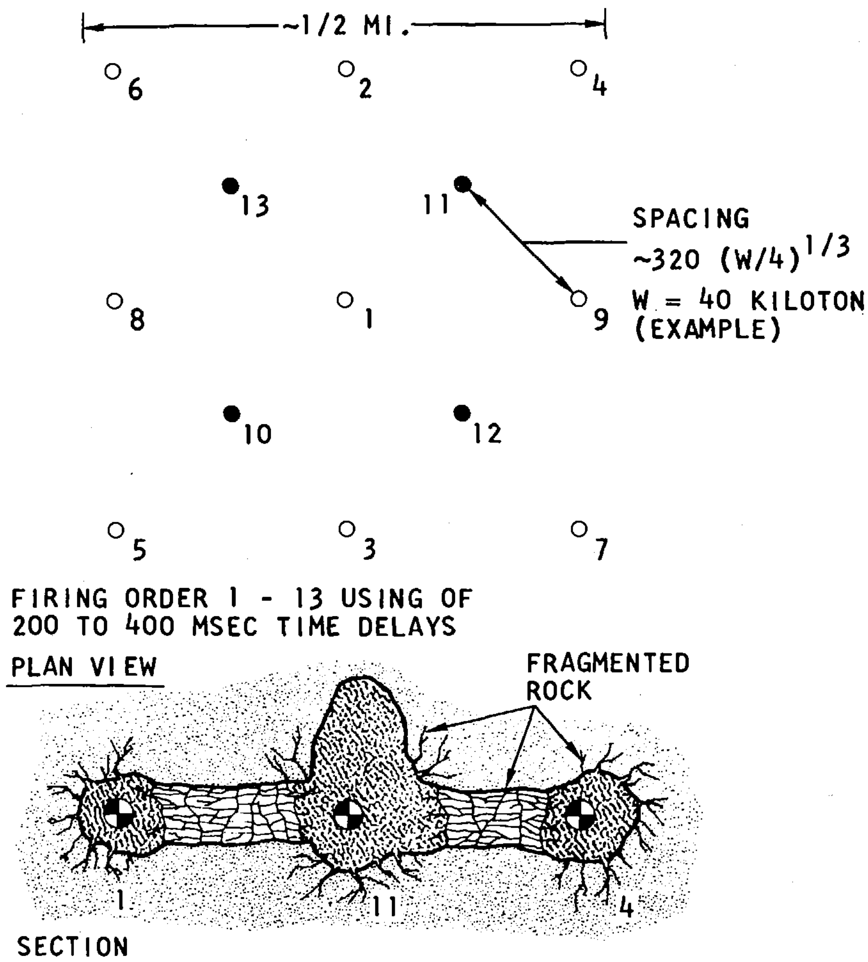

Fig. 6 — Concept for delay firing of nuclear explosives in an array to optimize permeable fracturing.

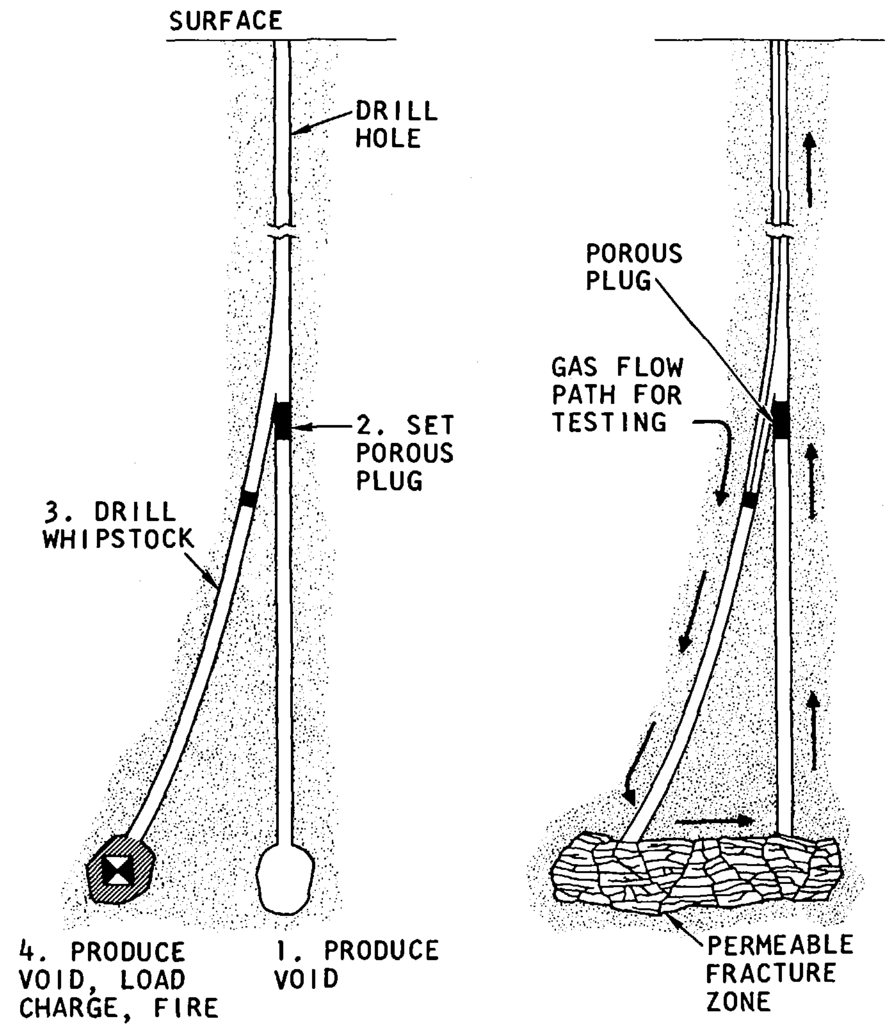

Fig. 7 — Concept for testing persistence of fracture permeability as a function of time.

Some reduction of the potential hazards is a natural by-product of some of the enhancement concepts previously described. Water added to the explosive emplacement greatly reduces induced tritium production and other neutron activation products that would normally be produced from the rock. The possibility exists for isolating some fraction of gaseous or volatile radioactive species from the chimney gas by initiating early chimney collapse. The use of tens to hundreds of tons of chemical explosives and blasting agents to help produce an underground void for some of the enhancement concepts also allows a seismic calibration of a new site prior to the actual nuclear explosion.

The concept of pre-splitting to terminate chimney growth may help reduce development of permeable paths to overlying aquifers or leakage to the atmosphere. At shallow scaled depths of burial and in applications involving multiple firing of nuclear explosive charges, the risk of leaking or venting radioactivity to the atmosphere is increased, and a theoretical and experimental base for prediction is not yet well defined. In the long run, it appears that more potential exists for reducing the radioactive hazards than the seismic hazards. However, the radioactivity is of more concern as another pollutant to the biosphere.

2.2.1. Radioactivity

The first place to try to modify and control those radioactive species that are hazardous if introduced into the biosphere is at the source. Some flexibility exists in the design and packaging of nuclear explosive systems, in the selection of the best explosive system for a particular application and geologic setting, and in the method of explosive emplacement. Advances in all of these areas are of the utmost importance if there is to be an applied nuclear explosion technology.[(4)]

In addition to adding water around the explosive, the same space can be considered for other additives that would modify the "fireball" chemistry. For thermonuclear explosives that produce large quantities of tritium (T), it is desirable to make the "fireball" oxidizing so that all hydrogen and thus tritium ends up with water as HTO. Although this does not eliminate tritium contamination of hydrocarbons introduced into the chimney, it changes the contaminating processes from direct gas mixing to slower chemical exchange processes. With tritium preferentially residing with water, the more water it mixes with, the smaller will be the amount of it that can exist as water vapor to exchange directly with added hydrocarbon gases.

A good oxidizing agent would thus be one that can be added to water and is cheap. An excellent candidate is ammonium nitrate (NH_4NO_3). It can be mixed with water and, if desired, cross-linking agents can be added to form a gel. This slurry could be added to the emplacement hole right after the storage volume is cleaned out. The nuclear explosive could be introduced at a later time. As the ammonium nitrate slurry is somewhat acid, the explosive should be protected from corrosion. Carbon-14 and tritium are activation products of NH_4NO_3, so the first foot or so around the explosive should be shielded by just water.

Ammonium nitrate is itself a blasting agent, and the nuclear explosive would act as a fantastic primer, causing the reaction $2NH_4NO_3 \rightarrow 2N_2 + 4H_2O + O_2$.

This reaction plus the additional water yields a large quantity of working gas, replacing much of the rock vapor produced in the "unboosted" case. The added nitrogen and oxygen gas represents an improvement over plain "water boosting." Since these additives reduce the amount of rock vapor present in the working gas and since water is a rather efficient heat exchanger, the cavity gas temperature should drop more rapidly upon chimney collapse. This drop could be speeded up by using delay charges to force collapse and increase chimney height as discussed earlier. This technique holds promise for trapping the radioactive tin and antimony in the glass that solidifies from the silicate rock melt, thus keeping I^{131}, the daughter product, more restricted to the glass.

Modification of the geometry of the emplacement hole around the nuclear explosive also holds considerable promise for isolating an appreciable fraction of the radioactivity from either the chimney or overlying aquifers. Declassification efforts are reputedly under way, and further open research in this area should prove of real value in the effort to control the distribution of radioactive debris.[5]

2.2.2. Seismic Vibrations

One of the most fundamental problems that arises from seismic vibrations produced by explosions is determining where the beginning of real seismic damage to structures occurs. It is somewhere above the point of human perception of the vibrations; and for practical considerations above normal excitation from walking in the building, slamming doors, and road traffic. This problem has faced the conventional blasting industries for years, and a number of classic investigations have provided the foundation for present guidelines to blasting practice. One criterion that seems to be generally confirmed by blasting experience is energy ratio, ER:[6,7]

$$ER = \frac{a^2}{f^2}$$

where a is acceleration in ft/sec^2 and f is frequency in cycles per second.

Figure 8 illustrates the general blasting guidelines, relating ER to amplitude and frequency.[6] The region below an ER of 3 is generally considered safe and free from plaster cracking where construction quality is good and the structures are not abnormally prestressed by such processes as settlement. An ER of 1 is generally thought to contain a safety factor but is well above vibration levels that are easily perceptible.

Figure 9 compares the spectral response of a hypothetical building in Hattiesburg to the 5-kt Salmon event with the corresponding response of another hypothetical structure in Las Vegas to ground motion produced by the 1.2-Mt* Boxcar event.[8] According to Nadolski, the pseudo-absolute acceleration (PSAA) is approximately twice the actual ground acceleration measured.[9] The corresponding ER is about 0.07 in Hattiesburg and 0.002 in Las Vegas for the same frequency of 3 to 4 cycles per second (see Fig. 9).

*Announced United States Nuclear Tests, USAEC, Nevada Operations Office, July 1, 1969.

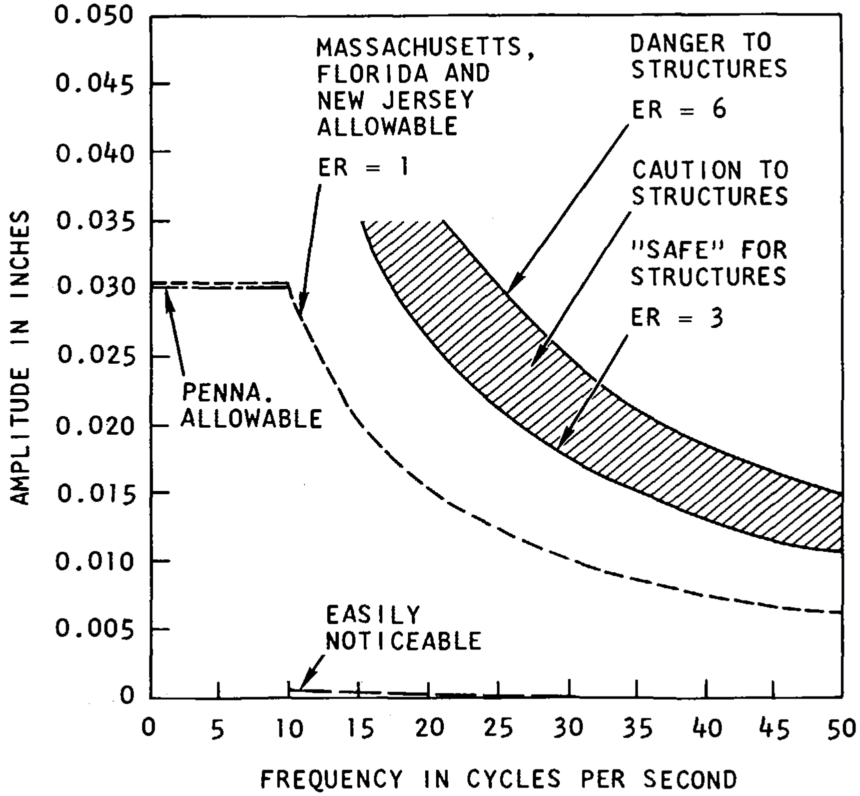

Fig. 8 — Energy ratios related to frequency, amplitude, and damage to structures.

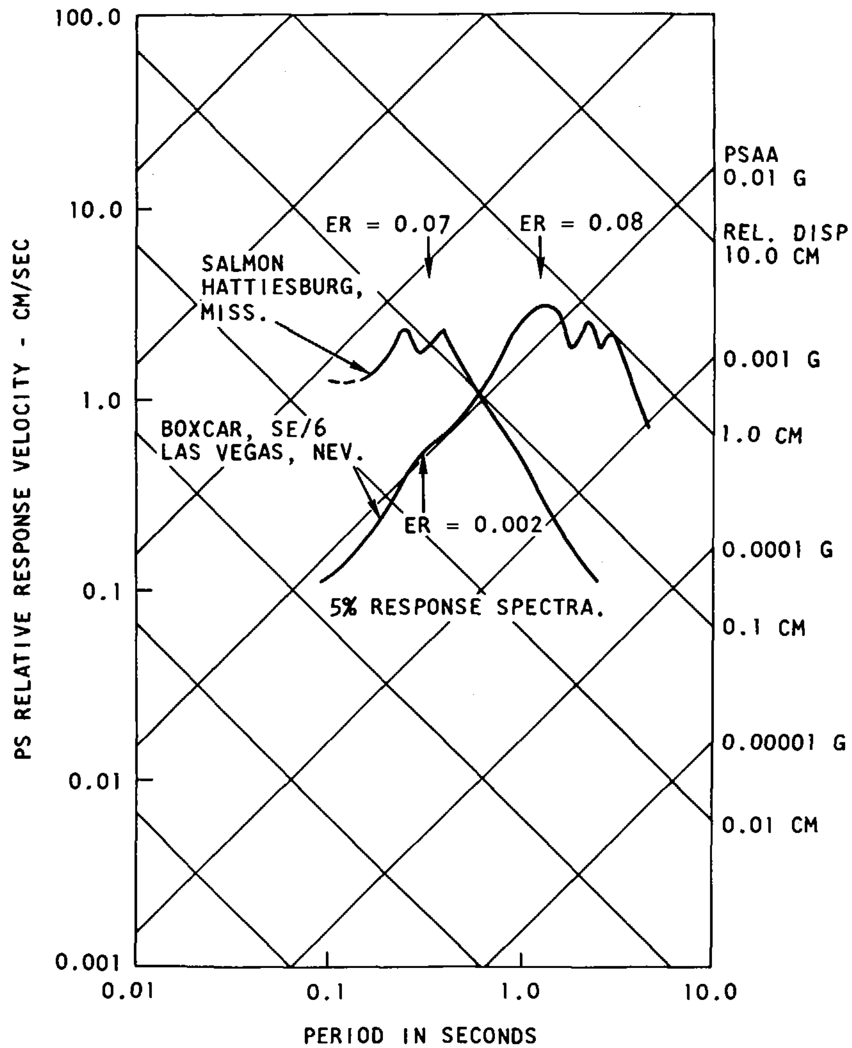

Fig. 9 — Comparison of response spectra and energy ratios for two nuclear explosions (four-way log plot).

The point of this discussion is to emphasize that the blasting industry has been applying acceleration and frequency criteria as indicators of potential damage. However, the important question is: What criterion does predict real damage to structures? Assuming that a building responds as a simple or even a very complex oscillator to the measured ground motion probably does not provide a proper model if the apparent damage observed on buildings is characteristic of foundation settlement.

Nuclear explosions, because of their size, can involve large populations that feel the seismic vibrations. One area where chemical explosions excite reactions in large populations is Dade County, Florida (the vicinity of Miami). In that area, near-swamp conditions exist and the porous Miami oolite formation is widespread within a few feet of the surface. Because of the population growth and the demand for aggregate and fill, there are many quarries and other blasting activities that can be felt in nearby residences and buildings. Vibrations from chemical explosions in the oolite material are naturally filtered to low frequencies (approximately 4 cps) over short distances. Damage complaints are commonly received from blasting down to an ER of 0.02 and even as low as an ER of 0.005. This extreme corresponds to an explosion in that area of 60 lb at a distance of 1.25 miles.[10] The state recognizes the blasting allowable up to an ER of 1, but the practice of granting blasting permits within the county commonly holds the ER to very low values--equal to or less than those measured in Hattiesburg from the Salmon event. This enforcement policy is judged to be an attempt to reduce damage complaints to near zero. Documentation before and after blasts in a sampling of nearby structures is routine, and over the years considerable information has been accumulated. Mr. Robert Banning is one person who performs this service in the Dade County area, and he has not observed damage caused by blasting below an ER of 1.[10]

It is extremely important, therefore, that such concepts as PSAA not be adopted as criteria for estimating seismic damage until considerable preshot and postshot documentation of actual minor architectural damage is developed. A PSAA of 10 to 15 cm/sec^2 may be a good estimate of the vibration energy sufficient to agitate a population so they will examine their structures and complain of cracks observed. The Florida experience is consistent with this PSAA value, and a similar ER value is on the order of 0.01. Ordinary ditch blasting in the vicinity of Niagara Falls precipitated 3000 damage claims.[11] It would be worthwhile to examine that experience in detail to see what evidence and documentation exist that are related to the causing of real damage.

There is still a great deal to be learned about how chemical explosions, nuclear explosions, and earthquakes can cause damage to a variety of structures in different geologic settings. This information is needed for improving building codes and building practice, refining blasting limits, and providing a greater degree of safety to the public. Good public relations and competent engineering seismology are required so that both nuclear explosion projects and projects conducted with chemical explosions are not unduly hampered.

III. CONCLUSION

Presently, the benefits and risks associated with the effects of nonexcavation nuclear explosions are not well established as a foundation for an applied technology. Suggestions have been made of possible ways to enhance the useful effects and minimize the hazards. Cross-fertilization of nuclear and chemical explosion technology will make a significant contribution to these goals and to the commercialization of nonexcavation explosive engineering techniques.

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